CRANFIELD UNIVERSITY

LAURA CUMPLIDO-MARIN

AGRONOMY AND ECONOMICS OF TWO NOVEL ENERGY CROPS: *SIDA HERMAPHRODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L.

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
PhD in Agrifood and Environment

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Supervisor: Dr. Anil R. Graves
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ABSTRACT

The PhD project of title "Agronomy and Economics of two novel energy crops: *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L." was first conceptualised within the international project SidaTim. The main aim of the PhD was to reduce the uncertainty associated with the adoption of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., through data gathering and evaluating their agronomic, economic and environmental performance. The main objectives of the PhD were: to review all available information and publications regarding the cultivation and energy production of the two species; to assess their agronomic performance in the UK; to examine the impact of their establishment on soil carbon; to determine their profitability against other potential crops across a European gradient; and to evaluate the greenhouse gas emissions associated with their cultivation. The novelty of the research lies on the establishment and assessment of two novel bioenergy crops in the UK compared across a range of climatic conditions, addressing the knowledge gaps regarding reliability and availability of information and assessment of their agronomic, economic and environmental performance.

The first year of the project was dedicated to background research, collecting and processing the first set of soil analyses, producing all *Silphium perfoliatum* (L.) seedlings from seed, importing *Sida hermaphrodita* (L.) Rusby seeds from Germany, and in 2017 establishing an experimental site in Silsoe, Bedfordshire, UK. During the first three years, the mean maximum height of *Sida hermaphrodita* (L.) Rusby originated from seedlings was 198 cm and the maximum stem diameters were 14-18 mm. The mean maximum height of *Silphium perfoliatum* (L.) was 158 cm over three years and the maximum stem diameters were 14-16 mm. As opposed to the expected increase in maximum heights and diameters with time until plantation maturity, an overall reduction in maximum heights and diameters was recorded with time for *Sida hermaphrodita* (L.) Rusby, whilst only maximum diameters of *Silphium perfoliatum* (L.) decreased with time.

Each year from February 2018, a winter harvest to measure the solid biomass production of *Sida hermaphrodita* (L.) Rusby and a summer harvest to measure the green biomass production of both *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. were carried out until September 2020. Mean dry biomass yields of *Sida hermaphrodita* (L.) Rusby plants grown from transplants for solid fuel for combustion were 1.7, 5.4, and 3.7 t DM ha^{-1} in 2018, 2019, and 2020 respectively. Green biomass yields of *Sida hermaphrodita* (L.) Rusby for anaerobic digestion were on average 10.8, 8.1, 6.0 t DM ha^{-1} in 2018, 2019, and 2020 respectively. The recorded declines in harvested biomass from *Sida hermaphrodita* (L.) Rusby are attributed to the combined effect of plant mortality, management and fertilisation practices. The corresponding mean green biomass yields of *Silphium perfoliatum* L. for anaerobic digestion were 4.6, 6.7, 8.9 t DM ha^{-1} in 2018, 2019, and 2020.

The second and third year focussed on objectives three and four, as well as collecting and processing the second set of soil analyses, data analysis, and writing up. The bulk density of the soil across 0-5 cm and 10-15 cm changed from 1.4-1.7 g cm^3 prior to cultivation in 2017, to a uniform 1.4 g cm^3 in 2020. The concentration of soil organic carbon at 0-5 cm decreased from 2.58% in 2017 to 1.85% in 2020, whereas at 10-15 cm, it increased from 1.86% to 2.12% over the three years. Overall, the mean soil organic carbon stocks (0-15 cm) declined from 65.0-67.6 t C ha^{-1} in 2017 in 55.2-58.3 t C ha^{-1} in 2020.

The profitability of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* (L.) was predicted over a rotation of 16 years and compared to that of an arable rotation and two other energy crops for the particular case of the UK and three other European countries. The calculated net present value (NPV) of *Sida hermaphrodita* (L.) Rusby was -1,591 £ ha^{-1} without subsidies and 1,075 £ ha^{-1} with subsidies; the corresponding net present values for *Silphium perfoliatum* (L.) were 3,031 £ ha^{-1} and 5,607 £ ha^{-1}. The study also calculated how much prices and costs would need to change for the NPV of the two crops to match the NPV of the most profitable energy crop or the arable rotation.

Using an Excel model developed based on the IPCC guidelines, the greenhouse gas emissions for *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* (L.) production were calculated for a 16-year period. On a per annum basis, overall greenhouse gas emissions were estimated respectively at 4.2, 0.3, 2.2, -4.0 and -0.6 t CO_2 eq ha^{-1} for the arable rotation, short rotation coppice, Miscanthus, *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* (L.) systems. The environmental assessment demonstrated that cultivating *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* (L.) could potentially contribute to reducing greenhouse gas emissions.

Keywords:

Bioenergy crops; soil carbon; biomass feedstock; crop economics; cost benefit analysis; greenhouse gas emissions

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LIST OF ABBREVIATIONS

ADF	Acid detergent fibre
ADL	Acid detergent lignin
AFOLU	Agriculture, forestry and other land use
ANOVA	Analysis of variance
BD	Bulk density
BMP	Biochemical methane potential
BPS	Basic payment scheme
CAP	Common Agricultural Policy
CBT	Continuous biogas test
CL	Cropland
DM	Dry matter
EF	Emission factor
ET	Evapotranspiration
EU	European Union
FM	Fresh mass
FW	Fresh weight
GHG	Greenhouse gases
GJ	Gigajoule
GWP	Greenhouse warming potential
HBT	Hohenheim biogas test
HC	Heat of combustion
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LHV	Lower heating value
LSD	Least significance difference
NDF	Neutral detergent fibre
NPV	Net present value
OC	Organic carbon
ODM	Organic dry matter
ODT	Oven dry tonnes
OSR	Oil seed rape
PLN	Polish Złoty
PM	Particulate matter
SFP	Single farm payment
SMY	Specific methane yield
SOC	Soil organic carbon
SOM	Soil organic matter
SRC	Short rotation coppice
STC	Soil total carbon
TC	Total carbon
TS	Total solids
VS	Volatile solids

1 INTRODUCTION

Chapter 1 describes the context of this research, in terms of the global challenges associated with energy production, the potential solutions, the SidaTim project which sponsored this PhD, the overall aims and objectives of the PhD, the structure of the thesis, and statement of authorship.

1.1 Context

Since the industrial revolution the world population has been increasing, as has the consumption of natural resources. As a result of the emission of anthropogenic greenhouse gasses (GHG) into the atmosphere, a process termed "climate change" has rapidly come to the forefront of international attention. Climate change has resulted in; global temperature rise, warming oceans, shrinking ice sheets, glacial retreat, decreased snow cover, sea level rise, declining Artic sea ice, increased number of extreme weather events, and ocean acidification (NASA, 2019). This has led to dramatic challenges for the agricultural sector in a number of ways, such as continuously evolving policies and limitations in the plant protection products allowed.

Due to the severity of the challenges associated with climate change and the environment, a wide range of policy initiatives that aimed to protect and preserve nature were enacted. From the 1970's to the 1990's the Common Agricultural Policy (CAP) provided subsidies to European farmers guided by agricultural production. In the UK, the Wildlife and Countryside Act (1981) was introduced to, in part, compensate farmers for the lost profit after implementing conservation practices. From the 1990's the reforms concentrated on supporting farmers and promoting rural development. Since then, the CAP increasingly rewarded the adoption of environment-friendly practices and increased sustainability. In 2003, the CAP shifted from production rewarded subsidies to a more inclusive approach, considering nature conservation, public and plant health, and animal welfare, by introducing the cross-compliance system of the Single Payment Scheme or Single Farm Payment (SFP) in the UK in 2005. From 2013, the CAP focussed on increasing competition, sustainability, innovation, rural economies, and productive land use (European Commission, 2021). In 2015, the SFP was replaced by the Basic Payment Scheme (BPS), allocating payment entitlements to farmers to supplement their income. As a result of Brexit, the UK government introduced the Agricultural Bill in 2020 and progressively started introducing the Environmental Land Management (ELM) scheme, to be fully implemented in 2024. The ELM scheme is a reward system for farmers who enhance the environment and adopt sustainable practices. Until the ELM is fully implemented, the Sustainable Farming Incentive, Local Nature Recovery and Landscape Recovery will be the temporary strategies supported by the UK Department for Environment, Food and Rural Affairs (DEFRA).

The challenge we face today is to minimise and offset climate change, by reducing the amount of fossil fuels we consume and increasing carbon sequestration through renewable biological resources. Renewable biological resources include fresh food, animal forage, timber, and forms of bioenergy. Moving towards more reduced greenhouse gas emissions and greater carbon sequestration will revise and transform daily activities, a wide range of sectors of the economy, an array of sciences and technologies, and both urban and rural populations (European Commission, 2012).

Bioeconomy is "the production and utilization of biological resources (including knowledge) to provide products, processes, and services in all sectors of trade and industry within the framework of a sustainable economy (German Bioeconomy Council, cited by Issa *et al*., 2019). A change to a bioeconomy will require change at all levels an within all industries and sectors, using government policies and educational programmes, across research and development strategies, to support green entrepreneurship. Local production, market diversification, economic growth, and employment would benefit from Research and Innovation (R&I) in the bioeconomy sector (European Commission, 2012).

To advance and consolidate the bioeconomy strategy, the EU promoted research through the Horizon 2020 programme. Scheduled between 2014 and 2020, it had a budget close to €80 billion (European Commission, 2019). The bioeconomy strategy is one of many measures to support the move to a fossil-fuel free future. To promote the bioeconomy, specific policies have been developed and implemented, funds have been provided, and frameworks created across the relevant sectors (EEA, 2017), some more successful than others.

The bioeconomy not only matters within the European Union, it is also important for the UK where the government continues to update its own bioeconomy strategy (HM Government, 2018). An assessment of the impact of the bioeconomy in the United Kingdom economy (Chambers *et al*., 2015), concluded that the bioeconomy represents 4.5% turnover of the British economy, creating £36.1 billion in gross value added (GVA), and supports 600,000 jobs. In addition, it links to £25.5 billion GVA and 436,000 jobs in upstream sectors, and £75.3 billion GVA and 2.6 million jobs in downstream sectors.

To develop the bioeconomy anywhere we need to create more sustainable and resilient ways of living requires society to reduce the quantity of GHG emissions to the atmosphere. Up to 2010, fossil fuel combustion and industrial processes accounted globally for 78% of the total increment in GHG emissions (IPCC, 2014). Therefore, to reduce GHG emissions, approaches need to be found that reduce the combustion of fossil fuels and upgrade and transform industrial processes so that they are more energy efficient, and possibly even carbon neutral.

Currently, about two thirds of global GHG emissions come from the use of fossil fuels to generate energy (EEA, 2017). Societies needs energy to function effectively so to move away from fossil fuels, whilst maintaining effective economies, is by adopting renewable energy sources; a transition that is already taking place. According to the statistical office of the European Union, 17.5% of gross final energy consumption in 2017 was produced from renewable energies (Eurostat, 2017).

During the 2000s, policy makers agreed and set targets to provide a percentage of their energy needs from renewable sources. In the Climate Change Act 2008, the UK committed to reducing greenhouse gas emissions by 100% by 2050, compared to 1990 levels (UK Government, 2019b). In 2019, energy supply from renewable energy sources were 12% of final energy consumption in the UK (BEIS, 2020c).

To satisfy our energy needs, locally produced renewable energy has a key role to play, enabling the move from a few large energy producers towards multiple small producers which could contribute to reduce GHG emissions and therefore climate change and its impact, whilst increasing energy security (EEA, 2017). A mix of renewable energy sources and technologies is required; there is no individual source of energy able to meet all needs. Sustainably produced bioenergy has an important role to play in the renewable energy mix. As a flexible (easy to store and able to adapt to changes, both in demand and technically) renewable energy, bioenergy has the potential to be used for heat and electricity generation, as well as in the transportation sector (DECC, 2012). In 2018, bioenergy alone accounted for 66.3% of all renewable energies used for electricity generation in the UK (BEIS, 2019b).

In examining bioenergy, it is important to define some terms. Bioenergy is "renewable energy that has been produced from living organisms". Biofuel is "a fuel derived immediately from living matter", and biomass is "organic matter used as a fuel, especially in a power station for the generation of electricity" (Oxford University Press, 2019). All official statistics include a number of substrates and technologies under the bioenergy category, e.g. data for the United Kingdom energy statistics (BEIS, 2019b) classes the following as bioenergy; biodegradable energy from waste, plant biomass, anaerobic digestion, animal biomass, waste wood, wood, sewage gas, and landfill gas.

Two types of biofuels can be distinguished: bioethanol and biodiesel. Bioethanol is typically made from carbohydrate-rich crops such as maize, sugar cane, hemp, and potatoes; whilst biodiesel is made from oils and fats. Depending on their origin, biofuels are classified into first generation biofuels, which originate from food crops, and second generation biofuels, originated from other sources not suitable for food consumption (EEA, 2017).

Biomass production is sometimes regarded as a complementary and small-scale source of energy, when in reality wood and other solid biofuels, together with renewable waste, are the largest renewable energy source in Europe accounting for 49.4% of produced renewable energy (Eurostat, 2018). This is the case not only at a European level but also in the UK (BEIS, 2019b). This may be because biomass is able to provide steady and reliable power, giving more security to producers and users. In addition, the various different types of biomass energy make it appropriate for a diversified energy mix, increasing energy security (DECC, 2012).

Ranging from 13.4 GJ t^{-1} for straw to 37.2 GJ t^{-1} for biodiesel (BEIS, 2018), biofuels have a wide range of net calorific values, which are low compared to fossil fuels but can provide consistent energy as long as stocks are available. However, the load factor[1] of bioenergy is the highest among renewable energies (BEIS, 2018), making biofuels the most reliable fuels. Although there is concern about the effect of biofuel production on food production, data suggest that in the UK only 2.2% of agricultural land, equivalent to 129,000 ha, is used for the production of bioenergy. However, nationally grown biofuels only represent 13% of the verified renewable fuel supplied to the UK, with the majority of biofuels imported from other countries (Department of Transport, 2021).

Bioenergy production in the UK can be divided into sectors depending on its use: the road transport and heat and power sectors. For the road transport sector, the main crops used to produce biofuels are wheat, sugar beet, oilseed rape, and maize, from approximately 60,000 ha. For the road transport market, only 39% of the biofuels used

[1] Ratio of energy produced and theoretical maximum energy that could have been produced in a period of time (López and Salies, 2006).

are produced in the UK. This means more than 550 million litres of biofuels are currently imported from other countries (DEFRA, 2019).

Nearly 3,000 ha of Short Rotation Coppice (SRC) and over 7,300 ha of Miscanthus are used to produce feedstock for the heat and electricity industry. The UK produces on average 11-12 million tonnes of straw as a by-product of cereal production each year. This straw is used as animal bedding, animal feed, and burnt in power stations to generate heat and electricity, or Combined Head and Power (CHP). Power stations used 730,000 tonnes of straw during 2016/2017 (DEFRA, 2019).

Anaerobic digestion is a relatively recent, yet important source of bioenergy in the UK. In 2017, over 1,100,000 tonnes of oil equivalent were produced via anaerobic digestion. Manure, slurry, crops, food waste, crop waste, and other waste, are used as feedstock. Crops, such as maize, grass, and oilseeds, are the greatest source of material for anaerobic digestion. In 2017, more than 50,000 ha of maize were cultivated for anaerobic digestion, an increase of 10% compared to the previous year (DEFRA, 2019).

Maize has been favoured because it is a well-known traditional crop with high biomass yields of 15-20 tonnes per ha, specific methane yield (SMY) of 330-365 m^3 per tonne ODM (Organic Dry Matter), and methane production of 7500-10200 m^3 per ha (Haag *et al*., 2015).

However, growing maize on agricultural land and using it exclusively to generate energy is problematic for a number of reasons. Firstly, it removes the use of fertile land to grow food crops, a controversy that has already been seen in Germany (Bauböck *et al*., 2014; Schäfer *et al*., 2015). In 2016, Germany had more than 2.5 million ha dedicated to the growth of green maize from which around 1 million ha was devoted to biogas production (FNR, 2017).

With more than 9,000 biogas plants producing 33 TWh per year, and a turnover of 9.4 million euros, these plants provide around 46,000 jobs and prevent GHG emissions of almost 20 million tonnes of CO_2 in Germany (Fachverband BIOGAS, 2017). In Poland, biogas production has significantly increased over the last few years, from nearly 700,000 tonnes of agricultural products in 2011 to using over 2 million tonnes in 2014 (Stolarski *et al*., 2017b).

Secondly, maize is an annual crop which is sown and harvested late, the crop can cause negative environmental impacts when grown in large areas, issue already faced by Germany. The problem is having entire areas where maize has become a monoculture with the consequent loss of biodiversity, destruction of the natural landscape, and other negative environmental impacts such as soil erosion and compaction (Bauböck *et al*., 2014; Schäfer *et al*., 2015).

There are also potential disadvantages of growing SRC and Miscanthus. SRC crops can have low dry matter yields, uncertainties about the origin of the fuel, high water consumption, and require a large initial investment, with no repayment for the first four years (Forest Research, 2016). In addition, SRC crops cannot be harvested every year. Traditional farmers are used to harvesting every year and obtaining an annual return profit from their crops. They are used to working in annual cycles and getting annual returns from arable crops, by carrying out the same operations every year, which is not possible with SRC because cycles are three to four years long. In addition, there is a need for customised or specialized machinery to carry out field operations, such as planting or harvesting. This implies a change of habits, and establishing a SRC system requires the farmer to be open-minded to change, as well as the need for additional initial investments compared to standard crops.

The need for data-driven economics (based on data analysis and interpretation), developing infrastructure and regional heat markets, reducing financial risk for farmers, as well as harmonizing production and demand were addressed as the main priority issues for the UK in particular, identified from the research undertaken as part of the Rokwood project under the EU 7th Framework Programme (Parra-López *et al*., 2017).

In their study, Parra-López *et al*. (2017) also identified common handicaps for the development of the SRC sector across six participating countries. They found that both politicians and farmers were generally unaware of the environmental, economic, and social benefits of developing the SRC sector. They detected there is not enough information available about energy crops. They emphasized the need for financial support for energy crops in order to make them competitive with arable crops. They point out how research and development is needed to determine and promote the socio-economic and environmental benefits of SRC.

Miscanthus was first promoted as a particularly attractive energy crop, with a calorific value of 17 MJ kg^{-1} (Defra, 2001), annual harvesting, and large yields. However, the costs of establishment are very high. On average, the costs of establishment are €2,075 ha^{-1} for rhizomes and €2,575 ha^{-1} for total establishment costs (Witzel and Finger, 2016). After reviewing 51 publications Witzel and Finger (2016) found a lack of homogeneity among data sources and considerable variation regarding; lifespan, yields, prices, costs and their units. Fouling and corrosion to equipment are common problems associated with the combustion of Miscanthus, as a result of high potassium and chorine, variously combined with silicates, alkali, chlorides, and sulphates (Jensen *et al*., 2017).

In addition, the high variability of the available information for Miscanthus, and as a consequence the uncertainty associated with its production, can make it a less attractive crop compared to arable alternatives. Additionally, national and European policies compensating for high establishment costs, risk, and opportunity costs are regarded as key drivers in farmers decision making (Witzel and Finger, 2016). The different issues outlined above explaining why traditional dedicated energy crops have not reached their full potential are summarised in Table 1.1. One drawback that both SRC and Miscanthus have in common is their use as dedicated energy sources, which makes them

Table 1.1 – Summary of issues identified for traditional dedicated energy crops.

Crop	Issue
Silage maize	Food vs. fuel dilemma Negative environmental impacts when grown in monocultures
SRC	Low dry matter yields Uncertainties about origin High water consumption Large initial investment with no immediate repayment Lack of annual income due to multi-annual harvest Specialised machinery Lack of information and economic data Insufficient infrastructure and regional markets High risk Insufficient coordination between supply and demand Unawareness of environmental, economic and social benefits Lack of versatility
Miscanthus	High establishment costs Lack of homogeneity among data sources Fouling and corrosion associated with combustion Lack of versatility

less versatile. If they had other uses or were included in the supply chain of higher value products, they could greatly benefit from added value in diverse supply chains. This would make them more appealing options for farmers (Witzel and Finger, 2016).

Between 2007 and 2013, the establishment of SRC and Miscanthus plantations was stimulated by the British Government through the Energy Crops Scheme, within the Rural Development Programme for England. Both the actual costs of establishment and on-farm costs were subsidized by 50% (Natural England, 2009). The area of both SRC and Miscanthus has not increased substantially since when the scheme finished and there has been no further public support or promotion. This could decrease the area dedicated to grow energy crops, and result in an increase of imports (Borkowska and Molas, 2013).

However there are environmental services provided by Miscanthus: Soil Organic Carbon (SOC) net accumulation rates of 1.84 t C ha^{-1} y^{-1}; minimal GHG emissions compared to fossil fuels; smaller NO_2 emissions than conventional arable crops; contribution towards flood and erosion control; improved drainage; reduction of nitrate leaching; improved earthworm diversity and density; provision of diverse environment throughout the year for wildlife to shelter in; and reduction of agrochemical inputs (McCalmont *et al*., 2017).

The ideal bioenergy crop is likely to produce high yields, be easy to decompose into essential elements, and cheap to store (Gansberger *et al*., 2015a). It should also contribute to enhanced biodiversity and enrich the landscape, compared to more traditional agricultural crops. In many parts of Europe, finding a crop that could be grown in poorer non-agricultural land and that could produce high dry matter yields would be an important step towards the wider acceptance of bioenergy.

Two approaches could be taken to incorporating energy crops in conventional agricultural systems. One would involve identifying the least productive areas of a field and establishing energy crops in those areas on a permanent basis. The other would involve introducing energy crops into the crop rotation cycle, as a long-term crop able to maintain and deliver environmental, or other productive, services with the added economic benefit of being able to harvest it as an energy feedstock. The use of marginal low productive land in this approach is also often proposed (Šiaudinis *et al*., 2015).

If the bioenergy sector is to be developed, it will need to be competitive. Several factors are crucial to achieve this goal: educational and awareness campaigns, availability of reliable information on energy crops, suitability of policies, reduced risk of financial investment, facilitating infrastructure, diversification and added value, as well as a consolidated market. When countries lack one or several of these factors they require policy reforms. Energy markets are often too unpredictable (Davis, 2018) making long-term investments, relative to the risk involved, very complex. A way to guarantee and secure prices externally could be through long-term contacts with energy providers. If direct funding is not possible, alternatives to secure sale value should be pursued, such as carbon taxes on fossil fuels, mandatory co-firing, monetisation of ecosystem services, or reforms on European funds (Witzel and Finger, 2016). The current climate crisis conditions provide an unparalleled scenario to root and progress the bioenergy sector.

The factors identified for the development of the bioenergy sector are summarised in Table 1.2.

Table 1.2. Summary of factors identified for the development of bioenergy.

Category	Factor
Data	Availability of reliable information
Social	Educational and awareness campaigns
Political	Suitable policies
	Supporting funds
Economical	Reduced risk of financial investment
	Diversification and added value
	Consolidated market
	Secure energy prices
Infrastructure	Availability of appropriate infrastructure
Environmental	Climate crisis

1.2 SidaTim joint research project

The Horizon 2020 scheme allowed the creation of FACCE SURPLUS programme, which aims to promote sustainable and resilient agriculture for food and non-food systems. FACCE SURPLUS is an ERA-NET cofounded programme, formed in collaboration between the European Commission and a partnership of 15 countries in the frame of the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE SURPLUS, 2019). In January 2015, FACCE SURPLUS opened a First Call, "Sustainable and Resilient agriculture for food and non-food systems", for joint proposals and ended in November 2015 by selecting 15 projects, including the SidaTim project.

The SidaTim consortium consisted of six institutions in four countries: Cranfield University (UK), West Pomeranian University of Technology Szczecin (PL), The Institute of Agro-environmental and Forest Biology (IT), the Council for Agricultural Research and Economics (IT), 3N Centre of Experts (DE), and the University of Freiburg (DE), acting as the project coordinator.

The SidaTim project had two research pillars:

- SidaTest: to investigate the performance of *Sida hermaphrodita* (L.) Rusby. During the preliminary meetings, it was agreed to also include a second species, *Silphium perfoliatum* L.
- AgroTim: to accelerate and foster the production of valuable timber in an agricultural landscape, focussing on marginal agroforestry systems (where valuable timber is produced on hedgerows, farm perimeters, and non cultivated arable land).

The project had international relevance for a number of reasons. The performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. was studied, monitored, and recorded in four different regions and climate conditions (UK, Italy, Germany, Poland), thus allowing comparisons with my PhD project. It introduced management concepts related to agroforestry and alternative/new energy crops in places where little was known about them (results yet to be published). The venture encompassed the production and collection of a large amount of data that would otherwise take a long time to put together. The study also allowed for quantification and comparison of agroforestry against monocultures, and the cultivation of perennial crops against annual crops. The competition and shadow effect of timber trees on the crops was assessed using Terrestrial Laser Scanning technology. The financial and economic impact of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. was also determined. The SidaTim project consisted of five work packages: work package 1 assessed of the growth of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.; work package 2 focussed on biochemical and structural analyses of the two crops; work package 3 evaluated the biodiversity effects of the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.; work package 4 monitored timber production in hedge and boundaries systems; work package 5 studied 3D structure of trees, light regimes and carbon sequestration. The results obtained during the project are still in the process of being published, contributing to fostering and build a future bio-based economy.

The work conducted for my PhD grew from Cranfield University's role within the SidaTim European joint research project. During the preliminary stages of the project it was decided to focus the research in perennial herbaceous crops because do not require annual planting, can be harvested over many years successively using existing farm equipment, and can enhance biodiversity at various levels. It has been proven that compared to annual energy crops, perennial energy crops are a more sustainable option (Ruf *et al*., 2018). Two novel biomass crops, *Sida hermaphrodita* (L.) Rusby (also known as Virginia fanpetals or Virginia mallow) and *Silphium perfoliatum* L. (known as cup plant) were identified as potential species meeting the above criteria.

Within this, I collaborated with the project partners in Italy, Germany, and Poland, developing the research programme and sharing information and data. The aim and objectives of my PhD were therefore developed to support the research programme that Cranfield University was undertaking for SidaTim.

1.3 Aim and objectives

The overall aim of my PhD was to reducing the uncertainty associated with and further evaluating the agronomic, economic, and environmental performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., selected crops for their potential to complement portfolio of dedicated energy crops. The individual objectives of my PhD project were:

1. To synthesise the existing knowledge on cultivation and energy production of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.
2. To assess the impact of establishment of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. on soil carbon.
3. To examine the survival, development and growth of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. and the effects of using seedlings or transplants.
4. To determine the profitability of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. against other potential crops.

5. To evaluate the greenhouse gas emissions emitted/captured during the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. compared to alternative crops.

1.4 Structure of the thesis

This thesis is composed of nine chapters including this introductory chapter. Chapter 2 comprises of an overall methodology and includes a description of the site for the experimental work. Chapter 3 addresses Objective 1 and comprises of a detailed literature review on *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.. This chapter has been published. Chapter 4 addresses Objective 2 and describes the effect of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. on soil carbon dynamics. Chapter 5 addresses Objective 3 and examines the agronomic performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in the UK. Chapter 6 focuses on Objective 4 and comprises of an economic analysis of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in Europe. Chapter 7 addresses the final objective and assesses the greenhouse gas emissions associated with the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in the UK. Chapter 8 synthesises the objectives, main findings and contribution to knowledge of each chapter, whilst the main conclusions extracted from the thesis are summarised in Chapter 9.

1.5 Authorship

Chapter 3: Laura Cumplido-Marin is the lead author of the paper presented in Chapter 3. Laura led the conceptualization of the research, the development of the methodology, the actual investigation, and led the writing of the original and subsequent versions of the manuscript, submission of the paper, and subsequent handling of revisions. Anil Graves and Paul Burgess supported the conceptualisation of the research and the methodology and provided editorial feedback on drafts of the paper. Laura also received feedback on drafts from partners on the project including Christopher Morhart, Pierluigi Paris, Nicholai D. Jablonowski, Gianni Facciotto, Reent Martens, Marek Bury, and Michael Nahm.

Chapter 4:

Laura Cumplido-Marin is the lead author of the paper presented in Chapter 4. Laura led the conceptualization of the research, the development of the methodology, the actual investigation, the data analysis, and led the writing of the original and subsequent versions of the paper. Michail Giannitsopoulos supported the data analysis and provided editorial feedback on drafts of the paper. Anil Graves and Paul Burgess also supported the conceptualisation of the research and the methodology and provided editorial feedback on drafts of the paper.

Chapter 5:

Laura Cumplido-Marin is the lead author of the paper presented in Chapter 5. Laura led the conceptualization of the research, the development of the methodology, the actual investigation, the data analysis, and led the writing of the original and subsequent versions of the paper. Michail Giannitsopoulos supported the data analysis and provided editorial feedback on drafts of the paper. Anil Graves and Paul Burgess also supported the conceptualisation of the research and the methodology and provided editorial feedback on drafts of the paper.

Chapter 6:

Laura Cumplido-Marin is the lead author of the paper presented in Chapter 6. Laura led the conceptualization of the research, the development of the methodology, the data collection, the actual investigation, and led the writing of the original and subsequent versions of the paper. Anil Graves, Christopher Morhart, Domenico Coaloa, Gianni Facciotto and Marek Bury supported the data collection. Anil Graves and Paul Burgess also supported the conceptualisation of the research and the methodology, supported the development of the model, and provided editorial feedback on drafts of the paper. Laura also received feedback on drafts from Christopher Morhart, Pierluigi Paris, Domenico Coaloa, Gianni Facciotto, Reent Martens, Marek Bury, and Michael Nahm.

Chapter 7:

Laura Cumplido-Marin is the lead author of the paper presented in Chapter 7. Laura led the conceptualization of the research, the development of the methodology, the actual investigation, and led the writing of the original and subsequent versions of the paper. Adrian Williams supported the development of the model and provided editorial feedback on drafts of the paper. Anil Graves and Paul Burgess also supported the conceptualisation of the research and the methodology and provided editorial feedback on drafts of the paper.

2 METHODOLOGY

This Chapter provides an overall description of the method used for the PhD. In the first instance, it describes the method for the literature review described in Chapter 3. It then describes the process undertaken to develop the experimental research described in Chapter 4 and 5, describing the selection of the experimental site, the experimental design, and how the growth and performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. were evaluated. It also describes the approach taken to the economic analysis, explaining how the data was collected, and describing the development of an economic model used to compare the economic performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. against a number of other arable and energy crops; more detail on these methods is provided in each of Chapters 3 to 7. The following diagram (Figure 2.1) was created to illustrate the links and interdependencies between the different chapters. From here onwards *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. will be referred as Sida and Silphium when appropriate.

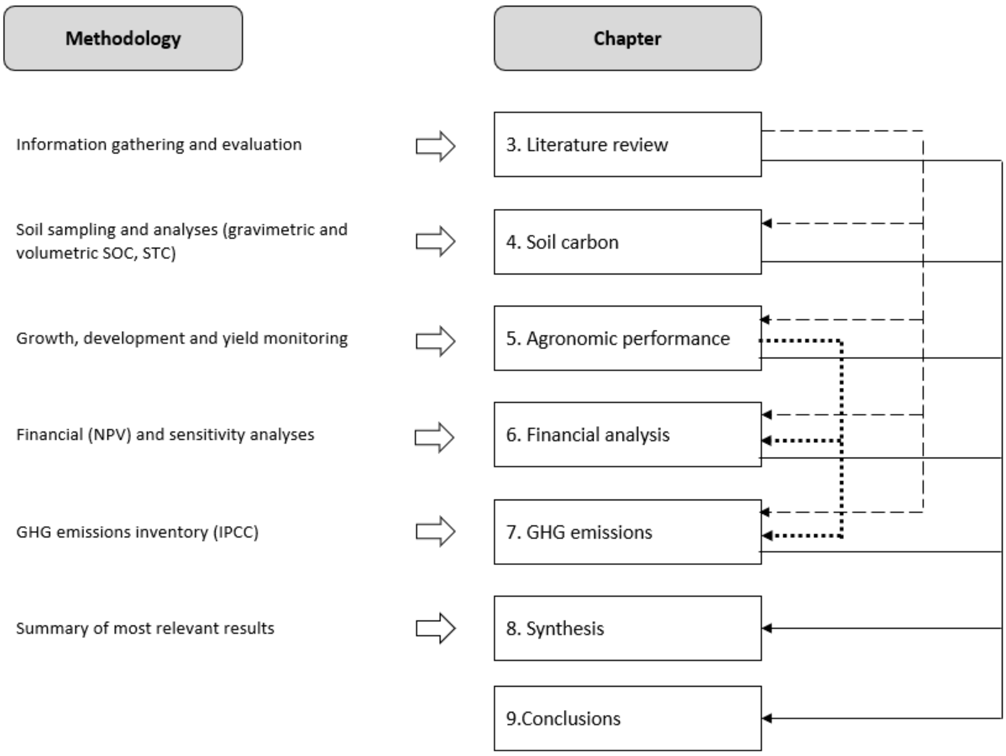

Figure 2.1 – Links and interdependies between main chapters of the thesis.

2.1 Literature review

A systematic review of the published peer reviewed literature for both Sida and Silphium was undertaken using articles from the Scopus database, complemented with Google Scholar. The key words used during the search were “Sida hermaphrodita”, “Virginia mallow”, “Virginia fanpetals”, “Silphium perfoliatum”, and “Cup plant”. The search was limited to articles published between 1985, which was the oldest article found, and 2020.

A total of 225 papers were initially identified in the screening process, as shown in Table 3.1. All relevant peer-reviewed publications describing the agronomic, energetic, and environmental aspects of both plant species were included in the review. Data was extracted, compiled, and organized into these key themes which form the broad thematic sections of the literature review. Only articles written in English, German and Polish were included in the review process.

The systematic review of literature supported Objective 1, the synthesis of existing knowledge on the cultivation and energy production of Sida and Silphium, and was published in the academic journal of Agronomy in the form of a peer reviewed article entitled “Two novel energy crops: *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. – State of knowledge” (Cumplido-Marin *et al.*, 2020), presented in Chapter 3. More detail on the method of the system review in shown in Chapter 3.

2.2 Site description

A site for a field experiment was identified in spring 2017 on the premises of the Cranfield University Farm at Silsoe in Bedfordshire, 28 miles from the main campus of Cranfield University (Figure 2.2). The experimental site is known by the name of “Rickyard’s field” (52.007897°N, 0.432112°W) and it has a total area of 0.68 ha (Figure 2.2). Based on local information, the site is considered to have been grassland since at least 2002 and was previously used for tractor driving lessons and grazing.

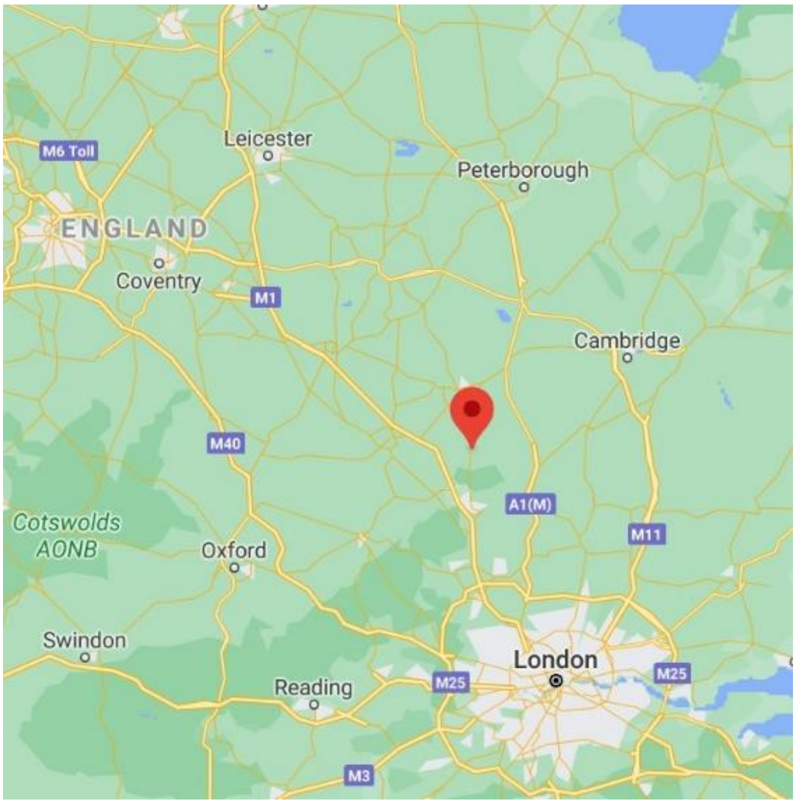

Figure 2.2 – Overview of the location of the experimental field in the South East of England (above); aerial view of the experimental field in 2017 (below).

2.3 Preliminary soil analysis

The soil in the experimental area is described as a freely draining slightly acidic loamy soil (Cranfield University, 2020a). According to LandIS, the soil had a loamy texture, was freely draining and had low topsoil carbon (Cranfield University, 2020b). The actual soil texture at the experimental site was determined from samples taken on 16 February 2017. A matrix of sampling points (Figure 2.3) was designed to suit the dimensions of the available space of 40 m x 60 m. Using a 20 cm deep Dutch auger, 30 samples were extracted, visually assessed in terms of texture according to the method of FAO (2000) and returned to the ground.

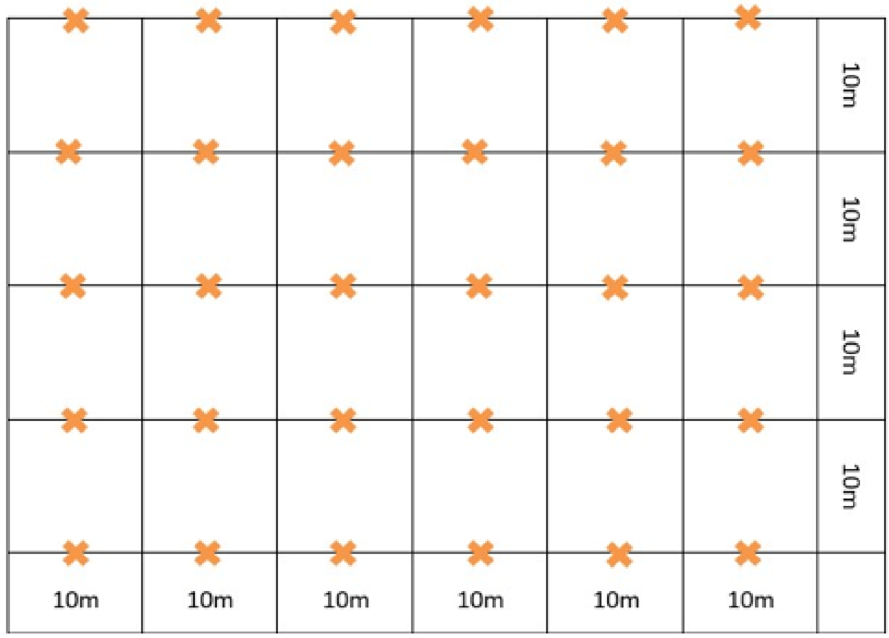

Figure 2.3 – Sampling matrix designed to assess the texture of the soil, following the methodology recommended by FAO (2000).

Using the above procedure all the samples had a clay loam texture. Individual sand grains were visible to the naked eye, the soil allowed careful handling without breaking, and it formed a thin smooth slick ribbon that could barely sustain its own weight. A random sample and the ribbon that could easily be made with your hands are illustrated in Figure 2.4. All the pictures of the samples and the ribbons that were captured during the procedure are included in Appendix A - Preliminary soil test.

Figure 2.4 - Example of random soil sample (above) and ribbon (below) taken during preliminary soil texture test at the Silsoe field site following the methodology recommended by FAO (2000).

Following the qualitative analysis, a particle size distribution analysis was carried out in April 2017 to quantify the texture of the soil. The methodology used for the analysis followed the Standard Operating Procedure (SOP) provided by the university, based on the British Standard BS 7755 Section 5.4:1998 (BSI, 1998). The results indicated that the soil contained 79.3% of sand, 18.0% clay, and 2.8% silt + clay, and therefore is classified to have a sandy loam / loamy sand texture. The results and calculations from the analysis are included in Appendix C, C.1 Soil texture.

Prior to the establishment of the plantation, the content of available N, P, and K in the soil was obtained in April 2017. The methodology followed for each analysis was in accord with the SOPs provided by Cranfield University. These analyses were repeated in March 2020, after 3 years of cultivation. All results and calculations from the analyses are included in Appendix C, C.2 Available nitrogen, phosphorus and potassium analyses.

2.4 Establishment of *Sida* and *Silphium* plants

2.4.1 Plant material

At the start of the project, a sealed postal package containing seeds of Sida and Silphium was received in April 2016. The package contained two bags of Sida seeds from two different origins, Hungary and Poland, hereafter named Sida1 and Sida2 respectively. Sida1 seeds had been supplied by Martin Klein (Landwirtschaft u. Energiepflanzen, Brühlweg 2, 88457 Kirchdorf, Germany) and Sida2 seeds from Dirk Helling-Junghans (Barenauer Weg 38, 49565 Bramsche/Kalkriese, Germany). Silphium seeds were received in two bags, both from N.L. Chrestensen Erfurter Samen- und Pflanzenzucht GmbH (Postfach 800854, 99034 Erfurt, Germany). All seeds had been purchased from plant nurseries in Germany. The material was stored in a dark dry environment at room temperature (20-25°C) in Cranfield University for 10 months, until February 2017.

The total weight of the individual bags as well as the 100 seed weight of each set was obtained using a calibrated scale in the laboratory. With the 100 seed weight, the 1000 seed weight was calculated, as well as the total number of seeds received. The results from seed weighing are included in Appendix D, D.1 Weight of seeds.

2.4.2 Production of seedlings

The method used to calculate the number of seedlings needed to produce was as follows. For the seedlings, three different treatments with four replicates per treatment were needed in total, having 12 experimental plots to transplant with seedlings. Multiplying the size of each experimental plot (36 m^2) by the number of experimental plots (12) the total experimental area to transplant with seedlings was 432 m^2. Multiplying seedling experimental area by the agreed planting density of 45 cm x 45 cm (4.9 plants per square metre), the total number of seedlings to produce was calculated to be 3,605 seedlings. Accounting for an average germination percentage of 70% plus a contingency percentage of 30%, and taking into account the number of holes of each seeding tray, the total number of seeds to plant was estimated at 3,413. Two thirds of this total were Sida seeds, and one third *Silphium* seeds, i.e., 2,404 and 1,202 respectively. Dividing the number of Sida seeds in two, it was calculated that 1,202 seeds were needed from each provenance.

Between 15 February and 1 March 2017, 3,640 seeds were placed in 35 seeding trays, 104 seeds per tray, filled with all-purpose compost. Specifically, the specific number of trays, number of seeds per treatment, and date of completion is shown in Table 2.1. It was noticed soon after that Sida showed a low germination percentage, extremely low for Sida2 in particular. Hence, 10 more seeding trays (1,024 seeds) were re-sown, accounting for a total of 4,664 seeds planted in the greenhouse.

Table 2.1- Calculation of the number of seedlings needed and number of seeds planted in the greenhouse for the establishment of the plantation in the field and date of completion.

Treatment	Seedlings (n)	Trays (n)	Seeds (n)	Date completed
Sida1	1138	11	1144	28/02/17 – 01/03/17
Sida2	1138	11	1144	24/02/17 – 27/02/17
Silphium	1138	13	1352	24/02/17 – 01/03/17
Sida2	1138	10	1024	21/03/17 – 23/03/17

A record of the counted germinated seeds allowed for the calculation of germination percentages. The average Silphium germination rate of Silphium seeds was 81.40%, Sida1 seeds germination percentage was 32.8%, and Sida2 germination percentage was below 1% (Table 2.2). Results from other researchers are discussed in section 3.4.2.2.1 Establishment by sowing. The second batch of re-planted Sida2 seeds showed similar results to the first. Trying to increase the low germination of Sida seeds, it was decided to carry out a germination experiment in laboratory conditions.

Table 2.2 – Seedling numbers and corresponding germination percentages (GP) recorded in the greenhouse during the seedling production process.

Date	**Sida1**	**GP (%)**	**Sida2**	**GP (%)**	**Silphium**	**GP (%)**
27/03/17	369	32.26	7	0.61	1,104	81.86
03/04/17	381	33.30	10	0.87	1,097	81.14

2.4.3 Germination experiment

The project was started from the premise that the germination percentages of the three types of seed would be high i.e. above 70%. Between 24 February and 1 March 2017, the seeds were sown into black plastic seed trays filled with general compost, which were then placed on a bench in a greenhouse at Cranfield University. Only one seed was inserted per cell in order to accurately record the germination process. The first seedlings emerged around 6 March (10 days after initial planting) and the majority appeared after 13 March (15 days after initial planting). Some seedlings continued to emerge for two more weeks until 3 April 2017. Because of the low germination rate of the Sida2 seeds, these were re-sown in the same condition between 21 and 23 March. Pictures were saved regularly for counting purposes as illustrated by Figure 2.5.

From 4 to 13 April 2017, three laboratory assays were undertaken to test three different scarification methods (Appendix D, D.2 Germination experiment). In treatment A (Sida1 and Sida2 seeds), the effect of a hydrochloric acid (0.5%) wash was tested. Treatment B (Sida2 seeds), tested immersion in distilled water for 30 minutes and

Figure 2.5 – Seedlings of *Sida hermaphrodita* (L.) Rusby (Sida1) (above) and *Silphium perfoliatum* L. (below) produced in the greenhouse; photographs taken on 27 March 2017.

subsequent addition of 80°C water, following the methodology described by Kurucz and Fári (2013). Treatment C (Sida2 seeds) used a hydrochloric acid wash, followed by immersion in distilled water for 2 h with an addition of gibberellic acid, following a combination of methods described by Packa *et al*. (2014) and Gansberger *et al*. (2015b). In addition, 20 seeds per cell of Sida1 and Sida2 were planted in a propagator inside a greenhouse (10 April 2017).

This germination experiment exposed the germination capacity of Sida and Silphium seeds after they had been stored at room temperature for ten months. The germination capacity of the two sets of seeds was poor and good respectively. The cause behind the low germination percentage of Sida and the effective long-term storage of seeds collected from previous years should be further investigated as it has implications for farmers and other stakeholders in the biomass sector. The results presented in this document are restricted to the acquired seed material for this project specifically and further work is needed to determine if it is a general response.

Due to the failed attempt to germinate Sida seedlings from seed, seedlings were purchased from the same suppliers that had provided the seeds. Hence, 1,000 and 850 seedlings of Sida1 and Sida2 respectively were ordered to be shipped from Germany. The seedlings arrived between 15-20 June 2017 and were stored under shade and watered regularly until they were transferred to the field. The results of the germination experiment are presented in Appendix D, D.2 Germination experiment.

2.4.4 Experimental layout

In order to tackle Objectives 3 and 4 of this PhD, a field experiment was developed to grow Sida and Silphium. The results of studying the effect of Sida and Silphium on soil carbon dynamics and their agronomic performance in the UK are reported in Chapter 4 and Chapter 5. Of the total field area available, 0.22 ha was selected to establish the experiment. Each experimental plot had a size of 4.5 m wide by 8 m long, making up an area of 36 m^2. The design involved four replications of each treatment in a Latin-square design, using seeds and seedlings from two separate provenances of Sida, referred as Sida1 and Sida2, and seeds and seedlings from one single provenance of Silphium. Consequently, there was a total of six treatments: Sida1 seeds, Sida1 seedlings, Sida2 seeds, Sida2 seedlings, Silphium seeds, Silphium seedlings. The layout is represented in Figure 2.6.

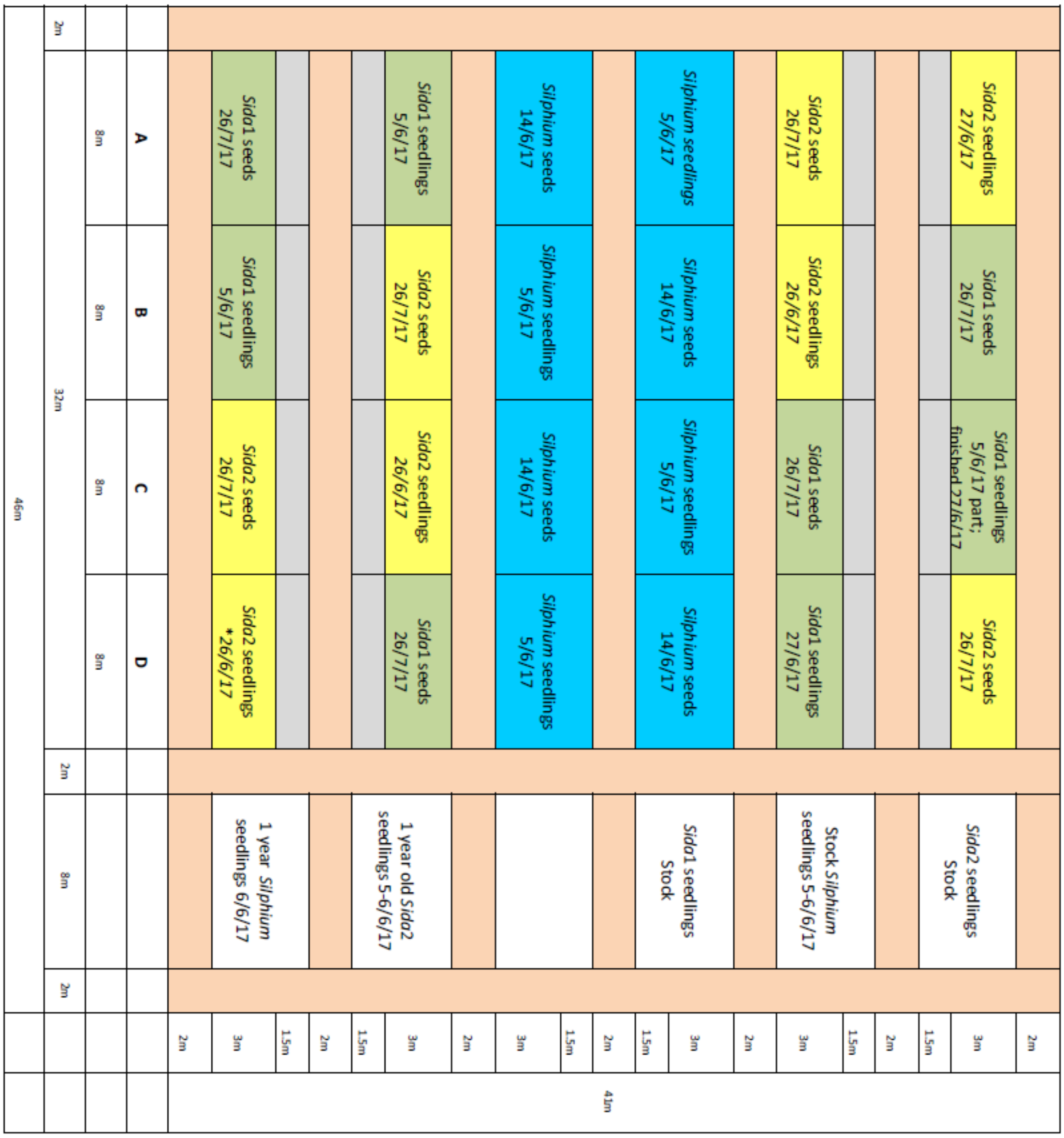

Figure 2.6 – Experimental layout of the plantation design following a randomised Latin-square design agreed with the partners in the project definition stage of the SidaTim project; the design is composed of a total of 24 plots, including two treatments (seeds/seedlings) of the three plants (*Sida hermaphrodita* (L.) Rusby (Sida1, Sida2) and *Silphium perfoliatum* L.) and four repetitions, all organised in six blocks.

2.4.5 Preparation of experimental area and planting

All agricultural operations involving the use of agricultural machinery were carried out by a qualified field technician. Initially, the grass was mowed on the 28 of February 2017 using a flail mower. The soil operations included spraying with glyphosate (3 l ha^{-1} in 200 l of water) on the 10 of March 2017 using a quad bike, ploughing at a depth of 20 cm on the 20 of March 2017, and power harrowing and ring rolling on the 28 of March.

On 5 April 2017 the experimental plots were laid and marked by wooden stakes. The authorisation for the fencing of the field was not granted until mid-May, significantly delaying the establishment of the plantation. On 16 May it was necessary to spray off the field a second time with glyphosate (2 l ha^{-1} in 200 l of water) because weeds had re-grown. The day prior to fencing, a furrow was ploughed out along the perimeter of the experimental area. Fencing using rabbit mesh was carried out by a contractor, who started on the 23 of May and finished on 1 June 2017. The bottom of the fence was covered with soil by ploughing back around the fence on the 13 of June.

Transplanting of seedlings was accomplished in two stages. The first stage, transplanting the Silphium seedlings, was done between 5-14 of June 2017. The second stage, transplanting the Sida seedlings, between 26-27 June 2017. The seedlings were transplanted at a density of 4.4 plants m^{-2}, equivalent to 160 plants per plot in 8 rows, keeping 45 cm between plants and 50 cm between rows. The surplus seedlings were transplanted into two stock plots (one for Sida and one for Silphium) at double density. Two additional plots using one year old seedlings (one of Sida and one of Silphium), were established on the empty space near a clump of mature poplar trees.

Half of the seed plots were sown between 9-15 of June 2017 and the remainder had to be delayed to the end of July (26 July) due to a heat wave. Due to this heat wave, it was necessary to install a sprinkler irrigation system to water the seedbeds and seedlings. During the establishment year (2017), the experimental plots were watered twice in

June (19, 27 June 2017), eight times in July (5, 10, 12, 13, 17, 19, 25, 27 July 2017), and one time in August (3 August 2017).

Because of the sensitivity of Sida and Silphium to herbicides, all weeding was done manually with a hoe. Fourteen sessions of weeding were carried out during 2017 (19 and 29 June; 3, 4 July; 9, 14, 15, 23, 29, 30 August; 5, 7, 12, 13 September).

2.5 Soil carbon dynamics

The methods used for investigating the soil carbon dynamics are expanded upon in Chapter 4, which deals with Objective 2 and hence only a brief methodology is described here. Bulk density (BD), soil organic carbon (SOC), and total carbon in the soil, were first analysed before the establishment of the plantation in March 2017 when the land was covered by grassland. Following the same steps and procedures, the analyses were repeated in March 2020 and both sets of data were compared.

Since soil carbon is difficult to measure due to natural variability in time, the change in soil carbon was measured using a “microsite” approach as proposed by Ellert *et al.* (2008). In this, the bulk density and soil carbon content of the soil were measured using a dense sampling approach due to its potential to measure small changes in SOC in a relatively short period of time (Ellert *et al.*, 2002). The approach uses a systematic design to ensure the precise location and relocation of sampling points (VandenBygaart, 2006). Sampson and Scholes (2000) reported that the approach can provide a relatively low-cost method to detect changes of 3.64 Mg C ha^{-1}, equivalent to increases that might be expected after 10 years by practices that preserve SOC.

2.6 Agronomic performance

The agronomic performance of Sida and Silphium was assessed by monitoring their growth and development (methodology fully described in Chapter 5), which tackles Objective 3. Both crops were monitored from 2017 to 2020. Additionally, the biomass yields of winter harvest for solid fuel for combustion of Sida and the summer yields for green biomass for anaerobic digestion of both Sida and Silphium were recorded.

The success of the different establishment methods (seeds vs. seedlings) and plant origins (Sida1 vs. Sida 2) was measured through the plant density of the experimental plots. Plant density was calculated relative to 100% coverage, which corresponded to 160 plants within each experimental plot (4.4 plants m^{-2} over 36 m^2). Hence, throughout the period 2017-2020 the corresponding plant density was estimated via plant surveys based on plant counts or visual assessments of plant coverage.

A subsample of 10 plants per plot were tagged, after being selected randomly from the middle of the plots to avoid edge effects. Measurements made included a count of the number of stem shoots, stem height, and stem width. In 2018, these measurements were combined with the measurements on the weight of shoots and roots in order to compare above and below ground biomass relationships. The dry weight of Sida leaves and stalks was also recorded separately by Sanchez Muñoz (2018) as part of the SidaTim work from the same plantation. Further measurements included those for the different growth phases of Sida and Silphium in the UK (2017-2020), the *Sida hermaphrodita* BBCH-code (Jablonowski *et al*., 2017) was used for Sida and the general BBCH-code was used for Silphium. Winter and summer biomass yields were recorded from 2017 to 2020. A part of each Sida plot was harvested in late February-March to measure the production of biomass for solid fuel combustion, and in late summer for the production of green biomass for anaerobic digestion. Silphium was only harvested in summer for the production of green biomass for anaerobic digestion.

2.7 Economics

A financial analysis of the establishment and 16-year rotation of Sida and Silphium was performed, comparing these two crops with SRC, Miscanthus, and an arable rotation. The economic analysis was undertaken for the four participating countries in the SidaTim project to reflect varying conditions (UK, Germany, Poland, and Italy), making sure as far as possible that the most relevant local crops and systems were modelled. This is detailed further in Chapter 7. A Microsoft Excel model was developed to provide an analysis of the discounted net revenue streams to calculate a Net Present Value (NPV). Data was obtained during field visits and personal communication with the partner organisations, where national and international statistical databases and reports, and expert opinion, were used to collate information on the associated yields, inputs, management, prices and costs. The financial analysis included a sensitivity analysis of prices, yields, costs and discount rates. The method for the economic analysis is fully described in Chapter 7 which tackles Objective 4 of the PhD.

2.8 Greenhouse gas emissions

The greenhouse gas (GHG) emissions associated with the establishment and cultivation of Sida and Silphium were calculated and compared with SRC, Miscanthus, and an arable rotation. To calculate the corresponding GHG emissions, a Microsoft Excel model was developed following the IPCC guidelines for national greenhouse gas inventories (IPCC, 2021).

The initial phase of the analysis involved defining the system boundaries, adopted as the farm gate in this study. Then the different sources of GHG emissions were identified to be emissions from fuel combustion activities, emissions from changes in carbon stocks, and N_2O emissions. The IPCC guidelines for National Greenhouse Gas Inventories (IPCC, 2021) were followed to develop a Microsoft Excel model to calculate the GHG emissions associated with the cultivation of Sida and Silphium, and compared to other arable and energy crops. The method for the GHG emissions analysis is fully described in Chapter 7 which tackles Objective 5 of the PhD.

3 TWO NOVEL ENERGY CROPS: *SIDA HERMAPHRODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. – STATE OF KNOWLEDGE

Chapter 3 describes a state-of-the-art review undertaken through a systematic review. The objective was to provide a comprehensive analysis of the literature on Sida and Silphium, particularly with respect to their cultivation and energy production. The resulting review of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. covers: origin and botany; agroclimatic requirements; establishment methods; weeds, pests and diseases; nutrient management; harvesting methods; yields; production of solid fuel for combustion; production of green biomass for anaerobic digestion; gasification; alternative uses; environmental benefits; economics; energy balances and LCAs. This review was published as a peer-reviewed paper in a Special Issue of Agronomy on the current status and future prospects of bioenergy crops by Laura Cumplido-Marin, Anil. R. Graves, Paul J. Burgess, Christopher Morhart, Pierluigi Paris, Nicolai D. Jablonowski, Gianni Facciotto, Marek Bury, Reent Martens and Michael Nahm.

Abstract: Current global temperature increases resulting from human activity threaten many ecosystems and societies, and have led to international and national policy commitments that aim to reduce greenhouse gas emissions. Bioenergy crops provide one means of reducing greenhouse gas emissions from energy production and two novel crops that could be used for this purpose are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. This research examined the existing scientific literature available on both crops through a systematic review. The data was collated according to the agronomy, uses, and environmental benefits of each crop. Possible challenges were associated with high initial planting costs, low yields in low rainfall areas, and for *Sida hermaphrodita* (L.) Rusby, vulnerability to *Sclerotinia sclerotiorum*. However, under appropriate environmental conditions, both crops were found to provide large yields over sustained periods of time with relatively low levels of management and could be used to produce large energy surpluses, either through direct combustion or biogas production. Other potential uses included fodder, fibre, and pharmaceutical. The review also demonstrated that environmental benefits, such as phytoremediation, biodiversity, pollination, soil health, and water quality advantages could be obtained from the use of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. relative to existing bioenergy crops such as maize, whilst at the same time reducing the greenhouse gas emissions associated with energy production. Future research should examine the long-term implications of using *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. as well as improve knowledge on how to integrate them successfully within existing farming systems and supply chains.

Keywords: bioenergy crops; Virginia mallow; Virginia fanpetals; Cup plant

3.1 Introduction

Governments from across the world committed themselves, in Paris in 2016, to restrict the mean rise in global temperature to no more than 1.5–2 °C above pre-industrial levels (UNFCCC, 2021). In order to achieve this, governments are seeking to reduce net greenhouse gas emissions with a particular focus on reducing the use of fossil fuels for electricity production, heating, and transport.

Bioenergy currently represents 17.5% of gross final energy consumption in the European Union (EU) (EurObserv'ER, 2018). In Europe in 2017, about 59% of renewable energy was provided from bioenergy, and globally about 10% of this is derived from agriculture (World Bioenergy Association, 2019). Important bioenergy crops in Europe include maize (*Zea mays* L.) to produce biogas and bioethanol, and short rotation coppice (Morhart *et al*., 2014) and Miscanthus (Krička *et al*., 2017) for the production of solid biofuel.

However, there are a number of challenges associated with the use of these crops. For example, maize is a spring-planted annual crop with high fertilisation and pesticide needs, which does not cover the ground in the winter and early spring, which can result in severe soil erosion and soil organic matter depletion. In the case of short rotation coppice, the woody material requires the use of specialised harvesting equipment, which is typically not found on farms. Disadvantages in the use of Miscanthus include problems of corrosion and slagging associated with its combustion. For these reasons, there is interest in perennial herbaceous crops that (i) do not require annual planting and can be harvested over many years successively, (ii) can be harvested using existing farm equipment, and (iii) can enhance biodiversity at a field- and farm-level. Recent research indicates that compared to annual energy crops, perennial energy crops are a more sustainable option (Ruf *et al*., 2018). Two novel biomass crops, *Sida hermaphrodita* (L.) Rusby (also known as Virginia fanpetals or Virginia mallow) and *Silphium perfoliatum* L. (known as cup plant) could fulfil all three of these criteria. From here onwards they will be referred as Sida and Silphium.

Although both plants originate from North America and have been studied in research institutions in Eastern Europe since the 1980s as fodder and energy crops, there remains a lack of collated information in English on Sida and Silphium. Some of the early research on these plants in Eastern Europe was published in Polish and German. The objective of this paper is therefore to synthesize in one location the existing information on the agronomy and uses of Sida and Silphium in a state-of-the-art review.

3.2 Materials and Methods

A systematic review of published peer reviewed literature for both Sida and Silphium was undertaken, with relevant articles and papers identified using Scopus as the main search engine, complemented with Google Scholar. The key words used during the search were “Sida hermaphrodita”, “Virginia mallow”, “Virginia fanpetals”, “Silphium perfoliatum”, and “Cup plant”. The search was limited to articles published between 1985, when the first article was published, and 2020.

A total of 225 papers were initially identified in the screening process, as shown in Table 3.1. The full list of papers is shown in Appendix B, B.1 Reviewed documents. All relevant peer-reviewed publications describing the agronomic, energetic, and environmental aspects of both plant species were included in the review. Data were extracted, compiled, and organized into these key themes which form the broad thematic sections of this literature review. Only articles written in English, German and Polish were included in the review process.

Table 3.1 - Screening process for the systematic literature review and number of articles.

	Sida	Silphium
Total number of documents initially found	122	103
Number of documents written in other than English, German, and Polish	1	10
Number of documents considered out of scope	3	2
Number of documents with restricted access/not available	12	11
Number of additional papers identified during the review	20	17
Number of documents finally reviewed	125	97

The results are described first for Sida and then Silphium in terms of (1) the origin and botany of each crop, (2) the agronomic requirements of each crop, including their; agro-climatic requirements, establishment method, pests and diseases, nutrient management, and harvesting. The bioenergy production aspects of both crops are then compared in terms of yields produced and timing of harvest. In addition, the use of the crops in terms of solid fuel production, biogas, and gasification are described. Lastly, the alternative uses of the crops, potential environmental benefits, the economics, energy balance, and life cycle assessments (LCA) are detailed. The paper finishes with recommendations for future research and a brief conclusion on the main points.

All economic data reported here in Pound sterling (GBP) and Euros (€) have remained unchanged, using current prices from when the research was conducted. Polish złoty (PLN) have been converted into Euros using an exchange rate of 4.18 PLN/€ (Statista.com, 2020a) for economic data reported for Poland in 2012 and 2014.

3.3 Review of *Sida hermaphrodita* (L.) Rusby

3.3.1 Origin and Botany

Sida is a perennial herbaceous species belonging to the Malvaceae family, and its common names include Virginia mallow and Virginia fanpetals. Sida is indigenous to North America, where it is found in or near to wetlands, floodplains, and rivers

(Borkowska and Molas, 2012; Remlein-Starosta *et al*., 2016). In the USA in 1985, large wild populations of Sida were documented in West Virginia and Ohio states, with isolated populations in Kentucky, Michigan, and Indiana (Spooner *et al*., 1985). Individual plants can reach heights up to 3 m, with hollow canes filled with pith, and delicate leaves of 20–50 cm^2 (Franzaring *et al*., 2015).

The potential use of Sida as a fodder and fibre crop was recognised during the 1930s when it was introduced into the former USSR. It found its way to Poland as a fodder and fibre crop in the 1950s, where it was still used for these purposes in the 1980s (Borkowska and Molas, 2012). Kurucz *et al*. (2014) described the first accidental introduction of the species into Hungary during the 1970s, after which Sida became more widespread through trade with Poland, to the point that in 2010 it was included in a list of species for which bioenergy funding could be obtained. In Poland, studies indicated that around 96 ha of Sida were cultivated in 2008 (Burczy *et al*., 2010) and an additional 750 ha was planted up to 2011 (Igliński *et al*., 2011). Sida is cultivated on about 100–150 ha of land in Germany, and small areas of land in other eastern European countries including Austria, Hungary, and Lithuania (Nahm and Morhart, 2018).

Sida was first studied by Russian botanists, then by Ukrainian researchers such as Mendvedev and Dmitrashko *et al*. (Spooner *et al*., 1985), who investigated its potential for fodder, fibre, honey production, and soil stabilization. The University of Life Sciences at Lublin in Poland began research on Sida for energy production in the 1980s because of its high yields, low moisture content when harvested in late winter, and ease of harvest, processing, and storage (Oleszek *et al*., 2013). Selective breeding has produced varieties up to 4 m in height that yield 12 to 20 t ha^{-1} y^{-1} of dry matter (DM) (Borkowska and Molas, 2012).

Once planted, Sida can be productive over a rotation of 10 years or more, and some authors have suggested that it can remain highly productive for 15–20 years (Pszczółkowska *et al*., 2012). Recently, Jablonowski *et al*. (2017) produced a BBCH-code for Sida (further details in Appendix B, B.2 Supplementary material B.2.1 *Sida hermaphrodita* BBCH-code) to help identify its different phenological stages, and allow for more accurate comparisons between field trials. There is limited information regarding the invasiveness of Sida. However, in the Netherlands an ecological risk assessment concluded that it presented a low risk (Matthews *et al*., 2015).

3.3.2 Agronomy of *Sida hermaphrodita*

3.3.2.1 Agroclimatic Requirements

Sida can tolerate low temperatures during the winter making it suited to continental climates (Kurucz *et al*., 2014). Jasinskas *et al*. (2014a) recommended that commercial production for a humid continental climate (Lithuania), requires a minimum annual precipitation of about 500–600 mm, as drought results in significant yield reductions (Borkowska *et al*., 2009; Slepetys *et al*., 2012). The high sensitivity of the yield of young Sida plants to drought is also reported by Franzaring *et al*. (2015). The sensitivity of Sida to drought is also suggested by wild populations being generally found in wet habitats (Spooner *et al*., 1985).

In the wild, Sida is typically found on silt loam, sandy clay loam, and clay loam soils (Spooner *et al*., 1985). The pH of these soils varies between 5.4 and 7.5, with a medium to high organic matter content. Yields can be depressed at low acidities, and Šiaudinis *et al*. (2015) demonstrated that liming of acid soils to raise the pH from 4.3 to 5.6 before establishment increased yields by almost 50%.

3.3.2.2 Establishment method

Sida can be established using seeds, seedlings or rhizomes. Nahm and Morhart (2018) included a clear table in their review which compiles the different densities used for the three methods in experiments between 2003 and 2011.

Krzaczek *et al*. (2006) reported that sowing was the most common method of establishment of Sida in Poland at the time. They also reported the importance of initial weed control, and they recommended keeping a wide distance between rows to allow for mechanical/chemical weed control (Kurucz *et al*., 2018). Pszczółkowska *et al*. (2012) advised against sowing on soils that tend to crust on the surface. By contrast, Borkowska and Wardzińska (2003), looking at survival on sewage-sludge treated soil, found that whereas only 10% of plants originating from seeds survived, seedlings had a 53% survival chance. Hence, yields from Sida established using seedlings were 7.7 t DM ha^{-1} y^{-1} greater than from Sida established using seeds.

Seedlings can be grown from seeds to then transplant them to the field. In Germany, Franzaring *et al*. (2015) sowed seeds in trays in March, observed germination after 11–25 days, depending on the temperatures, and then transferred the seedlings to the field in April. Having used the Kurucz-Fari method (Kurucz and Fári, 2013) to germinate seeds, Kurucz *et al*. (2018) produced their own over-wintered seedlings using the so called nurse-in-tray technology, increasing reliability and obtaining high yields.

The use of 8–12 cm rhizomes can also lead to rapid and successful plantation establishment (Antonkiewicz *et al*., 2017; Kurucz *et al*., 2018), although rhizomes can carry virus infections (Kurucz *et al*., 2018). Borkowska and Molas (2012) reported annual yields of 20 t DM ha^{-1} using rhizomes and recommended their use for the establishment of energy plantations. Jasinskas *et al*. (2014a) reported that rhizomes can be planted using potato planters.

3.3.2.2.1 Establishment by sowing

Sida seeds have an average weight of 3.4 g per 1000 seeds (Krzaczek *et al*., 2006); they are very small. Sida can be established in the field from seed either by sowing in early spring or in the preceding November (Šiaudinis *et al*., 2015). However establishment from seed can be “unpredictable, slow, and difficult” (Kurucz *et al*., 2014), with typical germination rates of 5–15% (Pszczółkowska *et al*., 2012). Because of this, researchers have attempted to find ways of improving the germination rate. During a four year experiment, Kurucz *et al*. (2014) found no relationship between germination and storage period of the seeds. Franzaring *et al*. (2014) kept seeds that had been sown in seeding trays under controlled conditions for four weeks, with alternating temperatures of 3 °C and 11 °C to overcome dormancy. Spooner *et al*. (1985) reported that scarification of the seeds should lead to germination rates of up to 92%. Their method involved perforating the seed coats and then incubating the perforated seeds for 15 days under controlled light (14 h of light at 20 µE m^{-2} s^{-1}) and temperature (35 °C during the day and 20 °C during the night) conditions.

Kurucz and Fári (2013) also reported germination rates of up to 80% by combining a floated-seed priming technique with a hot water pre-treatment. First, seeds were immersed in distilled water at 23–25 °C for 30 min. Then, the seeds that had sunk were taken and submerged in water at 80 °C for 2 min, placed on wet filter papers in Petri dishes in total darkness at 26 °C, and counted after three and six days. Borkowska and Molas (2012) have reported 20% yield benefits of using seed dressings containing the fungicides carbendazim (no longer approved for use in the EU) or tebukonazol.

Borkowska and Wardzińska (2003) compared 3, 6, and 9 kg ha^{-1} of seeds, finding no difference in yield. Stolarski *et al*. (2014b) compared sowing 1.5 and 4.5 kg ha^{-1}, obtaining higher yields with the higher sowing density. Feledyn-Szewczyk *et al*. (2019) used a seed rate of 1.5 kg ha^{-1}.

For their field trial at the University of Life Sciences in Lublin, Borkowska *et al*. (2009) applied 25 seeds m^{-2} (250,000 seeds ha^{-1}). The same density of 25 seeds m^{-2} was used again by Borkowska and Molas (2012) in their experiment on the effect of seed dressings. Molas *et al*. (2018) established their plantation again using the same density but this time with germinated seeds. A sowing density of 64,000 seeds ha^{-1} was reported by Pszczółkowska *et al*. (2012).

For sowing, Krzaczek *et al*. (2006) used the S071 KRUK seeder. This had a chain and sprocket transmission connected to a cam mechanism that in turn controlled a dosing disk. Working at 0.8 m s^{-1}, their experiment demonstrated the significant impact of the peripheral speed of the seeding disc on seed distribution, with an optimal speed of 0.23 m s^{-1} and decreasing efficiency at higher speeds. Kurucz *et al*. (2018) used the S071/B KRUK pneumatic seeder in their experiment. Hand powered seeders have also been used for establishing small-scale plantations of Sida (Borkowska and Molas, 2012).

3.3.2.2.2 Establishment by Transplanting Seedlings or Rhizomes

High densities for seedlings have sometimes, but not always, been associated with higher yields. In Hungary, Kurucz *et al*. (2018) reported that densities of 10,000, 13,300, and 20,000 seedlings ha^{-1} gave similar yields, but the plantation was more uniform at the lowest density. In Austria, in a comparison of 13,300, 17,700, and 26,600 seedlings ha^{-1}, von Gehren *et al*. (2019) recommended applying the middle density due to similar yields and reduced costs. Šiaudinis *et al*. (2017, 2015), Stolarski *et al*. (2018) and Feledyn-Szewczyk *et al*. (2019) used a seedling density of 20,000 seedlings ha^{-1}, equivalent to a spacing of 1.0 m × 0.5 m, and Jablonowski *et al*. (2017) used a spacing of 0.75 m × 0.5 m (27,000 seedlings ha^{-1}). Borkowska and Molas (2012) and Franzaring *et al*. (2014) planted seedlings at a density of 40,000–40,800 seedlings ha^{-1}, and a density of 44,000 seedlings ha^{-1} was used in the five field trials across Europe as part of the SidaTim project (Bury *et al*., 2019; Facciotto *et al*., 2018). Borkowska and Wardzińska (2003) found no differences in dry biomass yields of seedlings planted at 33,000, 50,000 and 100,000 seedlings ha^{-1}.

In the case of rhizomes, Pszczółkowska *et al*. (2012) proposed 10,000–20,000 cuttings ha^{-1}, and Stolarski *et al*. (2017b) and Krzyżaniak *et al*. (2018) used a density of 20,000 cuttings ha^{-1}. Pogrzeba *et al*. (2018) used 3 cuttings m^{-2}, equivalent to 30,000 cuttings ha^{-1}, and Antonkiewicz *et al*. (2018) used a spacing of 0.75 m × 0.4 m, equivalent to 33,300 cuttings ha^{-1}. Borkowska and Molas (2013, 2012) used a spacing of 0.70–0.75 m between rows and 0.33–0.35 m between plants to achieve 40,000–41,000 cuttings ha^{-1}, similar to the value of 44,000 cuttings ha^{-1} reported by Jankowski *et al*. (2016). Stolarski *et al*. (2014b) compared 20,000 and 60,000 cuttings ha^{-1}, obtaining higher yields at the highest density. Despite the risk of viral infections, the establishment of plantations using rhizomes has the potential to produce higher yields from the second year (Borkowska *et al*., 2009).

Irrespective of the method of propagation, as long as the original planting density is not too low, Borkowska and Wardzińska (2003) reported that it is common for a density of about 21 shoots per m^2 to establish by the third year. Similar stem densities have generally been reported in other studies. Shoots reached a constant density of around 24 shoots per m^2 (Borkowska *et al*., 2009) and 16–24 shoots per m^2 (Matyka and Kuś, 2018), although Borkowska and Molas (2013) reported a relatively high density of 37 shoots per m^2.

3.3.2.3 Weeds, pests and diseases

Weeding is essential during the establishment phase and it is generally done manually or mechanically due to the sensitivity of Sida to herbicides. In subsequent years, only minimal weeding is needed due to the early onset of the growth in March and its ability to create a closed canopy (Kurucz *et al*., 2014).

Sida is vulnerable to fungal infection by *Sclerotinia sclerotiorum*, which causes bleached and mouldy white stems. The origin of the inoculum of *Sclerotinia sclerotiorum* could be ascospores and mycelium growing on dead plant material (Remlein-Starosta *et al*., 2016). Symptoms, which appear in mid-May when plants are 0.5 m high, can destroy anything from just a few shoots to entire plantations. The same authors explored the potential of yeast-like fungi in controlling *Sclerotinia sclerotiorum* in order to develop a commercial biocontrol product. As such, Dr. G. Bedlan (2020) recommended the use of the antagonist *Coniothyrium minitans* (Contans WG, ©2020 Bayer Crop Science). Matyka and Kuś (2018) applied a fungicide (Horizon 250 EW 0.018%) with the active ingredient tebuconazole, in June of the first year after planting to control the disease. As *Sclerotinia sclerotiorum* is commonly found in oilseed rape (*Brassica napus* L.), Nahm and Morhart (2018) recommend that Sida should not be grown in fields previously used for oilseed rape.

Fusarium and *Botrytis cinerea* are two other potential diseases for Sida mentioned in the literature (Grzesik *et al*., 2011, cited in Pszczółkowska *et al*. (2012)). Pszczółkowska *et al*. (2012) also stated that Sida could be affected by the dock bug (*Coreus marginatus* L.) and the lygus bug (*Lygus* spp.).

In 2015, the symptoms of *Didymella sidae-hermaphroditae* sp. nov. were found on the upper side of leaves in the form of brown rounded spots with a dark outline in Austria (Bedlan, 2016). In June 2015 the occurrence of the fungus *Periconia sidae* on Sida was first also reported for Europe (Bedlan and Plenk, 2016). Out of the 190 species of the genus *Periconia*, only *Periconia byssoides* and *Periconia sidae* have so far been reported on Sida. *Periconia sidae* was visible on the upper leaf side as irregular, light brown, leaf spots, with dark brown border. Microscopic stems with conidia of *Periconia sidae* associated with *Epicoccum nigrum* were found on these spots on both sides of the leaves.

3.3.2.4 Nutrient Management

Numerous fertiliser trials on Sida have been reported in the literature (Table 3.2), with nitrogen applications ranging from 0 to 200 kg N ha^{-1}, phosphorus applications of 0 to 100 kg P ha^{-1}, and potassium applications of 0 to 150 kg K ha^{-1}. These ranges agree with the data gathered by Nahm and Morhart (2018), (0–200 kg N ha^{-1}; 0–90 kg P ha^{-1}; 0–120 kg K ha^{-1}). Once established, Sida is considered to have low requirements for N, P, and K because nutrients are allocated to and stored in the unharvested root system when harvest occurs during late winter (Franzaring *et al*., 2014; Pszczółkowska *et al*., 2012).

Table 3.2. Reported fertiliser application rates for *Sida hermaphrodita* (L.) Rusby (kg ha^{-1}); values are for N, P, and K unless indicated otherwise.

N	P	K	Reference
100/200	39/52	83	Borkowska *et al*., 2009
100	35	83	Borkowska and Molas, 2012
0/60 ^{e}/120	60 ^{e}	60 ^{e}	Slepetys *et al*., 2012
90	13–39	42–82	Pszczółkowska *et al*., 2012
100	39	75	Borkowska and Molas, 2013
158 ^{e}/79	88 ^{e}/44	116 ^{e}/58	Szyszlak-Bargłowicz *et al*., 2013
0/60/120	26	33	Šiaudinis *et al*., 2015
90 ^{e}/120	35 ^{e}/43	66 ^{e}/82	Jankowski *et al*., 2016
160	5%	8%	Nabel *et al*., 2016
0/60/120	60 SSP	31	Šiaudinis *et al*., 2017
68/136	23–58	55–204	Stolarski *et al*., 2017a
0/68/136	0/26/52	0/73/146	Stolarski *et al*., 2017b
120	30	80	Matyka and Kuś, 2018
85/170	13	33	Krzyżaniak *et al*., 2018
140	-	25	Facciotto *et al*., 2018
90/170	-	-	Tilvikiene *et al*., 2020
100/200	83	39	Molas *et al*., 2018
60 ^{e}/40–80	35 ^{e}	80 ^{e}	Bury *et al*., 2019
70	-	-	von Gehren *et al*., 2019
90	13	33	Stolarski *et al*., 2019
100 ^{e}/100	35 ^{e}/35	110 ^{e}/110	Siwek *et al*., 2019
120 ^{e}/150	44 ^{e}/44	82 ^{e}/82	Jankowski *et al*., 2019
80 ^{e}/80	26 ^{e}/26	44 ^{e}/44	Feledyn-Szewczyk *et al*., 2019
90/170	-	-	Tilvikiene *et al*., 2020

^{e} establishment year

Generally, higher rates of nitrogen fertiliser application increase the biomass production of Sida. Šiaudinis *et al*. (2015) obtained their highest yield of 8.12 t DM ha^{-1} y^{-1} at the highest nitrogen application rate they investigated (120 kg N ha^{-1}). Stolarski *et al*. (2017b) obtained a positive response of Sida to nitrogen, with the highest yields resulting from the highest nitrogen doses applied in dry digestate and mineral fertiliser. Molas *et al*. (2018) recorded their highest yield with the highest nitrogen application of 200 kg ha^{-1}. By contrast, Borkowska *et al*. (2009) found that increasing nitrogen from 100 kg ha^{-1} to 200 kg ha^{-1} had no significant effect on yield. In situations where the soil nitrogen status is high, it can be possible to obtain high yields without the addition of fertiliser in the initial years after planting. For example Slepetys *et al*. (2012) and Kurucz *et al*. (2018) obtained annual yields of 9.6 and 10.2–11.9 t DM ha^{-1}. However, nutrient depletion led to yield reduction in subsequent years (Kurucz *et al*., 2018).

Some authors recommend splitting the application of nitrogen into two equal doses to maximize nitrogen use efficiency. The suggested timing is generally just before growth starts and then just before canopy closure in July (Borkowska and Molas, 2012; Molas *et al*., 2018; Šiaudinis *et al*., 2017, 2015) or more specifically at BBCH 11 (Facciotto *et al*., 2018).

Analysis of the macro-element composition of Sida showed a nitrogen content in the harvested stems of 7.9–12.8 g N DM kg^{-1}, which is the same order of magnitude as nitrogen found in the stems and branches of poplar SRC (Table 3.3). Hence, a dry matter yield of 10 t DM ha^{-1} would result in the removal of 79–128 kg N ha^{-1}. Molas *et al*. (2018) studied the effect of different doses and fertiliser compound on the final composition of Sida. They observed that the highest dose of nitrogen doubled the sodium content and that the use of K_2SO_4 (instead of KCl) reduced Cl (by 45%), as well as N and crude ash in the plants.

Table 3.3 - Reported values of the nutrient content of harvested stems and branches (g kg^{-1} DM) of *Sida hermaphrodita* (L.) Rusby compared to poplar short rotation coppice.

Nutrient	Sida			Poplar
	Antonkiewicz *et al.* [a] (2018)	**Sienkiewicz *et al.* [b] (2018)**	**Bilandžija *et al.* [c] (2018)**	
N	8.8	7.9–12.8	-	7.8 (Paris *et al*., 2015)
P	0.4	1.8–2.8	-	0.6 (Navarro *et al*., 2016)
K	2.5	17.5–24.7	11.3	3.9 (Navarro *et al*., 2016)
Mg	0.4	1.3–1.9	0.5	0.9 (Navarro *et al*., 2016)
Ca	3.4	18.4–22.6	7.6	13.6 (Navarro *et al*., 2016)
Na	0.2	1.2–2.2	0.02	0.18 (Navarro *et al*., 2016)

[a] Receiving sewage sludge (Poland); [b] Receiving digestate or mineral fertiliser (Poland); [c] No fertilisation (Croatia)

If Sida is used solely for bioenergy production, and not used in the food chain, sewage sludge and digestates from anaerobic digestion can provide effective alternative sources of nutrients from mineral fertilisers (Barbosa *et al*., 2014; Krzywy-Gawronska, 2012; Sienkiewicz *et al*., 2018). In Poland, Antonkiewicz *et al*. (2018) reported that applying 60 t DM of sludge per hectare to Sida increased the annual yield from about 8 t ha^{-1} to 14.8 t ha^{-1}. They concluded that Sida is capable of efficiently using the nutrients from sewage sludge. Czyzyk and Rajmund (2014) compared the application of sewage sludge and sludge compost to Sida and Miscanthus and reported that it increased soil organic matter. They reported that about 8–12% of the applied nitrogen was leached, with the amount of leaching being less under Sida than Miscanthus, suggesting that Sida was relatively effective in using the applied nitrogen.

In a similar way, Nabel *et al*. (2014) in Germany used biogas digestate from maize silage as a fertiliser for Sida and obtained large increases in yield, estimating the optimum digestate application to be 40 t ha^{-1}, containing about 0.5% nitrogen, i.e., 200 kg N ha^{-1}. Nabel *et al*. (2016) also reported that Sida yields from applying 160 kg N ha^{-1} using maize fermentation digestate gave similar yields to the equivalent mineral fertilisers. Moreover, the increased organic matter in the soil improved soil health and biodiversity and reduced the amount of nitrogen leaching. Subsequent work in a pot experiment has demonstrated the yield benefits of soil injection rather than broadcasting of digestates (Nabel *et al*., 2018a), and that the nitrogen content in Sida biomass can be further enhanced (+30%) by legume intercropping (Nabel *et al*., 2018b). Saletnik *et al*. (2019) has also successfully demonstrated that biochars, which can help with water retention, can also increase the growth of seedlings. The use of organic fertilisers was also recommended by Kurucz *et al*. (2018).

In relation to the soil nitrogen cycle, in a comparison of five crop species, Wielgosz (2010) found that soil below Sida had the highest amount of proteases. Proteases decompose proteins ultimately into amino acids, and the capacity of Sida to remove nitrogen from the soil was proposed as an interesting area for research.

3.3.2.5 Harvesting methods

To maximise yield, the stems of Sida are typically harvested at about 0.10–0.20 m from the ground (Borkowska and Molas, 2012; Molas *et al*., 2018). Although combine/forage harvesters are the most common harvesting equipment, alternatives are often used. Examples of machinery used to harvest Sida are: forage harvesters in combination with drum choppers or balers (Jasinskas *et al*., 2014a; Streikus *et al*., 2019), self-propelled harvesters (Pokój *et al*., 2015), mowers (Feledyn-szewczyk et al., 2019; Šiaudinis et al., 2015), or cutters (Šiaudinis *et al*., 2017).

3.4 Review of *Silphium perfoliatum* L.

3.4.1 Origin and Botany

Silphium belongs to the daisy family (Compositae/Asteraceae), originating in the Centre and East of the USA and Canada (Kowalski and Kędzia, 2007), and is extensively grown for forage in China (Zhang *et al*., 2010). For the rest of this paper, it is referred to as Silphium. Its lush foliage is composed of up to 3 m tall stems (von Gehren *et al*., 2016) and large leaves of 85–120 cm^2 (Franzaring *et al*., 2015). Its yellow flowers of 4–8 cm (Schorpp *et al.*, 2016a) make it an attractive decorative plant and is a reason it was brought to Europe in the 18th century (Kowalski and Kędzia, 2007; Stanford, 1990).

Silphium is typically not harvested in the first year of cultivation because the growth is concentrated on the development of a rosette. From the second year onwards, Silphium stems reach average heights between 1.5 m and 2.5 m (Pichard, 2012). It can produce high annual yields for 15 years (Stanford, 1990), with generous seeding and generally straightforward cultivation (Zhang *et al*., 2010). An alien plant survey carried out in Italy in 2009 classified this species as casual (Celesti-Grapow *et al*., 2009) and nine years later it was seen as a naturalised neophyte (Galasso *et al*., 2018).

In the Netherlands, an ecological risk assessment concluded that the species presented low invasive risk (Matthews *et al*., 2015). Some organizations in North America regard Silphium as an invasive species due to its fast development (CABI, 2017). However, after research and cultivation of Silphium in Europe, this species has not shown signs of invasive character (Haag *et al*., 2015).

Its potential as an energy crop to produce biogas began to be studied in Germany in 2009 (Gansberger *et al*., 2015a), and by 2014, the area of cultivated Silphium had increased to 400 ha (Biertümpfel *et al*., 2013, cited in (Gansberger *et al*., 2015a)). Gansberger *et al*. (2015a) concluded their literature review by classifying Silphium as a "valuable, alternative energy crop for biogas production plant with low care requirements and production costs after the first year, promising biomass and bio-methane yields, and associated environmental benefits". The environmental benefits of Silphium have recently been recognised by the EU, which includes Silphium in the list of eligible species for Ecological Focus Areas (European Commission, 2018).

Differences between Silphium cultivars are relatively un-researched. Comparing Silphium plants of five different origins, Wever *et al*. (2019) reported few genetic differences between plants from the USA, Russia, Scandinavia and Germany, but they varied from plants from Ukraine derived from a Ukrainian breeding programme. Wever *et al*. (2019) advised increasing genetic diversity and the application of genetic breeding and genomics to guarantee Silphium domestication and breeding.

Franzaring *et al*. (2014) studied the performance of six different accessions, finding high variation between them, with the most popular accession in Europe having the highest productivity. Hartmann and Lunenberg (2016) explored the theory of yield being dependent on site conditions in six locations across Bavaria, Germany. They did not discover any difference in yield between the three Silphium varieties that they included in their experiment.

As part of the work done during the international joint research SidaTim project (please refer to Acknowledgements for more details) a new BBCH scale was created for Silphium, as included in Appendix B, B.2 Supplementary material, B.2.2 *Silphium perfoliatum* BBCH-code.

3.4.2 Agronomy of *Silphium perfoliatum*

3.4.2.1 Agroclimatic Requirements

Silphium is a flexible crop, able to adapt to different conditions (Gansberger *et al*., 2015a; Pichard, 2012; Van Tassel *et al*., 2017). Stanford (1990) described its optimal growing conditions to be sunny places with temperatures of around 20 °C and sandy soils close to water sources. It is a resilient species, able to withstand flooding (10–15 days) and winter temperatures down to −30 °C (Koshkin, 1875; Niqueux, 1981, cited in (Stanford, 1990)). Depending on the initial pH, Silphium can show a positive response to liming. For example, Jasinskas *et al*. (2014b) observed a 34% yield increase and Šiaudinis *et al*. (2015) recorded a 23% yield increase, both raising the soil pH from 4.2–4.4 to 5.6–5.7.

Waterlogged fields are areas where traditional arable crops struggle and fail to be highly productive. Some authors have indicated that Silphium could be grown and is able to produce high yields in water saturated areas and poor draining land ((Stanford, 1990), Albretch and Bures, 199, cited in Han *et al*. (2000b, 2000a)). Other authors are more cautious with their statements; Zilverberg *et al*. (2016) mentioned that it tolerates moderate flooding while Bauböck *et al*. (2014) acknowledged the resistance of Silphium to water. This observation is supported by Ruf *et al*. (2019), who demonstrated that Silphium not only can withstand waterlogging but benefits from it, doubling the amount of biomass production after waterlogging during the winter period. Interestingly, they observed a strong effect of moisture availability on root biomass (free draining soils resulted in four times root biomass than excess moisture soils).

Maximum yields of Silphium are obtained where it has access to sufficient water, with yield reductions of at least 30% under drought conditions (Schoo *et al*., 2017a, 2017c). The high leaf area index and long growing season can result in high evapotranspiration rates. From a five year field experiment in China, Pan *et al*. (2011) estimated Silphium to have an average annual evapotranspiration (ET) rate of about 600 mm. Water needs of Silphium are equivalent to maize, between 200–250 mm during the growing season, and

400–500 mm for the rest of the year (Grebe *et al*., 2012, cited in Gansberger *et al*. (2015a)). Schittenhelm *et al*. (2016) calculated the ET of Silphium to be between 300 and 550 mm. Using an agronomic model, Schoo *et al*. (2017c) estimated an annual evapotranspiration rate of 309 and 542 mm for rain-fed and irrigated Silphium respectively, over two years in Lower Saxony, Germany.

As Silphium is a C3 plant, its water use efficiency of 30–36 kg (ha^{-1} mm^{-1}) is lower than a C4 crop like silage maize, showing 45–55 kg (ha^{-1} mm^{-1}). Hence, under conditions of limited water availability, the yields of Silphium are likely to be lower than those for maize. Schoo *et al*. (2017a) maintained that Silphium will only produce similar yields to maize in cool areas with high precipitation.

Schoo *et al*. (2017b) carried out a detailed study of the rooting system and water uptake of Silphium. They characterised the rooting system as woody rhizomes, which prolong into coarse distributed roots. Although roots were found at maximum depths of 1.5–1.7 m, the greatest density of roots was found in the upper 0.3 m. They observed that for a mature stand, the root depth remained stable, but a large proportion of the rooting system was renewed every year. They concluded that the limited expansion of roots constrained the capacity of Silphium to uptake water, which combined with high water consumption makes Silphium a crop with high water needs. Conversely, because Silphium is a C3 plant, it can produce higher yields than maize under cool conditions, and hence Schittenhelm *et al*. (2017) recommend its use for erosion control in cool and high altitude environments.

Franzaring *et al*. (2015) completed a detailed comparison of the responses of Silphium to increased temperatures, CO_2 concentrations, and drought. Compared to current climatic conditions in Germany, CO_2 fertilisation (550 cm^3 m^{-3}) had a positive response, increasing yield by 26%. In the same study, higher temperature (by 4 °C) and reduced water supply (by 50%), negatively affected growth dynamics and energy output. Specific methane yield (SMY) was found to have a negative correlation with protein content and the proportion of senescent leaves.

3.4.2.2 Establishment Method

3.4.2.2.1 Establishment by Sowing

Although Silphium can be established from seeds sown directly in the field, an important focus of research is to develop systems that can produce high-quality seeds with a high germination rate, that can achieve rapid field emergence (Gansberger, 2016). The ripening of the infructescence of Silphium seeds occurs irregularly and over an extended period due to the constant new formation of flowers, resulting in the harvesting of ripe, unripe, and sterile seeds (Gansberger, 2016). In addition, Silphium seeds are not homogeneous, complicating the singling process (Schäfer *et al*., 2016). The dimension of seeds varies between 9–10 mm long, 4.5–6 mm wide, and 1–1.5 mm thick, with an average weight of 16–20 g per 1000 seeds (Schäfer *et al*., 2018, 2017; von Gehren *et al*., 2016).

Standard commercial precision drillers can be used to sow Silphium (Köhler and Biertümpfel, 2016). Gansberger *et al*. (2015a) recommended using a precision seeder at 15–20 mm depth. The use of a precision seeder (model ED302) to sow Silphium seeds at 15 mm depth can enable uniform emergence (Schäfer *et al*., 2015). Von Gehren *et al*. (2016) proposed sowing at a more shallow depth of 10 mm. According to Köhler and Biertümpfel (2016), sowing depth is a compromise between sufficient deep storage (good water supply to avoid drying out) and sufficiently flat placement for high and fast field emergence rates as well as a good density. In light soils with poorer water supply and a low tendency to crust, sowing should be a maximum of 15–20 mm depth; whilst on heavy clay soils, soils prone to erosion, and silty soils with sufficient water, it is recommended that sowing depth should be 10–15 mm in depth (Köhler and Biertümpfel, 2016). Schafer *et al*. (2016) observed no significant differences between emergence and different sowing depths.

Schafer *et al*. (2016) adjusted a precision seeder, a pneumatic single-grain seeder type ED 302 Amazone equipped with six contour sowing units and a row spacing of 0.5 m. For their sowing trials, a spacing within the row of 0.16 m was chosen, corresponding to 6.4 holes in the row in combination with a row spacing of 0.5 m, leading to 12.8 holes per square meter (2.0–2.2 kg seeds ha^{-1}). Due to the high proportion of holes per square meter and the goal of maximum cover, single discs with a hole diameter of 1.2 mm were most suitable.

Continuing their previous research, Schäfer *et al*. (2018) studied the size, geometry, singling and their impact on germination ability and power of Silphium seeds. They observed significant differences in size between years, better germination of two fractions of seeds (second and third), and a correlation between the thousand seeds weight and germination power (best results at 18 g per 1000 seeds). Following their directions, a sowing rate of 12 seeds m^{-2} would be sufficient, reducing costs consequently.

For seeds, Köhler and Biertümpfel (2016) report that the optimal sowing time is not a specific date, but depends on the optimal soil and weather conditions to ensure rapid seed germination. On erodible soils, heavy rains after sowing may seriously delay germination or even lead to a total die back of the seedlings due to silting and crusting. Thus, reduced tilling can be beneficial at such sites where the seedbed meets the high requirements of Silphium (Köhler and Biertümpfel, 2016). Other authors have reported that sowing can be done two weeks before the first frost at the end of autumn (Gansberger *et al*., 2015a) or from April (Jasinskas *et al*., 2014b; Pan *et al*., 2011; Šiaudinis *et al*., 2015) to May in spring, but not later (Gansberger *et al*., 2015a). Recommended sowing densities vary substantially from 2.04–2.28 kg ha^{-1} (Schäfer *et al*., 2017) and 2.0–2.5 kg ha^{-1} (Gansberger *et al*., 2015a) up to 8–10 kg ha^{-1} (Han *et al*., 2000a; Pichard, 2012).

There are various ways of improving the germination rate of Silphium seeds. Von Gehren *et al*. (2016) compared five sowing dates between late April and mid-June and tested nine pre-treatments on the seeds, including seed pellets. The highest field emergences were recorded for the earliest sowing date, in late April, and cooling of seeds at 7 °C for 7 days. They recommend seed pelletization to improve mechanical sowing and advise early sowing. Gansberger (2016) described the seed ripening and the germination process of Silphium, developed a reproducible method for seed processing, and adapted the *Helianthus annuus* method to define the viability of seeds. His method was based on mechanical seed screening. He examined the effectiveness of sieving plus gravity precipitation to separate the most viable seeds. Using a screening machine with a set of rounded hole sieves (8.5 mm), followed by elongated hole sieves (3 mm and 1.5 mm) and a weight reader, and resulted in a minimum seed viability of 97.5%, filtering about 50% of the starting material at the end of the process. Gansberger *et al*. (2017), emphasized the need to treat Silphium seeds to increase germination and observed the positive effects of gibberellic acid, alternating light, and temperature regimes (12 h at 20/30 °C), and chilling to enhance germination capacity.

Schäfer *et al*. (2017) also recommend the screening out of small seeds to improve field germination. Incorporating such screening techniques should help improve the field germination of seeds. They also recommend the use of hygroscopic substances to coat the seeds to absorb moisture and avoid death of young seedlings by desiccation.
An existing biogas plant in south-west Germany recently developed and patented their own *S. perfoliatum* seeds with increased establishment success (von Cossel *et al*., 2020), under the name of Metzler and Brodmann Saaten GmbH (2020).

3.4.2.2.2 Establishment by Transplanting Seedlings

A Silphium field can also be established by transplanting seedlings grown in a nursery. Although this is expensive and time consuming (Schäfer *et al*., 2015), it is often more effective than using seeds of variable germination rates, because of the earlier and more regular development of ground cover and higher yields (Bauböck *et al*., 2014; Facciotto *et al*., 2018; Gansberger *et al*., 2015a; Schäfer *et al*., 2017, 2015). In Europe, seedlings should be established no later than May or early June (Gansberger *et al*., 2015a). Franzaring *et al*. (2015) sowed in trays in March, observing the germination after 22 days, or 9 days in case of increased temperatures (+4 °C), and then transferred the seedlings to the field in April at a density of 4 plants m^{-2}. Zilverberg *et al*. (2016) produced their seedlings in a greenhouse before transferring them to a field experimental site in mid-June.

Vegetable or strawberry planters are commonly used for the mechanical planting of Silphium seedlings (Schäfer *et al*., 2015). Spacing used between rows have varied from 0.5 m (Hartmann and Lunenberg, 2016; Pan *et al*., 2011; Schoo *et al*., 2017c) to 0.6 m (Pichard, 2012), 0.75 m (Gansberger *et al*., 2015a) and 1 m (Jasinskas *et al*., 2014b; Šiaudinis *et al*., 2017, 2015). The distance between plants inside rows has ranged from 0.12 m (Pichard, 2012) to 0.50 m (Gansberger *et al*., 2015a; Jasinskas *et al*., 2014b; Schoo *et al*., 2017c; Šiaudinis *et al*., 2017, 2015).

Slepetys *et al*. (2012) established their Silphium experimental area at 10,000 plants ha^{-1}. Šiaudinis *et al*. (2017, 2015, 2012), planted in early June at 20,000 plants ha^{-1}. Pichard (2012) selected a higher plant density of about 140,000 plants ha^{-1}. Zilverberg *et al*. (2016) left 30 cm between plants, which would correspond to over 110,000 plants ha^{-1}. Franzaring *et al*. (2015) and Gansberger *et al*. (2015a) both recommended a planting density of four plants per square meter, equivalent to 40,000 plants ha^{-1}. This planting density was also used by other researchers (Hartmann and Lunenberg, 2016; Schittenhelm *et al*., 2016; Schoo *et al*., 2017c, 2017b).

In the second year after planting, Silphium can produce 5–7 flowering stems per plant equating to about 38–40 stems per m^2 (Niqueux, 1981, and Puia and Szabo, 1985, cited in Stanford (1990)). Mueller and Dauber (2016) also reported about 6–7 stems by plant, whereas Gansberger *et al*. (2015a) reported 10–25 flowering stems per plant. The number of stems increases with age, with Šiaudinis *et al*. (2017) reporting 5–6 stems per plant on the second year of cultivation, increasing to about 12 stems per plant in the fourth year.

3.4.2.3 Weeds, Pests, and Diseases

Weed control is critical during establishment as Silphium seedlings are uncompetitive (Gansberger *et al*., 2015a). Köhler and Biertümpfel (2016) highlight that successful weed control in the first year is essential for high yields and the cost reduction of maintenance and weed control in the second year. Schorpp and Schrader (2017) describe the use of a cultivator for the mechanical control of weeds.

The place occupied by Silphium in the rotation can be important too. According to Köhler and Biertümpfel (2016), Silphium should follow weed-suppressing crops, e.g., root crops, cereals, as well as maize but should not follow unfavourable previous crops like rape, sunflowers, peas, vegetables, and potatoes because these are generally regarded as possible host plants for the fungal disease *Sclerotinia*.

Sclerotinia and *Botrytis* can affect the stems and flower buds of Silphium respectively (Niqueux, 1981, cited in Stanford (1990)). The susceptibility of Silphium to *Sclerotinia* spp. was also mentioned by Köhler and Biertümpfel (2016) and Gansberger *et al*. (2015a). Recently, a new species of fungi (*Ascochyta silphii* sp. nov.) causing dark spots on the leaves of Silphium was discovered in Austria (Bedlan, 2014), but the impact was not significant. Franzaring *et al*. (2014) noticed heavy wilting and necrotic spots on one out of four different accessions, suspected to be caused by the bacteria *Pseudomonas syringae*. Schoo *et al*. (2017c) applied boscalid and pyraclostrobin against *Botrytis cinerea*.

There are reports of three species of moth affecting Silphium leaves primarily: the silver Y moth *(Autographa gamma)*; the mouse moth *(Amphipyra tragopogonis)*; and the broad-barred white moth *(Hecatera bicolorata*) (Neumerkerl *et al*. 1978, cited in Gansberger *et al*. (2015a)). The larvae of the giant Eucosma moth (*Eucosma giganteana*)

(Johnson and Boe, 2011; Johnson *et al*. 2012, cited in Gansberger *et al*. (2015a)) and the tumbling flower beetle (*Mordellistena* cf. *aethiops* Smith) have been reported (Johnson *et al*. 2012, cited in Gansberger *et al*. (2015a)). Additionally, one species of aphid (*Uroleucon* cf. *ambrosiae*), a parasitoid wasp (*Acanthocaudus n.sp*.), and a fruit fly (*Neotephritis finalis*) are included in the reports (Johnson and Boe, 2011, cited in Gansberger *et al*. (2015a), Reinert *et al*. (2020)). Gansberger *et al*. (2015a) identified larvae of the giant Eucosma moth (*Eucosma giganteana* Riley) as the most concerning pest of Silphium.

3.4.2.4 Nutrient Management

Varying application rates have been used in experimental studies, ranging for nitrogen from 0 to 400 kg N ha^{-1}, rates of phosphate up to 175 kg P ha^{-1}, and potassium up to 237 kg K ha^{-1} (Table 3.4).

Table 3.4 - Reported fertiliser application rates of *Silphium perfoliatum* L. (in kg ha^{-1}).

N	P	K	Reference
150	-	-	Han *et al*., 2000b
100	80	100	Kowalski, 2007
92^{e}	79^{e}	66^{e}	Pan *et al*., 2011
0/60/120	26	33	Slepetys *et al*., 2012
0/60/120	26	33	Šiaudinis *et al*., 2012
200^{e}/0–400	0–175	55^{e}/110	Pichard, 2012
0/60/120	26^{e}	33^{e}	Jasinskas *et al*., 2014b
160	-	-	Emmerling, 2016
150^{e}	40^{e}	150–200^{e}	Frölich *et al*., 2016
170	30–41	199–237	Schoo *et al*., 2017b
0/60/120	26	33	Šiaudinis *et al*., 2017
140	-	25	Facciotto *et al*., 2018
50/100/150	21	27	Ustak and Munoz, 2018
90	13	33	Stolarski *et al*., 2019
60^{e}/40–80	35^{e}	80^{e}	Bury *et al*., 2019
60	60	60	Šiaudinis *et al*., 2019
100^{e}/150	-	-	Wever *et al*., 2019

^{e} establishment year exclusively

Jasinskas *et al*. (2014b) reported a yield benefit of 27% at a nitrogen application of 120 kg ha^{-1}, compared to the yield at 60 kg N ha^{-1}. Šiaudinis *et al*. (2012) tested different doses of ammonium nitrate, i.e., 0, 60, and 120 kg N ha^{-1}, the latter split in two doses between mid-April and end of July. The application of 120 kg N ha^{-1} produced the greatest yield, 21.94 t DM ha^{-1} y^{-1}. They repeated their experiment using the same fertiliser doses in a subsequent field experiment, this time harvesting 13.67 t DM ha^{-1} y^{-1} at the highest N dose. Han *et al*. (2000b) recommended applying 150 kg N ha^{-1} to Silphium. Pichard (2012) also found a significant yield response up to 100 kg N ha^{-1} with only moderate yield increases above this value. Pan *et al*. (2011) in China applied 92 kg N ha^{-1} in their experiment, an amount that was chosen based on the averages used by local farmers.

Applications of 26 kg P and 33 kg K ha^{-1} at establishment have been common in various trials (Slepetys *et al*., 2012). For phosphorus, the highest application of 175 kg P ha^{-1} (400 kg P_2O_5 ha^{-1} as a triple superphosphate) was reported in an experiment by Pichard (2012), and the results suggested that Silphium has very low requirements for P, having no impact on yield after a baseline is reached. By contrast, Šimkūnas *et al*. (2018) in Lithuania observed a negative effect on Silphium yields of an increased soil phosphorus concentration from 220 to 290 mg P_2O_5 kg^{-1}. In Germany, Frölich *et al*. (2016) recommended the application of magnesium in the year of establishment (50–70 kg ha^{-1} Mg), with organic fertilisation afterwards. The German specialist agency in renewable resources, *Fachagentur Nachwachsende Rohstoffe e.V.* (FNR) recommended the application of 50 kg N ha^{-1} in the establishment year, and 130–160 kg N ha^{-1}, 55–70 kg ha^{-1} P_2O_5, 180–240 K_2O, and 80–120 kg ha^{-1} MgO annually (Aurbacher *et al*., 2012).

Per unit dry mass, harvesting Silphium removes broadly similar amounts of nitrogen, phosphorus, and potassium as a maize crop (Lunenberg and Hartmann, 2016) (Table 3.5). According to the Thuringian State Institute of Agriculture (TLL), Silphium extracts 140–160 kg N ha^{-1}, 25–30 kg P ha^{-1}, 200–250 kg K ha^{-1}, 50–70 kg Mg ha^{-1}, and 250–300 kg Ca ha^{-1} (Conrad *et al*., 2009). Assuming a dry matter yield of 10 t ha^{-1} y^{-1}, the annual harvest of a Silphium crop would remove about 81 kg N, 21 kg P and 141 kg K. The levels of magnesium in harvested Silphium are significantly greater than in harvested maize, an observation also reported by Ustak and Munoz (2018). This could help explain why Frölich *et al*. (2016) applied magnesium fertiliser during crop establishment.

Table 3.5 - Mean concentration of five nutrients (g kg^{-1} DM) of harvested *Silphium perfoliatum* L. in comparison to silage maize (Lunenberg and Hartmann, 2016).

Species	N	P	K	Mg	Ca
Silphium	8.1	2.1	14.1	3.9	22.1
Silage maize	11.0	2.6	12.5	1.2	2.1

In a similar way to the work on Sida, studies on Silphium have indicated that some nutrients can be provided by application of digestates. For example, Ustak and Munoz (2018) applied 48.6 fresh tonnes of digestate per hectare (3.33 t DM ha^{-1}; 7.8% DM), but this was supplemented with mineral fertilisers to supply potassium, sulphur, calcium, magnesium, copper, cobalt, and boron. Šiaudinis *et al*. (2019) compared mineral fertilisation to granulated sewage sludge, recording better performance as well as increased soil quality and microbial activity at a granulated sewage sludge dose of 45 t ha^{-1}.

3.4.2.5 Harvesting Methods

Silphium plants are typically harvested at a height of between 0.05–0.10 m (Pan *et al*., 2011; Šiaudinis *et al*., 2015), 0.18 m (Pichard, 2012), and 0.2 m (von Cossel *et al*., 2020) above ground. Silphium, like Sida, can be cut with a great range of machinery including a rotary mower (Šiaudinis *et al*., 2012) or rotary reaper (Jasinskas *et al*., 2014b). Forage harvesters and balers are recommended by Jasinskas *et al*. (2014a). Von Cossel *et al*. (2020) also noted the use of a forage harvester on an existing commercial Silphium plantation. Standard maize harvesters are suitable for Silphium harvest (Franzaring *et al*., 2015; Gansberger *et al*., 2015a). Schoo *et al*. (2017a) used a single-row chopper attached to a tractor.

3.5 Use of *Sida hermaphrodita* and *Silphium perfoliatum* to Produce Bioenergy

Both Sida and Silphium can be used for bioenergy production. As perennial crops, the yields from Sida and Silphium increase during the first five years after establishment. However, the optimum timing of harvest and the associated dry matter and energy yields depends on the form of bioenergy production (Figure 3.1). In broad terms, both crops can potentially be used to produce (i) biomass for direct combustion or (ii) biomass to produce biogas. However, it is generally recommended that Silphium is used for biogas production only. There has also been research on the use of Sida for gasification.

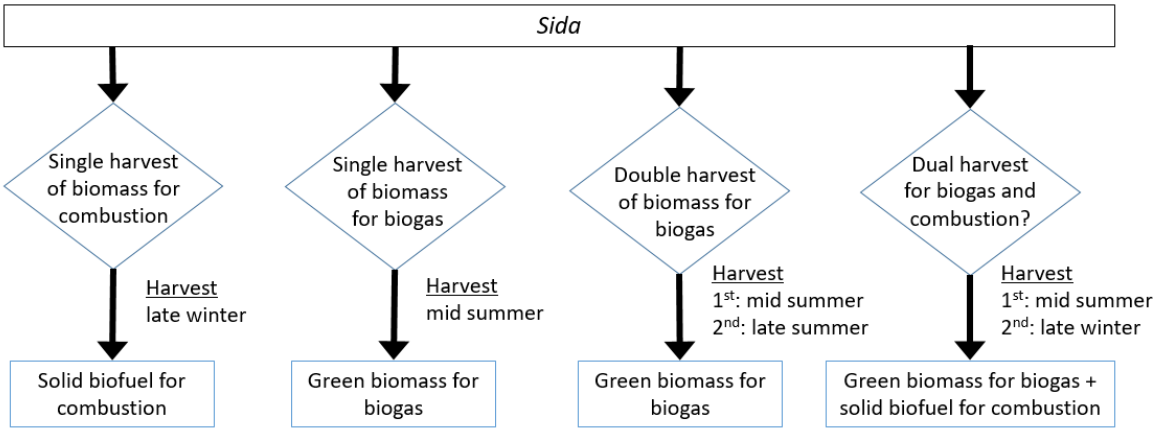

Figure 3.1 – *Sida hermaphrodita* (L.) Rusby can provide biomass for combustion or biomass for biogas; *Silphium perfoliatum* L. is generally only harvested as green biomass for biogas.

3.5.1 *Sida hermaphrodita* and *Silphium perfoliatum* Yields

3.5.1.1 *Sida hermaphrodita* Yield

The yield of Sida, for a given plant spacing, has been related to the number of shoots per plant and the mean diameter of the shoots (Matyka and Kuś, 2018). For Sida, yields vary greatly depending on soil type, climatic conditions, fertilisation, and weed control (Nahm and Morhart, 2018). Depending on the establishment method and intended use, yields in the first year of cultivation can vary from 0.4 to 6.6 t DM ha^{-1} y^{-1} (Facciotto *et al*., 2018). In the initial year, the dry matter yields obtained by harvesting biomass for combustion tend to be less than those obtained for biogas. In the first year, von Gehren *et al*. (2019) harvested 1.0–2.1 t DM ha^{-1} y^{-1} for combustion and 1.2–2.4 t DM ha^{-1} y^{-1} for a single cut for biogas production, and Facciotto *et al*. (2018) obtained 0.4–4.3 t DM ha^{-1} y^{-1} for combustion and 2.8–6.6 t DM ha^{-1} y^{-1} for biogas.

Mean annual yields tend to increase in the second and third year with values ranging from 2.9 to 20 t DM ha^{-1}. Facciotto *et al*. (2018) reported second year annual yields of 2.9–10.2 t DM ha^{-1} for combustion and. 2.9–15.1 t DM ha^{-1} for biogas. Other second year annual yields have been: 5 t DM ha^{-1} (Franzaring *et al*., 2015; Šiaudinis *et al*., 2017); 8.4 t DM ha^{-1} (Borkowska *et al*., 2009); 10.2–11.9 t DM ha^{-1} (Kurucz *et al*., 2018), and 20 t DM ha^{-1} (Jablonowski *et al*., 2017).

Mean yields in the second and third years continue to vary with establishment method and the sort of biomass harvested. Stolarski *et al*. (2014b) reported average annual yields from the second and third years of 10.4 t DM ha^{-1} from seeds, 11.2 t DM ha^{-1} from rhizomes, and 11.8 t DM ha^{-1} from seedlings. After the second year, the yield benefit of harvesting for biogas, rather than for combustion, seems to reverse. For the second and third year of Sida cultivation, Bury *et al*. (2019) recorded 5.8–10.7 t DM ha^{-1} y^{-1} for combustion and 6.0–19.5 t DM ha^{-1} y^{-1} for biogas. Siwek *et al*. (2019) obtained biogas yields of 9.2–15.1 t DM ha^{-1} y^{-1} and 4.8–8.5 t DM ha^{-1} y^{-1} on the second and third year respectively. Von Gehren *et al*. (2019) harvested respectively 7.1–9.7 t DM ha^{-1} y^{-1} and 13.2–14.3 t DM ha^{-1} y^{-1} on the second and third year of cultivation for combustion, and 6.6–9.5 t DM ha^{-1} y^{-1} (second year) and 7.3–8.6 t DM ha^{-1} y^{-1} (third year) for biogas production.

From the second to fourth year of cultivation, Tilvikiene *et al*. (2020) reported a mean yield of 12.30 t DM ha^{-1} y^{-1}. Jankowski *et al*. (2016) obtained a yield of 11.5 t DM ha^{-1} y^{-1} on the fourth year of cultivation. After the fourth year, yields typically plateau (Borkowska and Molas, 2013, 2012; Pszczółkowska *et al*., 2012). Borkowska *et al*. (2009) harvested 8.4 t DM ha^{-1} from the first to the fourth year. Molas *et al*. (2018) obtained on average 12.4, 8.8, 13.7 t DM ha^{-1} y^{-1} from the third, fourth, and fifth year of cultivation. Šiaudinis *et al*. (2015) obtained increasing yields of 4.7, 6.2, 6.0, 7.4 t DM ha^{-1} y^{-1} on the third, fourth, fifth, and sixth years of experiment respectively. Harvesting for biogas in a six years experiment, Jankowski *et al*. (2019) recorded average yields of

4.1–5.4 t DM ha^{-1} y^{-1} (increasing yield up to 9.4 t DM ha^{-1} y^{-1} on the third year and progressively reducing to 2.9 t DM ha^{-1} y^{-1} on the sixth year).

From a nine years experiment, Matyka and Kuś (2018) reported average yields of 1–2 kg DM m^{-2} y^{-1}, corresponding to 10–20 t DM ha^{-1} y^{-1}. From their fifteen years experiment, Krzyżaniak *et al*. (2018) report total yields from 42.9 t ha^{-1} (lowest) to 86.7 t DM ha^{-1} (highest), equivalent to 2.9–5.8 t DM ha^{-1} y^{-1} for the control and dried digestate fertilised options respectively.

Yields from a single annual harvest varied between 8 and 14 t DM ha^{-1} (Oleszek *et al*., 2013). Reported yields from double harvesting are 7–10 t DM ha^{-1} y^{-1} *(*von Gehren *et al*., 2019), 10–12 t DM ha^{-1} y^{-1} (2019), 15–20 t DM ha^{-1} y^{-1} (Oleszek *et al*., 2013). However, Oleszek *et al*. (2013) indicated that double harvests could reduce the life span of the crop in the long term. In line with this theory, von Gehren *et al*. (2019) observed a reduction in the yield after the second year from double harvesting of Sida for biogas production. Another possibility with Sida is dual harvesting, harvesting initially at BBCH 55 in summer for biogas production and then harvest a second time at BBCH 98 in winter for combustion (Jablonowski *et al*., 2017).

The highest Sida yields are obtained when it is grown on rich soils but not too heavy, with good water supply and aeration, under favourable weather conditions (Matyka and Kuś, 2018). Yields of 15–20 t DM ha^{-1} y^{-1} are reported for water-retentive clay loamy soils (Borkowska, 2007, cited in (Borkowska *et al*., 2009)), compared to 13 t DM ha^{-1} y^{-1} on clay sandy soils (Borkowska and Molas, 2013) and 8.4 t DM ha^{-1} y^{-1} on light sandy loams (Borkowska *et al*., 2009). Szwaja *et al*. (2019a) mentioned yields of 10 t DM ha^{-1} y^{-1} without including further details. Tilvikiene *et al*. (2020) reported an average of 12 t DM ha^{-1}. Feledyn-Szewczyk *et al*. (2019) harvested 17.7 t DM ha^{-1} y^{-1} as opposed to 14.5 t DM ha^{-1} y^{-1} from two plantations established by seedlings and seeds respectively.

3.5.1.2 *Silphium perfoliatum* Yield

For Silphium, a rosette is produced in the establishment year and the crop is not harvested. Flowering occurs from the second year, and maturity is achieved in the fourth-fifth year after planting (Stanford, 1990). Annual yields in the second year after planting range from 4.5–8.5 t DM ha^{-1} (Šiaudinis *et al*., 2012), 5.5 t DM ha^{-1} (von Gehren *et al*., 2016), 7 t DM ha^{-1} (Šiaudinis *et al*., 2015), 11.5 t DM ha^{-1} (Franzaring *et al*., 2015), to 9.5–26.6 t DM ha^{-1} (Facciotto *et al*., 2018). Siwek *et al*. (2019) obtained yields of 14.5/25.7 t DM ha^{-1} y^{-1} and 19.9/12.2 t DM ha^{-1} y^{-1} from single/double harvesting on the second and third year respectively. From three year Silphium plantations, reported annual yields vary from 7.5 t DM ha^{-1} (Slepetys *et al*., 2012), 10.2–18.0 t DM ha^{-1} (Bury *et al*., 2019), 13.5 t DM ha^{-1} (Šiaudinis *et al*., 2017), and 11.5–22 t DM ha^{-1} (Šiaudinis *et al*., 2012).

After the third year, yields can start to stabilise. Šiaudinis *et al*. (2019) harvested 5.5, 12.9, and 12.0 t DM ha^{-1} on the 2nd, 3rd, and 4th years. From the 2nd, 3rd, 4th, and 5th years, von Cossel *et al*. (2019) collected 17.3, 18.1, 21.7, and 27.8 t DM ha^{-1}. Šiaudinis *et al*. (2015) harvested 13.1, 13.5, 11.1, 12.4 and 8.2 t DM ha^{-1} on the 3rd, 4th, 5th, 6th and 7th year of experiment, respectively. These values are similar to predicted yields from the PIXGRO model developed by Ruidisch *et al*., (2015) ranging from 12.7 to 23.3 t DM ha^{-1} y^{-1} over a 10 year period. From two six-year old plantations Schorpp and Schrader (2016) harvested between 13–18 t DM ha^{-1} y^{-1}.

Mature reported Silphium yields range between 12 t DM ha^{-1} y^{-1} and 21 t DM ha^{-1} y^{-1}. Reported annual DM yields per hectare include 12–18 t (Ustak and Munoz, 2018); 13 t (Jasinskas *et al*., 2014b); 15 t (von Cossel *et al*., 2020); 15.6 t by double harvest (Šiaudinis *et al*., 2012); 15 t (Frölich *et al*., 2016); 15.5 t (Wever *et al*., 2019), 17.6 t (Conrad M., 2015, cited in Gansberger *et al*. (2015a)), and 15–21 t (Pichard, 2012). A yield of 18.3 t DM ha^{-1} y^{-1}, based on an actual average yield from East Central Germany, was used to calibrate the PIXGRO model (Ruidisch *et al*., 2015). Combining mineral and organic fertilisation, Vetter *et al*. (2010, cited in Gansberger *et al*. (2015a)) obtained 20 t DM ha^{-1} y^{-1}. Zilverberg *et al*. (2016) recorded 25 t DM ha^{-1} y^{-1}.

In their literature review, Gansberger *et al*. (2015a) noted a reduction in the yield of Silphium grown at high latitudes, explained by short growing season. They estimated an average yield of 15 t DM ha^{-1} y^{-1} and concluded that this species "can compete with current energy crops in terms of dry matter yield". However Franzaring *et al*. (2015) has highlighted that Silphium yields can increase when the crop is grown at high altitudes, perhaps because of the increased water availability. Hartmann and Lunenberg (2016) in a study of Silphium yields across six locations across Bavaria, Germany, also identified water availability and nutrient-rich soils as a key determinant for high yields, and Ruidisch *et al*. (2015) found a similar correlation with the yields of Silphium in a modelling study increasing from lowland to highland sites in Germany. Schittenhelm *et al*. (2016) also highlight the importance of water availability obtaining 16.1 t DM ha^{-1} y^{-1} from irrigated plants and 10.8 t DM ha^{-1} y^{-1} from non-irrigated plants.

The above yield results suggest that Sida and Silphium, in the correct environment and with the correct management, can achieve similar yields to other biomass crops such as maize and short rotation coppice. In their modelling study, Ruidisch *et al*. (2015) reported that Silphium (13–23.5 t DM ha^{-1} y^{-1}) could produce higher yields than silage maize (9.8–15.4 t DM ha^{-1} y^{-1}). However Schoo *et al*. (2017a) reported that Silphium could only achieve similar yield to maize in cool areas with high precipitation.

3.5.2 Growing *Sida hermaphrodita* and *Silphium perfoliatum* as Solid Biofuel for Combustion

An important positive aspect of bioenergy crops for combustion is the low moisture content of the biomass at harvest, simplifying the logistics of biomass. Because of this, biomass for direct combustion is best left to be harvested in winter when (i) the moisture content is reduced due to the absence of green leaves, and (ii) nutrients are reallocated back to the unharvested roots (Frölich *et al*., 2016).

Comparing the combustion of three tree species and three energy crops including Sida, Majlingová *et al*. (2018) concluded energy crops to be more advisable for the production of bioenergy, based on energy properties and yields.

Biomass quality for combustion is defined by its moisture content, which changes with harvest time. If Sida is to be used for biomass combustion, delaying harvest until the end of winter allows the material to dry on the field, lowering moisture and ash content (Bilandžija *et al*., 2018), achieving moisture contents of around 20% and, therefore, minimizing drying costs. In contrast, willow and poplar contain 45–60% moisture when harvested (DEFRA, 2004), which does not vary much with harvest date (Stolarski *et al*., 2014a). Pszczółkowska *et al*. (2012) and Šiaudinis *et al*. (2015) recommend that Sida stems for combustion should be harvested after late September and before the start of new growth in March. Harvesting late in winter enables the stems to naturally dry in the field as the moisture content can decline from 28–40% in November to 14–20% in February–March (Borkowska and Molas, 2013; Pszczółkowska *et al*., 2012). Stolarski *et al*. (2014a) compared five harvest times (November-April) and eleven energy crops. They recorded that spring harvested Sida had lower moisture content, lower ash and sulphur content, higher lower heating value (LHV), higher carbon content, higher hydrogen content, and generally was the highest quality solid fuel among all. In the same line, Bilandžija *et al*. (2018) compared three harvest times, obtaining lower moisture, ash, nitrogen, sulphur, and carbon, and higher fixed carbon contents in spring.

In their literature review, Nahm and Morhart (2018) reported average higher heating values (HHV) and lower heating values (LHV) for Sida of 18.4 MJ kg^{-1} and 16.1 MJ kg^{-1} respectively. The reported calorific value of Sida stems ranges from 15.0 (LHV) to 19.4 (HHV) MJ kg^{-1} (Table 3.6). At the upper range, this value is similar to industrial wood (BEIS, 2018).

Table 3.6 - Reported calorific value, and moisture, ash, and sulphur content of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. for biomass combustion.

		Calorific value (MJ kg^{-1})	Moisture Content (%)	Ash Content (%)	Sulphur Content (%)	Details	Reference
Sida	**Stems**	16.0 (CV)	-	-	-	December/April	Franzaring *et al*., 2014
		18.7 (CV)	14.1/5.9	-	-	chaff/mill	Jasinskas *et al*., 2014a
		18.7 (HHV); 14.9 (LHV)	18.0	2.4	0.029	April	Stolarski *et al*., 2014a
		19.2 (HHV); 15.0 (LHV)	20	1.8	0.03	March	Stolarski *et al*., 2018
		16.1 (LHV)	14.0	-	-	-	Kurucz *et al*., 2018
		18.7 (HHV); 15.6 (LHV)	32.2	2.9	-	-	Zachar *et al*., 2018
		17.6 (LHV)	18.6	1.9	0.23	spring	Bilandžija *et al*., 2018
		16.1 (CV)	9.9	-	-	-	Schonhoff *et al*., 2019
		17.0–17.7 (LHV)	19.0–23.6	2.1–5.1	0.024–0.042	BBCH 98	von Gehren *et al*., 2019
		18.0 (HHV); 16.6 (LWV)	10	1.57	-	-	Szwaja *et al*., 2019b
		17.3–19.4 (HHV)	-	-	-	-	Jankowski *et al*., 2019
		17.5 (HHV)-16.2 (LHV)	7.5	0.55	0	mill	Magdziarz *et al*., 2020
		17.8 (HHV)-16.5 (LHV)	6.9	1.97	-	-	Śliz and Wilk, 2020
	Pellets	17.5–18.4 (LHV)	9.6	6.1	0.17	-	Šiaudinis *et al*., 2015
		16.8 (CV)	7.7	2.9	0.07	-	Zajac *et al*., 2017
		19.5 (HHV); 16.5–17.2 (LHV)	12	2.7–3.0	0.024–0.028	-	Jablonowski *et al*., 2017
		17.4 (CV)	9.6	-	-	-	Streikus *et al*., 2019
		17.2 (CV)	7.1	-	-	-	Schonhoff *et al*., 2019
		17.5 (LHV)	7.8	2.6	-	-	von Gehren *et al*., 2019
Silphium	**Stems**	16.5 (CV)	-	-	-	September	Šiaudinis *et al*., 2012
		18.9 (HHV); 14.9 (LHV)	18.5	3.0	0.034	April	Stolarski *et al*., 2014a
		17.2–17.5 (CV)	15.2/8.2	-	-	chaff/mill	Jasinskas *et al*., 2014a
		18.8 (HHV); 14 (LHV)	22	3.4	0.04	March	Stolarski *et al*., 2018
	Pellets	17.2–17.5 (LHV)	11.6	10.0	0.07	-	Šiaudinis *et al*., 2015

HC: Heat of combustion; CV: Calorific value; HHV: Higher heating value; LHV: Lower heating value

If harvest is delayed too long, then the calorific value of the biomass can decline. Franzaring *et al*. (2014) observed a reduction in the calorific value from 17.4 to 15.8 MJ kg^{-1} when Sida stems were harvested in early December compared to mid-April. After monitoring the heating value of Sida for six years, Jankowsk*i et al*. (2019) noted an increase of the HHV with the age of the plantation (from 18.5 to 19.4 MJ kg^{-1}).

After harvest, the stems of Sida can be used to produce high quality pellets that meet the standards of solid biofuels (von Gehren *et al*., 2019) using common wood pellet production technology: chopping, milling followed by horizontal array granulator, and pressing (Jasinskas *et al*., 2014a; Streikus *et al*., 2019). The reported calorific values for Sida pellets range from 16.5 to 19.5 MJ kg^{-1} (Table 3.6). After combustion, they found minor slag formation and recorded ash to be around 3%. Von Gehren *et al*. (2019) obtained better quality pellets, lower energy consumption, and greater process stability after using a pan grinder mill and a flat die press. They suggested replacing artificial drying with storage, allowing Sida stems to dry naturally for six months. Urbanovičová *et al*. (2017) produced Sida briquettes using a hydraulic press, reporting a calorific value of 15 MJ kg^{-1}. They reported that the briquettes had a similar density, durability, moisture content, and calorific values as briquettes produced from other crops.

The ash and sulphur content of bioenergy crops can be a major constraint to their use in biomass burners, but the ash and sulphur content of Sida are remarkably low. Among more than 10 herbaceous plants as well as three woody species, Slepetys *et al*. (2012) found this species to contain among the lowest amounts of sulphur and the smallest of ash, i.e., 2.80%. Additionally, the ash composition after the combustion of Sida was studied (Jablonowski et al., 2017; Szwaja et al., 2019a). They attempted to characterize the ash melting point and were able to say that it is higher than 1500 °C. This suggests that issues of ash melting and deposition are less likely during the combustion of this material. Von Gehren *et al*. (2019) detected high levels of Ca and Mg in the ashes from Sida, indicating positive ash melting behaviour. Szwaja *et al*. (2019a) detected high levels of Ca, K, and P_2O_5. The fertilising potential of the ashes from the combustion of Sida need further investigation. In addition, Stolarski *et al*. (2018) demonstrated how moisture and ash content decrease in concentration, and how the heating value increases for both Sida and Silphium as the harvest date is postponed, improving in March.

The concentration of emissions originated during the combustion process of Sida pellets has also been investigated. In comparison to standard wood pellets, Zajac *et al*. (2017) observed that the combustion of Sida pellets produced very low sulphur dioxide emissions, lower CO_2 emissions, and higher concentrations of other pollutants (CO, NO, NO_x). Streikus *et al*. (2019) and von Gehren *et al*. (2019) both analysed the combustion of Sida pellets recording the composition of the gas emitted in the process, registering adequate levels of CO and NO_x, but high levels of particulate matter (PM).

Some studies have more recently focussed on the combustion process itself. Using a three pseudo-component model, Trinh *et al*. (2019) studied the kinetics of the thermal decomposition process of Sida, obtaining the derivative thermogravimetric (DTG) curves and kinetic data. Continuing the experiment, Werle *et al*. (2019) published the corresponding thermogravimetric (TG) and DTG curves, observing that variations in thermal composition between sites were caused by the different pH and heavy metal composition of the soils.

Calorific values for Silphium stems of about 16.5–18.9 MJ kg^{-1}, and for pellets values of 17.2–17.5 MJ kg^{-1} have been reported (Table 3.6). Wrobel *et al*. (2013) studied the mechanical durability and specific density of Silphium briquettes manufactured under different conditions. According to their experiments, crushing the plant material is adequate for briquette fabrication, observing a correlation between compaction pressure and durability. They concluded encouraging the use of this plant for briquette production, classifying it as a "suitable raw material". After considering chaff and mill fractional composition, Silphium was found more suitable for pelletizing than common mugwort (*Artemisia vulgaris* L.) (Jasinskas *et al*., 2014b).

Jasinskas *et al*. (2014a) used a drum chopper to harvest Silphium, followed by the use of a hammer mill and subsequent pressing for pelletizing, including a granulator with horizontal array, followed by evaluation of the fraction composition. They obtained moisture contents of 15.2% and 8.2% for chopped and milled material, respectively. Styks *et al*. (2020) studied the density and durability of Sida and Silphium pellets. They observed best results at a compaction pressure of 262 MPa and a moisture content of 8% for Silphium and 11% for Sida. Šiaudinis *et al*. (2015) analysed the fractional composition and pellet characteristics of both Silphium and Sida, obtaining moisture contents of 9.6% and 11.6%, respectively. They concluded recommending the use of the first species for biogas production and the second as solid biofuel.

3.5.3 Growing *Sida hermaphrodita* and *Silphium perfoliatum* as Green Biomass for Anaerobic Digestion

Sida has been recommended as biomass feedstock for the production of methane through the process of anaerobic digestion (Michalska *et al*., 2012). Silphium has been used in the same process in Germany, where extensive research has been conducted and where Silphium is seen as an interesting biogas feedstock alternative, as well as a complementary option to forage maize, from both an economic and ecological point of view (Frölich *et al*., 2016). Methane yields of Silphium differ only 5–10% from methane yields of maize (Ustak and Munoz, 2018). Frölich *et al*. (2016) introduced the patented idea of growing Silphium together with maize as cover crop.

The capacity of a biomass source to produce methane depends on the dry matter content, which determines the concentration of lignin, hemicellulose and cellulose, and ultimately the amount of carbohydrates, proteins, and fats. The higher the lignin, hemicellulose and cellulose contents, the lower the methane yield. The carbon nitrogen ratio in Sida varies substantially from 22.4:1 reported by Oleszek *et al*. (2013) to 198.8:1 reported by Slepetys *et al*. (2012); the carbon nitrogen ratio in Silphium ranges from 75:1 to 124:1 (Slepetys *et al*., 2012), as can be seen in Table 3.7.

Table 3.7 - Physicochemical properties of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. for anaerobic digestion.

	Sida							Silphium		Maize
Parameter	**Michalska *et al.*, 2012**	**Slepetys *et al.*, 2012**	**Oleszek *et al.*, 2013**	**Pokój *et al.*, 2015**	**Dębowski *et al.*, 2017**	**Rusanowska *et al.*, 2018**	**Dudek *et al.*, 2018**	**Slepetys *et al.*, 2012**	**Haag *et al.*, 2015**	**Pokój *et al.*, 2015**
Material			Silage	Silage	Silage	Silage	Silage		Silage	Silage
Time of harvest		October	July	Flowering	BBCH 55			October	August	BBCH 12
Dry matter, DM (%) [a]		51.0	25.55		37.43	28	27.60	38.5	24.65	
Organic dry matter, ODM (% DM) [b]			90.91		77.12	92.20	91.90		22.02	
pH			5.53		7.24	7.6–7.9				
C (%)	45.9	47.3	39.21	44.7	43.95 $C_{T\ org} = 39.77$	41.3	41.7	44.67		43.9
N (%)	0.3	0.34	$N_{org} = 1.68$ $N_{am} = 0.13$	1.5	0.28	0.5	0. 5	0.50		1.6
C:N		129.7–198.8	22.43		142.55			75.0–124.4		
S (%)	0.0	0.05						0.04		
Ash (%)	3.6	3.75	9.46			6.8 (%DM)		9.76	10.6	
Neutral detergent fibre, NDF (%)		81.17		60.2				69.83	54.9	40.0
Acid detergent fibre, ADF (%)		71.40		50.3				62.73	47.7	25.0
Lignin content (%)	19.1	12.60		8.5				12.97		3.6

[a] Dry Matter (DM) = Total Solids (TS); [b] Organic Dry Matter (ODM) = Volatile Solids (VS)

By contrast, biogas production is maximised if the biomass has appropriate quantities of sugars, proteins, and fats, hence the highest yields are typically achieved by harvesting the crop during the summer. Maximising biogas production requires that both crops are harvested at the right time. As the crop develops, the levels of acid detergent fibre (ADF) and neutral detergent fibre (NDF) vary, crude protein declines, and the proportion of dry matter tends to increase (Majtkowski *et al.*, 2009, cited in (Gansberger *et al*., 2015a). Early harvests also imply lower content of ash, ADF, NDF, and higher content of favourable compounds for anaerobic digestion (Franzaring *et al*., 2015), (Majtkowski *et al*., 2009, cited in Gansberger *et al*. (2015a)). Franzaring *et al*. (2015) reported that the specific methane yield from Silphium decreased with reduced water supply as the level of protein and crude ash increased. Increased concentrations of both ADF and acid detergent lignin (ADL) in Silphium have a negative influence on specific methane yield (Wever *et al*., 2019).

Reported biogas and methane yields for Sida and Silphium are summarised in Table 3.8. Biogas yields of Sida vary between 256 dm^3 kg^{-1} organic dry matter (ODM) (Jablonowski *et al*., 2017) and 730 dm^3 kg^{-1} ODM (Rusanowska *et al*., 2018) and methane yields vary between 131 dm^3 kg^{-1} ODM (Jablonowski *et al*., 2017) and 394 dm^3 kg^{-1} ODM (Rusanowska *et al*., 2018). Methane yields of Silphium vary between 227 dm^3 kg^{-1} ODM (Haag *et al*., 2015) and 315 dm^3 kg^{-1} ODM (Schittenhelm *et al*., 2016).

Sida can be harvested once or twice to produce biogas. Single harvesting Sida should be performed at the flowering phase in summer (Pokój *et al*., 2015), at BBCH 55 (Jablonowski *et al*., 2017), or BBCH 71 (Jankowski *et al*., 2019). Double harvesting is recommended to be done at BBCH 55 and 71 (Jablonowski *et al*., 2017).

Initially, the recommended harvest date of Silphium for the production of biogas was unclear. Some authors mentioned quite a wide window ranging from late August or early September (Schorpp and Schrader, 2016), to mid-end September (Šiaudinis *et al*., 2012), and some advised harvesting at the end of flowering, corresponding to BBCH 69,

Table 3.8 - Values of the biogas and methane yields from *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. reported in the literature.

	Details	**Biogas yield (dm^3 kg^{-1} ODM)**	**Methane yield (dm^3 kg^{-1} ODM)**	**Reference**
Sida	Double harvest	435	220	Oleszek *et al*., 2013
	BBCH 55	420	204	Jablonowski *et al*., 2017
	BBCH 77	269	131	Jablonowski *et al*., 2017
	BBCH 91	256	125	Jablonowski *et al*., 2017
	Novel reactor	630–730	340–394	Rusanowska *et al*., 2018
	Batch/Continuous	-	316/252	von Gehren *et al*., 2019
Silphium	BMP *	-	260	Gansberger *et al*., 2015a
	BMP	-	290	Franzaring *et al*., 2015
	CBT */HBT *	-	227/251	Haag *et al*., 2015
	-	-	296/315	Schittenhelm *et al*., 2016
	Batch	-	254–298	Ustak and Munoz, 2018
	HBT	-	266	Wever *et al*., 2019
	Batch	-	260	von Cossel *et al*., 2019
	Real biogas plant	-	300	von Cossel *et al*., 2020

* BMP = Biochemical methane potential; CBT = Continuous biogas test; HBT = Hohenheim biogas yield test

or at the start of seed ripening (Gansberger *et al*., 2015a; Ustak and Munoz, 2018) (BBCH 81). Depending on the harvest date, the dry matter content of harvested Silphium material ranges from 20–25% in spring (Šiaudinis *et al*., 2012) to 51% at the end of summer (Slepetys *et al*., 2012), and the dry matter content can be used to identify the best harvest date. More recently, some authors have recommend harvesting Silphium to maximise biogas production when the dry matter content is specifically 26–28% (Hartmann and Lunenberg, 2016) or 30% (Ruf *et al*., 2019).

Using Silphium for biogas production can also be done as a single or double harvest. Bury *et al*. (2019) harvested once in October. Double harvest has been recommended to increase yields (Šiaudinis *et al*., 2012). The harvest date for double harvesting vary in literature: mid-June (during early development of flower buds) and September (prior to the first frost) (Sokolov and Gritsak, 1972; Neumerkel, 1978, cited in Gansberger *et al*. (2015a)), mid-July and mid-October (Han *et al*., 2000b), July and October (Facciotto *et al*., 2018).

Compared to single harvesting, Siwek *et al*. (2019) obtained higher yields per ha after double harvesting on the second year but lower yields on the third year. This could indicate the same effect as observed in Sida: double harvesting might increase yields in the short term but be counterproductive in the long term, reducing yields in years to come. Pichard (2012) experimented with different harvest dates, obtaining their highest yields from single harvesting.

Regarding biogas and methane production based on kg^{-1} DM, Michalska *et al*. (2012) reported the production of 26.1 dm^{-3} kg DM^{-1} from the anaerobic digestion of Sida, producing biogas that contained 65% methane. Using a double harvesting strategy on a six year stand, Oleszek *et al*. (2013) produced biogas and methane yields of 99/50 dm^3 kg^{-1} FM (fresh mass), 395/201 dm^3 kg^{-1} DM.

Haag *et al*. (2015) compared the Hohenheim biogas test (HBT) and the continuous biogas test (CBT) for the anaerobic digestion of Silphium, obtaining average specific methane yields of 251 dm^3 kg^{-1} ODM and 227 dm^3 kg^{-1} ODM, respectively. Although the batch method produced higher amounts of methane, the results from the continuous method are considered more realistic and therefore recommended to use for further calculations.

Siwek *et al*. (2019) estimated the biogas yields per ha of both crops, Sida (double harvesting) and Silphium (single/double harvesting), based on their composition. From the concentration of crude fibre, crude protein, crude fat, and crude ash, they calculated the specific biogas and specific methane yields, 505–514 dm^3 kg^{-1} DM for Sida and 483–504 dm^3 kg^{-1} DM for Silphium. From those they obtained the methane content in the biogas (51.0–52.5%) and the methane yield per ha, accounting on average for 4759 m^3 ha^{-1} and 8598 m^3 ha^{-1} for Sida and Silphium respectively. They observed significant differences in plant composition depending on the weather conditions, the establishment method, and the harvest regime.

Von Cossel *et al*. (2020) recently published a case study of an existing biogas plant in Baden-Württemberg (Germany) that used a mix of Silphium, maize, manure, grass, whole-crop cereals silage and apple pomace. They analysed the effect of increasing Silphium cultivation from 44 to 70% of the cultivated area (replacing maize) using a SMY of 254 dm^{-3} kg^{-1} ODM in their calculations despite the reported 300 dm^{-3} kg^{-1} ODM obtained from the plant.

A variety of pre-treatments to increase biogas production have been applied prior to the anaerobic digestion of Sida: chemical hydrolysis (Michalska *et al*., 2012), chemical and enzymatic hydrolysis (Borkowska *et al*., 2001; Damm *et al*., 2017; Michalska *et al*., 2015), mechanical, chemical plus enzymatic hydrolysis (Goryachkovskaya *et al*., 2015), as well as various mechanical (Dudek *et al*., 2018; Rusanowska *et al*., 2018; Zieliński *et al*., 2019b), thermal (von Gehren *et al*., 2019; Zieliński *et al*., 2019a, 2017a, 2017b), and thermochemical treatments (Nowicka *et al*., 2019).

Ensiling of Sida is common practice prior to anaerobic digestion (Jankowski *et al*., 2016; Pokój *et al*., 2015). From their two-step hydrolysis of Sida, using 5% NaOH and the addition of both cellulase and cellobiase, Michalska *et al*. (2015) generated a biogas yield of 316.3 dm^3 kg DM^{-1}, containing 63% methane.

After the application of ultrasounds, Dudek *et al*. (2018) recorded highest yields from the fermentation of Sida together with cattle manure, obtaining 1011 dm^3 kg^{-1} ODM with a methane content 66–69%. Kisielewska *et al*. (2020) also demonstrated the effectiveness of ultrasound in increasing solubilisation and biogas production from a mix of Sida and cattle manure, obtaining methane yields of up to 337.9 dm^3 kg^{-1} ODM. After applying hydrodynamic cavitation to a mix of Sida and cattle manure for 20 min, Zieliński *et al*. (2019b) produced a maximum methane yield of 439.1 dm^3 kg^{-1} DM. They recorded the highest process efficiency for the 5-minute treatment, which increased biogas production by 30%.

Von Gehren *et al*. (2019) used heat to pretreat Sida before anaerobic digestion, increasing biogas yields by 23.6%-36.7% in the batch test and 13% in the continuous test. Nowicka *et al*. (2019) combined the application of microwaves and sodium hydroxide on the mix of Sida silage and bovine slurry, obtaining 1311 dm^{-3} kg^{-1} ODM. Zieliński *et al*. (2019a) compared the use of microwaves and hot water on Sida silage and cattle manure, producing maximum methane yields (at 150 °C, 15 min) of 590 dm^3 kg^{-1} ODM and 575 dm^3 kg^{-1} ODM, respectively. They developed two regression functions to calculate the methane and energy output for both treatments.

In terms of Silphium, Bauböck *et al*. (2014) used the BioSTAR model to determine that triticale and Silphium could produce comparable biomass yields as maize. Gansberger *et al*. (2015a) introduced the idea of ensiling Silphium prior to the production of biogas. This approach was tested by Haag *et al*. (2015) in their laboratory biogas experiments in which they incorporated seven varieties of Silphium using the HBT against a CBT. A continuous anaerobic digestion experiment was carried out by Vetter *et al*. (2007, cited in Gansberger *et al*. (2015a)) who co-digested 20% of Silphium with 80% of cow manure and obtained 185 dm^3 kg^{-1}. Comparing five origins, Wever *et al*. (2019) produced on average 266 dm^3 kg^{-1} ODM.

Some studies have focussed on improving the biogas and methane yield by mixing Sida with other biomass. Dębowski *et al*. (2017) mixed Sida silage and microalgae (*Chlorella* sp. and *Scenedesmus* sp.) at different ratios, observing increased biogas and methane yields, better C:N ratios, and a more stable anaerobic digestion process in general. The highest yields were obtained at 40% microalgae to 60% Sida and 60% microalgae to 40% Sida, achieving biogas and methane productions of 540–595 and 344–352 dm^3 kg^{-1} ODM respectively. Zieliński *et al*. (2017a) obtained the highest biogas and methane yields of 385 and 210 dm^3 kg^{-1} ODM respectively, from a hybrid bioreactor combining suspended sludge and immobilized biomass technologies.

In practice, Silphium is commonly used as a co-substrate to aid the fermentation of maize (Franzaring *et al*., 2015), producing methane yields of 292 dm^3 kg^{-1} ODM (Ustak and Munoz, 2018). Ustak and Munoz (2018) attributed the enhanced biogas yield to the improvement of overall digestibility of the anaerobic digestion process, due to the high concentration of macro and microelements in Silphium.

There have been studies of the composition of digestates obtained after the anaerobic digestion process. Pokój *et al*. (2015) compared the composition of 10 digestates, including Sida and maize (Table 3.9) as fertilisers in agriculture. Interestingly, Sida was the digestate containing the least amounts of heavy metals. The authors generally encourage the use of biomass digestates as fertilisers in agriculture.

Table 3.9 - Physicochemical composition of digestates from *Sida hermaphrodita* (L.) Rusby and maize.

Parameter	**Sida**		**Maize**
	Pokój *et al*. (2015)	**Sienkiewicz *et al*. (2018)**	**Pokój *et al*. (2015)**
DM (%)	3.66	4.04	3.39
ODM (% DM)	76.5		76.2
pH	7.35		9.96
Electric conductivity (mS cm$^{-1)}$	7.9		9.7
N (% DM)	1.8	0.07	4.1
P (% DM)	0.66		3.48
Available P (% DM)	0.50	0.11	0.44
K (% DM)	3.46	0.22	0.59
Mg (% DM)	0.37	0.00	3.62
Ca (% DM)	1.33	0.05	0.37
Heavy metals (mg kg^{-1} DM)	0.0 Cd, 8.4 Cu, 5.1 Ni, 0.0 Pb, 23.4 Zn		0.15 Cd, 81.6 Cu. 10.9 Ni, 0.0 Pb, 80.6 Zn

3.5.4 Using *Sida hermaphrodita* for Gasification

Gasification is a high temperature process that is used to convert carbon-based fuels (under conditions of low oxygen) to hydrogen, carbon dioxide, and carbon monoxide. It can be a sustainable way to produce hydrogen gas. Smoliński *et al*. (2011) compared the gasification of four biomass crops, including Sida, with lignite and hard coal. Through the gasification of biomass between 59–62% of the produced gas was hydrogen gas, compared to 59–94% from hard coal and 66–67% from lignite. Overall biomass gas yield was about half in comparison with coal gasification. Lower calorific values were recorded for biomass fuels, being 11.95 MJ kg^{-1} for Sida.

Steam gasification combined with Carbon Capture and Storage (CCS) can be a sustainable way to generate hydrogen (Howaniec and Smoliński, 2011). In their steam gasification experiment, Howaniec and Smoliński (2011) provide a calorific value for Sida of 15.03 MJ kg^{-1}. This experiment showed Sida to have the highest char reactivity for 50% carbon conversion, being also the quickest to achieve this point among the tested feedstocks. The addition of CaO for CCS was also tested, demonstrating to increase the hydrogen yield by 22–23%, as well as to increase the heating value by 22–27% at the lowest temperature (650 °C).

Through gasification it is possible to control the output emissions and destiny of heavy metals, minimizing emissions to the atmosphere and obtaining energy from heavy metal contaminated biomass (Pogrzeba *et al*., 2018). Werle *et al*. (2017a) studied the biomass of three bioenergy crops grown in contaminated land, including Sida, as feedstocks for gasification. Their results indicate the output gas of the three crops to have similar carbon, hydrogen, and oxygen composition, volatile matter and moisture content, with Sida containing the lowest amounts of ash. After a series of gasification experiments, they found Sida to be acceptable for gasification, with best results at an air ratio of 0.18:1.

Uchman *et al*. (2017) conducted a three-step experiment comprising a gasification test, a thermodynamic cogeneration analysis, and an economic analysis, including a sensitivity analysis of electricity and heat generation from Sida grown on contaminated land. They calculated a lower heating value of 19 MJ kg^{-1}.

Werle *et al*. (2017b) studied the gasification of Sida and seven other energy crops grown on contaminated land. They combined thermogravimetric analysis (TG) with spectroscopy (Fourier Transform Infrared, FTIR), concluding it is an “excellent and easy way to characterize biomass thermal treatment processes”.

Smoliński and Howaniec (2017) obtained 11.52% more volume of gas during gasification of Sida at 900 °C than at 700 °C. They observed that total gas volume increased in co-gasification of biomass as opposed to single feedstock gasification. The greatest volumes after the gasification of Sida were recorded for 40% *w*/*w* blends at 700 °C and the highest amounts of hydrogen gas were obtained after co-gasification of 20% *w*/*w* blends.

3.6 Alternative uses

3.6.1 Forage and Fibre

Sida was originally brought to Eastern Europe as a potential fodder plant, among other potential utilisation purposes. The potential replacement of traditional concentrate feedstock in the diet of cattle with a mix of 50% Sida and 50% *Vicia faba* L., was assessed by Tarkowski (2008). Chemical and nutritional properties of the resulting milk were equivalent, only finding 4% to 7% milk fat and protein increase. The author suggested this forage mix could complement traditional diets of dairy cows. Several authors described the fodder nutritional content of Sida and its similarity to alfalfa (*Medicago sativa* L.) (Borkowska and Styk, 2006, cited in Borkowska and Molas (2012), Antoszkiewicz *et al*. (2019)). Fijałkowska *et al*. (2017) also studied the silage produced from Sida after harvesting at the bud formation stage, in early-mid June, identifying that the species had a similar chemical constitution to alfalfa, as well as favourable protein and carbohydrate contents for cattle feed.

The concentration of beta-carotene, tocopherols, and vitamin E equivalent in fresh and silage Sida was analysed, detecting similar amounts to grasses and legumes (Antoszkiewicz *et al*., 2019). A higher content of beta-carotene and tocopherols in fresh Sida and variations accompanied with cutting height and harvest date, recording higher results when the material was cut at 35–45 cm and later harvest dates could be found.

Purwin *et al*. (2019) tested the inclusion of dehydrated Sida in the diet of rabbits, showing that it could replace up to 20% of dried alfalfa.

The potential of Silphium as a forage plant has been studied in Wisconsin since 1990 (Han *et al*., 2000b). If Silphium is to be used as fodder it can be harvested from mid-June (Han *et al*., 2000a) to mid-August, as late as possible before the first frost (Gansberger *et al*., 2015a). Stanford (1990) recommended dual harvesting to obtain high yields, doing the first harvest when the first flower buds open and the second when the first flower buds of the regrowth open. In their *in-vitro* experiment, Han *et al*. (2000a) found this species to have analogous digestion parameters to alfalfa, as well as high digestibility with maturity. According to Pichard (2012) double harvest slightly reduces the yield of the second harvest but increases its nutritional content.

Silphium is a rich and appealing forage for the first and second vegetative stages when digestibility is very high and crude protein contents are high, before protein levels decrease (Pichard, 2012). Silphium has been compared with alfalfa, red clover (*Trifolium pratense* L.) (Pichard, 2012), and maize (Stanford, 1990) in terms of production and chemical composition. Although these species have higher nutritional value they are not productive for so long (Pichard, 2012).

A very effective way of preserving fodder is ensiling, but the ensilage of crops containing low dry matter content at harvest deteriorate easily. Dry matter content varies with harvest date and can increase if the material is left to dry on the field. Han *et al*. (2000b) studied the influence of different moisture contents on the fermentation components of Silphium harvested in June and October. They found moisture management crucial to produce high quality silage from Silphium, benefiting from drying on the field for 48 h, which increased DM by 42%. Piłat *et al*. (2007) observed that ensilaged Silphium forage had the most suitable fermentation coefficient of 36.54, when collected at the beginning of seed setting (125 days after start of regrowth).

The potential use of Sida as a source of fibre for the paper and pulp industry is also mentioned in the literature (Spooner *et al*., 1985). After studying more than ten herbaceous plants and three woody species, Slepetys *et al*. (2012) found Sida to contain the highest amount of fibre.

Klímek *et al*. (2016) have demonstrated the suitability of Silphium stems to be used to manufacture particleboards of standard density, 600 kg m^{-3}. Despite displaying weaker mechanical properties than boards made of spruce (*Picea abies* L.) particles, particleboards using methylene diphenyl diisocyanate (MDI) as adhesive, still met the Class P2 EN312 standards for general-purpose items in dry conditions.

According to Martens (2017), Sida also has the potential to be used in the manufacturing of natural fibre products, such as alternative turf, and it could even be used as raw material to produce 3D printing resin. Rumpf *et al*. (2020) found that through organosolv pulping, they could achieve a high quality lignin yield of 15.7% from Silphium that could be used to manufacture biodegradable plastics.

3.6.2 Other uses

Extracts from Sida seeds have shown antifungal properties against *Candida albicans* (Lewtak *et al*., 2019). Potentially useful biosurfactants were isolated from a bacteria (*Pseudomonas putida* E41) extracted from Sida roots (Bernat *et al*., 2019). Disposing of heavy metal contaminated biomass can be done through the production of biochars. To reduce leaching risk of toxic metals and improve oxidation resistance and carbon stability of Silphium biochars, Du *et al*. (Du *et al*., 2019) recommended using higher pyrolysis temperatures (750 °C).

The use of biochars as a soil amendment is becoming increasingly popular. The production of biochars from Sida has been studied. Madej *et al*. (2016) recorded high quality and low content of polycyclic aromatic hydrocarbons (PAHs) in the biochar obtained from several crops, including Sida. After elemental analysis of the biochars, they concluded that the material met the standards of the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI). They suggested that the continuous removal of syngas via continuous nitrogen flow could be the key to obtaining low PAHs.

Bogusz *et al*. (2015) investigated the adsorption properties of the biochar produced with *Triticum* straw and Sida to remove Cd, Cu, and Zn from contaminated water. They found both materials to be suitable for the purpose, but the biochar from Sida was more effective at capturing heavy metal ions. They propose the use of this biochars to lock up these substances in contaminated soils.

From a strong positive correlation between the carbon content of Sida biochars and the acetic acid of the condensate, Szwaja *et al*. (2019b) obtained a polynomial function useful to supervise the quality of the biochars during the torrefaction process. They also found a negative correlation between carbon and hydrogen content of biochars and a negative correlation between the ash content and volatile matter of biochars. Szwaja *et al*. (2019a) focussed on the composition of biochar and condensate, noticed how it is affected by torrefaction temperature, and established that such temperature should not go above 400 °C. They suggested potential chemical usefulness of the condensates.

Hydrochars are a form of char produced via a different production process. Magdziarz *et al*. (2020) investigated the production of hydrochars through hydrothermal carbonization of Sida. They characterised both the hydrochars and resulting liquid, using thermogravimetric and gas chromatography analyses to study the combustion and pyrolysis of the hydrochars. Śliz and Wilk (2020) analysed the fuel properties of hydrochars produced from Sida at different temperatures and different reaction times, using a number of analyses, observing combustion behaviour and surface changes. Von Cossel *et al*. (2020) described how digestates from anaerobic digestion could be treated using hydrothermal carbonization, followed by acid leaching and struvite precipitation to recover phosphorus.

A wide range of useful chemical substances have been isolated from Silphium leaves, stalks, inflorescences, and rhizomes with potential applications in different industries (Kowalska *et al*., 2020). Only for the pharmaceutical sector the following substances have been studied: sesquiterpenes from roots (Paquette and Leone-Bay, 1983), trypsin from seeds (Konarev *et al*., 2002), flavonoids from leaves (El-Sayed *et al*., 2002), sesquiterpenoids (Blay *et al*., 2006), phenolic acids (Piłat *et al*., 2007), alcohol extracts from roots (Kowalski and Kędzia, 2007), and oleanolic acid from leaves (Kowalski, 2007). Feng *et al*. (2014) even isolated a kaempferol trioside from the aerial parts of Silphium and proved the efficiency of this substance to inhibit and delay the proliferation of certain carcinogenic cells in laboratory conditions.

Silphium has potential application in multiple industries, such as construction (Wever *et al*., 2019), pharmaceutical, agrochemical industry, or the food industry. The following substances contained in Silphium have been investigated:

- lipophilic substances from leaves, inflorescences, and roots (Kowalski, 2005);
- essential oils (Kowalski and Wolski, 2005);
- phenolic acids, oleanolic acids, ursolic acids, amino acids, flavonoids, terpenes, and essential oils from roots and seeds (Jamiolkowska and Kowalski, 2012; Kowalski, 2009; Kowalski and Wolski, 2003);
- stabilizers: Kowalski (2009) verified the stabilizer action of extracts from three Silphium species on fatty acids of sunflower oil. Their research shows the extracts to have a similar effect to artificial stabilizers, even outperforming them in some cases, such as Silphium rhizome extracts after 120h heating of the sunflower oil;
- triterpenoid glycosides: Davidyans (2011) demonstrated the effect of them on seed germination, noticing that these compounds increased α-amylase and total amylase activity, as well as total protein content;
- saponins: obtained from Silphium leaves reduced cholesterol from 12–19% in rats (Syrov *et al*., 1992, cited in Oleszek *et al*. (2019));
- anti-fungal properties: Zabka *et al*. (2011) found inhibitory effects of extracts made from Silphium leaves on *Fusarium oxysporum, Fusarium verticillioides, Penicillium*

brevicompactum, Aspergillus flavus, and Aspergillus fumigatus. Jamiolkowska and Kowalski (2012) tested the antifungal properties of alcohol extracts from Silphium leaves on common fungal pathogens of pepper plants, obtaining very positive results and recommending its use for the creation of an organic antifungal control product. The highest growth inhibition was observed on *Alternaria alternata* and *Colletotrichum coccodes*, followed by *Botrytis cinerea* and *Fusarium oxysporum*;

- polysaccharides: Shang *et al*. (2017) studied both extraction and drying methods and their antioxidant properties. They estimated the parameters for extraction of the highest number of polysaccharides and indicated freeze-drying as the best drying process to preserve antioxidant properties. Wu *et al*. (2020) compared a variety of extraction methods and the antioxidant properties of the resulting polysaccharides, identifying the enzyme-assisted extraction method as most effective. Based on this result, Guo *et al*. (2020) used the enzyme assisted extraction method and a purification method to isolate a polysaccharide with antioxidant as well as hypoglycaemic abilities;
- proteins: von Cossel *et al*. (2020) described a protein extraction process from Silphium, suggesting that the residues after extraction could then be used in a biogas feedstock mix. They calculated that it is possible to extract 1479 kg of crude protein per ha from Silphium. They suggested this could increase the economic output of farms and create positive environmental impacts by reducing the use of soya for protein (von Cossel *et al*., 2020).

Kowalski and Kędzia (2007) also mentioned the use of the execrated resin and whole Silphium plants in traditional American Indian medicine to treat numerous illnesses, as well as studies done in the late 1980s and 1990s that demonstrated regenerative, anti-cholesterol, anti-sclerotic, and antifungal properties. Silphium was selected among 24 other native perennials for its aptitude to attract natural enemies against common pests as the plant develops, outperforming commonly used annual exotics (Fiedler and Landis, 2007).

3.7 Environmental benefits

3.7.1 Phytoremediation and phytostabilization

Spooner *et al*. (1985) reported the ability of Sida to grow on disturbed environments, like land on the sides of roads and railways, where it could help with soil stabilisation. Zhang *et al*. (2010) mentioned that Silphium could be used for the same purposes. Borkowska *et al*. (2001) compared the heavy metal intake of four bioenergy species including Sida. Under the experimental conditions, Sida produced the highest yield (6.8 t DM ha^{-1} y^{-1}) and it captured the most heavy metals. Sida was also reported to improve the soil structure (Borkowska and Wardzińska, 2003). Sida has also been quoted as a candidate plant species, in an examination of the effect of laser radiation on the uptake of heavy metals by plants (Dobrowolski *et al*., 2012).

Krzywy-Gawronska (2012) monitored the content of heavy metals in Sida under various fertilisation programs. Intense bioaccumulation was found for Cd, Cu, Ni, Pb, and Zn when fertilized with high calcium brown coal ash; for Ni, Pb, and Zn when fertilized with municipal sewage sludge compost and high calcium brown coal ash; and for Pb when fertilized with sewage sludge compost. She concluded that Sida displayed average to intense capacity for the absorption of heavy metals. Among the fertilizing programs, she found that the application of sewage sludge generally favoured the uptake of larger quantities of heavy metals.

Wierzbowska *et al*. (2016) compared the use of wet sewage sludge and pelleted sewage sludge to traditional nitrogen and phosphorus mineral fertilisation. Potassium was added in the form of potassium chloride. They sorted the accumulation of heavy metals on the aerial parts of Sida from highest to lowest as follows: Cd > Cu > Cr > Ni > Zn > Mn. They found that two forms of sewage sludge promoted the accumulation of higher quantities of certain heavy metals than mineral fertilisation on both the plant biomass and the soil. After their literature review on the phytoremediation potential of several energy crops, including Sida, Prelac *et al*. (2016) expressed the outstanding potential of this species to remove Cd, Ni, Pb, and Zn plus its storage capacity of Cr and Cu.

Kocoń and Jurga (2016) compared the bioaccumulation factors of Sida and Miscanthus *x giganteus* on two types of soil. Sida accumulated more Cd, Cu, Ni, Pb, and Zn in aerial parts during the first year of cultivation on loamy soils. The crops performed better on sandy soils, giving 4.4 and 2.6 times more yields respectively, and accumulated higher quantities of Zn but lower quantities of Cd. Since the bioaccumulation factor is the ratio of heavy metal concentration in the aerial parts to the heavy metal concentration in the soil, it does not account for the accumulation of heavy metals in the roots of plants. This could potentially have a significant impact on the results and should be taken into account in future research.

Antonkiewicz *et al*. (2017) compared the phytoextraction potential of Sida and *Rosa multiflora* var. 'Jatar'. They noticed that the amounts of heavy metals extracted from the soil that had been fertilized with sewage sludge, increased with the dose of sludge and the yield of plants. However, the highest percentage of heavy metals recovered was associated to the lowest sludge dose. These results could indicate that high levels of heavy metal accumulation can become toxic and reduce the effectiveness of removal. The authors ranked the efficiency of Sida to uptake heavy metals in the following decreasing order: Cd > Zn > Ni > Cr > Cu > Pb.

Antonkiewicz *et al*. (2017) additionally studied the activity of microorganisms in the soil under Sida, which was confirmed to be positively influenced by the use of sewage sludge. They recorded increased levels of enzymatic activity with increasing sludge doses and found a correlation between enzymatic activity and heavy metal uptake.

Pogrzeba *et al*. (2018) compared the heavy metal bioaccumulation factor between two types of arable land, heavy metal contaminated and sewage dewatering. They observed that Sida was able to extract 12 and 18 times more Cd and Zn (bioaccumulation factors of 0.21–0.55 and 0.23–0.86) from heavy metal contaminated land, with a 7% higher LHV. Werle *et al*. (2019) compared and characterised the plant composition of Sida grown on heavy metal contaminated arable land in Poland, and a former sewage sludge dewatering site in Germany. They observed variation in plant composition and the thermogravimetric analysis due to differences in soil. Khanh-Quang *et al*. (2020) however, found higher phytoextraction potentials for Miscanthus compared to Sida and provided kinetic parameters to use as model and system design inputs.

In one contaminated soil experiment (Zhang *et al*., 2010) Silphium showed evidence of Zn to be detrimental for its growth. Zhang *et al*. (2010) found Silphium capable of storing Cd in the rhizomes without it spreading to the rest of the plant, exhibiting high tolerance to this heavy metal. Wrobel *et al*. (2013) also mentioned the potential of Silphium to restore degraded areas.

3.7.2 Biodiversity and Pollination

Because Sida and Silphium are perennial crops present throughout the year, they provide relative stable habitats for a range of earthworms and small animals. Silphium can contribute about 8 t DM ha^{-1} y^{-1} of litter (Schittenhelm *et al*., 2016), and this can be positive for the diversity and activity of soil organisms. Chmelíková and Wolfrum (2019) recorded the beneficial effect of Silphium cultivation on arthropod diversity. Emmerling (2014) and Schorpp and Schrader (2016) report that Silphium increased the number and species of earthworms compared to arable crops. Although the highest numbers were found in grasslands, Burmeister and Walter (2016) also reported a six-fold increase in the density of earthworms in Silphium rather than arable plots. A study in the Czech Republic (Heděnec *et al*., 2014) suggests that novel species such as Silphium may result in lower abundance of soil meso- and macrofauna than indigenous perennial crop species such as willow and reed canary grass (*Phalaris arundinacea* L.).

Schorpp *et al*. (2016a) in Germany found a greater abundance and double the number of springtail (Collembola) families under Silphium plants, compared to maize. Although Silphium did not increase the diversity of nematodes, compared to maize, they observed more herbivorous and fungivorous species and less bacterivorous species. Although high numbers of the plant parasitic nematode *Helicotylenchus* spp. were reported, these did not have an impact on yield. A follow-up paper by Schorpp and Schrader (2017) ratified the above mentioned results and provided evidence that the most stable food webs occurred in the oldest plots. They suggested that changes in the fungal decomposing pathway and slower nutrient cycling was related to an increase in soil fertility.

Whilst weeds are detrimental to biomass yields, the presence of some weeds can help support farmland biodiversity. Feledyn-Szewczyk *et al*. (2019) monitored weed density and species associated with energy crops, including Sida, compared to arable crops. They registered an increase of 11% in perennial species, 10% in ruderal species, 7% in grassland species, and 4% in forest species.

Both Sida and Silphium produce a great number of flowers. Sida provides an extended source of food for pollinators due to its long flowering season. Blooming from early summer till the first frost in autumn (Kurucz *et al*., 2018; Spooner *et al*., 1985), Sida can be used to produce from 110 kg to 315 kg of honey per ha (Borkowska and Styk, cited in Pszczółkowska *et al*. (2012). From a three year experiment, Jabłonski and Kołtowski (2005) reported that Sida can produce an average of 230 kg of honey ha^{-1}. Kurucz *et al*. (2014) indicated the direct correlation between precipitation and flowering of Sida, consequently affecting seed formation. Franzaring *et al*. (2015) also observed that flowering was greatest with higher temperatures and rainfall.

Silphium provides a long blossoming season for pollinators from July to September (Fiedler and Landis, 2007), with highest flower abundance in August (Mueller and Dauber, 2016). Silphium produces 10–25 flowering stems and 8–10 flowers from each stem (Gansberger *et al*., 2015a), and the number of flowers produced per plant each season is between 64 and 250 flowers. After monitoring the entire flowering period, Mueller *et al*. (2020b) calculated an average of 188 flowers (inflorescences) per plant each season and highest pollen and nectar production during the second fortnight of August. They calculated that a single flower (inflorescence) of Silphium produces 1.75 ×

10^6 pollen grains on average, 12.5×10^{12} pollen grains per ha, and 80 kg of nectar sugar per ha each season, potentially providing for 34 honey bee larvae per season, and 6 worker honey bees per day. They analysed the composition of pollen and nectar, recording low levels of total amino acids but high levels of specific essential amino acids. They recommend postponing the harvest of Silphium to the end of flowering to maximise the flowering window for pollinators, whilst combining Silphium with other flowering crops to provide a rounded diet. According to Schorpp *et al*. (2016a), this species produces from 14,106–14,200 pollen grains per inflorescence. Considering the average amount of inflorescences per plant to be 150 per season, they calculated that this species produces 2.12–2.13 million of pollen grains per inflorescence. They also calculated that every flower contained 0.09 mg of sugar in its nectar produced per day (each flower head/inflorescence has 117–128 tubular flowers), as opposed to the lack of pollen/nectar in maize. Mueller *et al*. (2020a) studied the effect of different water regimes on floral resources and pollinators, finding more inflorescences, more nectar sugar, double visits from honeybees, and later maturation in irrigated, rather than rainfed, Silphium plants. The use of Silphium as an ornamental and melliferous (i.e., honey producing) plant is often mentioned in literature, having demonstrated to produce about 560 kg on average of honey per hectare (Jabłonski and Kołtowski, 2005). The flowering ability of Silphium could be valuable from a landscape perspective.

Compared to maize, Silphium produces nectar and pollen for pollinators (Mueller *et al*., 2020b, 2020a). Burmeister and Walter (2016) recorded honeybees (*Apis mellifera*), bumblebees (*Bombus* spp.), and members of several other families including hymenoptera, syrphidae, diptera, coleoptera, and lepidoptera. In Germany, Mueller and Dauber (2016) demonstrated the benefit from the cultivation of Silphium on farms for hoverflies, counting a total of 30 species. Microphagous hoverflies such as *Eristalis tenax* benefited from the semi-natural habitat, and zoophagous hoverflies benefited from increased crop diversity.

A particular feature of Silphium is the capacity of the leaves to capture rainfall next to the stems; Schoo *et al*. (2017c) estimated the amount of water contained in these cups is about 4 mm per month, representing only about 2% of total evapotranspiration (ET), being most likely an adaption to provide water for pollinators. For all the above mentioned positive effects on biodiversity, Schorpp *et al*. (2016a) classified Silphium as a more sustainable crop for bioenergy than silage maize.

3.7.3 Soil Health Regulation

Sida and Silphium can result in less soil erosion and less use of pesticides than bioenergy crops such as maize. The perennial nature of the crop means once the year of establishment has passed, there is very little soil disruption, and field operations are restricted to fertilisation and harvest (Gansberger *et al*., 2015a; Haag *et al*., 2015; Ruidisch *et al*., 2015; Schorpp *et al*., 2016a). After the first year, if the crops establish a full canopy, weeds are suppressed (Frölich *et al*., 2016) which minimises the need for herbicides.

Both Sida and Silphium are a good crop choice in areas where nitrogen leaching is an issue. This is due to the capacity of the crops to take up nitrogen and the relatively low fertilisation and pesticides needs (Pichard, 2012; Pszczółkowska *et al*., 2012). Intercropping with legumes has been reported to reduce nitrogen application and leaching (Nabel *et al*., 2018b), however often aspects of the effects of Silphium on soil nitrogen dynamics are complicated. Under laboratory conditions, Schorpp *et al*. (2016b) observed that NO_2 emissions increased under Silphium due to the increased denitrification induced by enhanced anecic earthworm population. They recommended that field experiments were needed to study the actual impact of Silphium on emissions of nitrogen oxides. According to Ruf *et al*. (2019), the use of Silphium on waterlogged conditions lead to improved shoot-root gas exchange and root exudation of sugars and amino acids, which induced higher microbial activity.

Beyond farmland, there may also be a role for Sida in terms of directly controlling soil erosion and flooding. Flood plains are among the natural habitats of Sida (Spooner *et al*., 1985), making it an ideal candidate to be included in flood mitigation strategies. Stolarski *et al*. (2014a) observed Sida to withstand flooding relatively well compared to ten other energy crops. In addition the benefits of perennial crops for earthworms (see previous section) can in turn have positive effects on soil aeration and water infiltration, thus reducing erosion and run-off (Schorpp *et al*., 2016a; Schorpp and Schrader, 2016).

Integrated on farms, Silphium could help support the biological control of common agricultural pests (Fiedler and Landis, 2007). Initial research suggests that Silphium is not a host to European corn borer (*Ostrinia nubilalis* Hübner) or the Western corn rootworm (*Diabrotica virgifera* LeConte), important maize pests.

In general, the lack of annual cultivation would be expected to result in an increased level of soil carbon compared to an annual crop where cultivation occurs annually (Emmerling, 2014). Schoo *et al*. (2017b) recorded that an average of 8.4 t DM ha^{-1} is produced from Silphium roots alone, which was double that of silage maize roots (4.0 t ha^{-1}). Where Sida or Silphium receives organic fertilisation, this can further increase soil carbon (Nabel *et al*., 2017, 2014; Šiaudinis *et al*., 2019).

Ruf *et al*. (2018) examined the organic carbon, microbial biomass, and aggregate stability of three different land use systems, with permanent grassland ranking highest, followed by perennial energy crops (including Sida and Silphium), and lastly annual energy crops. For a six-year perennial energy plantation, they found positive correlations between soil organic carbon and clay content, rooting depth, microbial biomass, and age of plantation. Negative correlations were observed between soil organic carbon and both higher mean annual temperatures and inorganic carbon. They recorded soil organic carbon content to increase steadily with the age of the plantation until the tenth year. In their two year pot experiment, Ruf *et al*. (2019) recorded an increase of soil organic carbon content from 13.0 g kg^{-1} in the control treatment to 19.8–20.9 g kg^{-1} under Silphium.

3.8 Economics of *Sida hermaphrodita* and *Silphium perfoliatum* cultivation

Sida and Silphium are long-term crops and their financial and economic impact should ideally be calculated over the length of a rotation. The costs of establishment are large, but decommissioning costs should also be included; these have been estimated at 234 € ha^{-1} (Stolarski *et al*., 2014b) for Sida. Costs for establishing of Sida have been calculated as 1860–2715 € ha^{-1} (Pszczółkowska *et al*., 2012). Total costs of establishment for Sida of 1159 € ha^{-1} using seeds and 8096 € ha^{-1} using seedlings were reported by Stolarski *et al*. (2014b) and Franzaring *et al*. (2015) reported a cost of establishment about 5000 € ha^{-1} for seedlings. Franzaring *et al*. (2015) also reported a total cost of establishing Silphium using seedlings of over 5000 € ha^{-1}, which is similar to values reported by Biertümpfel and Conrad (2013, cited in Gansberger *et al*. (2015a)) (Table 3.10). They calculated that the establishment cost per tonne of dry matter was greater for transplanted rather than sown stands of Silphium (Köhler and Biertümpfel, 2016). Von Cossel *et al*. (2020) indicated that establishment costs could be greatly reduced from 5159 € ha^{-1} (establishment using seedlings) to 1950 € ha^{-1} (establishment using seeds).

Table 3.10 - Cost comparison of planting vs. direct sowing of *Silphium perfoliatum* L. (Biertümpfel and Conrad 2013, cited in Gansberger *et al*. (2015a)).

Method	**Total (€ ha^{-1})**	**Plant Material (€ DM t^{-1})**
Sowing	3,159–3,190	129–138
Transplanting	5,159–5,190	148–161

For the detailed analysis of establishment costs for Sida, in Poland, the cost of 1 kg of seeds was 287 €, rhizomes costed between 0.06 € (Stolarski *et al*., 2014b) and 0.17 € per unit (Pszczółkowska *et al*., 2012), and seedlings 0.12 € per unit (Stolarski *et al*., 2014b). For Hungary, Kurucz *et al*. (2018) calculated the cost of self-production of Sida seedlings to be 0.38–0.61 € per unit. Depending on the establishment method, the cost of material accounted for 37–89% of total establishment costs (Stolarski *et al.*, 2014b). In turn, the cost of establishment accounted for 15–51% of total production costs (Stolarski *et al.*, 2014b).

The cost of Silphium seeds is €600 kg^{-1} (Schäfer *et al.*, 2018), equivalent to 1700 € ha^{-1} (Schäfer *et al.*, 2017). Schäfer *et al*. (2017) explained that the cost of Silphium seeds is due to the highly demanding and time consuming collection because of irregular maturation. In addition to processing, further mechanical scarification is needed to improve germination. The additional cost of coating with a hygroscopic substance will increase the cost by 200 € kg^{-1}. Following the observations made by Schäfer *et al*. (2018) the cost Silphium seeds could be potentially reduced to 1100–1400 € ha^{-1}.

At harvest, production costs of Sida chips were calculated to be between 34–52 € per tonne, for sown and transplanted seedlings respectively, 415–828 € ha^{-1} ex-farm, 61–426 € ha^{-1} y^{-1} (Stolarski *et al.*, 2014b). Considering a plantation cycle of 20 years, Kurucz *et al*. (2018) calculated the production costs of Sida to be between 36–60 € DM t^{-1}. Producing an extra tonne of biomass through fertilisation had associated costs of 13.8 € (Kurucz *et al.*, 2018).

The price of one tonne of Sida in the market varies widely in the literature. Sida for combustion has been reported to be about 66–68 € t^{-1} (Stolarski *et al.*, 2014b), 36–60 € t^{-1} (Kurucz *et al.*, 2018). Sida pellets are sold at 215 € t^{-1} and Sida for biogas is sold at 55 € DM t^{-1} (Kurucz *et al.*, 2018). On a per hectare basis, Stolarski *et al*. (2014b) reported a price of 825–1080 € ha^{-1}.

The investment costs associated with the production of pellets and briquettes are significant, between 12,080–12,400 € (Kurucz *et al.*, 2018). The extra processing costs associated with manufacturing are 101 € t^{-1} y^{-1} and 111 € t^{-1} y^{-1} for pellets and briquettes respectively (Kurucz *et al.*, 2018). Total production costs of Sida pellets and briquettes was calculated to be 137–161 € t^{-1} and 147–171 € t^{-1} by Kurucz *et al*. (2018).

Streikus *et al*. (2019) estimated the cost of pellet production from Sida at 0.013 € kg^{-1} (dried artificially) and the cost of energy production at 0.006 € MJ^{-1} and 0.017 € KWh.

Stolarski *et al*. (2014b) calculated that a profit of 252–433 € ha^{-1} ex-farm could be made establishing a Sida plantation using seedlings and seeds respectively. Kurucz *et al*. (2018) calculated the profit per tonne that could be obtained through the various final uses of Sida: through direct combustion 70–94 €, via pelleting 54–78 €, briquetting 7–31 €, by the production of biogas from -4–20 €, and the production of honey 144 €. In order to counteract the production cost of Sida, Stolarski *et al*. (2014b) calculated that a farmer should produce more than 6.2 t ha^{-1} when the plantation was established by seeds or 12.3 t ha^{-1} when the plantation was established by seedlings.

In a different analysis, focused on a cogeneration gasification system using Sida as fuel, Uchman *et al*. (2017) concluded that break-even prices of the electricity were between 48–90 € MWh^{-1}. They concluded that these costs were uncompetitive, and the system would only be economically viable if environmental benefits were also included. The need to include payments for environmental benefits to improve the competitiveness of Silphium has also been proposed by von Cossel *et al*. (2020). Kurucz *et al*. (2018) estimated that placing on the value of the CO_2 sequestered by Sida would equate to an addition 2 € DM t^{-1}. Another way to aid the economics of Sida and Silphium is the production of honey. Both species have proven to produce good quantities of smooth and aromatic honey, honey that can be sold for more than 5 € per 250 g.

3.9 Energy balances and LCAs

If Sida and Silphium are to be large-scale bioenergy crops then it is important to understand their energy and environmental impacts. A positive energy balance occurs if the energy produced by the crops is larger than the energy invested (excluding solar radiation). The annual energy inputs (excluding solar radiation) required to produce Sida range from a low of 9 GJ ha^{-1} (Stolarski *et al*., 2014b) to a mean of 36 GJ ha^{-1} over six years including 128 GJ ha^{-1} in the year of establishment (Jankowski *et al*., 2019). By contrast, the energy outputs from Sida if combusted range from 51 GJ ha^{-1} y^{-1} (Krzyżaniak *et al*., 2018) to 439 GJ ha^{-1} y^{-1} (Jablonowski et al., 2017) (Table 3.11). Hence the reported energy ratios ranged from 4:1 to 20:1, with the ratio increasing from planting to the sixth year (Stolarski *et al*., 2019). The methane yields from Sida (2370–3780 m^3 ha^{-1}) typically result in a lower energy yield (85–135 GJ ha^{-1}) than combustion (Jablonowski *et al*., 2017). Von Gehren *et al*. (2019) also recommended the use of Sida as a solid fuel for combustion rather than biogas. The highest methane yields are typically achieved by having two harvests rather than one harvest per year (Jablonowski *et al*., 2017). The application of pre-treatments can increase methane yields, but they incur additional energy costs (Dębowski *et al*., 2017; Nowicka *et al*., 2019; Rusanowska *et al*., 2018). For example, Kisielewska *et al*. (2020) concluded that the increase in biogas and methane yields after ultrasound pre-treatments could not be justified from an energy balance perspective. Szwaja *et al*. (2019a) estimated that 56 GJ ha^{-1} y^{-1} of electricity could be produced from Sida through a Rankine cycle (35% efficiency).

If Silphium is combusted, then depending on the yields and technology, the annual energy output can be 188 to 362 GJ ha^{-1} (Šiaudinis *et al*., 2012) (Table 3.11). The associated annual energy inputs range between 7 and 28 GJ ha^{-1} (Šiaudinis *et al*., 2012), resulting in an energy out: energy in ratio of between 12:1 and 25:1. Silphium is also widely used for methane production. Annual rates of production include 2189–3161 m^3 ha^{-1} (Haag *et al*., 2015), 3100 m^3 ha^{-1} (Gansberger *et al*., 2015a), 3600–4250 m^3 ha^{-1} (Ustak and Munoz, 2018), 3697–4634 m^3 ha^{-1} (Wever *et al*., 2019), 4855 m^3 ha^{-1} (von Cossel *et al*., 2019), 8598 m^3 ha^{-1} (Siwek *et al*., 2019), and 3854–6414 m^3 ha^{-1} (von Cossel *et al*., 2019). Assuming a methane energy density of 36 MJ m^{-3}, these values are equivalent to energy yields of 79 to 309 GJ ha^{-1}. Haag *et al*. (2015) reported that Silphium produced methane yields between grass and maize silage.

Life cycle assessments of Sida have examined the energy balance, and also the effect on climate change, human toxicity, particular matter formation, terrestrial acidification, freshwater eutrophication, and terrestrial and freshwater ecotoxicity

Table 3.11 - Reported energy requirements and energy outputs, and corresponding energy balances for *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L..

	Technology	**Input (GJ ha^{-1} y^{-1})**	**Output (GJ ha^{-1} y^{-1})**	**Energy gain (GJ ha^{-1} y^{-1})**	**Energy Efficiency Ratio**	**Reference**
Sida	Combustion	9–19	172–226	185	12–20	Stolarski *et al*., 2014b
		19	79–101	71	4.7	Šiaudinis *et al*., 2015
		22	152	123	7.0	Jankowski *et al*., 2016
		19	78	59	4.1	Stolarski *et al*., 2017b
		-	51–102	-	-	Krzyżaniak *et al*., 2018
		-	218	-	-	Molas *et al*., 2018
		8.4	177	-	7.3–21.8	Stolarski *et al*., 2019
		30–36	60–75	30–40	2.0–2.1	Jankowski *et al*., 2019
	Combustion: 2 cuts	-	439	-	-	Jablonowski *et al*., 2017
	Biogas: 1 cut	-	85	-	-	Jablonowski *et al*., 2017
	Biogas: 2 cuts	-	136	-	-	Jablonowski *et al*., 2017
	Dual harvest	-	212	-	-	Jablonowski et al., 2017
	Electricity	-	56	-	-	Szwaja *et al*., 2019a
Silphium	Combustion	7–28	188–362	180–334	12–25	Šiaudinis *et al*., 2012
		19	200–236	199	11.5	Šiaudinis *et al*., 2015

(Krzyżaniak *et al*., 2018). In a comparison of the cultivation of Sida under different fertilizing regimes, the fewest negative environmental effects were obtained when fertiliser was applied as a digestate. The application of digestates helps to minimise the energy costs associated with mineral fertilisers and the environmental effect of nutrient leaching (Jankowski *et al*., 2019). In a study of energy generation from Sida on 16 categories, Schonhoff *et al*. (2019) reported that, although the negative environmental impacts of producing Sida chips or pellets were greater than for Miscanthus pellets, they were lower than for standard wood chips. The process of pelletizing Sida uses about 0.53 GJ t^{-1} (von Gehren *et al*., 2019). When the multi-criteria decision making model MULTIMOORA was applied in Lithuania (Balezentiene *et al*., 2013), both Sida and Silphium ended up within the top five energy crops to use. This multi-criteria assessment included the following categories: photosynthesis type, soil carbon sequestration, water adaptation, N input requirement, erosion control, DM yield, and energy yield.

3.10 Recommendations for future research

Future research on Sida and Silphium could cover genetic improvement, field management, and methods to increase energy efficiency after harvest, improve environmental impact, and increase profitability (Haag *et al*., 2015).

Genetic improvement: Kurucz *et al*. (2014) pointed out the lack of research in the genetics and biotechnology areas, which could greatly benefit Sida and help this crop to achieve its full potential. Jablonowski *et al*. (2017) reported that plant breeding would help to have a more uniform cultivation, characteristics, and yields.

For Silphium, van Tassel *et al*. (2017) emphasized the need for genetic studies to characterise existing populations and to help produce desirable characteristics. After their genetic study of five Silphium populations, Wever *et al*. (2019) advised selection (targeting height and diameter) and breeding to reduce variation in biomass and methane yield, and increase genetic diversity (using wild populations). Schittenhelm *et al*. (2016) suggested the production of varieties with smaller leaves in order to increase yields and decrease yield variability. Cultivar selection could help to identify if there are specific high-value natural chemicals associated with the crops, which could enhance the value and hence the profitability of the crops.

Seed technology: Functioning seed technology would contribute to lower the establishment costs of Silphium (Gansberger *et al*., 2015a). The same applies for Sida.

Field management: the need for field trials of Sida has been emphasized to test the performance of this crop: in separate regions with different climate and soil conditions from an agronomical and energetic point of view, including multiple harvest and determining optimum harvest dates (Franzaring *et al*., 2014); for diverse agricultural practices and ecological conditions (Jankowski *et al*., 2019); under digestate depot fertilisation (Nabel *et al*., 2018a); to study root distribution dynamics of legume intercropping with Sida on marginal soils (Nabel *et al*., 2018b).

Jankowski *et al*. (2019) emphasized the urgency to investigate weed and disease control methods, seed technology, and the use of organic fertilisers to maximise energy efficiency of Sida. Nahm and Morhart (2018) observed a lack of research on pre-treated seeds to lower establishment costs, studies on the pathogens, competitiveness and invasive potential of Sida, and determination of its optimal growth conditions, plantation life financial analysis, as well as the establishment of value chains and appropriate marketing strategies.

For the field management of Silphium, Franzaring *et al*. (2014) recommended that there was a need to evaluate the crop in different climate and soil conditions with different harvest dates, with a particular focus on places with temperate humid weather (Franzaring *et al*., 2015), and on marginal land (Ruidisch *et al*., 2015). The possibility of growing Silphium on land which is often saturated with water (Ruf *et al*., 2019), needs further investigation including a variety of soil textures, as well as comprehensive photosynthesis and water monitoring experiments. Von Cossel *et al*. (2019) recorded the superior methane production of wild plant mixtures grown under maize as cover crop. This experiment could be replicated for wild plant mixtures to be sown under Silphium to maximise biogas production and control of weeds, which could increase biodiversity simultaneously. Optimising the establishment (Schäfer *et al*., 2015) and cultivation (Schäfer *et al*., 2017) of Silphium are requirements to increase its cultivation area. Šiaudinis *et al*. (2017) regard the development of weed control technology for the establishment year as one of the principal causes stopping the widespread cultivation of Silphium. It is also necessary to study how signal processing affects photosynthesis and growth of Silphium (2018).

Post-harvest energy studies: further research is necessary to determine the precise causes of enhanced biogas production obtained after co-digesting maize and Silphium (Ustak and Munoz, 2018). Potential ways to raise Silphium dry matter content need further investigation (von Cossel *et al*., 2020).

Nutrient recycling: the recovery process of phosphorus from biogas digestates would benefit from expanded research (von Cossel *et al*., 2020).

Environmental impact: there is a particular interest in how perennial crops affect the wider environment, including at landscape-scale (Ruf *et al*., 2018). Von Gehren *et al*. (2019) suggested that research is needed to decrease PM emissions and ash removal during the combustion process of Sida. The fertilising potential of the ashes from the combustion of Sida needs further investigation. Stolarski *et al*. (2019) also highlighted the importance of researching environmental LCAs too. Chmelíková and Wolfrum (2019) pointed out the need to explore the effect of Silphium and other perennial energy crops on arthropods within the agricultural landscape. Schoo *et al*. (2017c) advised the study of the long-term effects of no-tillage cultivation of this kind of crops on soil properties. Schoo *et al*. (2017a) recommended examining the positive environmental impacts associated to its cultivation and determining the requirements for the cultivation of Silphium. Mueller *et al*. (2020a) encouraged studying the impact of water availability on inflorescence production. The potential use of Silphium biochars produced from heavy metal contaminated land for water purification and soil remediation was suggested by Du *et al*. (2019).

Ruidisch *et al*. (2015) encouraged the inclusion of factors like environmental benefits in planning strategies, as well as the creation and development of local and regional databases that will feed the models and eventually help making decisions.

Profitability: Borkowska and Molas (2013) accentuated the need for economic analyses to help in the decision making process, by providing sufficient and reliable information, maintaining profitability and minimising environmental impacts. Nahm and Morhart (2018) also reported the need for plantation life financial analysis, as well as the establishment of value chains and appropriate marketing strategies. Financial and economic models will also help with regional economic evaluation, supporting both farmers and decision makers by providing output data to be used for up-scaling potential, different land-use scenarios, and calculations on crop profitability (Ruidisch *et al*., 2015).

3.11 Conclusions

The research highlighted the potential utility of Sida and Silphium within farming systems. Both crops can generate large energy surpluses with environmental benefits such as improved pollination, soil health, and water quality relative to current bioenergy crops, such as maize and Miscanthus. The process of completing this synthesis has highlighted the substantial amount of research that has already been completed on these two crops and addressed the knowledge gap existing prior to the completion of the study. Having a single document where information has been organised and analysed should help advisors and farmers who are interested in growing the crop in other regions, not just in Europe, but elsewhere. Some of the reviewed literature is not freely available to the public and some was not available in English.

Future research needs to focus on the long-term agronomic and environmental behaviour of Sida and Silphium as well as the development of knowledge on how to integrate them successfully into farming systems, supply chains, and integrated biorefineries. Further breeding and cultivar selection of Sida and Silphium are needed, particularly in terms of field establishment from seed, as well as appropriate seed technology. Successful and cost-effective establishment methods are critical to the successful upscaling of both crops. Some studies found high inter-annual variability in Sida yields, which may have been due to inter-annual variations in the standard of field management in terms of weed, pest and disease control, or irrigation. Long-term field experiments including high and low management regimes could help test this theory. Most of the field studies provide results for only two to three years research, which is not long enough to characterize all the key agronomic and energy properties of Sida and Silphium or determine how these evolve over their full rotations which can be as long as 16 to 20 years. Additional research is also needed on the greenhouse balance of the crops, as well as their invasive potential. From an economic perspective, the economic impact of scaling up Sida and Silphium production needs to be investigated. At the same time, Sida and Silphium provide other valuable by-products that could be extracted before they are used in energy production. The economics and energy balances associated with this need to be investigated.

The environmental costs associated with maize, such as biodiversity loss and increased soil erosion, do not appear on a standard net margin analysis. This puts less damaging crops such as Sida and Silphium at a disadvantage. In the EU, modifications to the Common Agricultural Policy are seeking increasingly to pay farmers when they provide public goods such as carbon sequestration. Schemes that recognise the ecosystem services provided by Sida and Silphium, could be used to support farmers for their relatively high costs of establishment, increasing the overall profitability of the crops, and creating an incentive for farmers to adopt them.

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4 EFFECT OF *SIDA HERMAPRHODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. ON SOIL CARBON DYNAMICS

This chapter describes the differences observed in the bulk density and soil carbon between two sampling periods; the first year of the experiment in March 2017, and the last year of the experiment in March 2020. The chapter includes a description of the experimental site, soil characteristics, methodologies used for the collection and processing of the soil samples, bulk density and soil carbon results obtained both in 2017 and 2020, as well as the interpretation of the relevant statistical analyses. The chapter concludes with a discussion on bulk density, soil carbon, effect of tillage on bulk density and soil carbon, and future research recommendations. The chapter will be presented as a scientific paper by Laura Cumplido-Marin, Anil R. Graves, Michail Giannitsopoulos, and Paul J. Burgess.

Abstract: This paper examines the soil bulk density, organic carbon and total carbon concentration following the establishment of two bioenergy crops: *Sida hermaphrodita* (L). Rusby and *Silphium perfoliatum* L. on a previous grassland area in Bedfordshire in the UK. Measurements were made at soil depths of 0-5 cm and 10-15 cm before establishment of the energy crops and three years later. Whereas the bulk density at 0-5 cm remained at 1.4 g cm^{-3}, the bulk density at 10-15 cm decreased from 1.7 to 1.4 g cm^{-3}. The soil organic carbon content (0-20 cm) decreased from 64.7-67.3 t ha^{-1} prior to establishment to 54.3-57.0 t ha^{-1} three years later. The corresponding total carbon (including inorganic carbon) decreased from 69.2 t ha^{-1} to 56.8 t ha^{-1}. The results support previous studies demonstrating initial reductions in soil carbon when planting perennial crops on grassland.

Key words: soil carbon, land-use change, bioenergy crops, Virginia fanpetals, Cup plant

4.1 Introduction

Climate change and associated extreme weather events have encouraged 195 countries to sign the Paris Agreement to commit to limiting global warming to at least 2°C below preindustrial revolution levels (UNFCCC, 2021). To achieve this, we will need to increase the use of renewable energies, reduce emissions from fossil fuels, and use processes such as carbon sequestration and carbon capture and storage. Two potential novel bioenergy crops are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., and they were the focus of the SidaTim project (3N Kompetenzzentrum, 2021). From here onwards we will refer to *Sida hermaphrodita* (L.) Rusby *and Silphium perfoliatum* L. as Sida and Silphium respectively.

Both Sida and Silphium have the potential to contribute towards increased biodiversity, pollen and nectar production, increased soil organic carbon, increased water management, reduced chemical inputs, reduced nitrogen leakage, and reduced soil compaction (Cumplido-Marin *et al.*, 2020). Some research has demonstrated that the use of organic fertilisers in the cultivation of Sida can help to increase soil organic carbon at a relatively quick pace, particularly when intercropped with legumes (Nabel *et al*., 2018b, 2017, 2016, 2014).

Measuring soil organic carbon (SOC) and recording changes in SOC associated with changes in land-use is important for two reasons. Firstly, SOC levels are closely associated with soil organic matter (SOM) levels (SOM is about 58% SOC; DPIRD WA, 2020). Secondly, SOM has direct positive effects on soil health and structure, and crop productivity, the regulation of soil erosion, improved retention of water, and improved water quality (Ontl and Schulte, 2012). Soils are also one of the greatest stores of carbon of the planet and land use changes can affect the amount of C stored in the soil, with the potential to both release CO_2 to the atmosphere or to fix it into the soil. FAO (2017) estimated that the top 30 cm of the world’s soils contain about 680 billion tonnes of carbon (FAO, 2017a).

Increased temperatures, associated with climate change, could alter SOC accumulation rates and even disturb ancient recalcitrant carbon (Post *et al*., 1982). Schlesinger and Andrews (2000) reported that the greatest losses of carbon, due to temperature increase, could occur in boreal forests and tundra areas. In addition to permafrost thawing, increased temperatures can also increase the microbial priming effect, and synergies between the C and N cycles (Heimann and Reichstein, 2008). In the UK, there is evidence of SOC loss at a relatively large scale from a long-term study conducted between 1978 and 2003 in England and Wales (Bellamy *et al*., 2005), where SOC was recorded to decrease on average 0.6% y^{-1}. Bellamy *et al.* also found a negative linear relationship between the speed of variation in SOC and the initial SOC content.

SOC levels depend on the carbon inputs and outputs from the soil, and the soil environment (Paul *et al.*, 2002). Litter production and rhizodeposition contribute towards carbon accumulation and decomposers consume carbon, therefore controlling soil carbon storage (Jandl *et al*., 2007). Analogously, Hoyle *et al*., (2006) reported that the labile fraction[2] is controlled by the quantity of organic matter incorporated into the soil.

SOC levels can vary with soil type, land cover, and land management. Cultivations involving ploughing oxidise the soil and can redistribute organic carbon in the surface layers (Post and Kwon, 2000). Upson *et al*. (2016) in Bedfordshire (UK) reported lower initial organic carbon storage rates when planting trees on grassland. However it is possible that fully established forests and woody plants can deposit a considerable amount of biomass (e.g. leaves and roots) which can slowly degrade and become incorporated into the soil (Post and Kwon, 2000).

This paper examines the soil carbon concentration of a grassland field in 2017, prior to ploughing and the establishment of Sida and Silphium, and then three years later in

[2] active fraction of the soil, accessible for plants and organism to use and with a turnover of weeks to decades (Muir et al., 2013)

2020. The principal research question was whether three years was enough time to see significant changes in soil carbon following the cultivation of Sida and Silphium. Our research hypothesis was that the soil organic carbon of grassland would decrease during the first three years of cultivation of Sida and Silphium.

4.2 Methodology

4.2.1 Experimental site

The 0.68 ha experiment was established in the spring of 2017 in "Rickyard's field" (52.007897°N, 0.432112°W) on the Cranfield University Farm at Silsoe in Bedfordshire (Figure 4.1). The field had been planted to grass for at least 15 years; it had previously been grazed and had been used briefly for tractor driving lessons. In March 2017, the site was mowed, sprayed (glyphosate at 3 l ha^{-1} in 200 l of water), ploughed at 20cm, power harrowed, ring rolled and re-sprayed prior to establishing the crops (May 2017). Two establishment methods were compared, seeds and seedlings, completing the establishment stage by July 2017. A visual summary of the steps involved to establishing the plantation is presented in Figure 4.2.

Figure 4.1 – Location of the experimental site at Silsoe relative to the UK.

Figure 4.2 – Ploughing (a), planting of seedlings (b), manual seeder used to sow the seed plots (c), and overview of the experimental site once established in October 2017 (d).

4.2.2 Soil characteristics

In existing soil databases, the experimental area is described as a freely draining slightly acidic loamy soil (Cranfield University, 2020a). According to LandIS (Cranfield University, 2020b), the soil has a loamy texture, is freely draining, and has low fertility and low top soil carbon. According to the UKSO map viewer, the soil texture in the experimental area was medium to heavy, with bulk density of 1.16 g cm^{-3}, and soil organic carbon content of 3.76% (UKRI, 2020). Prior to the establishment of Sida and Silphium, a particle size distribution and available N, P, K analyses were completed. The methodologies applied to these analyses followed the corresponding Standard Operating Procedures (SOP) provided by Cranfield University, developed from British Standards. Details of the specific methodologies and results from these analyses are included in Appendix C, C.1 Soil texture and C.2 Available nitrogen, phosphorus and potassium analyses. The results indicated that the soil contained 79.3% of sand, 18.0% clay, and 2.8% silt + clay, and is therefore classified to have a sandy loam/loamy sand texture.

4.2.3 Soil sampling approach

The bulk density and soil carbon content of the soil was measured using a sampling approach proposed by Ellert *et al*. (2008). The Ellert *et al*. (2008) methodology, recommended by the Canadian Society of Soil Science, has been termed a "microsites approach". The approach was selected due to its potential to measure small changes in SOC in a relatively short period of time (Ellert *et al*., 2002). The approach usesa systematic design to ensure the precise location and relocation of sampling points (VandenBygaart, 2006). Sampson and Scholes (2000) reported that the approach can provide a relatively low-cost method to detect changes of 3.64 Mg C ha^{-1}, equivalent to increases that might be expected after 10 years by practices that conserve SOC.

The approach by Ellert *et al*. (2002) focusses on soil organic carbon changes at small microsites within a field site. The approach reduces the variability inherent in soil organic carbon sampling, which tends to increase with sampling density and the area sampled. The sampling process is important not only for SOC measurements, but also for soil bulk density, as an accurate baseline is a key component of the original Equivalent Soil Mass (ESM) technique (Ellert and Bettany, 1995), here onwards referred as "fixed mass approach", which could be more accurate over the traditional fixed-depth method (Ellert *et al*., 2002; Lee *et al*., 2009).

The selected design used four randomly selected plots within the treatment plots (forming four sampling areas) plus one control. The approach recommended marking the sampling points with permanently buried markers but for practical reasons it was decided to only record the sampling coordinates with a GPS. In each area, six sampling points were selected following a W shape (Figure 4.3) within each of the five sampling areas. In each sampling point, soil cores were taken at 0-5 cm and 10-15 cm deep, collecting a total of 120 samples (6 x 2 x 5) both in 2017 and 2020. Once the cores were secured in labelled plastic bags, the holes in the ground were refilled.

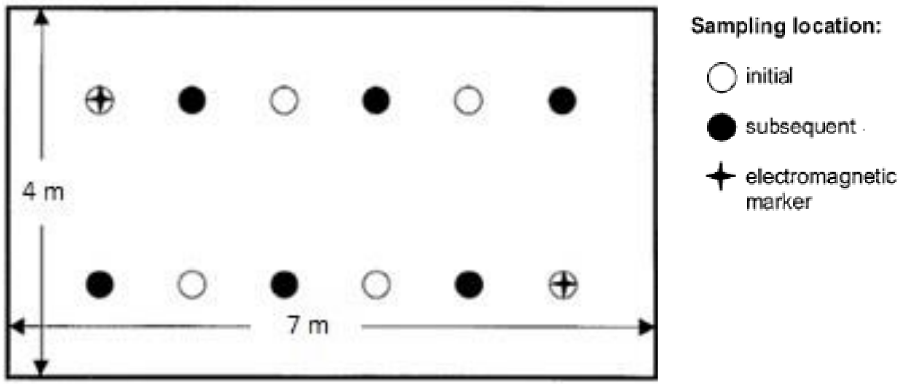

Figure 4.3 – Sampling pattern, extracted from Ellert *et al*. (2002).

Sampling areas 1-4 were located inside experimental plots and sampling area 5 corresponded to the control area. The first set of samples (March 2017) was taken before any establishment operations had taken place, when the land had grass cover. The second set of samples (March 2020) was taken after three years of the cultivation of the energy crops in areas 1-4. Area 5 was left fallow and was covered with naturally regenerated grass. Re-sampling in 2020 was done by retrieving each sampling point using the same GPS from 2017. The sampling areas are illustrated within the experimental field in Figure 4.4.

We used a bulk density sampling kit with 5 cm stainless steel rings for bulk density samples (0-5 cm and 10-15 cm) and one 8 mm diameter gouge auger for SOC samples (0-10 cm and 10-15 cm). The sampling depths (0-5 cm and 10-15 cm) were selected to correspond the depth at which the soil had been ploughed during site preparation (20 cm). By doing so, the variability in soil organic carbon content is potentially reduced (VandenBygaart, 2006). Previous studies have demonstrated that changes in soil carbon are most likely to be detected in these surface layers (Schrumpf *et al*., 2011). In addition, soil organic carbon content is generally higher in the topsoil (Baumert *et al*., 2016).

Figure 4.4 - Location of the sampling points within the experimental field, image showing sampling areas 1 (red), 2 (blue), 3 (yellow), 4 (green), 5 (white).

4.2.4 Bulk density and soil carbon analyses

The bulk density of the soil was determined following the SOPs of Cranfield University, based on the British Standard 11272:2014 Soil quality - Determination of dry bulk density (BSI, 2014). Sample collection of bulk density cores took two days in 2017 (13, 15 March 2017) and two days in 2020 (10, 11 March 2020). The soil cores were stored in sealed plastic bags and then taken to the laboratory, where they were placed in tins of known mass and the wet mass of each sample plus individual tin was recorded to a precision of 0.1 g. The samples were then air dried, passed through a <2 mm sieve, and oven dried at 105°C ± 2°C for 24 hours. After cooling in a desiccator, the dry mass of each sample plus individual tin was recorded to a precision of 0.1 g. Using the known volume of the original cores and the calculated dry mass of the soil, the bulk density was thus obtained.

Organic Carbon and Total Carbon (TC) samples were processed using the corresponding SOP, based on the British Standard 7755 Section 3.8:1995 (BSI, 1995a). The soil samples were air-dried for 24 h, milled using a ball mill, passed through a <2 mm sieve and about 5 g of soil placed in plastic tubes, the remainder soil material stored. The plastic tubes were then placed in the oven (lids open) at 105°C for 2 h ± 10 min. For the total carbon content test, a subsample of 50-100 mg was placed into an aluminium foil capsule and tightly packed. For the organic carbon test, silver tin capsules were used. The silver tins containing 0.001 mg of soil were placed on glass trays, where 4 mol l^{-1} of hydrochloric acid was added to remove carbonates, dried at 90°C for 4 h and tightly packed into a larger capsule. The packed capsules where then transferred to the elemental analyser (Vario EL III Elementar Analysensysteme GmbH, Donaustrasse, Germany), which extracted the concentration of total and organic carbon by oxidising the carbon into CO_2 and measuring its flux. In 2017, two days were needed to process the samples (30-31 of May 2017) and two days (8-9 June 2017) to obtain the organic carbon and total carbon. Subsequently, carbon stocks were calculated, following both the traditional and the fixed mass approach (Ellert *et al*., 2008). In 2020, it took another two days to process the soil samples (12-13 March 2020) and prepare them for the STC and SOC analyses (14-15 July 2020).

The obtained bulk density, organic and total carbon concentration data were analysed statistically using analyses of variance (ANOVA) followed by least significant differences tests (lsd) for individual years and included two factors, area and depth. All analyses were performed using the software R (R Core Team, 2020).

4.3 Results

4.3.1 Bulk density analyses

The ANOVA showed that there were significant main effects of area ($p = 0.004$) and depth ($p < 0.0001$), in the bulk densities measured in 2017 (see Appendix C, C.3 Bulk Density). In 2017, the mean bulk density of the 0-5 cm layer was lowest in areas 2 (1.31 g cm^{-3}) and 1 (1.37 g cm^{-3}), slightly higher in areas 3 (1.40 g cm^{-3}) and 4 (1.44 g cm^{-3}); and highest in area 5 (1.51 g cm^{-3}) (Table 4.1). The corresponding mean bulk density at 10-15 cm was lowest in areas 3 (1.69 g cm^{-3}) and 2 (1.70 g cm^{-3}), slightly higher in areas 1 and 4, equal to 1.72 g cm^{-3} and 1.73 g cm^{-3}; and highest in area 5, equal to 1.75 g cm^{-3}. The mean bulk density of the 0-5 cm (1.40 g cm^{-3}) was lower than the mean value) at 10-15 cm (1.72 g cm^{-3}) (Table 4.1).

Table 4.1 - Effect of area and depth on the mean bulk density (± standard deviations) in 2017.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	1.37 ± 0.058	1.31 ± 0.161	1.40 ± 0.055	1.44 ± 0.085	1.51 ± 0.092	1.41 ± 0.113
10-15 cm	1.72 ± 0.025	1.70 ± 0.062	1.69 ± 0.054	1.73 ± 0.076	1.75 ± 0.020	1.72 ± 0.054
Mean	1.54 ± 0.189	1.50 ± 0.233	1.54 ± 0.162	1.58 ± 0.174	1.63 ± 0.144	

The effect of area on bulk density in 2020 was only statistically significant at p = 0.1, and there was no statistical difference effect of depth (between 0-5 and 10-15 cm) in 2020 (Table 4.2). The mean bulk density of the 0-5 cm layer in areas 2 and 3 (1.32-1.36 g cm^{-3}) was effectively the same as those in areas 1 and 5, equal to 1.45 g cm^{-3} and 1.47 g cm^{-3} respectively; and in area 4, equal to 1.50 g cm^{-3}. The corresponding mean bulk density at 10-15 cm was also similar ranging from 1.38-1.39 g cm^{-3} in areas 2, 3 and 5, to 1.45 g cm^{-3} in area 4, and 1.48 g cm^{-3} in area 1. After three years, in 2020, of the land use change and cultivation of Sida and Silphium, the mean bulk densities at 0-5 cm and 10-15 cm was similar at about 1.41-1.42 g cm^{-3}.

Table 4.2. Effect of area and depth on the mean bulk density (± standard deviations) in 2020.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	1.45 ± 0.075	1.32 ± 0.068	1.36 ± 0.056	1.50 ± 0.057	1.47 ± 0.069	1.41 ± 0.094
10-15 cm	1.48 ± 0.265	1.39 ± 0.116	1.38 ± 0.076	1.45 ± 0.141	1.39 ± 0.205	1.42 ± 0.166
Mean	1.47 ± 0.186	1.35 ± 0.098	1.37 ± 0.064	1.48 ± 0.106	1.43 ± 0.152	

We can observe in Table 4.1, lower standard deviations at 10-15 cm than 0-5 cm in 2017. However, in 2020 (Table 4.2) there was a greater spread in the bulk densities measured at 10-15 cm, particularly in area 5. Area 5 corresponds to the control area that was left fallow, being mown every season to restrict the growth of grass and weeds.

4.3.2 Soil Carbon analyses

The results of the gravimetric organic and total carbon obtained from the elemental analyser are included in Appendix C, C.4 Soil Carbon. The gravimetric organic carbon concentration, volumetric organic carbon (calculated using both the classic and the fixed mass approach (Ellert et al., 2008), gravimetric total carbon and calculated volumetric total carbon from the six cores taken for each sampling area at two different depths are presented in Table 4.3, Table 4.4 and Figure 4.5.

The ANOVA showed that there were significant ($p<0.05$) differences in the OC concentration between the two sampled depths in 2017. In addition, there were significant effects between the interaction of factors area and depth in 2017 (see Appendix C, C.5 Statistical Analyses). In 2017, mean organic carbon concentration within the two depth increments within the five areas ranged from 1.79% to 2.73% (Table 4.3). The mean OC concentration of the 0-5 cm layer in 2017 was lowest in area 5 (2.34%), slightly higher in areas 4 (2.53%) and 1 (2.59%); and highest in areas 3 (2.69%) and 2 (2.73%) (Table 4.3). The corresponding mean organic carbon concentration at 10-15 cm was lowest in areas 4 (1.79%), 3 (1.81%) and 2 (1.82%), slightly higher in area 1, equal to 1.89%; and highest in area 5, equal to 1.93%. The mean OC of the 0-5 cm (2.58%) was higher than the mean value at 10-15 cm (1.85%) (Table 4.3).

There were no significant effects between the OC (organic carbon) concentration of the two sampled depths in 2020 (Table 4.4). This was reflected by the mean organic carbon concentration that ranged from 1.72% to 2.51%, equal to 1.86% in the 0-5 cm layer and 2.12% in the 10-15 cm layer. In 2020, the organic carbon concentration of the 0-5 cm layer in area 5 was 1.75%, similar to that in the other four areas (1.72-2.13%), whereas it was 2.51% at 10-20 cm in area 5, compared to 1.87-2.13% in the other four sites.

Regarding the total carbon (TC) concentration, the results from the statistical analyses indicate that there were significant differences between the TC concentration of the two sampled depths in 2017 ($p<0.05$). The analysis also revealed significant effects between the interaction of factors area and depth in 2017 (see Appendix C, C.5 Statistical

Analyses). In 2017, mean TC concentration within the two depth increments within the five areas ranged from 1.92% to 2.87% (Table 4.5.). The mean TC concentration of the 0-5 cm layer in 2017 was lowest in area 5 (2.51%), slightly higher in areas 4 (2.60%) and 1 (2.68%); and highest in areas 3 (2.81%) and 2 (2.87%) (Table 4.5). The corresponding mean TC concentration at 10-15 cm was lowest in areas 2 and 3 (1.92%), slightly higher in area 1, equal to 1.97%; and highest in areas 4 and 5, equal to 2.00%. The mean TC of the 0-5 cm (2.70%) was higher than the mean value at 10-15 cm (1.96%) (Table 4.5).

There were no significant effects between the total carbon concentration results from two sampled depths in 2020. This was reflected by the mean total carbon concentration that ranged from 1.88% to 2.54%, equal to 1.97% in the 0-5 cm layer and 2.19% in the 10-15 cm layer (Table 4.6.). In 2020, the total carbon concentration of the 0-5 cm layer in area 5 was 1.89%, similar to the other four areas (1.88-2.17%), whereas it was 2.54% at 10-20 cm in area 5, compared to 1.93-2.20% in the other four areas.

Overall, in 2017 the total carbon concentration of the 0-5 cm layer was 2.70% and for the 15-20 cm layer it was 1.96%. In 2020, the total carbon concentration of the 0-5 cm layer was 1.97% and for the 15-20 cm layer it was 2.19%. We can observe then the soil carbon concentration, both organic and total carbon, decreased in the upper layer but increased in the lower layer.

Table 4.3. Effect of area and depth on the organic carbon content (%) (± standard deviations) in 2017.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	2.60 ± 0.317	2.73 ± 0.419	2.69 ± 0.470	2.53 ± 0.354	2.34 ± 0.390	2.58 ± 0.392
10-15 cm	1.89 ± 0.157	1.82 ± 0.306	1.81 ± 0.226	1.79 ± 0.215	1.93 ± 0.311	1.85 ± 0.238
Mean	2.24 ± 0.442	2.28 ± 0.591	2.25 ± 0.577	2.16 ± 0.476	2.13 ± 0.398	

Table 4.4. Effect of area and depth on the organic carbon content (%) (± standard deviations) in 2020.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	1.74 ± 0.236	2.13 ± 0.410	1.95 ± 0.072	1.72 ± 0.186	1.75 ± 0.160	1.86 ± 0.276
10-15 cm	2.13 ± 1.244	1.97 ± 0.402	2.11 ± 0.186	1.87 ± 0.516	2.51 ± 1.067	2.12 ± 0.769
Mean	1.94 ± 0.877	2.05 ± 0.395	2.03 ± 0.160	1.79 ± 0.379	2.13 ± 0.828	

Table 4.5. Effect of area and depth on the total carbon content (%) (± standard deviations) in 2017.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	2.68 ± 0.355	2.87 ± 0.420	2.81 ± 0.505	2.60 ± 0.355	2.51 ± 0.406	2.70 ± 0.405
10-15 cm	1.97 ± 0.190	1.92 ± 0.383	1.92 ± 0.286	2.00 ± 0.232	2.00 ± 0.355	1.96 ± 0.279
Mean	2.33 ± 0.462	2.39 ± 0.630	2.37 ± 0.605	2.30 ± 0.426	2.25 ± 0.451	

Table 4.6. Effect of area and depth on the total carbon content (%) (± standard deviations) in 2020.

Depth	Area 1	Area 2	Area 3	Area 4	Area 5	Mean
0-5 cm	1.91 ± 0.213	2.17 ± 0.397	1.99 ± 0.097	1.88 ± 0.154	1.89 ± 0.171	1.97 ± 0.241
10-15 cm	2.18 ± 1.295	2.08 ± 0.453	2.20 ± 0.222	1.93 ± 0.507	2.54 ± 1.058	2.19 ± 0.782
Mean	2.04 ± 0.897	2.13 ± 0.409	2.09 ± 0.197	1.90 ± 0.359	2.22 ± 0.797	

In 2017, the calculated mean volumetric organic carbon content (0-20 cm) was 67.63 t C ha^{-1} and 65.03 t C ha^{-1} for the classic and fixed mass approach respectively. The corresponding value for the mean volumetric total carbon was 69.26 t C ha^{-1}. In 2020, the calculated mean volumetric organic carbon (0-20 cm) declined to 55.20 t C ha^{-1} and 58.50 t C ha^{-1} for the classic and fixed mass approach respectively. The corresponding mean volumetric total carbon was 57.73 t C ha^{-1}.

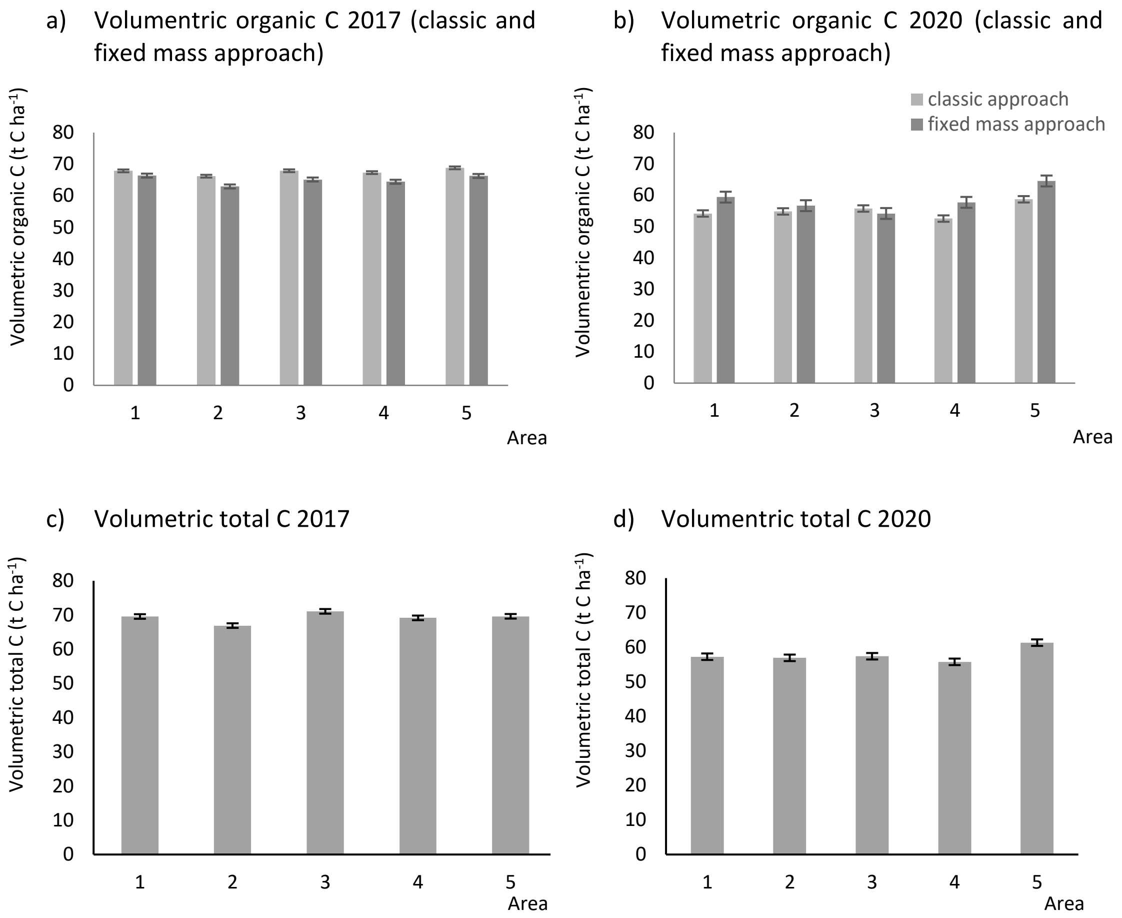

Figure 4.5 – Volumetric organic carbon (a) before the establishment and (b) after three years of cultivation; volumetric total carbon 0-20 cm (c) before establishment and (d) after three years of cultivation. The small size of the error bars indicate that the results are a good representation of the population.

4.4 Discussion

4.4.1 Bulk density

Studies investigating the bulk density of the soil under Sida and Silphium are scarce. Compared to the control samples (no fertilisation), Šiaudinis *et al*. (2019) observed how the growth of Silphium reduced soil bulk density with time. From 2015 to 2017, the bulk density of the control samples declined from 1.39 g cm^{-3} to 1.33 g cm^{-3} and in those plots receiving annual sewage sludge, the bulk density declined from 1.30-1.33 g cm^{-3} to 1.12-1.19 g cm^{-3}. In the current study we recorded a decrease in bulk density in three years of 0.3 g cm^{-3} at 10-15 cm. The observed reduction in the bulk density of the 10-15 cm layer could be caused by establishment operations, the absence of annual tillage for three years, and/or the growth of the plants.

4.4.2 Soil carbon

Before establishment, the land was covered with grass. Soils under grassland are typically rich in carbon and typically have higher carbon levels than areas allocated to arable crops (Guo and Gifford, 2002; Miller and Donahue, 1990). When a soil is disrupted, changes in soil organic carbon can take about ten years to be detectable (Schrumpf *et al.*, 2011). According to the review by Zawadzka and Corstanje (2013), after 5 year of the establishment of eucalyptus, Miscanthus and poplar plantations on former grassland, a mean variation was recorded of respectively 0.7 t C ha^{-1} y^{-1}, -0.6 t C ha^{-1} y^{-1} and -0.1 t C ha^{-1} y^{-1}. In the long-term (20 years); they observed that eucalyptus and poplar increased soil carbon (at a mean rate of 0.4 and 0.3 t C ha^{-1} y^{-1}), whilst Miscnathus decreased it (mean rate of -0.1 t C ha^{-1} y^{-1}). This raises the question whether each bioenergy species behaves differently, however the number of data points for the calculations was limited.

Comparing the results from calculating the volumetric organic carbon from the classic and the fixed mass approach, we can observe a clear difference in the mean soil organic carbon levels in areas 1-4 during the first three years after establishment of Sida and Silphium (2017-2020). Using the classic approach the mean organic carbon levels (0-20 cm) declined from 67.3 t ha^{-1} to 54.3 t ha^{-1}. Using the fixed mass approach the mean organic carbon levels (0-20 cm) declined from 64.7 t ha^{-1} to 57.0 t ha^{-1}. Hence in 2017, the values from the fixed mass approach in 2017 were slightly lower than the classic approach; however, in 2020, the levels of volumetric organic carbon obtained with the fixed mass approach were higher than the levels obtained with the classic approach. The difference in the results reflects how the microsite approach by Ellert *et al*. (2008) accounts for soil mass conservation in the calculation.

In our study, the organic carbon concentration of area 5, that was ploughed but kept under grass as a "control" treatment, was highest among all sampled areas both at the start and the end of the experiment. This indicates that that area was able to accumulate carbon at a higher rate than other areas. There are few studies that have investigated the soil carbon content of field-grown Sida and Silphium. In a two-year pot experiment, Ruf *et al*. (2019) showed that the addition of organic fertiliser could increase the soil carbon concentration below Silphium from 1.3% to 2.0%. In their pot experiment of Sida, Nabel *et al*. (2014) and Nabel *et al*. (2016) observed increased soil carbon concentrations with increases in digestate dose. Acording to Nabel *et al.* (2017), the total carbon after one year of cultivation of Sida, varied 0.0-1.3% and after three years, it ranged between 0.1-3.1%. The highest values corresponded to rich soil areas with digestate fertilisation and the lowest values to marginal soil areas with no fertilisation. In another pot experiment of Sida, Nabel *et al.* (2018b) observed that the combination of digestate fertilisation and legume/grass mixture intercropping can further increase soil carbon concentration.

The total carbon concentration under Sida and Silphium following the field conditions at Silsoe was 2.3% in 2017 and 2.0% in 2020. These are higher values than the values of 1.5-1.6% reported by Šiaudinis *et al*. (2017) for Silphium and Sida sites. The relatively high carbon content at Silsoe could partly be a result of the initial grass cover.

After three years of Silphium cultivation, Šiaudinis *et al*. (2019) recorded how the concentration of organic carbon varied from 1.26% in the first year, to 1.25% in the fourth year under no fertilisation and 1.75-1.79% when fertilised using sewage sludge. From a nine year experiment comparing woody to herbaceous crops, Bazrgar *et al*. (2020) recorded no significant differences in the amounts of stored SOC between the two groups over the nine years, i.e. 11.0 and 9.8 t C ha^{-1}. The initial SOC (0-30 cm) that they recorded varied from 64.0 to 69.1 t C ha^{-1}, result that is in line with the results of the current research. We obtained 67.3 t C ha^{-1} in 2017 and in 2020, SOC was 54.3 t C ha^{-1} under the Sida and Silphium plots.

Comparing arable crops with six year old perennial energy crops from 25 sites, Ruf *et al.* (2018) found that perennial systems (including Silphium ans Sida), established on previously arable land, increased SOC by 16.3% on average. They noticed that soil organic carbon in perennial energy systems increased until they were 10 years old, from where further increases were not significant (Figure 4.6). There was substantial variance in the data.

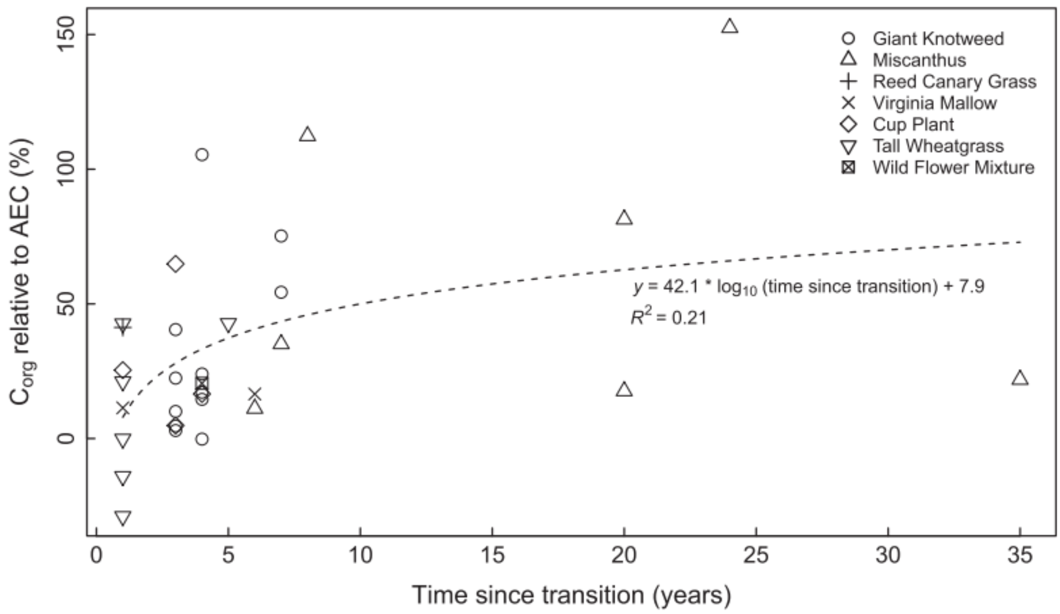

Figure 4.6 – Soil carbon content evolution under perennial energy crops (previously arable) compared to annual crops .

4.4.3 Effect of tillage on bulk density and soil carbon

Tillage practice can have a significant effect on bulk density. Whilst some consider the reduction of tillage a necessary requirement of a more sustainable agriculture to reduce soil erosion and preserve soil moisture, the topic is complex. For example Giannitsopoulos *et al.* (2019) in central England demonstrated that decreasing initial bulk density through conventional tillage can improve arable crop establishment compared to low disruption tillage. Ploughing the experimental site at Silsoe can be expected to reduce the level of surface soil residues compared to minimum tillage practices (Giannitsopoulos *et al*., 2020). By contrast, Giannitsopoulos *et al*. (2020) also observed direct positive correlations between crop residue and soil organic carbon (10% residue induced 0.24 t C ha^{-1}), crop residue and earthworm abundance, as well as soil stable aggregates and soil organic carbon.

Because we want both to maximise plant establishment and favour carbon storage in the soil, it is possible that intermediate tillage systems may be able to produce a balanced result of the two factors for arable crops. In the case of energy crops such as Sida and Silphium, although establishment may result in initial carbon loss, the perennial nature of the crops will eventually promote carbon storage whilst supporting a healthy soil, akin to the effect provided by young secondary woodlands (Ashwood *et al*., 2019). Further long-term measurements at the field site are needed to support this premise.

4.4.4 Future research recommendations

After conducting this experiment, we can give advice on a number of points. When establishing a perennial energy crop on grassland, a three-year period was not enough time to detect positive changes of SOC. In fact the SOC levels tended to decline, possibly due to field cultivation. Soil carbon levels depend on a balance between inputs and outputs and it may take a number of years before a perennial crop produces sufficient biomass (in excess of that harvested) to start increasing soil organic carbons above an initial level. Another recommendation for future research is comparing the changes of carbon content in the soil under an arable rotation with the soil under a mature Sida/Silphium plantation, with a space between sampling times of at least 5 years and sampling one replicate area per experimental treatment to increase the accuracy of the results. Further research is needed to decipher the cause of the observed reduction in bulk density at a depth of 10-15 cm which potentially benefited the soil by reduced compaction, whether it is due to the soil operations to establish the crops or the effect of the growth of the roots from the energy crops.

4.5 Conclusions

In 2017, prior to cultivation, the bulk density of a grassland field at 0-5 cm (1.40 g cm^{-3}) was lower than that (1.72 g cm^{-3}) at a depth of 10-15 cm. After three years of the establishment and cultivation of Sida and Silphium, in 2020, the mean bulk density at both 0-5 and 10-15 cm was 1.42 g cm^{-3}. Regarding the levels of STC and SOC, both decreased from 2017 to 2020. In 2017, prior to cultivation, total carbon (including inorganic carbon) in the soil of a grassland field (at 0-20 cm) was recorded to be 69.2 t ha^{-1} and soil organic carbon was 64.7-67.3 t ha^{-1}; after three years of the establishment and cultivation of Sida and Silphium, in 2020, mean soil total carbon decreased to 56.8 t ha^{-1} and soil organic carbon decreased to 54.3-57.0 t ha^{-1}.

SOC was highest in the control area (grass) both prior to the establishment operations and after three years of establishment. The organic carbon concentration in this area was reduced after ploughing the field but recovered at a quicker pace than areas where Sida and Silphium were grown. Additional long-term measurements are needed to determine the long-term effect of Sida and Silphium on organic carbon storage.

Acknowledgements:

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5 AGRONOMIC PERFORMANCE OF *SIDA HERMAPHRODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. IN THE UK

This chapter describes the growth and development of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. established in Silsoe in Bedfordshire in 2017. The chapter starts by describing the experimental site, weather conditions, experimental design, planting material, establishment process, data collection, and data analyses. The research covered by this chapter compares two establishment methods (seeds/seedlings) for both species and two different origins of *Sida hermaphrodita* (L.) Rusby, records the changes in plant density with time, a characterisation of the structure of *Sida hermaphrodita* (L.) Rusby, the height and diameter of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., the solid fuel biomass yields of *Sida hermaphrodita* and green biomass yields of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., and interprets relevant statistical analyses. The chapter concludes with a discussion on the establishment method and plant density, morphology, yields, implications for farmers, and recommendations for future research. The chapter has been prepared in the form of a scientific paper by Laura Cumplido-Marin, Anil R. Graves, Michail Giannitsopoulos, and Paul J. Burgess.

Abstract: The agronomic performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. was studied in the UK for the first four years of cultivation. The experiment, established in 2017, compared the establishment using seeds or transplanted seedlings for both crops, and two provenances of *Sida hermaphrodita* (L.) Rusby. *Sida hermaphrodita* (L.) Rusby can be harvested in the summer to produce biogas or in the winter to produce solid fuel for combustion; *Silphium perfoliatum* L. was only harvested to produce green biomass for biogas. For the summer harvests, transplanted plants of *Sida hermaphrodita* (L.) Rusby produced 10.7-10.8, 8.2-8.0, 4.9-7.1 t DM ha^{-1} y^{-1} in the second, third and fourth years respectively. The corresponding dry matter yields obtained in winter were lower: 1.3-2.1, 4.9-5.9, and 3.6-3.7 t DM ha^{-1} y^{-1} in the second, third and fourth years respectively. Establishing *Sida hermaphrodita* (L.) Rusby from seed in the field was difficult and the yields were typically half that of the transplanted

Sida *hermaphrodita* (L.) Rusby plants. By contrast, no statistical differences were observed between establishing *Silphium perfoliatum* L. using seeds or seedlings. Green biomass yields of *Silphium perfoliatum* L. increased annually, recording 4.0-5.1, 6.1-7.2, 8.4-9.4 t DM ha^{-1} y^{-1} in years two, three and four. The results from the experimental cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in the UK, indicate that 4-7 t DM ha^{-1} y^{-1} and 9 t DM ha^{-1} y^{-1} could be produced with minimal maintenance after 3-4 years of cultivation. Results from longer-term cultivation of both species would be necessary to draw conclusions on the performance and total production of the crops along their rotation.

5.1 Introduction

Reducing greenhouse gas emissions is of crucial importance to minimise climate change and its impacts. To encourage each other to work towards this goal, 195 nations signed the Paris Agreement in 2016. In the UK, the Government set the target of net zero greenhouse gas emissions for 2050 (UK Government, 2019a). Achieving this target requires careful consideration of all the renewable energy technologies available. Within the bioenergy sector, energy crops such as short rotation coppice (willow/poplar) and Miscanthus have not been as widely planted as originally anticipated, due to their high establishment costs, risk undertaken, and opportunity costs (Witzel and Finger, 2016). By contrast, the growing of maize for biogas has been a popular choice for farmers in recent years due to its high revenues, but its extended and long-term cultivation has negative environmental impacts (Bauböck *et al*., 2014; Schäfer *et al.*, 2015). There is a gap to be filled by profitable and environment-friendly energy crops. It is within this context that research was undertaken to study the two novel bioenergy crops *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., from here onwards referred as Sida and Silphium.

Sida and Silphium are perennial energy crops that can grow 3 m tall and last for 15 years or longer in full production. The crops grow well in wet climates with cold winters and hot summers; similar to the conditions found in their indigenous environment of eastern

USA and south-east Canada. Sida can be established from seeds, seedlings, or rhizomes whilst Silphium can be established from seeds or seedlings. Sida has been cultivated in eastern Europe to produce solid fuel for decades. Silphium has been long cultivated in China for fodder and has only recently been a focus of research during the last decade as an alternative biogas source to maize. Mature Sida yields vary between 5 and 20 t DM ha^{-1} (Cumplido-Marin *et al.*, 2020), depending on growing conditions. Mature Silphium yields tend to be more consistent 12-21 t DM ha^{-1} (Cumplido-Marin *et al.*, 2020). Reported environmental benefits associated with the cultivation of Sida and Silphium, relative to maize, include increased biodiversity, pollen and nectar production, increased soil organic carbon, reduced chemical inputs, reduced nitrogen leakage, and reduced soil compaction (Cumplido-Marin *et al.*, 2020).

One of the multiple research gaps identified for both crops is their cultivation in different climatic conditions (Franzaring *et al*., 2014). To fill this gap, the SidaTim project established five twin experiments in four countries across Europe (Poland, Germany, Italy and the United Kingdom). All the experiments included the use of seeds and seedlings for both crops and two different origins for Sida. In the UK, the field trial was established by Cranfield University at the University Farm at Silsoe, Bedfordshire. The objective of this paper is to report the agronomic performance of Sida and Silphium in the UK for the period 2017-2020.

5.2 Methodology

5.2.1 Site location and description

The experiment was established in the spring of 2017 on the premises of the farm owned by Cranfield University in Silsoe (Bedfordshire), 28 miles from the university (
Figure 5.1). The piece of land known as “Rickyard’s field” (52.007897°, -0.432112°) has a total area of 0.68 ha. Historically, the land was used for grazing, tractor driving lessons for a short period of time, and had been left as grassland for the last 15 years.

Figure 5.1 – Location of the experimental site at Silsoe relative to the UK.

5.2.2 Weather conditions

Weather data is available from a field station at Woburn (52.017000°, -0.600000°), 16 miles away from Silsoe. For the period 1981-2010, the records for Woburn are available from the Met Office. The annual mean maximum temperature was 14.1°C, the annual mean minimum temperature was 5.8°C, the mean annual rainfall was 657 mm, and in a mean year, the site receives 1,471.6 h of sunshine (Met Office, 2020a).

Weather data for the years 2017-2020, provided by the Met Office (2020b) is included in Appendix D, D.3 Climate data. Over the four years, the highest monthly mean maximum temperature was 26.5°C in July 2018 and the lowest mean minimum temperature was -0.6°C in February 2018. The daily mean temperatures varied between 3°C and 20°C during the four years. Greater than 10 mm of rainfall occurred in each month, apart from June 2018 and May 2020.

5.2.3 Experimental design

The design, agreed with the partners in the project definition stage of the SidaTim project, involved four replications of six treatments in a Latin-square design (

Figure 5.2), using seeds and seedlings from two separate provenances of Sida (hereafter referred as Sida1 and Sida2), and seeds and seedlings from one single provenance of Silphium. The designed including two treatments (seeds/seedlings) of the three plants (Sida1, Sida2, Silphium) and four repetitions, all organised in six blocks, was thus composed of a total of 24 plots. Since each experimental plot had a size of 4.5 x 8 m (36 m^2), the experiment consisting of 24 individual plots covered an area of 0.22 ha.

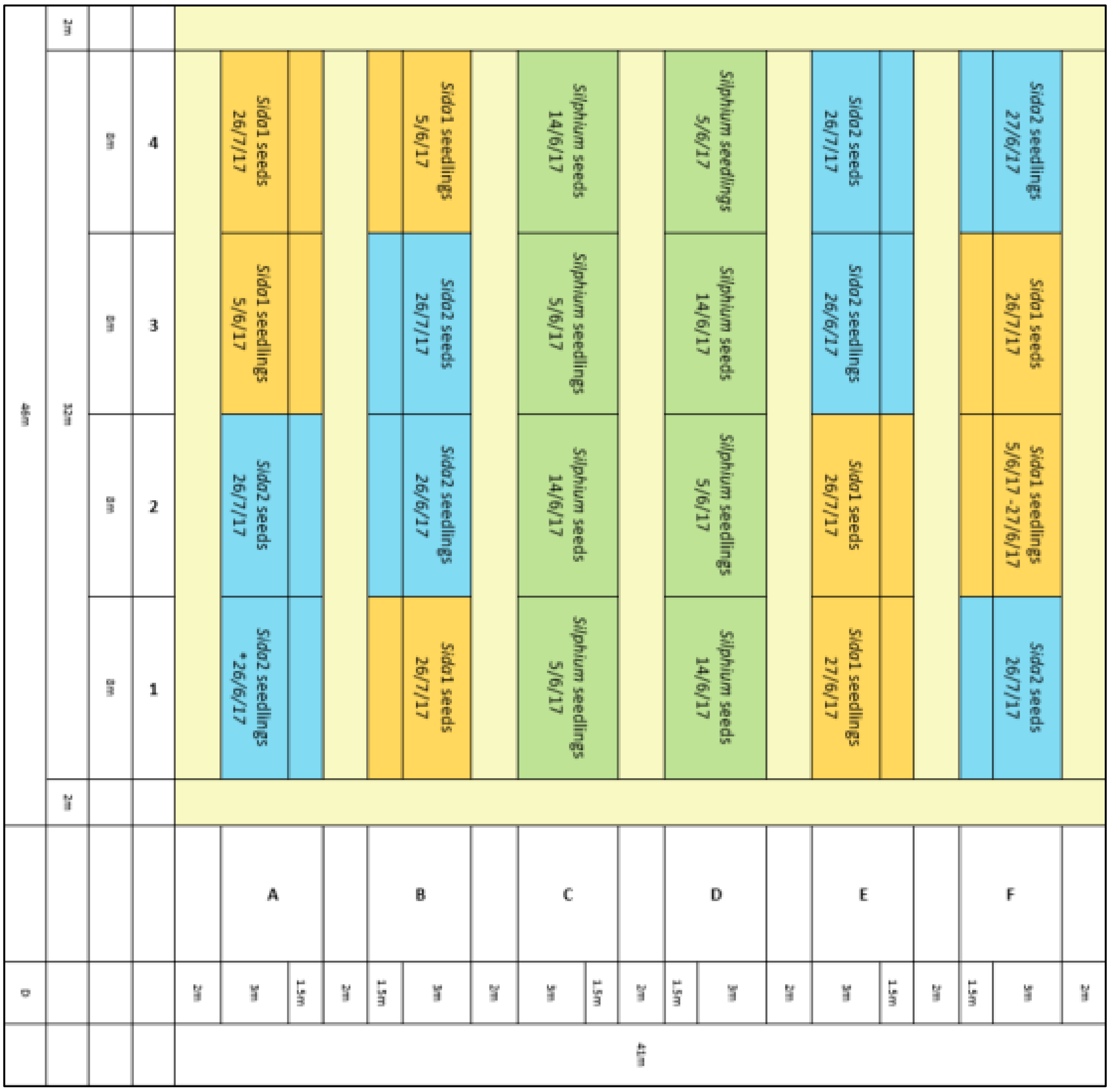


Figure 5.2 – Experimental layout of the plantation design following a randomised Latin-square design.

5.2.4 Planting material

All Silphium seedlings were produced from seed in the greenhouse at Cranfield University, from February to April 2017. The seeds provided by N.L. Chrestensen Erfurter Samen- und Pflanzenzucht GmbH (Postfach 800854, 99034 Erfurt, Germany) had been stored in a dark, dry environment at room temperature (20-25°C) in Cranfield University for 10 months, until February 2017.

Sida seedlings from two different origins, Sida1 and Sida2, were imported from German suppliers. Sida1 seedlings were supplied by Martin Klein (Landwirtschaft u. Energiepflanzen, Brühlweg 2, 88457 Kirchdorf, Germany) and Sida2 seedlings from Dirk Helling-Junghans (Barenauer Weg 38, 49565 Bramsche/Kalkriese, Germany). Sida seedlings arrived between 15-20 June 2017 and were stored under shade and watered regularly until they were transferred to the field.

5.2.5 Establishment process

In late February – early March 2017, the grass was mowed, spraying with glyphosate (3 l ha^{-1} in 200 l of water), ploughed at a depth of 20 cm, power harrowed, and ring rolled. After analysing the content of available N, P, K in the soil, 50 kg ha^{-1} of N and 110 kg ha^{-1} of K were applied in late March 2017. The experimental plots were laid and marked with wooden stakes into the ground in early April 2017. Due to administrative issues, the establishment of the plantation was delayed to early June. By mid-May weeds had regrown and the field was re-sprayed (2 l ha^{-1} per 200 l of water).

Transplanting of seedlings was accomplished in two stages. The first stage, transplanting of the Silphium seedlings, was done between in early June 2017. The second stage, transplanting the Sida seedlings, occurred at the end of June 2017. The seedlings were transplanted at a density of 4.4 plants m^{-2}, equivalent to 160 plants per plot in 8 rows, keeping 45 cm between plants and 50 cm between rows.

Half of the seed plots were sown in mid-June 2017 and the remainder had to be delayed to the end of July due to a heat wave. It was then necessary to install a sprinkler irrigation system to water the seedbeds and seedlings. During the establishment year (2017), the experimental plots were watered twice in June, eight times in July and one time in August. Because of the sensitivity of Sida and Silphium to herbicides, all weeding was done manually, carried out in fourteen sessions across 2017.

5.2.6 Data collection

The success of the different establishment methods (seeds vs. seedlings) and plant origins (Sida1 vs. Sida 2) was measured through the plant density of the experimental plots. Plant density was calculated relative to 100% coverage, which corresponded to 160 plants within each experimental plot (4.4 plants m^2 over 36 m^2). Hence, throughout the period 2017-2020 the corresponding plant density was estimated via plant surveys based on plant counts or visual estimations of plant coverage.

To record other parameters, 10 plants per plot were selected by default from the middle of the plot, tagged, and measured to minimise edge effects. In February 2018, the number of shoots and length of each shoot was measured to characterise Sida plants and the weight of shoots and roots was recorded and compared to study the relationship between aerial parts and roots of Sida. In July 2018, the weight of Sida leaves and stalks was recorded separately by Sanchez Muñoz (2018), included in Appendix D, D.7 Leaves-stalks biomass.

To record plant development of Sida and Silphium in the UK (2017-2020), the *Sida hermaphrodita* BBCH-code (Jablonowski *et al*., 2017) was used for Sida and the general BBCH-code was used for Silphium.

To keep records of the growth, both height and diameter were measured repeatedly during the growing season (2017-2020) until harvest, from each different treatment. The Sida and Silphium plots next to the poplar trees on the west side of the experiment were measured in 2019 to account for water/light competition (Appendix D, D.5 Growth records of plots adjacent to poplar trees).

Winter and summer biomass yields were recorded from 2017 to 2020. Sida was harvested in late February-March for the production of solid fuel for combustion and in late summer for the production of green biomass for anaerobic digestion. Silphium was only harvested in summer for the production of green biomass for anaerobic digestion. Sida plots were first harvested in February 2018 for solid biofuel production. In 2018, a third of Sida plots were harvested in two cuts (BBCH stages 55 and 71) for green biomass production in summer. From 2019 onwards, a third of Sida plots was harvested in one cut (BBCH stage 71) for green biomass production in summer and two thirds of Sida plots were harvested in February for solid biofuel. Silphium plots were harvested only once in summer (when the dry matter was about 36%), apart from summer 2018 when they were harvested twice.

From each replication, 10 samples were selected from middle rows, cut about 5 cm above ground level, and taken to the laboratory. In the laboratory, the fresh mass (kg) was recorded, the samples were dried in the oven at 105°C until constant weight, and the dry mass (kg) was recorded, calculating the dry matter content of the biomass. All remaining plants on the field were harvested and the fresh weight of every plot was recorded. With the data obtained, the dry matter (DM) per ha was estimated.

Growth and yield records during the year 2018 were produced by Sanchez Munoz (2018) and by Dr. A. Graves. Yield data from field experiments using the same layout and plant material established in Germany, Italy and Poland (Facciotto *et al*., 2018 and Bury *et al.*, 2019), allowed for comparisons to be made at a European scale.

5.2.7 Data analysis

The yields were analysed in terms of species, origin and establishment method, and the distribution of the individual data groups. A linear regression analysis was also used to determine if there was a correlation between yields of Sida and plant density.

Yield reduction of Sida with time in this experiment is attributed to both low management and consequence of mortality resulted from the presence of disease (*Sclerotinia sclerotiorum*, evidence in Appendix D, D.4 Pictures of Sida affected by *Sclerotinia sclerotiorum*). Whilst during 2017 weed control was kept to high standards and fertiliser was applied before planting, no weed control and no fertilisation was applied in 2018-2020. Double harvesting occurred in summer 2018, which can negatively affect future yields (Oleszek *et al*., 2013).

We observed that the combined effect of double harvesting in summer 2018, no weed control and no fertilisation for the period 2018-2020, plus the effect of *S. sclerotiorum* had a negative impact on the long-term survival and growth rate of Sida. In 2020, plant densities of Sida (compared to the target density) varied from 0 plants m^{-2} to 2.8 plants m^2, which ultimately affected yields negatively, reducing them over time. Silphium had the same management and fertilisation treatment but was more resilient to the effect of the disease, maintaining a plant density of 1.8-3.2 plants m^{-2}.

To unravel potential significant effects of the plant origin and the establishment method, as well as potential interactions between them, the data set of yields for combustion and biogas (with values of 0 kg DM ha^{-1} removed) were analysed separately for each year using an analysis of variance (ANOVA) followed by a least significance difference (LSD) test. The independence of data, normality, and homogeneity of variance assumptions were tested prior to the analysis of variance (Appendix D, D.8 Statistical analyses).

5.3 Results

5.3.1 Establishment method and plant density

In October 2017, after the first growing season, there was a uniform establishment of Sida plants established from seedlings, but the establishment from seeds was uneven. The level of establishment was greater in the plots with Sida2 than Sida1 seeds. The mean seedling establishment was 14.1% for Sida1 and 71.4% for Sida2. In September 2020, the mean plant density was 9.9% for Sida 1 and 30.0% for Sida2 (

Figure 5.3).

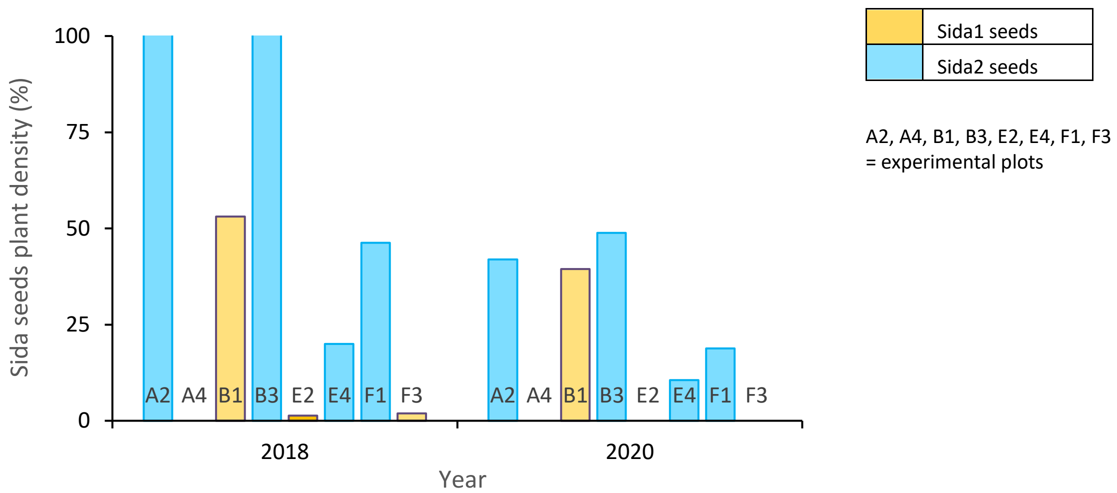


Figure 5.3 – Plant density (expressed as a proportion of the target density) of eight different plots originated from Sida seeds in 2018 and 2020.

The establishment of Silphium via seeds or seedlings produced similar results. Towards the end of the first growing season of the year of establishment (October 2017), all Silphium plots had a relatively uniform plant coverage, visually estimated to have similar plant density of 100%, irrespective of the establishment method. In June 2018, the plant density of Silphium plants originated from seeds, ranged from 55.0% to 95%, with an average of 83.3%. In September 2020, the average plant density of plots originated from Silphium seeds was 56.9%, compared to 64.9 % for plants originated from seedling. All the records of plant counts and visual estimations are included in Appendix D, D.6 Plant density records 2017-2020.

The plant density recorded in September 2020 is shown in

Figure 5.4., box plot that shows the mean markers, the upper and lower quartiles and the variability outside quartiles. Regarding the two different seed origins of Sida (Sida1 and Sida2), Sida2 had greater establishment success, both in the year of establishment and after three years of cultivation. Comparing the establishment via seeds and seedlings, the establishment of Sida with seedlings resulted in higher survival rate and smaller variation than using seeds. The establishment of Silphium using seeds or seedlings resulted in 8.0% higher survival rate on average from seedlings.

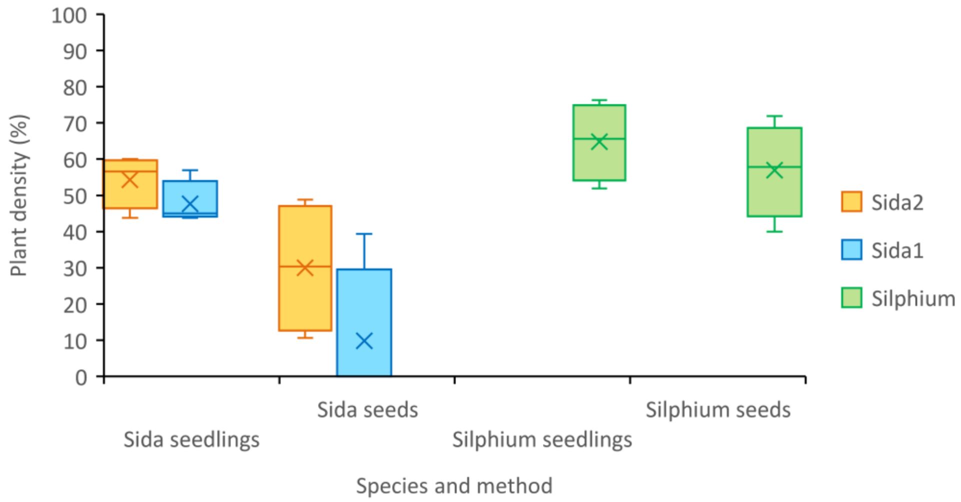


Figure 5.4 – Plant density at the end of the experiment (September 2020).

5.3.2 Plant characterisation of Sida

The structure of a Sida plant, represented in Figure 5.5, was characterised in February 2018, prior to the first winter harvest. A Sida plant had on average three primary shoots, two secondary shoots, and five tertiary shoots. The mean length of the primary shoots was 128 cm, the mean length of secondary shoots was 91 cm, and the mean length of tertiary shoots was 38 cm. The mean diameters were 11 mm for the primary shoots, 7 mm for the secondary shoots and 4 mm for the tertiary shoots.

The measurements of the root to shoot biomass of Sida obtained in February 2018 (Figure 5.6), indicated that the aerial part of Sida plants made up 31% of the total plant biomass and that the underground part, a mass of coarse rhizomes, was 69% of the total plant biomass. The mean length of the measured Sida roots in February 2018 was 17.4 cm.

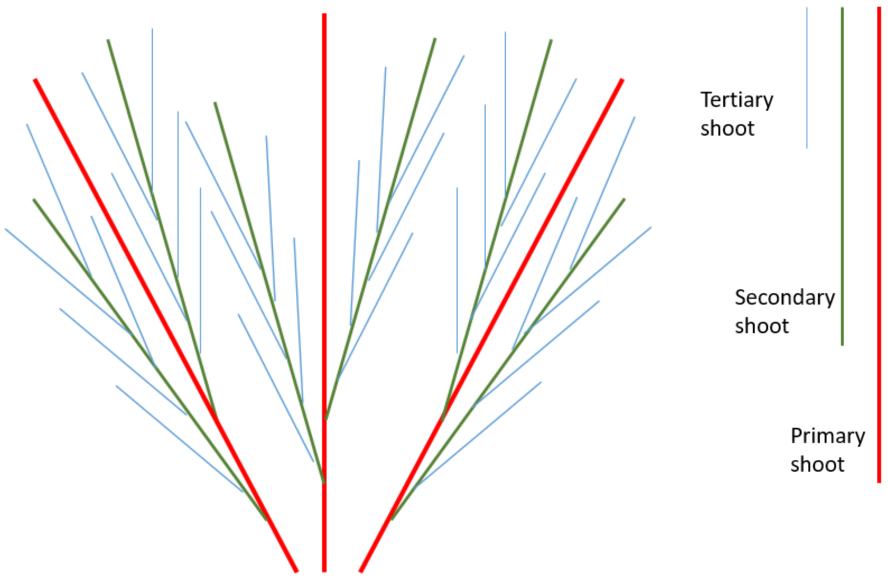


Figure 5.5 – Scaled diagram of the structure of a *Sida hermaphrodita* (L.) Rusby plant.

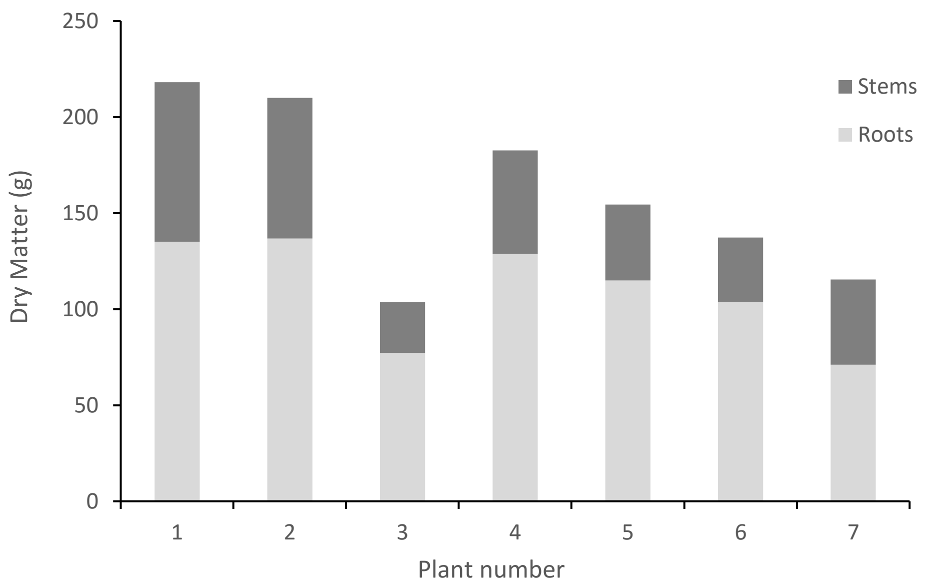


Figure 5.6 - Root-to-shoot dry biomass of *Sida hermaphrodita* (L.) Rusby from 7 plants (own results).

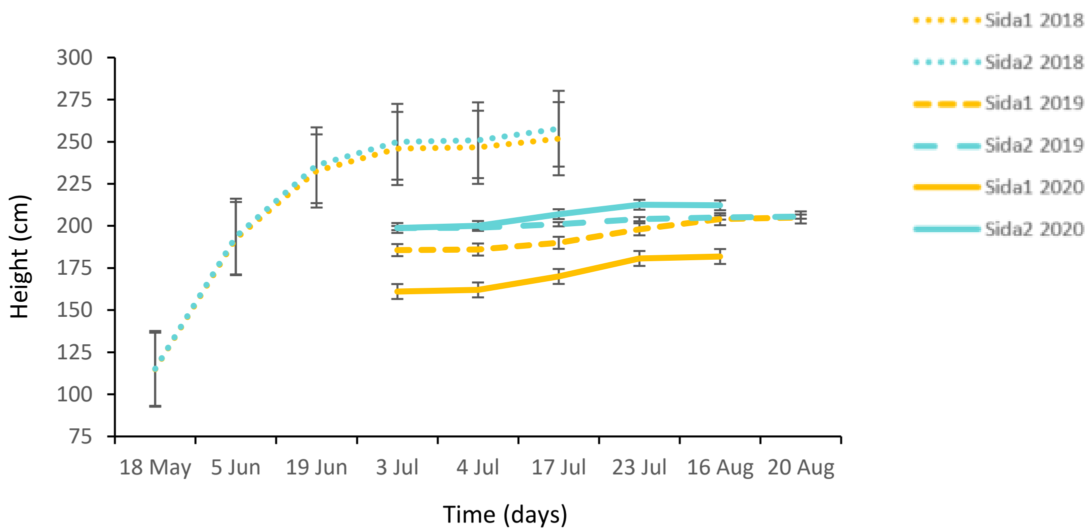
5.3.3 Growth monitoring

The heights and diameters of the Sida plants are shown in Figure 5.7. In 2017, the Sida1 and Sida2 plants reached maximum average heights of 175 cm and 87 cm respectively (not shown). In 2018, the maximum measured height of the Sida1 (252 cm) and Sida2 (258 cm) crops was recorded on 17 July (Figure 5.7.a), being similar to each other and higher than in 2017. In 2019, the maximum measured heights of the Sida were recorded in August, with similar values for Sida1 (205 cm) and Sida2 (206 cm), less than in 2018. In 2020, the maximum height in July was shorter for the Sida1 plants (182 cm) than for Sida2 (213 cm).

The diameter of Sida generally showed a similar response to the heights (Figure 5.7.b), although the maximum diameter was typically achieved in June compared to after June for the achievement of maximum height. In 2017, the maximum diameter of the Sida1 plants (28.8 mm) was substantially greater than that (12.2 mm) of the Sida2 plants (data not shown). In 2018, Sida1 and Sida2 had similar mean maximum diameters of 17.5-17.6 mm and mean final diameters of 16.9-17.2 mm. In 2019, the mean maximum and mean final diameter of Sida1 was 14.8 mm; the mean maximum diameter of Sida2 was 13.9 mm at the start of July and 13.4 mm at the end of August. In 2020, the mean maximum diameters achieved by Sida1 and Sida2 were 12.7 mm and 14.0 mm respectively at the end of July, declining slightly to 12.4 mm and 13.5 mm for mid-August.

In September 2017, Silphium plants originated from seedlings reached a mean height of 57 cm. In 2018, Silphium reached a height of 173 cm for plants propagated from seeds and 174 cm for plants propagated from seedlings by mid-June (Figure 5.8.a). Whereas the height of the transplanted plants remained at the same level, plants derived from seeds had a final height of 160 cm. In 2019, the mean heights remained relatively stable from July to August, with the mean height of the plants from seed (165 cm) again shorter than those from seedlings (196 cm). In 2020, Silphium achieved maximum (and final) heights of 155 cm and 181 cm respectively for plants originated from seeds and seedlings.

a) Sida height (cm)



b) Sida diameter (mm)

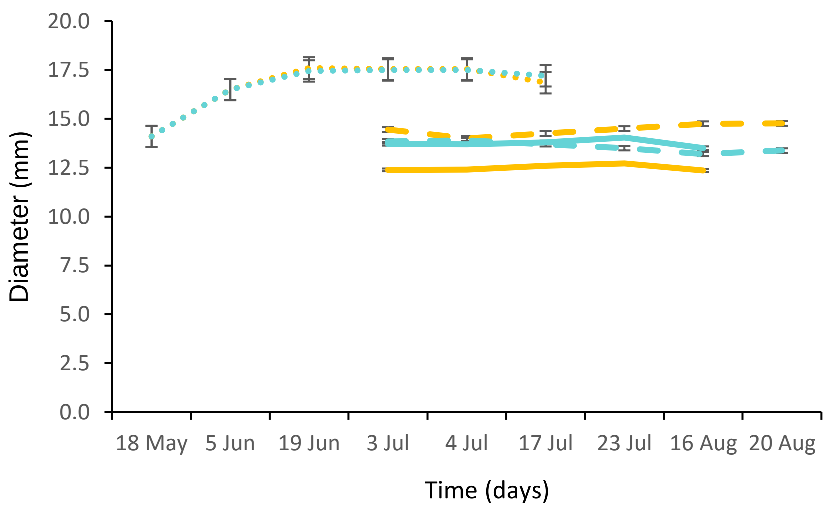


Figure 5.7 – Showing: (a) the height (cm) and (b) the diameter (mm) of *Sida hermaphrodita* (L.) Rusby recorded at the Silsoe experimental sin 2018, 2019 and 2020. Note that the x-axis in not linear.

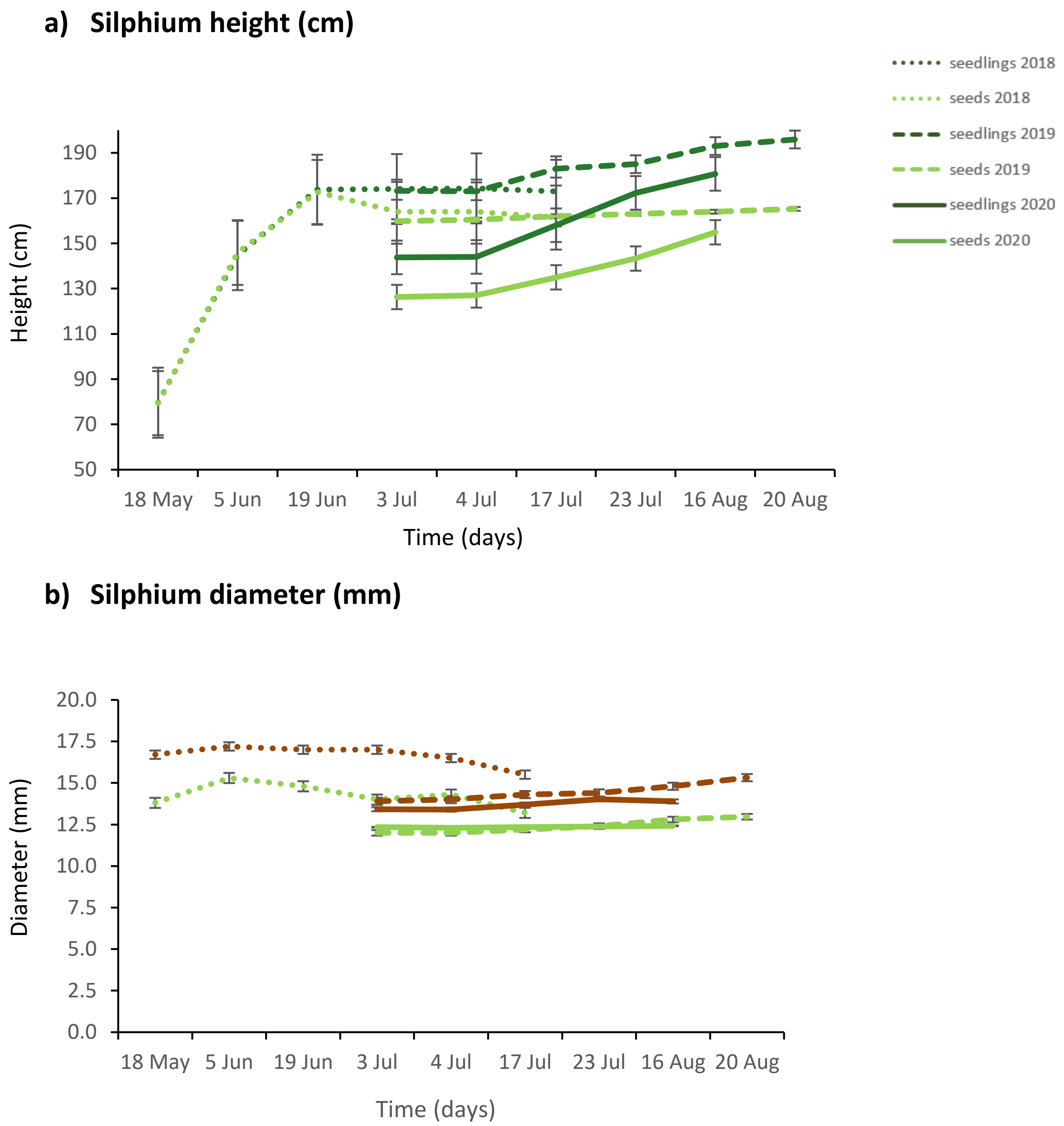


Figure 5.8 - Showing: (a) the height (cm) and (b) the diameter (mm) of *Silphium perfoliatum* L. recorded at the Silsoe experimental sin 2018, 2019 and 2020. Note that the x-axis in not linear.

The rosette of Silphium plants originated from seedlings had a mean diameter of 37.5 cm in September 2017 (Figure 5.8.b). In 2018, transplanted Silphium plants had a mean maximum stem diameter 17.2 mm compared to 15.3 mm for plants propagated from seed, with lower final diameters of 15.5 mm and 13.2 cm respectively. In 2019, the transplanted Silphium plants had mean maximum diameters of 15.3 mm compared to 13.0 mm for plants propagated from seeds. In 2020, Silphium achieved maximum diameters of 14.0 mm and 12.4 mm at the end of July for plants derived from transplants and seeds respectively, with a final diameter for transplanted plants of 13.9 mm in mid-August (Figure 5.8.b).

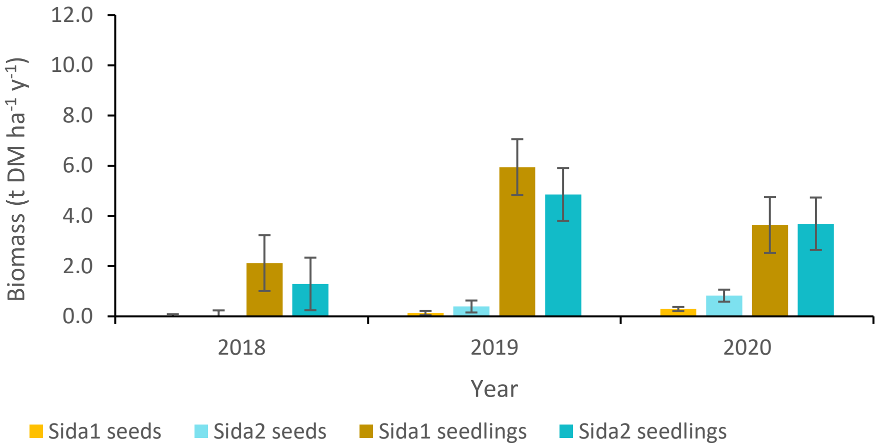
5.3.4 Yields

The biomass yields of Sida for three consecutive years (2018-2020) are represented in Figure 5.9. The first harvest year (2018), Sida plants originated from seeds were too small to be harvested. In subsequent years, the yields obtained from plants propagated from seeds for solid biofuel production for combustion are also very small: 0.3 t DM ha^{-1} and 0.6 t DM ha^{-1} in the 2nd and 3rd year respectively. Sida1 transplants produced a yield of 2.1 t DM ha^{-1} in year 1 (2018) compared to 1.3 t DM ha^{-1} y^{-1} for Sida2. Similarly Sida1 transplants provided a yield of 5.9 t DM ha^{-1} in the second year (2019) compared to 4.9 t DM ha^{-1} for Sida2 (2019). By contrast the yield of solid fuel for combustion from Sida1 (3.6/3.7 t DM ha^{-1}) and Sida2 (3.7 t DM ha^{-1}) were similar in the third year (2020).

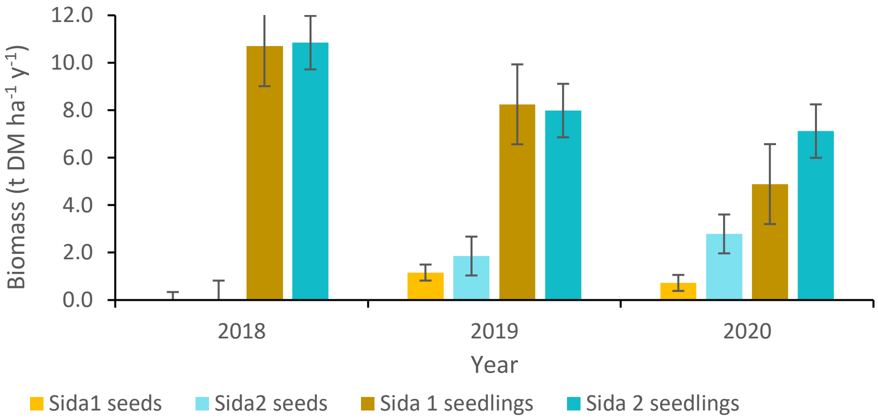
In terms of harvesting Sida for biogas production, the plants originated from seeds were too small to be harvested in 2018, and the yields remained low in 2019 (1.2 t DM ha^{-1}) and the third year (0.7 t DM ha^{-1}). The plant dry matter yields (for biogas production) for transplants of Sida1 and Sida2 were 10.7 and 10.8 t DM ha^{-1} respectively in the first year (2018). In the second year (2019), the yields for Sida 1 (8.2 t DM ha^{-1}) and Sida 2 (8.0 t DM ha^{-1}) were again similar. In the third year (2019), the Sida1 produced a dry matter yield of 4.9 t ha^{-1} compared to 7.1 t ha^{-1} for Sida2.

The yields obtained from Silphium (Figure 5.9.c), considering a unique use for anaerobic digestion, were 4.0/5.1 t DM ha^{-1} y^{-1} in the first year (2018), 6.1/7.2 t DM ha^{-1} y^{-1} in the second year (2019), and 9.4/8.4 t DM ha^{-1} y^{-1} in the third year (2020) for plants originated from seeds/seedlings respectively.

a) Sida – Combustion



b) Sida – Biogas



c) Silphium – Biogas

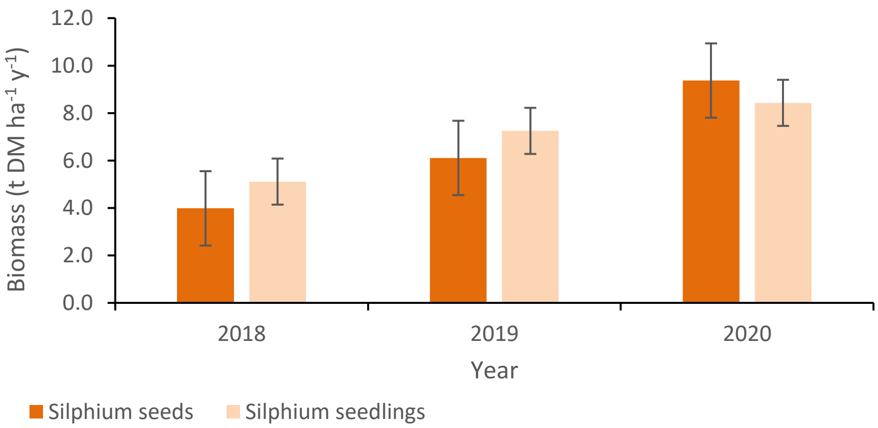


Figure 5.9 – Showing harvested biomass (t DM ha^{-1} y^{-1}) of: (a) *Sida hermaphrodita* (L.) Rusby for solid fuel for combustion (b) *Sida hermaphrodita* (L.) Rusby for green biomass for biogas (c) *Silphium perfoliatum* L. green biomass for biogas.

5.3.5 Yields and plant density

A linear regression analysis of the dry matter yields for Sida in 2020 suggested that 47.4% of the variation in yield (t DM ha^{-1}) could be explained by differences in plant density (Figure 5.10). To try and decipher the remainder of the variation in yields and whether this was due to the treatments or interactions between them we carried out the ANOVA and LSD analyses (explained in detail in the following section).

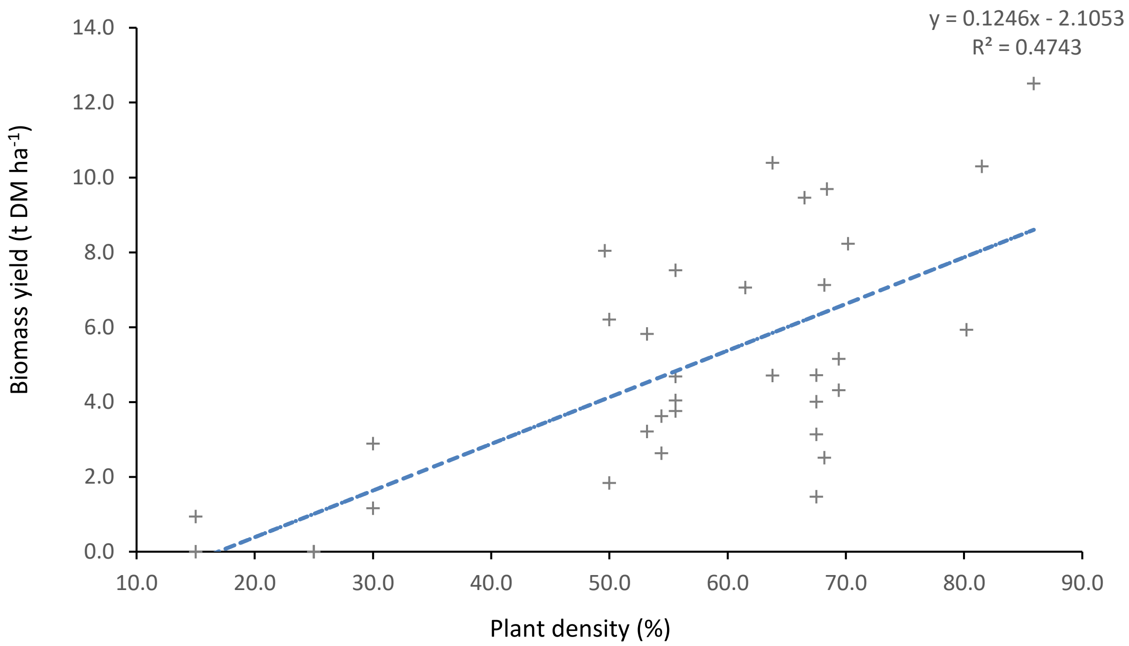


Figure 5.10 – Linear regression of harvested yield vs. plant density of *Sida hermaphrodita* (L.) Rusby in 2020.

5.3.6 Treatment effects

Standard tests to check that the assumptions of independence of data, normality, and homogeneity of variance were carried out on for the yield data set and are included in Appendix D, D.8 Statistical analyses. The distribution of the yields of Sida1, Sida2, and Silphium under different establishment methods were examined using a boxplot (Figure 5.11). The median yields from the plots with Sida1 seedlings and Sida2 seeds are approximately in the middle of the box but the whiskers are not equidistant from the median with a slight skewed distribution of the data towards lower yields. The median yields of Sida2 seedlings and Silphium plants (seeds and seedlings) showed a skewed distribution within the boxes, but data points outside the boxes were generally symmetrical.

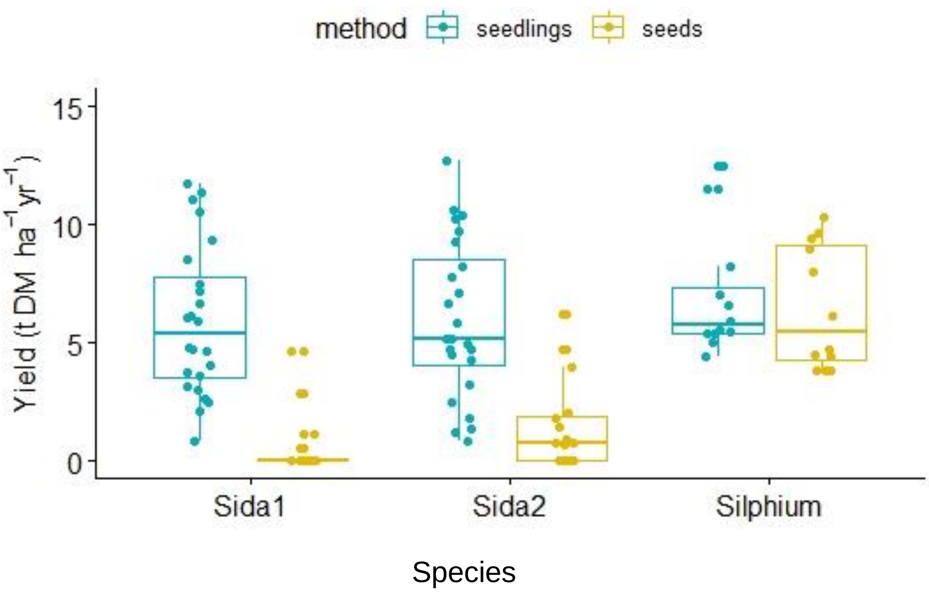


Figure 5.11 – Boxplot of yields obtained from the period 2017-2020 (R Core Team, 2020), showing the difference between plants that were grown in the field from seed, and plants that were transplanted.

For combustion, the results (Table 5.1) from the ANOVA test for Sida yields indicated significant effects of the treatment, the year, and treatment x year interactions. The mean transplanted yields (3.3-3.9 t DM ha^{-1} y^{-1}) were greater than the seed yields (0.2-0.6 t DM ha^{-1} y^{-1}). The highest mean yield was obtained in 2019 (3.0 t DM ha^{-1}), and that in 2020 (2.6 t DM ha^{-1}) was greater than that in 2018 (1.7 t DM ha^{-1}). For the biogas yields, the ANOVA indicated significant treatment and treatment x year interactions (Table 5.1). The mean yields from the transplanted Sida plants (7.9-8.7 t DM ha^{-1} y^{-1}) were generally greater than those grown in the field from seed (0.9-2.3 t DM ha^{-1} y^{-1}). The mean yields from the Silphium plants were similar if grown from transplants or from seed. For Sida transplanted seedlings, high yields were obtained in 2018 (10.7-10.8 t DM ha^{-1}), with the yield of Sida1 being lower (4.9 t DM ha^{-1}) in 2020. By contrast, for Silphium grown from seed, higher yields were obtained in 2020 (9.4 t ha^{-1}) than 2018 (4.0 t ha^{-1}).

Table 5.1 – Yields (t DM ha^{-1} y^{-1}) and significance letters obtained in the LSD tests.

	2018	2019	2020	Mean
Combustion				
Sida1 seeds	-	0.5 [b]	1.2 [a]	0.2
Sida2 seeds	-	0.8 [b]	1.7 [a]	0.6
Sida1 seedlings	2.1 [a]	5.9 [a]	3.6 [a]	3.9
Sida2 seedlings	1.3 [a]	4.9 [a]	3.7 [a]	3.3
Sida mean	1.7	3.0	2.6	
Biogas				
Sida1 seeds	-	4.6 [a]	2.9 [a]	0.9
Sida2 seeds	-	2.5 [a]	3.7 [a]	2.3
Sida1 seedlings	10.7 [a]	8.2 [a]	4.9 [a]	7.9
Sida2 seedlings	10.8 [a]	8.0 [a]	7.1 [a]	8.7
Silphium seeds	4.0 [b]	6.1 [a]	9.4 [a]	6.5
Silphium seedlings	5.1 [b]	7.2 [a]	8.4 [a]	6.9
Sida mean	10.8	5.8	4.7	
Silphium mean	4.6	6.7	8.9	

* Sida1 seeds 2019, 2020: 3/4 plots were bare; Sida2 seeds (combustion) 2019, 2020: 2/4 plots were bare; Sida2 seeds (biogas): 1/4 plots were bare.

The results from the ANOVA and posterior LSD tests (Table 5.1) on the yields for combustion indicated that the crop (Sida1/Sida2 seeds/seedlings) showed a significant effect on the recorded yields only in certain years. There was a significant difference on Sida yields produced between plants originated from seeds and seedlings in 2019 ($p<0.05$). The results from the statistical analyses on the yields for biogas, indicated that the crop (Sida1/Sida2 seeds/seedlings) also had a significant effect on the recorded yields in certain years. There was a significant effect of seedling or seed establishment on Sida yields in 2018 ($p<0.05$). For further details on the analyses see Appendix D, D.8 Statistical analyses.

5.4 Discussion

5.4.1 Establishment method and plant density

In this UK experiment, there were low survival rates from growing Sida plants from seed in the field. By contrast, corresponding results from experiments in Germany, Poland, and Italy have shown that it is possible to establish Sida plants directly from seed in the field (Appendix D, D.9 SidaTim European joint project yield results). The low survival rate in this experiment could be a result of the field conditions or the preparation and storage of the seed. For example, the Sida seed were planted relatively late in the spring of 2017. This effect, combined with relatively low levels of management and high mortality from the presence of *S. sclerotiorum* in subsequent years, resulted in the lower plant densities recorded in September 2020. It is worth underlining the distinctly higher plant densities recorded for Sida2 seeds and Sida2 seedlings. This could be a result of a fungicide seed coating applied to Sida2 seeds, which appeared to increase both the success of establishment and the long-term survival of Sida plants. Apart from seed coatings, Sida seeds benefit from treatments to break their dormancy (Franzaring *et al*., 2014; Kurucz and Fári, 2013).

5.4.2 Morphology

In February 2018, before the beginning of the growing season, the rhizomes and roots comprised about 70% of the total dry mass of the Sida plants (Figure 5.6). The capacity of the rhizomes and roots to store biomass from one season to the next is one reason why the early season growth of Sida can be so high. The high proportion of biomass allocated below-ground should also help to increase the level of soil carbon.

There are few studies of the height and diameter of Sida plants that can be used for comparison with the results presented here. Šiaudinis *et al*. (2017) (Lithuania) recorded average Sida heights of 198 cm from the second to fourth year of cultivation. Borkowska *et al*. (2009) (Poland) recorded increasing Sida heights every year of 152-191 cm, 222-242 cm, 248-298 cm and 290-299 cm in the second, third, fourth and fifth year of cultivation. In the UK experiment reported here, transplanted Sida plants (Sida1 and Sida2) reached a maximum height of 252-258 cm in the second year (2018). The Sida1 plants reached shorter heights of 205 cm in 2019 and 182 cm in 2020. The Sida2 plants were 206 cm in 2019 and 213 cm in 2020. A similar pattern was observed for the mean diameter declining from 17.6-17.5 mm in 2018, to 14.8-13.9 in 2019 and 12.7-14.0 mm in 2020. One potential reason for the greater heights and diameter in 2018, is that the plants were less nutrient stressed than in 2019 and 2020, as the plots were fertilized prior to establishment.

In case of Silphium, Franzaring *et al.* (2015) (Germany) recorded average heights of 54.7 cm for 1 year old plants, very similar to the 57.0 cm reached by plants propagated from seedlings at the end of the establishment year in the present experiment. Šiaudinis *et al*. (2017) (Lithuania) recorded average heights of 163 cm from the second to fourth year of cultivation, in agreement with the values of 161-183 cm measured in our UK experiment. In contrast to the Sida plants, the decline in the height with time was less; being 173-174 cm in year 2 (2018), 165-196 cm in year 3 (2019), and 155-181 cm in year 4 (2020). However, there was a clearer decline in the mean stem diameter from 15.3-17.2 mm in 2018, to 13.0-15.3 mm in 2019, and 12.4-14.0 mm in 2020, indicating a positive response of Silphium to fertilisation.

5.4.3 Yields

For the Sida crop, the dry matter yields harvested in the summer (for biogas) were greater than those reported in the subsequent winter (for combustion). For example in 2018, the dry matter yield for Sida transplants was 10.7-10.8 t DM ha^{-1} in the summer compared to 1.3-2.1 t DM ha^{-1} in the winter. In 2019, the yield in the summer of 8.0-8.2 t DM ha^{-1} was again greater than the yield of 4.9-5.9 t DM ha^{-1} in the winter. In 2020 the corresponding values were 4.9-7.1 t ha^{-1} in summer and 3.6-3.7 t ha^{-1} in winter. The reduced winter yields were caused by the loss of leaves during autumn and winter and the difference could also represent the potential amount of litter that could be returned to the soil. This would amount to 4.8-5.9 t DM ha^{-1} y^{-1} and 4.3-4.6 t DM ha^{-1} y^{-1} for the 2018-2019 and 2019-2020 seasons respectively.

Because the common plant material and experimental design, the yields in this experiment can be compared to those obtained by the SidaTim project partners in the other countries (Appendix D, D.9 SidaTim European joint project yield results). The establishment of Sida using seedlings in the three other countries to produce solid biofuel for combustion provided a mean yield of 2.3 t DM ha^{-1} in year 2, 9.2 t DM ha^{-1} in year 3, and 8.2 t DM ha^{-1} in year 4 (Table 5.2). Hence taking the mean value, the UK values were 74% of these values in year 2, 59% in year 3, and 45% in year 4. Regarding the green biomass yields for biogas in the three other countries provided a mean yield of 4.4 t DM ha^{-1} in year 0, 12.6 t DM ha^{-1} in year 1, and 11.8 t DM ha^{-1} in year 2 (Table 5.2). Hence taking the mean value, the UK values were 85% of these values in year 1 and 69% in year 2.

Table 5.2 – Mean yields recorded by the SidaTim project.

Crop (use)	**Country**	**0 year old** (year 1)	**1 year old** (year 2)	**2 year old** (year 3)	**3 year old** (year 4)
Sida (combustion)	Poland	-	1.3	9.8	10.5
	Germany	-	1.4	8.7	7.8
	Italy (North)	-	3.2	7.7	6.2
	Italy (South, irrigated)	-	3.4	10.6	na
	UK	-	1.7	5.4	3.7
Sida (biogas)	Poland	4.4	15.0	7.6	-
	Germany	4.4	9.1	18.0	-
	Italy (North)	4.8	11.2	6.6	-
	Italy (South, irrigated)	4.2	15.05	15.1	-
	UK	-	10.8	8.1	6.0
Silphium (biogas)	Poland	-	25.7	14.9	-
	Germany	-	14.2	18.0	-
	Italy (North)	-	14.0	14.5	-
	Italy (South, irrigated)	-	15.7	19.5	-
	UK	-	4.6	6.7	8.9

The absolute and relative declines in the UK Sida yields are different from those reported elsewhere where Sida yields tend to increase from first to the third and fourth year (Borkowska and Molas, 2012). For example, Von Gehren *et al.* (2019) obtained yields of 1.0-2.1, 7.1-9.7, 13.2-14.3 t DM ha^{-1} y^{-1} after 1, 2 and 3 years of cultivation for combustion. For biogas, the same authors obtained 6.6-9.5 and 7.3-8.6 t DM ha^{-1} y^{-1} in the 2nd and 3rd year of cultivation. After 4 years, Sida plantations from other experiments yielded 6.2 t DM ha^{-1} y^{-1} (Šiaudinis *et al*., 2015), 8.8 t DM ha^{-1} y^{-1} (Molas *et al*., 2018) and 11.5 t DM ha^{-1} y^{-1} (Jankowski *et al*., 2016). The probable reason for the lower proportional yields at the UK site is that the plants were not fertilised and nutrient deficiency is likely to have led to reduced yields. For example Kurucz *et al.* (2018), from a zero fertilisation regime, obtained 10.2-11.8 t DM ha^{-1} in the 2nd year of cultivation and observed a reduction in yield over time (5.7-9.4 t ha^{-1} in the 4th year) similar to the effect in the current experiment.

Unlike the Sida plants, the Silphium plots (from both seeds and seedlings) showed a steady increase in yields from year 2 to 4. The Silphium yields obtained in the current experiment were 4.0-5.1 t ha^{-1} in year 2, 6.1-7.2 t ha^{-1} in year 3, and 8.4-9.4 t DM ha^{-1} in year 4. However the absolute yields were lower than those reported across three other sites in Germany, Poland, and Italy, i.e. 26% of the value in 2018 and 40% in 2019. When Silphium achieves maturity, after 3-4 years of cultivation, yields typically range from between 12 t DM ha^{-1} y^{-1} (Ustak and Munoz, 2018) and 21 t DM ha^{-1} y^{-1} (Pichard, 2012). Possible reasons for the lower yields in the UK include a lack of annual fertilisation and higher level of weed competition at the UK site.

5.4.4 Implications for farmers

The above results demonstrate that it was possible to establish a Sida crop from transplants and a Silphium crop from seeds and transplants under UK conditions. In practice, the establishment of the two crops was labour intensive as it was necessary to minimise weed competition by hand in the initial year. For a crop to be commercially viable, methods of controlling weeds mechanically or using herbicides are likely to be necessary.

For the UK experiment site, we did not apply mineral or organic fertilisers beyond the first year. Hence it is possible that both the yields of Sida and the Silphium in the second, third, and fourth years were limited by the availability of nitrogen. In theory, it is possible that the lack of fertilisation and low maintenance regime could still produce enough yield for the crops to be profitable. An economic assessment is necessary to answer this question.

5.4.5 Recommendations for future research

The relatively high yield of Sida obtained for biogas in the second year in the current experiment (10.7-10.8 t DM ha^{-1}) suggests that the UK could present favourable conditions for the cultivation of Sida. However, the significant yield decrease in subsequent years associated with plant mortality and low maintenance, indicates that this species requires moderate to high levels of maintenance to achieve high yields. To confirm the performance of Sida in the UK, the existing experiment should be continued with a higher level of nutrient input and weed control. There is also a need to control the level of *S. sclerotiorum*.

In the case of Silphium, the yields obtained in the current experiment indicate that this species has potential for the production of biogas in the UK, which could be maximised given appropriate fertilisation and maintenance. A continuation of the existing experiment would determine the longevity of Silphium yields, with time from planting, under UK conditions.

5.5 Conclusions

The experiment demonstrated that it was possible to establish a Sida crop under UK conditions using transplants. Having no annual fertilisation and minimal maintenance, the mean yields (in the winter if used for combustion) using transplants increased from 1.7 t DM ha^{-1} in year 1, to 5.4 t DM ha^{-1} in year 2, to 3.7 t DM ha^{-1} in year 3. The mean yields from transplants, if harvested in the summer for biogas (with no annual fertilisation and zero maintenance), were higher: 10.8 t DM ha^{-1} in year 1, 8.1 t DM ha^{-1} in year 2, and 6.0 t DM ha^{-1} in year 3. The higher summer yields were due to the additional harvest of the leaves.

The establishment of Sida from seeds in the field was unsuccessful. Possible reasons for this include the poor germination rate of the seed or poor field conditions for establishment. The observed reductions in Sida transplant yields with time from planting include the presence of *Sclerotinia sclerotiorum*, a lack of fertilisation, and increasing weed competition.

Under UK weather and the specific growing conditions of this study (no annual fertilisation and minimal maintenance), the experiment demonstrated that the establishment of Silphium via seeds or seedlings are both viable options. Silphium plants produced green biomass yields for biogas of 4.0-5.1 t DM ha^{-1} in year 1, 6.1-7.2 t DM ha^{-1} in year 2, 8.4-9.4 t DM ha^{-1} t DM ha^{-1} in year 3.

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6 ECONOMICS OF *SIDA HERMAPHRODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. IN EUROPE

This chapter includes a description of the economic model and financial analysis developed using Excel, implementation of the model, selection of the case studies, crop yields, and financial data and costs. The results presented correspond to the Net Present Values, discounted cash flow values, sensitivity analyses, and shift in values to hit the NPV of the most profitable arable and energy crop for the four countries. The chapter concludes with a discussion on the yields, profitability of energy crops, biomass price, funding, support and extra income, and environmental valuation. The chapter will be presented as a scientific paper by Laura Cumplido-Marin, Paul J. Burgess, Christopher Morhart, Michael Nahm, Gianni Facciotto, Domenico Coaloa, Marek Bury, Pierluigi Paris, Anil. R. Graves.

Abstract: To achieve the carbon neutral target for 2050 set by European governments, European countries will benefit from a consideration of all forms of renewable energy. One form of renewable bioenergy is maize, but converting large areas of land to an annual crop like maize for energy production can create environmental challenges such as soil erosion and loss of biodiversity. Two alternative bioenergy crops that potentially provide a more sustainable alternative are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. In order to determine the financial benefits or costs of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., the two crops were modelled using discounted cash flow analysis to obtain the Net Present Value alongside a rotation of other arable crops including maize, and the two energy crops of short rotation coppice and Miscanthus. The model was first developed for the UK and fully adapted to Italy, Germany and Poland, producing a total of four independent models. The results showed that with no subsidies, the profitability of *Sida hermaphrodita* (L.) Rusby would be unattractive in all four countries relative to other crop options. *Silphium perfoliatum* L., however, was an economically viable option in each country. Both *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. can offer greater environmental benefits than other arable crops, and the profitability of each crop would be further

enhanced if additional payments for such public services were made to farmers, and if there were secure markets for the sale of the biomass.

Keywords: economic analysis, Virginia fanpetals, Virginia mallow, cup plant, energy crops

Figure 6.1 – Graphical abstract of the economic model and financial analysis.

6.1 Introduction

In 2016, 196 governments signed the Paris climate change agreement which committed them to limiting global temperature rises to no more than 2°C above pre-industrial revolution conditions (UNFCCC, 2021). To comply with the agreement, each country agreed to implement strategies and measures to offset and reduce their greenhouse gas (GHG) emissions. In June 2019, the UK announced the target to be carbon neutral for 2050, and it is supporting the replacement of fossil fuels with low-GHG emitting renewable energy sources such as solar, wind, and bioenergy. In Western Europe, commonly cited bioenergy crops on agricultural land are short rotation coppice (SRC) species and Miscanthus (*Miscanthus x giganteus*), to produce woodchips and straw, and forage maize (*Zea mays* L.) to produce biogas. Two alternative crops that have been used in Eastern Europe are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., referred as Sida and Silphium in the rest of the paper. From 2016 to 2019, within the SidaTim project, the performance of these two crops was studied in Italy, Germany, Poland, and the UK.

Sida can be used to produce solid fuel for combustion if the plants are harvested at the end of winter when the shoots are still standing and have a moisture content of about 20%. However this species can also be harvested in summer as green biomass for anaerobic digestion. Silphium is harvested in summer, when the dry matter content is about 30%, to produce biogas only. Compared to some other biomass crops, the environmental advantages of the two crops include increased production of pollen and nectar production, reduced cultivation and hence increased soil carbon sequestration, and reduced levels of nitrogen and pesticide applications (Cumplido-Marin *et al*. 2020).

At present, there is a lack of financial data and analysis about the revenue and costs associated with Sida and Silphium production. Therefore the aim of this study is to develop an economic model for the two crops and to use it to compare their profitability with other major biomass crops and an arable rotation. The study also includes a sensitivity analysis and is undertaken for four countries: the UK, Italy, Germany, and Poland.

6.2 Methodology

6.2.1 Economic model and financial analysis

The economic model for Sida and Silphium was developed following the net present value approach described by Graves *et al.* (2007). For comparison of annual arable crops, it is usually sufficient to consider the gross margin because labour and machinery costs are "fixed" on the farm, and the relative profitability of different crops is determined largely by the relationship between gross output and variable costs such as seed, fertilisers, and sprays. The gross margin is determined as the revenue (*R*: £ ha^{-1}) minus variable costs (*V*: £ ha^{-1}) (Equation 6.1).

$$Gross\ margin = R - V \qquad \text{Equation 6.1}$$

In this analysis, since there are substantial differences in the machinery and labour demands between annual crop enterprises and long-term multi-annual enterprises such as Sida and Silphium, the comparison was made on a net margin basis which includes labour and machinery costs as "assignable fixed costs" (*A*: £ ha^{-1}) (Equation 6.2).

$$Net\ margin = R - V - A \qquad \text{Equation 6.2}$$

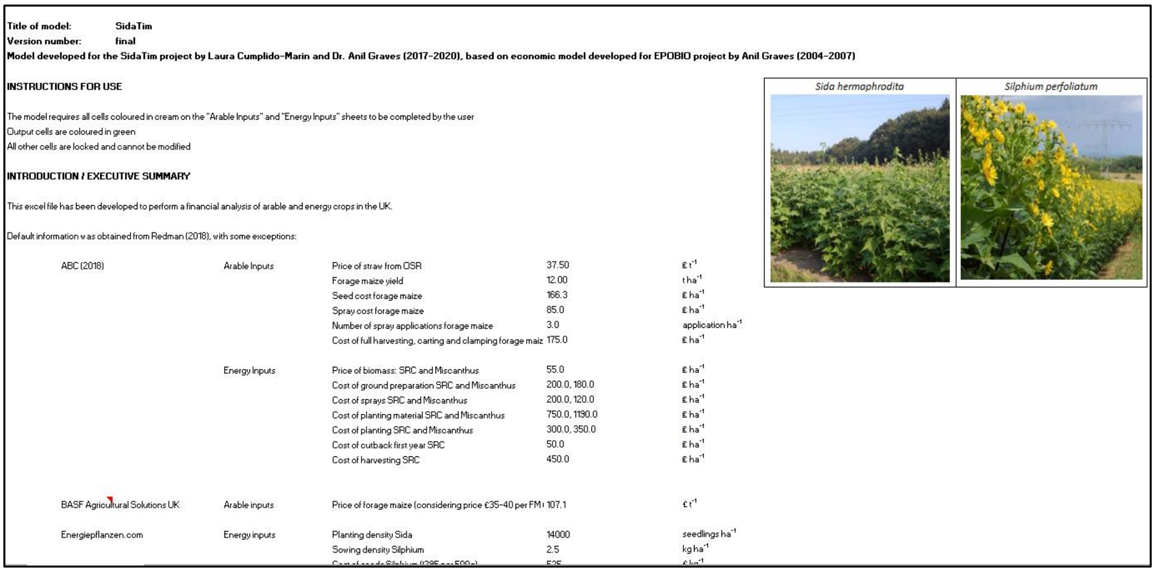
Since Sida and Silphium are perennial crops with a multi-annual cycle, it is appropriate to evaluate their financial performance using long-term financial analyses. Since there is a time preference for consumption of benefits in the short- rather than in the long-term, financial analyses discount future revenue streams using a discount factor which reflects a time preference for money. The choice of discount rate depends on the purpose of the analysis and the socio-economic circumstances of the population for which the analysis is undertaken. The calculation of an aggregated discounted value that reflects the time preference for future income as a present value is referred to as the net present value (NPV) and is calculated using the approach developed by Faustmann (1849) with Equation 6.3:

$$NPV = \sum_{t=0}^{t=T} \frac{(R_t - V_t - A_t)}{(1 + i)^t} \qquad \text{Equation 6.3}$$

where: *NPV* (£ ha^{-1}) is the present value of aggregated future discounted net cash flow stream from year 0 to *T; T* is the time horizon in years; *R, V*, and A_t (£ ha^{-1}) are respectively the revenue, variable costs, and assignable fixed costs in year *t*, and *i* is the discount rate.

6.2.2 Model implementation

The above equations were implemented in a spreadsheet model called the “SidaTim Economic Model” that can be used to include input data on prices, grants, variable and fixed costs over a 16 year time horizon, for up to five arable crops and four energy crops on a one hectare scale. Starting with crop yields and inputs, the economic model was developed as a Microsoft Excel workbook including separate worksheets for the four countries of the UK, Italy, Germany, and Poland, as well as a number of master sheets summing up the values of the individual countries. First, an introductory page (Figure 6.2) explains how the model is organised and the sources of the data. Then, the model calculates the annual margins and the discounted cash flows for a period of 16 years to obtain the NPV. Additionally, the infinite NPV (NPV_i) and the Equivalent Annual Value (EAV) are determined.



Title of model: SidaTim
Version number: final
Model developed for the SidaTim project by Laura Cumplido-Marin and Dr. Anil Graves (2017-2020), based on economic model developed for EPOBIO project by Anil Graves (2004-2007)

INSTRUCTIONS FOR USE

The model requires all cells coloured in cream on the "Arable Inputs" and "Energy Inputs" sheets to be completed by the user
Output cells are coloured in green
All other cells are locked and cannot be modified

INTRODUCTION / EXECUTIVE SUMMARY

This excel file has been developed to perform a financial analysis of arable and energy crops in the UK.

Default information was obtained from Redman (2018), with some exceptions:

ABC (2018)	Arable Inputs	Price of straw from OSR	37.50	£ t^{-1}
		Forage maize yield	12.00	t ha^{-1}
		Seed cost forage maize	166.3	£ ha^{-1}
		Spray cost forage maize	85.0	£ ha^{-1}
		Number of spray applications forage maize	3.0	application ha^{-1}
		Cost of full harvesting, carting and clamping forage maiz	175.0	£ ha^{-1}
	Energy Inputs	Price of biomass: SRC and Miscanthus	55.0	£ ha^{-1}
		Cost of ground preparation SRC and Miscanthus	200.0, 180.0	£ ha^{-1}
		Cost of sprays SRC and Miscanthus	200.0, 120.0	£ ha^{-1}
		Cost of planting material SRC and Miscanthus	750.0, 1190.0	£ ha^{-1}
		Cost of planting SRC and Miscanthus	300.0, 350.0	£ ha^{-1}
		Cost of cutback first year SRC	50.0	£ ha^{-1}
		Cost of harvesting SRC	450.0	£ ha^{-1}
BASF Agricultural Solutions UK	Arable inputs	Price of forage maize (considering price £35-40 per FM	107.1	£ t^{-1}
Energiepflanzen.com	Energy inputs	Planting density Sida	14000	seedlings ha^{-1}
		Sowing density Silphium	2.5	kg ha^{-1}

Figure 6.2 – Main sheet of the Microsoft Excel workbook introducing the SidaTim economic model.

6.2.3 Selection of the case study sites

Four contrasting sites in the UK, Italy, Germany and Poland were selected where yield data for Sida and Silphium were available. In 2016, experiments were established in Casale Monferrato in the north of Italy, at Werlte in north Germany, and at Lipnik in south Poland (Table 6.1). In the UK, the experiment was set in 2017 on a sandy loam soil in the east of England in Silsoe (Bedfordshire). The mean air temperature at the sites ranged from 8.5-9.9°C in Germany, Poland, and the UK, to 12.5°C in Italy. The rainfall ranged from 555 mm in Poland to 784 mm in Italy (Facciotto *et al*., 2018).

Table 6.1 – Location of the four sites in the four countries and description of characteristic soil, temperature and rainfall.

Site	**Latitude and longitude**	**Altitude (m)**	**Soil type**	**Mean air temp. (°C)**	**Mean annual rainfall (mm)**
Casale Monferrato (IT)	45.13°N; 8.51°E	116	Sandy loam	12.5	784
Werlte (GE)	52.85°N; 7.67°E	34	Sand	9.0	768
Lipnik (PL)	53.20°N; 14.58°E	47	Sand	8.5	555
Silsoe (UK)	52.07°N; 0.63°W	50	Sandy loam	9.9	657

6.2.4 Crop yields

For each site, yield profiles were derived for Miscanthus, SRC, Sida and Silphium (Table 6.2). The same Miscanthus yield profile was assumed at each site reaching a plateau of 12.54 t ha^{-1} at four years after planting. In north Italy it was assumed that the first SRC harvest would take place in year 2 with a harvest of 26 t DM ha^{-1} every two years (Bacenetti *et al.*, 2016). In Poland, Germany and the UK, the first harvest of the SRC was assumed to be in year 4 with a yield of 30 t ha^{-1} (ABC Ltd, 2019a) in the UK, 30 t ha^{-1} in Germany and 25 t ha^{-1} in Poland (Bury, 2020). Sida was assumed to be harvested each year while Silphium was assumed to be initially harvested in year 2 and then on an annual basis. For Italy, the assumed mature yields of Sida and Silphium were 10.0 and

Table 6.2 - Assumed yield profiles (t DM) of the perennial biomass crops in the four case studies considered.

	Miscanthus	**SRC**			**Sida**		**Silphium**	
Year		Italy	Poland	Germany and UK	Italy	Other sites	Italy	Other sites
1	0.60				1.76	2.05	0.00	0.00
2	3.92	26.00			7.12	8.27	9.14	9.93
3	11.10				9.41	10.93	13.53	14.70
4	12.54	26.00	25.00	30.00	10.00	11.62	14.48	15.73
5	12.54				10.00	11.62	15.00	16.30
6	12.54	26.00			10.00	11.62	15.00	16.30
7	12.54		25.00	30.00	10.00	11.62	15.00	16.30
…								
16	12.54	26.00	25.00	30.00	10.00	11.62	15.00	16.30

15.0 t DM ha^{-1} (Facciotto and Coaloa, 2019). The equivalent mature yields of Sida and Silphium at the other three sites were 11.62 t DM ha^{-1} and 16.30 t DM ha^{-1}. The plateau yield of each crop was assumed to continue until year 16.

A potential biomass crop is forage maize, but it is typically grown in a rotation. The assumed rotation in the UK was wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L. subsp. *vulgaris* 'altissima'), maize, oilseed rape (OSR) (*Brassica napus* subsp. *napus*), and oats (*Avena sativa*) (Table 6.3). In Italy the assumed rotation was wheat, soya (*Glycine max* (L.) Merr,), sunflower (*Helianthus annus* L.), OSR, maize. In Germany the sequence was wheat, sugar beet, maize, OSR and oats and in Poland the rotation was barley (*Hordeum vulgare* L.), OSR, wheat, sugar beet, and maize. The yields in the UK were mainly derived from the ©John Nix Pocket Book for Farm Management (ABC Ltd, 2019b). For Italy, Germany and Poland data was extracted from online websites, country-specific publications, and personal communication with experts.

Table 6.3 - Assumed annual yields (t ha^{-1}) of the annual crops at the five sites.

	UK	Italy	Poland	Germany
Wheat	8.3[a]	5.5	4.6	7.5
Sugar beet (FW*)	78.0[a]	-	56.8	63.1
Sunflower	-	2.1	-	-
Forage maize	12.0[b]	9.4	12.0	8.1
Oilseed rape	3.5[a]	2.6	3.5	3.3
Soya	-	3.1	-	-
Oats	6.3[a]	-	-	4.1
Barley	-	-	2.5	-
Reference	[a](ABC Ltd, 2019b) [b] (ABC Ltd, 2019a)	(CREA, 2017)	(Bury, 2020)	(Statista.com, 2020b)

*FW = Fresh weight

6.2.5 Financial data and costs

Country-specific currencies were used in the analysis to keep it directly relevant to the corresponding countries and different stakeholders. The conversion rate applied for Italy and Germany, converting Pound Sterling (GBP) into Euros was 1.13 €/£ (Morhart, 2020), and the conversion rate applied for Poland was 4.90 PLN/£ (Bury, 2020). The price of biomass was assumed to be the same for all energy crops within a country, equal to

55 £ t^{-1} in the UK, 43.8 € t^{-1} in Italy, 72.0 € t^{-1} (Morhart, 2020) in Germany, and 269.5 PLN t^{-1} in Poland (Table 6.4). The values of the arable crops were derived from published reports. In addition, agricultural production in each country can received single farm payments (SFP) which amounted to 220 £ ha^{-1} in the UK in 2019 (ABC Ltd, 2019b). The Common Agricultural Policy (CAP) receipts for the crops in Italy, Germany, and Poland were respectively 330 € ha^{-1}, 176 € ha^{-1}, and 472 PLN ha^{-1}.

Table 6.4 - Assumed value of crops at the four sites.

	UK (£ t^{-1})	**Italy (€ t^{-1})**	**Germany (€ t^{-1})**	**Poland (PLN t^{-1})**
Biomass	55.0	43.8	72.0	269.5
Forage maize	107.1[b]	94.3	182.8	724.0
Wheat	162.0[a]	210.0	193.7	867.0
Oats	140.0[a]	-	154.8	-
OSR	335.0[a]	197.0	345.1	1645.0
Sugar beet	27.2[a]	-	26.0	120.0
Sunflower	-	235.6	-	-
Soya	-	310.8	-	-
Reference	[a] ABC Ltd, 2019b [b] BASF SE, 2018	CREA, 2017	Statista.com, 2020b	Bury, 2020

Management data and input data for the perennial biomass crop in each country were collected from secondary data sources and personal communication. The initial costs of establishment included ground preparation, planting out, plant materials, fertilising and spraying costs. The planting material were cuttings for the SRC, rhizomes for Miscanthus, seedlings for Sida, and seeds for Silphium. Plant protection was applied in each country during the establishment year and years 2-3 for energy crops. Mineral fertilisers were applied during establishment, and on a recurring basis after every harvest to maintain soil nutrient status at a similar level to the arable crops. For illustration, the assumptions for the UK are shown in Table 6.5; details of other sites are presented in Appendix E, E.2 Inputs for energy crops. The management costs of the arable crops were taken from a range of sources including farm management handbooks, and regional, national, and European level statistical publications and databases available for the UK, Italy, Germany, and Poland. Variable costs included use of seeds, fertilizers, and agrochemicals for pest and weed management. Fixed costs included use of standard approaches and costs for ploughing and seedbed preparation, followed by drilling, and fertiliser and spray operations for pest control. Management also included the costs of combine harvesting and carting for grain and straw collection.

Table 6.5 - Assumed costs for SRC, Miscanthus, *Sida hermaphrodita* (L.) Rusby, and *Silphium perfoliatum* L. in the UK.

		SRC	Miscanthus	Sida	Silphium
Establishment costs					
Planting material *	(£ ha^{-1})	750.0	1190.0	4361.0	1312.8
Planting *	(£ ha^{-1})	300.0	350.0	126.3	45.0
Ground preparation	(£ ha^{-1})	200.0	180.0	180.0 [i]	180.0 [i]
Fertilisers *	(£ ha^{-1})	126.3	117.7	162.0	177.7
Fertiliser application *	(£ ha^{-1})	16.1	16.1	16.1	16.1
Sprays	(£ ha^{-1})	200.0	120.0	120.0 [i]	120.0 [i]
Spray application *	(£ ha^{-1})	40.3	40.3	20.2	20.2
Mechanical weeding *	(£ ha^{-1})	-	-	120.8	120.8
Cutback end first year	(£ ha^{-1})	50.0	20.0 [ii]	20.0 [i]	20.0 [i]
Recurring costs					
Mechanical weeding *	(£ ha^{-1})	-	-	161.0	161.0
Fertilisers *	(£ ha^{-1})	126.3	117.7	162.0	177.7
Fertiliser application *	(£ ha^{-1})	16.1	16.1	16.1	16.1
Sprays *	(£ ha^{-1})	100.0 [iii]	60.0 [iii]	-	-
Spray application *	(£ ha^{-1})	40.3	40.3	-	-
Harvesting	(£ ha^{-1})	450.0	-	100.0 [iv]	-
Mowing and baling	(£ ha^{-1})	-	240.7 [v]	-	-
Harvesting and clamping	(£ ha^{-1})	-	-	-	175.0 [vi]
Decommissioning	(£ ha^{-1})	170.0 [vii]	170.0 [vii]	170.0 [vii]	170.0 [vii]

Notes: * Default 4% discount rate. [i] Assumed same as Miscanthus; [ii] (ABC Ltd, 2019b); [iii] Assumed half cost of sprays (establishment); [iv] Assumed same as forage maize harvesting only; [v] (Witzel and Finger, 2016); [vi] Assumed same as forage maize full harvesting operation; [vii] (P&L Cook and Partners, 2007);

* Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (2019a) unless indicated otherwise:

- Ground preparation cost: SRC and Miscanthus 5.0 h ha^{-1} and Silphium 6.0 h ha^{-1}.
- Planting material cost: considering Sida at €350 per 1,000 seedlings (Helling-Jughans, 2017) and 14,000 seedlings per ha (Energiepflanzen.com, 2020a); Silphium at €295 per 500 g seeds and 2.5 kg seeds per ha (Energiepflanzen.com, 2020b).
- Planting cost: Sida same cost as potato planting at £126.29 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize (ABC Ltd, 2019a).
- Fertiliser cost (establishment): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*. (2020).
- Fertiliser application cost (establishment): all crops x1 extra for variable rate application at £16.07 ha^{-1} and 1.2 h ha^{-1} (assumed same time as wheat).
- Spray application cost (establishment): considering x4 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus and x2 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at £40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).

- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at £40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser cost (recurring): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al.* (2020), only applied on harvest years.
- Fertiliser application cost (recurring): all crops x1 extra for variable rate application at £16.07 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat), only applied on harvest years.
- Spray application cost (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

6.3 Results

6.3.1 Net Present Values

The predicted NPV for the perennial crops and the arable rotations over 16 years, at a default discount rate of 4%, in the UK, Italy, Germany, and Poland with/without CAP or single farm payments (SFP) are shown in Table 6.6. With grants in the UK, the NPV of the arable rotation was 4593 £ ha^{-1}. With grants, Silphium was the most profitable crop (5697 £ ha^{-1}) followed by Miscanthus (4962 £ ha^{-1}) and SRC (4432 £ ha^{-1}). Because of its high establishment costs, Sida was the least profitable crop (1075 £ ha^{-1}).

Table 6.6 - The net present value (NPV), for the arable rotation and four energy crops with and without the single farm payment (SFP) in: the UK, Italy, Germany, and Poland. The time horizon used was 16 years and the discount rate was 4%. The most profitable crop in each location without grants is shown in bold.

			Rotation	SRC	Miscanthus	Sida	Silphium
UK	NPV without SFP	(£ ha^{-1})	1927	1765	2296	-1591	**3031**
	NPV with SFP	(£ ha^{-1})	4593	4432	4962	1075	5697
Italy	NPV without CAP	(€ ha^{-1})	-3392	**766**	-1501	-4875	-734
	NPV with CAP	(€ ha^{-1})	877	3665	2769	-606	3536
Germany	NPV without CAP	(€ ha^{-1})	-641	2188	2471	-510	**5241**
	NPV with CAP	(€ ha^{-1})	1492	4321	4604	1622	7373
Poland	NPV without CAP	(PLN ha^{-1})	-6602	5407	-54597	-16022	**9458**
	NPV with CAP	(PLN ha^{-1})	886	11122	-48881	-10306	15173

With grants in Italy, the NPV of the arable rotation (877 € ha^{-1}) was only just positive, and the NPV of Sida (-606 € ha^{-1}) was negative due to low predicted yield and relatively high planting material costs. Silphium was the second most profitable crop after SRC (3665 € ha^{-1}) but ahead of Miscanthus (2769 € ha^{-1}). In Germany, assuming the inclusion of the CAP payment, Silphium (7373 € ha^{-1}) was the most profitable crop, followed by Miscanthus and SRC. Sida (1622 € ha^{-1}) had a similar level of profitability as the arable rotation of wheat, sugar beet, maize, OSR, and oats (1492 € ha^{-1}). In Poland, the NPV of the arable rotation with CAP payments was just positive (886 PLN ha^{-1}). The most profitable crop was Silphium (15173 PLN ha^{-1}) followed by SRC (11122 PLN ha^{-1}). Sida resulted in a negative return (-10306 PLN ha^{-1}) and the Miscanthus resulted in a very negative return (-48881 PLN ha^{-1}) due to high establishment costs.

6.3.2 Discounted cash flow values

Farmers' decisions on crop choice can also be dependent on the cash flow of the different crops. The cumulative cash flow of the perennial crops in the UK, Italy, and Germany (Figure 6.3) typically show a negative balance for the initial five to eight years, whereas the arable rotation provides a positive return from the first year. However by the end of 16 years, the cumulative cash flow of the perennial crops tend to be similar or greater than that from the arable rotation with two exceptions. Firstly, the cumulative cash flow of Sida in each country remained below or similar to the arable rotation after 16 years. Secondly, the values obtained for Miscanthus are extremely negative in Poland due to the high establishment costs.

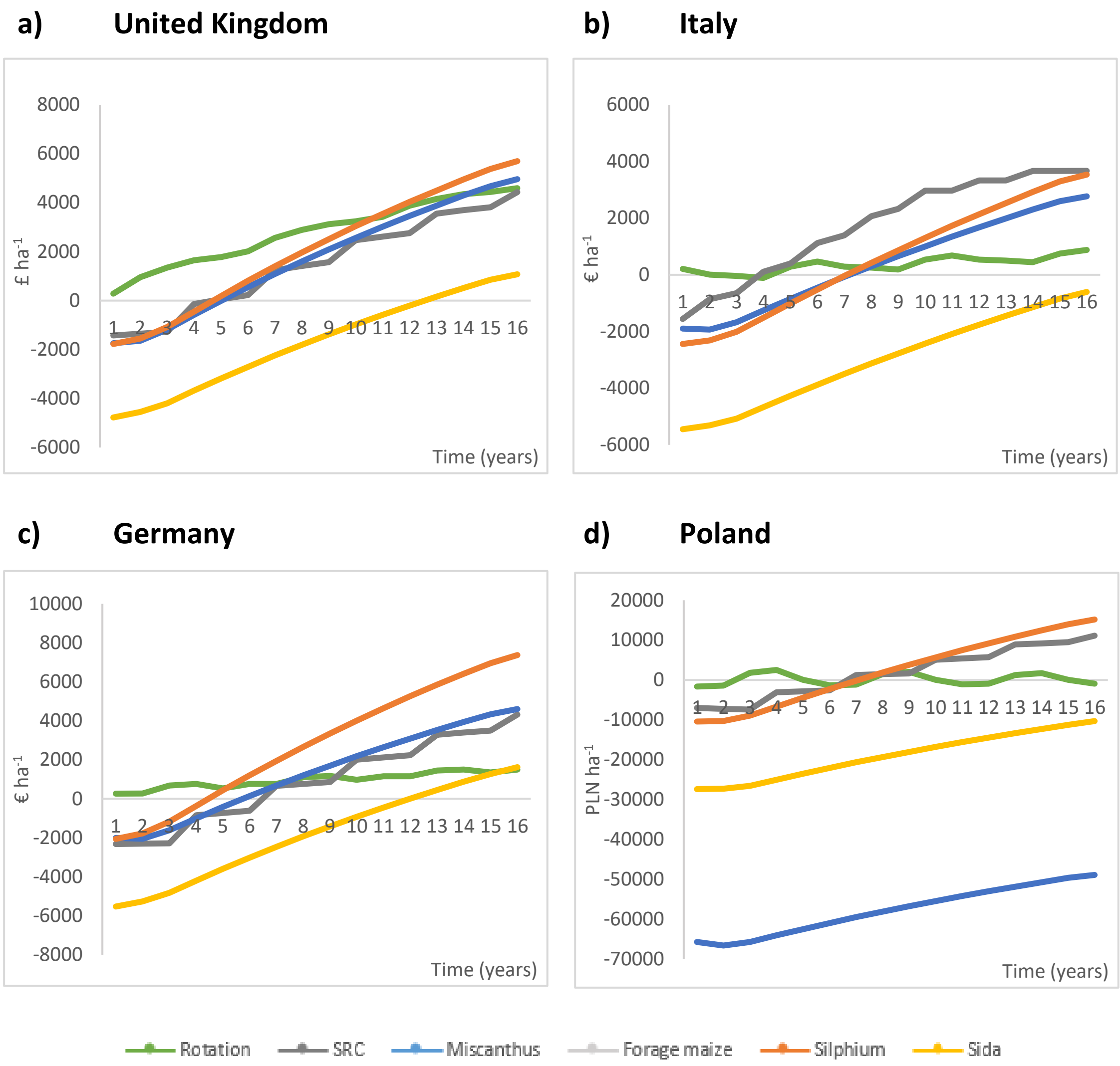


Figure 6.3 – Discounted cumulative net margins with grants included.

6.3.3 Sensitivity analyses

The results from the sensitivity analysis of the NPV of Sida, Silphium, SRC, Miscanthus, forage maize, and the arable rotation to systematic alterations in prices, costs, and discount rate are shown in Figure 6.4, Figure 6.5, Figure 6.6
Figure 6.6, and Figure 6.7. The data underlying these graphs are shown in Appendix E, E.4 Sensitivity analyses. In the UK under default assumptions, Silphium was the most profitable system. However if crop prices were assumed to be 15% or more higher than the default values, the annual crop rotation became the most profitable system (Figure 6.4). Conversely, if crop prices decreased by more than 50%, SRC and Miscanthus became more profitable than Silphium. Sida remained the least profitable option for any increase in price but became

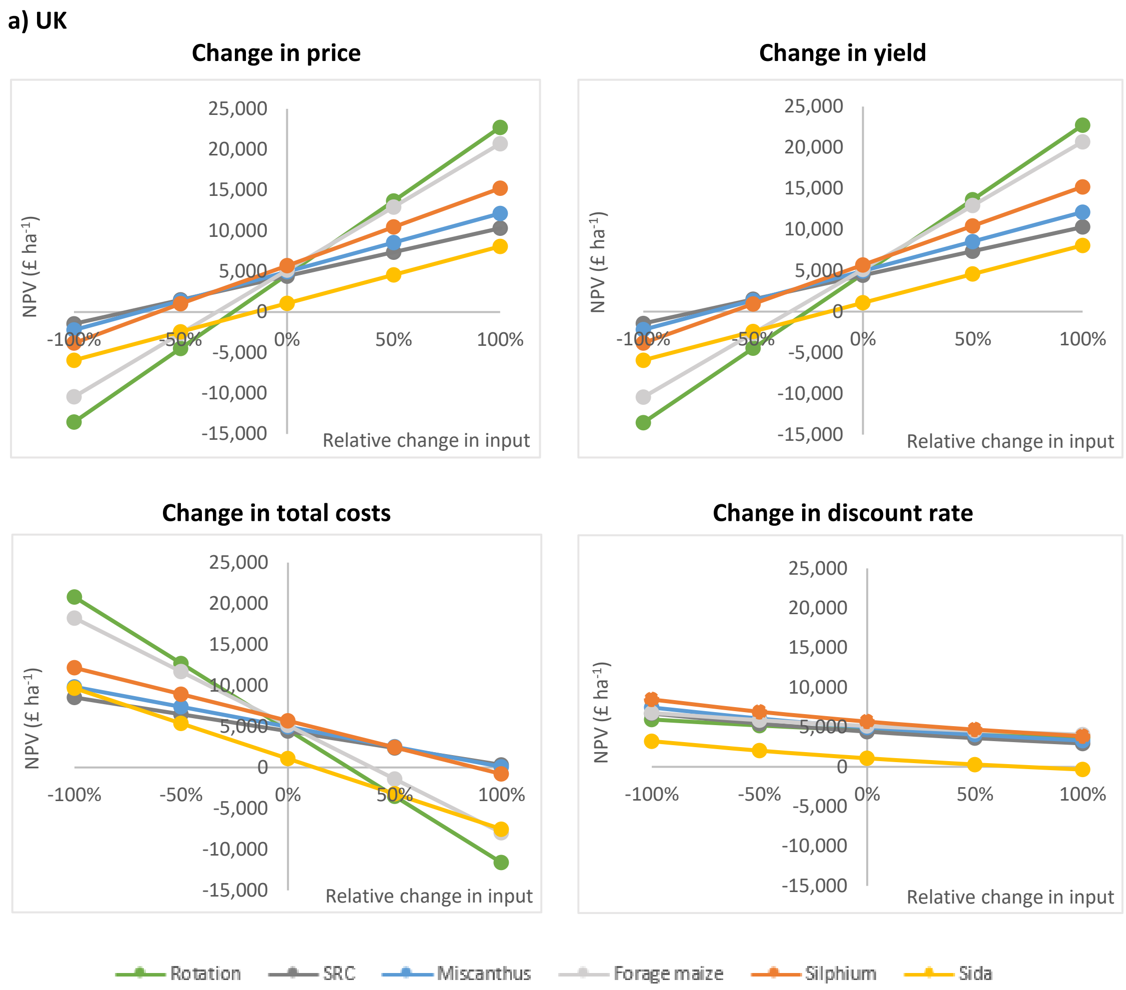


Figure 6.4 - Sensitivity of the NPV (over 16 years at 4% discount rate) of four biomass crops and an arable rotation including maize to changes in a) prices, b) yields, c) costs, and d) discount rates in the UK.

more profitable than the arable rotation and forage maize for decreases in price over 25% and 50% respectively. As costs increased by more than 50%, Miscanthus became marginally more profitable than Silphium. As costs decreased 10-25%, forage maize was most profitable, whilst beyond a 35% decrease in costs, the arable rotation became most profitable. As costs changed, Sida was the least profitable option, except for increases in cost beyond 50% and decreases in cost beyond 70%. For changes in the discount rate, Silphium remained the most profitable crop, followed by Miscanthus, SRC, forage maize, and the arable rotation.

In Italy, under the default assumptions, the SRC option was marginally more profitable than Silphium option (Figure 6.5). As prices increased, Silphium remained marginally less profitable than SRC but converged in profitability with SRC and forage maize when prices increased to 100%. The arable rotation became the most profitable option when prices increased over 60%. As prices decreased over 50% Silphium became marginally less profitable than Miscanthus. When costs increased the profitability of Miscanthus was marginally lower than that of Silphium, almost converging at 100% increase. As costs decreased beyond 45% the arable rotation option became the most profitable option, closely followed by the forage maize option. The profitability of Sida turned positive as prices increased. As prices decreased, the profitability of Sida was higher than that of

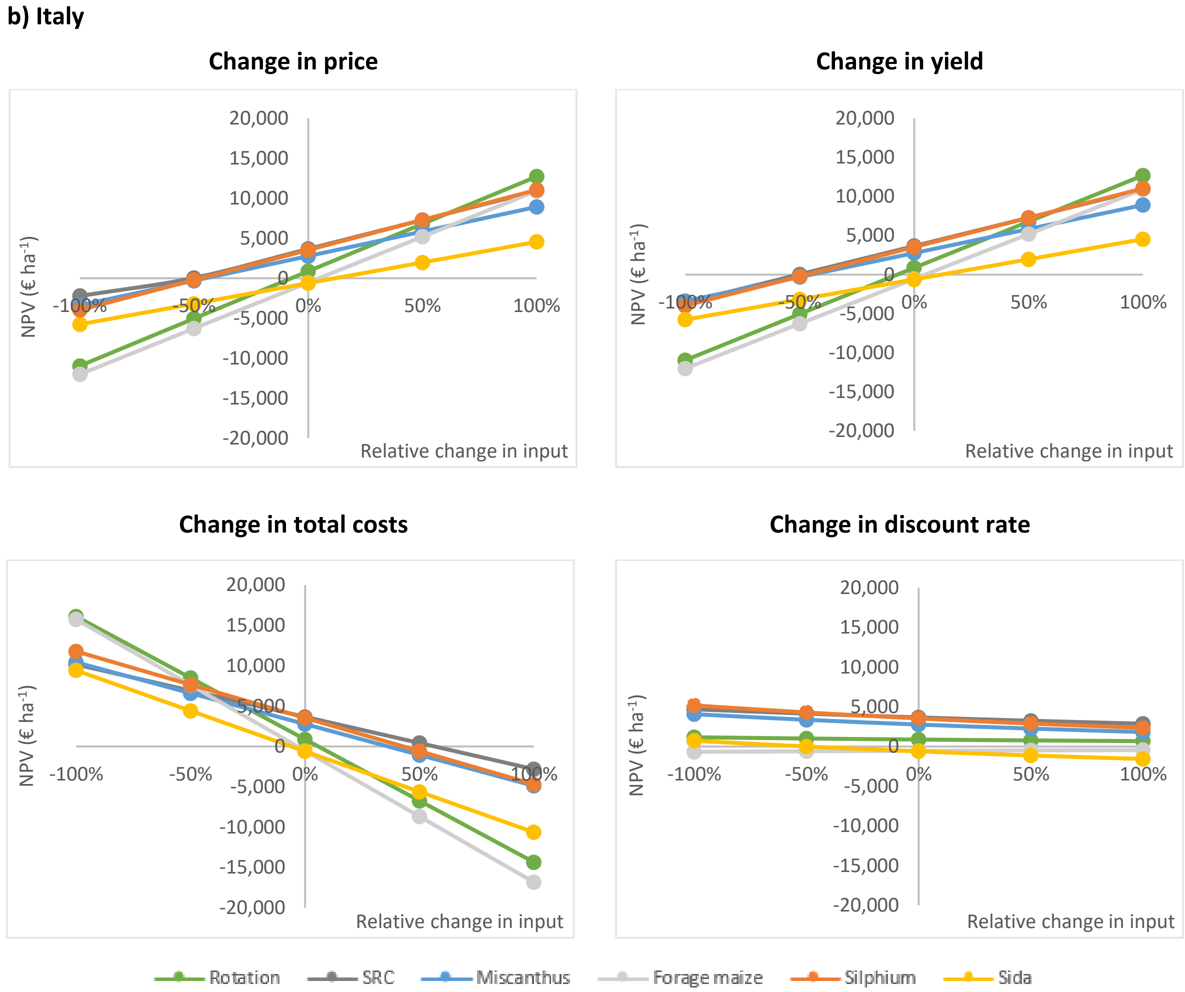


Figure 6.5 – Sensitivity analysis of the net present value (NPV) of different crops in Italy in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

the forage maize option and beyond a 25% decrease in prices even higher than the arable rotation option. As costs increased, Sida was more profitable than the forage maize and with a greater than 25% increase in costs it became more profitable than the arable rotation. As costs decreased, Sida remained the least profitable option. Sida was marginally more profitable than the forage maize option only as discount rates decreased, but was marginally less profitable than the arable rotation at other discount rates.

Under the default assumptions in Germany, Silphium had the highest NPV and remained relatively robust to variations in price, costs, and discount rate (Figure 6.6).As prices increased beyond 40%, forage maize became more profitable than Silphium. As prices decreased more than 60%, SRC became marginally more profitable than Silphium, and the profitability of Miscanthus converged with that of Silphium. Sida remained the least profitable option for price increase. At any decrease in prices, Sida was more profitable than the arable rotation option and beyond price decreases of 50% and over it was also more profitable than the forage maize option. As costs increased, Silphium remained the most profitable crop and Sida was more profitable than the arable rotation and marginally overcame the profitability of forage maize, when costs increased 90% or more. As costs decreased more than 20%, forage maize became the most profitable option, and for decreases in costs over 50% the arable rotation became more profitable than Silphium. Sida remained the least profitable option for decreases in cost up to 60%. Beyond a decrease of 60% in costs, Sida became more profitable than SRC, converging in profitability with Miscanthus. The response to fluctuations in discount rate showed that lower discount rates favoured Silphium in particular. As discount rates increased towards 100%, forage maize became increasingly more profitable in comparison with Silphium and its NPV converged to almost the same value as for Silphium. The arable rotation was consistently less profitable than Sida at lower discount rates, but its profitability converged and marginally overcame that of Sida as discount rates increased.

c) Germany

Figure 6.6 – Sensitivity analysis of the net present value (NPV) of different crops in Germany in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

In Poland, under the default options, forage maize was generally the most profitable option and Miscanthus the least profitable option for any variation in price, costs, and discount rate (Figure 6.7). The profitability of Sida became positive for increases in prices over 30%. Up to increases in price of 60%, Silphium remained the second most profitable system. As prices decreased beyond 40%, SRC became the most profitable option and the profitability of Silphium and Sida exceeded that of forage maize, the arable rotation and, Miscanthus. As costs increased, the relative profitability of forage maize decreased and for costs increases over 60% SRC became more profitable. When costs increased by 100%, the profitability of Silphium converged with that of forage maize. For costs increases over 40% Sida became more profitable than the arable rotation. As costs decreased beyond 50%, the arable rotation became more profitable than Silphium. As costs decreased by over 60%, the Sida became marginally more profitable than SRC, converging with the profitability of Miscanthus at 100% costs decrease. As discount rates increased, forage maize profitability remained the highest, the NPV of the SRC option converged to almost the same values as those for the Silphium option, and the NPV of Sida was marginally lower than the arable rotation but converged at 100% decreases in discount rate.

d) Poland

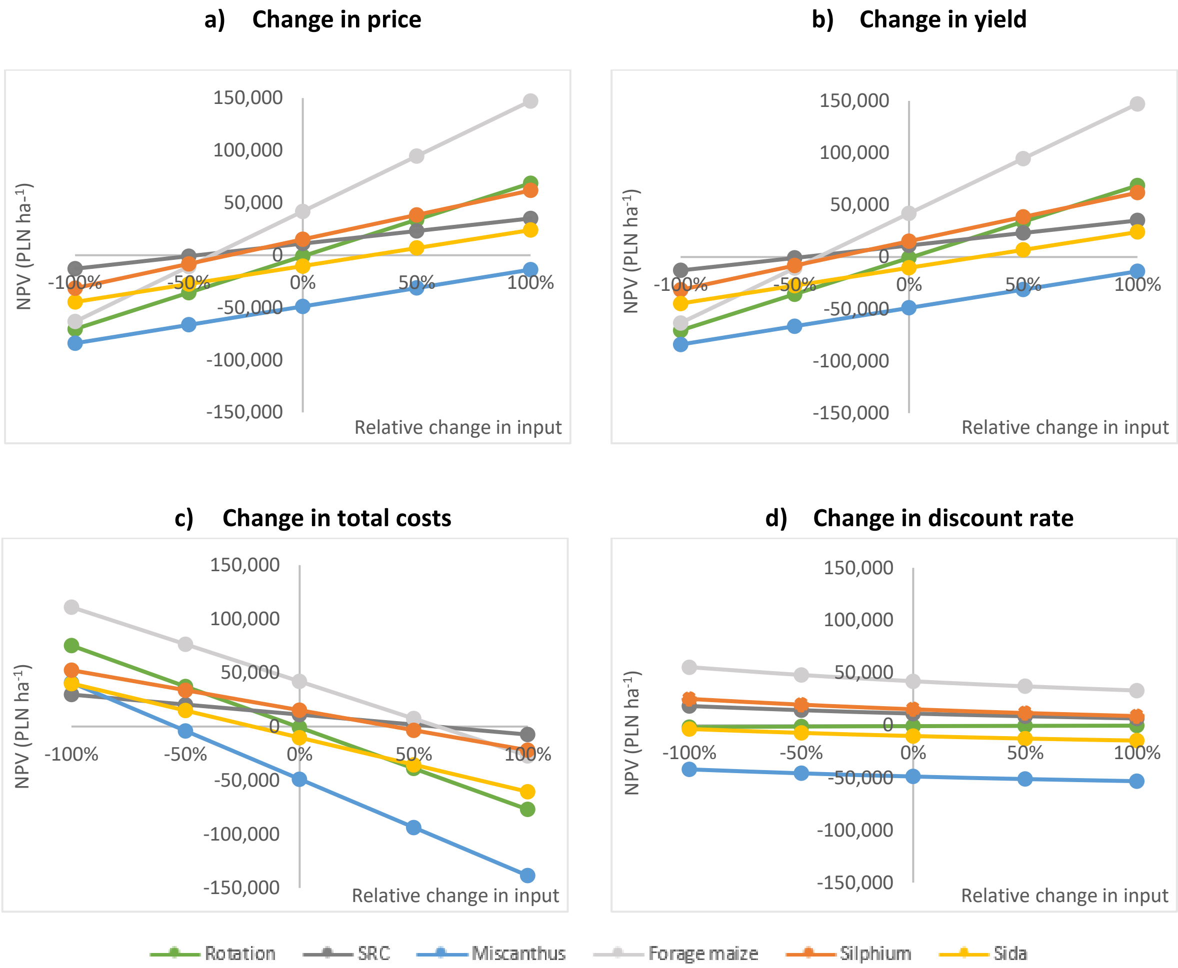


Figure 6.7 – Sensitivity analysis of the net present value (NPV) of different crops in Poland in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

6.3.4 Shift in values to hit NPV of most profitable arable and energy crop

The sensitivity analysis was further used to determine how much prices and costs for the Sida and Silphium would have to increase from their current values to make them profitable, relative to the most profitable energy crop and the arable rotation in the baseline (Table 6.7).

Table 6.7 - Changes in prices and costs required to make *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. as profitable as the most profitable arable crop, the most profitable energy crop, the arable rotation, and to break even (NPV value = 0).

	NPV = 0	**Max energy crop NPV**	**Arable rotation NPV**
a) UK (£ ha^{-1})			
Baseline value	0	5697	4593
Relative change required to achieve baseline value:			
Sida price/yield (%)	-15	66	50
Silphium price/yield (%)	-60	0	-12
Sida cost (%)	13	-54	-41
Silphium cost (%)	88	0	17
b) Italy (€ ha^{-1})			
Baseline value	0	3655	877
Relative change required to achieve baseline value:			
Sida price/yield (%)	12	83	29
Silphium price/yield (%)	-47	2	-35
Sida cost (%)	-6	-43	-15
Silphium cost (%)	43	-2	32
c) Germany (€ ha^{-1})			
Baseline value	0	7373	1492
Relative change required to achieve baseline value:			
Sida price/yield (%)	-18	63	-1
Silphium price/yield (%)	-59	0	-47
Sida cost (%)	17	-59	1
Silphium cost (%)	>100	0	81
c) Poland (PLN ha^{-1})			
Baseline value	0	15173	-886
Relative change required to achieve baseline value:			
Sida price/yield (%)	30	74	27
Silphium price/yield (%)	-33	0	-34
Sida cost (%)	-20	-51	-19
Silphium cost (%)	41	-0	43

In the UK, Silphium was the most profitable energy crop and the price and costs for Sida would have to rise by 66% or decrease by 54% respectively to match this value. For Silphium to match the return of the arable rotation, the price of Silphium biomass would need to decrease by 12% or the costs of Silphium production would need to increase by 17%. Sida would only match the arable rotation with a 50% increase in price or a 41% decrease in costs. Sida prices would have to decrease by 15% or costs would have to increase by 13% to make the Sida unprofitable (NPV = 0). For Silphium, prices would have to decrease by 60% or costs increase by 88% for the Silphium to become unprofitable. Regarding yields, for Sida to reach the NPV of the arable rotation and the maximum energy crop, its yield would need to increase respectively by 50% and 66%, corresponding to 17.4 t DM ha^{-1} and 19.3 t DM ha^{-1}. For Silphium to reach the NPV of the rotation its yield would need to decrease by 12%, corresponding to 14.3 t DM ha^{-1}. For Sida and Silphium to become unprofitable (NPV = 0), their yields would need to decrease by 15% and 60%, corresponding to 9.9 t DM ha^{-1} and 6.5 t DM ha^{-1} respectively.

The sensitivity of Sida and Silphium profitability In Italy was generally similar to that in the UK, except that under the default assumptions Sida had a negative NPV. The price of Sida biomass would need to rise by 83% to match the most profitable energy crop, and by 29% to match the NPV of the arable rotation. Silphium prices would have to rise by 2% to match the NPV of the most profitable energy crop and decrease by 35% to match the NPV of the arable rotation. A reduction in costs by 43% and 15% would allow Sida to become as profitable as the most profitable energy crop and the arable rotation respectively. Silphium costs would need to decrease by 2% for it to become the most profitable energy crop and could increase 32% to match the NPV of the arable rotation.

The point at which Sida became unprofitable (NPV = 0) would require a 15% increase in prices or a 13% decrease in costs. Prices would have to decrease by 60% or costs increase by 88% for Silphium to become unprofitable. For Sida to reach the NPV of the rotation and the maximum energy crop, its yield would need to increase respectively by 29% and 83%, corresponding to 12.9 t DM ha^{-1} and 18.3 t DM ha^{-1}. For Silphium to reach the NPV of the rotation and the maximum energy crop, its yield would need to decrease by 35% and increase by 2% respectively, corresponding to 20.2 t DM ha^{-1} and 15.3 t DM ha^{-1}. For

Silphium to become unprofitable (NPV=0), its yields would need to decrease by 47%, corresponding to 8.0 t DM ha^{-1}.

In Germany, Silphium was the most profitable biomass crop. Sida biomass prices would need a 63% increase or the costs would need to decrease by 59% to match the profitability of Silphium. Prices would need to decrease by 1% or costs increase by 1% for the NPV of Sida to match the NPV of the arable rotation. For Silphium, prices needed to decrease by 47% to match the NPV of the arable rotation. For Silphium, costs needed to increase by 81% to match the NPV of the arable rotation. Sida would break even (NPV = 0), if prices decreased by 18% or costs increased to 17%; Silphium would become unprofitable if prices decreased by 59% and cost increased by more than 102%. For Sida to reach the NPV of the rotation and the maximum energy crop in Germany, its yield would need to decrease by 1% and increase by 63%, corresponding to 11.5 t DM ha^{-1} and 18.9 t DM ha^{-1} respectively. For Silphium to reach the NPV of the rotation, its yield would need to decrease by 47%, corresponding to 8.6 t DM ha^{-1}. For Sida and Silphium to become unprofitable (NPV=0), their yields would need to decrease by 18% and 59%, corresponding to 9.5 t DM ha^{-1} and 6.7 t DM ha^{-1} respectively.

Silphium was also the most profitable biomass crop in Poland. Sida prices would need to increase by 74% and 27% to match the NPVs of Silphium and the arable rotation respectively. The corresponding values for a decrease in costs were 51% and 19%. For Silphium, prices needed to decrease by 34% or costs increase by 43% to match the NPV of the arable rotation. Sida would have an NPV of zero, if prices increased by 30% or costs decreased by 20%. Silphium, which was profitable, would require a price decrease of 33% or a cost increase of 41% to produce an NPV of zero. For Sida to reach the NPV of the rotation and the maximum energy crop in Poland, its yield would need to increase by 27% and 74%, corresponding to 14.8 t DM ha^{-1} and 20.2 t DM ha^{-1} respectively. For Silphium to reach the NPV of the arable rotation, its yield would need to decrease by 34%, corresponding to 10.7 t DM ha^{-1}. For Silphium to become unprofitable (NPV=0), its yield would need to decrease by 33%, corresponding to 10.9 t DM ha^{-1}.

6.4 Discussion

6.4.1 Yields

Yields and crop prices are important determinants of crop profitability. The mature yields of Sida and Silphium in this study were based on experimental results and in line with yields reported elsewhere. For example Energiepflanzen.com (Sperr, 2019) report that the yields of Sida and Silphium are 7.0-12.0 t ha^{-1} and 10.0-20.0 t ha^{-1} respectively.

The profitability of Sida is currently limited by its relatively low yields. When Sida is harvested at the end of winter for the production of solid fuel, the plants are dry and have very few leaves. The mean yields of Sida for combustion in five experimental sites participating in the SidaTim project ranged from 6.2 to 10.6 t DM ha^{-1} in the third year of cultivation (Bury *et al*., 2019). However, when Sida is harvested in summer as green biomass, yields can be higher because of the inclusion of green leaves. The mean yield of Sida for biogas obtained in the SidaTim project ranged from 7.6 to 15.1 t DM ha^{-1} (Bury *et al*., 2019) showing that commercial plantations could potentially produce greater amounts of biomass.

When compared to other arable and energy crops in the present study, Silphium is a highly profitable and competitive crop. The theoretical mature yields used for the economic model of 16.3 t DM ha^{-1} for the UK, Germany and Poland, and 15.0 t DM ha^{-1} for Italy, correspond with the experimental results obtained in the SidaTim project. Mean yields of Silphium ranged from 14.3 to 18.0 t DM ha^{-1} in the third year. This is one of the main assumptions of the model, that once the plantations reach maturity, the yields will remain constant for the remainder of the rotation.

In reality, this will not be the case, assuming the establishment was successful and management is consistent, yields will vary annually responding to climatic conditions. Hence, it is reasonable to expect higher yields in humid years and lower yields in drier years, as it has been observed during the duration of the experiment. To determine the accuracy of the model regarding said annual variation in yields due to climatic conditions, one would need to collect annual yields over the entire maturity period of the crops, which are unavailable, and compare that recorded mean with the mean used as input for the model.

From the data collated during the literature review, we have observed that in research trials, which are few and generally limited to the first three years of growth, the annual yields of Sida and Silphium vary greatly from year to year. Under poor management practices, high pest or disease impacts, or challenging environmental conditions, Sida and Silphium yields have tended to be low. The converse has also been true. In the establishment year, annual Sida yields have varied between 1.8 to 4.7 t DM ha^{-1}; from year 2 to year 9, annual Sida yields have ranged from 2.9 to 21 t DM ha^{-1} (beyond year 9, no data are available). In general, mean annual Sida yields vary from 4.3 to 17.7 t DM ha^{-1} (overall mean of 11.6 t DM ha^{-1}; standard deviation of 4.7 t DM ha^{-1}). Annual yields of Silphium also have considerable variation. From year 2 to year 7, annual Silphium yields have ranged from 5.5. to 27.8 t DM ha^{-1} (beyond year 7, no data are available). Mean annual Silphium yields have generally varied from 13.0 to 25.0 t DM ha^{-1} (overall mean of 17.1 t DM ha^{-1}; standard deviation of 3.3 t DM ha^{-1}). Accounting for variation in annual yields within the model for the full rotation of Sida and Silphium was therefore not possible in the economic assessment, due to the limited number of data available for both species.

However, it can be surmised that in some years, yields might not be sufficient to result in profitable production. This would then have implications for the net cash flow of the farm. Such depressions in income, depending on their probability and magnitude, could prove to be challenging for the farmer and potentially act as an impediment to adoption. Assessing the economic implications would ideally require several full datasets covering the full commercial life span of the plants, so that yield variation above and below the mean could be properly quantified. Such datasets do not exist, because research in Sida and Silphium is relatively new, niche, and requires long-term monitoring programmes, which are expensive and challenging to maintain.

6.4.2 Profitability of energy crops

Studies of the profitability of energy crops are uncommon and the results vary greatly. Research of Sida and Silphium has mainly focussed on their production with few studies looking at their production costs. To assess the validity of the SidaTim model and the results obtained for Sida and Silphium, we considered it necessary to at least compare the results from the model for SRC and Miscanthus with results by other researchers.

Our reported profitability of SRC coppice in the UK assuming no subsidies of 1765 £ ha^{-1} (*i.e.*, 1932 € ha^{-1}) at 4% discount rate over 16 years is in line with the results reported elsewhere. For a study in Wales, Heaton *et al.* (1999) observed the NPV of SRC ranged from 979 to 2956 £ ha^{-1} with yields of 6 and 12 t DM ha^{-1} y^{-1} respectively (at 4% discount rate). In Croatia, Posavec *et al.*, (2017) obtained a NPV of 1055 € ha^{-1} at 7% discount rate. Styles, Thorne and Jones (2008) analysed the profitability of SRC and Miscanthus in Ireland under different scenarios, calculating EAVs of € 211-270 and € 326-383 ha^{-1} y^{-1} respectively at 5% discount rate, mid production conditions and funding of € 125 ha^{-1} y^{-1}. Feeding exactly the same grants in the SidaTim model for SRC and Miscanthus in the UK, the results are equivalent to € 295 and € 346 ha^{-1} y^{-1} respectively, at 4% discount rate, within the above given ranges. On the other hand, the results obtained by Fradj and Jayet (2018) for Miscanthus vary greatly from the SidaTim model results. For a medium yield scenario (12-18 t DM), NPVs ranged from €500 to €800, as opposed to the €2543 ha^{-1} (2296 £ ha^{-1}) we obtained. The discrepancy in the results is probably due to the lower establishment costs and annual costs used included in the SidaTim model.

Establishment costs are crucial in determining the profitability of energy costs. Within the SidaTim model, the high establishment costs for Sida, which were obtained from a plant nursery in Germany, make the profitability of Sida low compared to other options. However, the establishment costs in the literature shows wide variability ranging from

1860 to 2715 € ha^{-1} (Pszczółkowska *et al*., 2012) through to 5000 € ha^{-1} (Franzaring *et al*., 2015), 8096 € ha^{-1} (Stolarski *et al*, 2014), compared to 5658 € ha^{-1} (5106 £ ha^{-1}) used in the SidaTim model. If treated seeds with a high germination percentage became available, the costs of establishment of Sida could be in the region of 1159 € ha^{-1} (Stolarski *et al*., 2014b).

6.4.3 Biomass price

The price of biomass has a great impact on the profitability of energy crops. The present study considered a relatively conservative price of £55 $(t\ DM)^{-1}$ for all energy crops, as indicated by ABC Ltd (2019a) for SRC and Miscanthus. If the biomass obtained from Sida and Silphium was higher, then the profitability of both crops rises. We can observe in the UK sensitivity analysis that when prices are increased by 100% to £110 $(t\ DM)^{-1}$, the NPVs (with grants) would rise to 8079 and 15219 £ ha^{-1} for Sida and Silphium respectively. A price of 110 £ $(t\ DM)^{-1}$ is certainly plausible as the price achieved by forage maize supplied to the biogas industry (£35-40 per tonne at 35% DM (BASF SE, 2018)) is equivalent to £107 $(t\ DM)^{-1}$.

The market prices of Sida and Silphium in Italy, Germany and Poland are about €45, €72, and €59 per tonne respectively. These prices are actual market prices being paid to farmers in the three different countries, which reflect the variation in the value of the same product between individual countries within the EU. Within the sensitivity analysis, the relatively conservative price of £55 (€61) per tonne DM was chosen as the default, as for the UK, but in reality the price of Sida and Silphium would depend on the agreed price in the contract between the farmer and, for example, a power plant operator.

6.4.4 Funding, support and extra income

The study demonstrates how funding affects the profitability of energy crops. For many years, agricultural grants have been provided by the EU shaping the decisions made by farmers. Within this analysis we have assumed that agricultural biomass crops are fully eligible for single farm payments through the CAP. However it could be argued that biomass crops could be eligible for additional payments because of the additional ecosystem services that they provide. If crops like Sida and Silphium were granted an environmental services reward of £220 ha^{-1} y^{-1} (equal to the SFP generally provided to arable crops), their NPVs automatically would jump to £1075 and £5697 per ha respectively. Alternatively, if the costs of establishment were fully funded, the NPVs of Sida and Silphium would be £3515 ha^{-1} and £5023 ha^{-1} without any further support. An alternative to government support is to secure additional income from related products. Sida and Silphium crop income could be supplemented by the production of honey (Cumplido-Marin *et al.*, 2020), that can produce about 230 and 450 kg per ha (Jabłonski and Kołtowski, 2005). Considering the price of honey to be £20 per kg, this would amount to extra £4600 and £9000 per ha per year for Sida and Silphium respectively.

6.4.5 Environmental valuation

The results of the analysis undertaken here suggest that Silphium could provide profitable and competitive option in comparison with other arable and energy crops that farmers might currently use. Sida would need to be established and maintained in optimum conditions to produce a high yield and provided with an establishment fund for it to be a competitive option. A clear current need, given the challenge of maintaining global warming levels within the limits set by the Paris Agreement and the need to tackle related environmental challenges, such as the loss of pollinators and biodiversity in rural areas in general, is to evaluate the systems through a broader ecosystems perspective. This would allow the systems to be compared on the basis of their broader environmental and social impacts, as well as on the basis of their financial profitability. Such an evaluation could use approaches such as life cycle assessment and environmental valuation to derive a more complete analysis of the benefits of these different systems.

6.5 Conclusions

Without any funding, Silphium was the most profitable option in the UK, followed by Miscanthus, the arable rotation and SRC, whilst the profitability of Sida was negative. In Italy, SRC was the most profitable and only option with a positive NPV. In Germany, Silphium was the most profitable, followed by Miscanthus and SRC, whilst both Sida and the arable rotation had negative NPVs. In Poland, Silphium was again the most profitable option, followed by SRC, whilst Miscanthus, Sida and the arable rotation had negative NPVs. When funding was included in the analysis, the profitability of all crops increased accordingly, turning most unprofitable options into profitable ones, except for the case of Sida in Italy and Poland and Miscanthus in Poland. The profitability of Miscanthus in Poland was extremely negative because of the high establishment costs. The profitability of the arable rotation varied between countries, reflecting the differences in productivity, prices and costs.

The analysis suggests that given the assumptions made regarding input prices and costs in the United Kingdom, Italy, Germany, and Poland, Silphium could on the whole provide a profitable and viable alternative to conventional arable and energy crops to strengthen and support the bioeconomy. For Sida to be a profitable and viable crop, yields need to be above 12 t DM ha^{-1} and would greatly benefit from establishment grants or functioning seed technology. Whilst the sensitivity analysis of NPVs includes forage maize to facilitate comparisons, in practice the continuous production of forage maize is not possible; it needs to be grown in a rotation to reduce the build-up of pests, and to maintain soil health. Assuming a generalised and hypothetical rotation of the arable crops in equal proportions over time, the results showed that Silphium could provide a highly competitive alternative to an arable rotation and to other energy crops in the United Kingdom, Italy, Germany, and Poland. Sida was less profitable than other options.

The sensitivity analysis and the shift in values to hit NPV of most profitable arable and energy crop identified suggested that, on the basis of the assumptions made, both Sida and Silphium were both profitable with subsidies and that large decreases in prices and increases in costs would be needed for the crop to show a negative financial return. Sida was generally outperformed by other crops in each of the four countries. In the UK, Silphium was less profitable than the forage and the arable rotation but out-performed the SRC and Miscanthus under favourable conditions. In Italy and Germany, Silphium was highly profitable and performed at a level that made it attractive as an alternative to an arable rotation and other energy crops. In Poland, the results showed that Silphium was generally less profitable than forage maize, but it outperformed the arable rotations and most of the other energy crop options.

The current study is based on the assumption that energy crops produce a stable yield throughout their mature life. In reality this may not be the case because especially perennial plantations can lose some of their productivity over the years, resulting in reduced yields or may be damaged by wildfires, major pest or diseases, or by deer. In the occurrence of such events, the productivity will also be reduced according to the extent of the damage and the cost of replacing the damaged areas or treating against the external agent should be taken into consideration.

Acknowledgements:

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7 GREENHOUSE GAS EMISSIONS ASSOCIATED WITH THE CULTIVATION OF *SIDA HERMAPRHODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. IN THE UK

This chapter first describes how the model to calculate the GHG emissions associated with the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. compared to an arable rotation and other energy crops was developed in Excel, based on the IPCC guidelines for greenhouse gas inventories. After, the results obtained from the model are analysed and discussed within the context of the life cycle of the crops and a rotation of 16 years. The chapter will be presented as a scientific paper by Laura Cumplido-Marin, Dr. Anil R. Graves, Dr. Paul J. Burgess, Dr. Adrian Williams.

Abstract: Before using novel energy crops as alternative/complementary crops to produce bioenergy, feasibility studies should consider their carbon footprint. The current study developed a greenhouse gas emissions model to study the greenhouse gas emissions associated with the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. The model followed the Intergovernmental Panel on Climate Change (IPCC) guidelines, comparing the establishment and cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. with an arable rotation, short rotation coppice (SRC) and Miscanthus. Under the particular circumstances specified in the current study, the results indicate that the cultivation (16 years rotation) of SRC, Miscanthus, *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. would produce (+) or sequester (-) respectively about 0.3, 2.2, -4.0 and -0.6 t CO_2 eq ha^{-1} y^{-1}.

7.1 Introduction

Reducing greenhouse gas emissions (GHG) is essential to tackle climate change. Climate change has become such a critical issue 195 countries agreed to sign the Paris Agreement, by which signatories committed to limit global warming to less than 2°C compared to pre-industrial revolution levels (UNFCCC, 2021). To work towards this goal, the United Kingdom set the target of being carbon neutral by 2050 (UK Government, 2019b). Achieving carbon neutrality implies maximising the use of all renewable energies. The bioenergy sector has not yet achieved its full potential; there is an opportunity to produce sustainable biomass on less productive or marginal land using alternative/complementary energy crops. The SidaTim European Joint Project (3N Kompetenzzentrum, 2021) identified the crops *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., referred as Sida and Silphium from here onwards, as having great potential.

Sida and Silphium can produce mature yields that range between 5-20 t DM ha^{-1} y^{-1} and 12-21 t DM ha^{-1} y^{-1} (Cumplido-Marin *et al.*, 2020) and remain productive for over 15 years. Research has primarily focussed on the performance, energy production and environmental services. Cumplido-Marin *et al.* (2020) reviewed several studies, providing evidence of the environmental benefits associated with the cultivation of both crops, namely phytoremediation and phytostabilization, biodiversity and pollination, and soil health regulation. However, considering the current climate emergency and before fully endorsing the cultivation of Sida and Silphium, the greenhouse gas (GHG) emissions associated with their cultivation should be considered. To the authors' knowledge there was no previously published research in English language evaluating the GHG from cultivating Sida or Silphium at the time that this study was conducted. Hence, we fill this gap with a GHG emissions accounting model using the IPCC guidelines.

7.2 Methodology

The soil carbon sequestration ability of Sida and Silphium can potentially contribute to an overall reduction of greenhouse gas (GHG) emissions compared to arable crops. To study this phenomenon, the SidaTim GHG emissions model was developed for the UK which compares an arable rotation and four energy crops, including Sida and Silphium.

The current GHG study followed the IPCC guidelines for National Greenhouse Gas Inventories (IPCC, 2019a, 2006a). For the Agriculture, Forestry, and Other Land Use

(AFOLU) sector, this method accounts for carbon stock variations as CO_2 emissions and removals, along with non-CO_2 emissions.

7.2.1 Land of study

For the model calculations, the present study considered that the plants were all cultivated in a piece of land located in Silsoe (Bedfordshire, UK), characterised by cool temperate wet weather and sandy soil. The study compared the emissions produced from five agricultural systems over a rotation of 16 years. The systems included a theoretical arable rotation made of wheat, sugar beet, forage maize, OSR and oats (to maintain consistency with throughout the thesis); SRC; Miscanthus; Sida; and Silphium. No land-use changes were considered, because the land-use category is cropland remaining cropland (CL remaining CL).

7.2.2 Definition of system boundaries and key categories

To concentrate the study on the cultivation on the crops and allow comparisons between crops, the farm-gate was selected as the system boundary (Figure 7.1). Based on the IPCC guidelines for National Greenhouse Gas Inventories, Volume 4 AFOLU sector (IPCC, 2006b), the key categories should include significant land-use and management activities, significant CO_2 emissions or removals by sinks from various carbon pools, and significant non-CO_2 gases. The required tier or level of assessment was identified using a decision tree for land remaining in the same land-use category (cropland remaining cropland) as Tier 1. Country-specific emission factors (EF) were used when available.

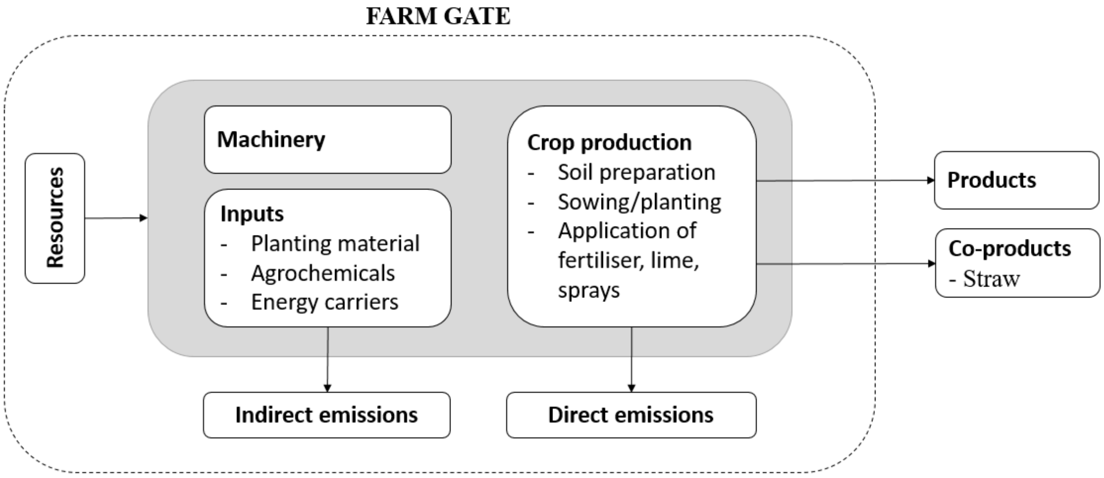

Figure 7.1 – Diagram of the system boundaries of the current study, based on (FAO, 2017b).

The greenhouse gas emissions and removals included in this study are the emissions derived from the agricultural activity. The emissions are associated with cultivation and crop production, which include emissions from fossil fuels used during agricultural operations, carbon stock changes, and N_2O emissions from managed soils. The greenhouse gas emissions and removals resulted during the production of the planting material, manufacturing of machinery or agrochemical products, and emissions resulting beyond the farm-gate were out of scope. The key categories identified in this study involve the emissions included in Table 7.1.

Table 7.1 - Emissions associated with the cultivation and production of the crops included in the SidaTim GHG emissions model.

Emissions	Code	CO_2	CH_4	N_2O
1. Emissions from fuel combustion activities	1A4	x	x	x
2. Carbon stock change in biomass pool	3B2a			
3. Carbon stock change in mineral soil	3B2a	x		
4. Carbon stock change in litter pool	-	x		
5. Direct N_2O emissions from managed soils	3C4			x
6. Indirect N_2O emissions from managed soils	3C5			x

7.2.3 Emissions from fuel combustion activities

All of the agricultural operations required for the establishment, maintenance and harvest of crops involve the use of tractors (and other self-propelled machines), powered by diesel. Diesel combustion produces three main GHG to the atmosphere:

CO_2, CH_4, and N_2O. These emissions were calculated by multiplying the corresponding emission factor by the fuel consumed, as outlined by the guidelines (IPCC, 2006c), see Appendix F, F.1.1 Emissions from fuel combustion activities for further details.

The EF for carbon dioxide, methane, and nitrous oxide were obtained from the UK Government GHG Conversion Factors for Company Reporting database (BEIS and DEFRA, 2019). Diesel consumption per unit area ($l\ ha^{-1}$) was calculated using Equation 7.1 to Equation 7.4. The data sources needed for the calculation of diesel consumption are outlined in Table 7.2. The whole data set of calculations is included in Appendix F, F.1.1 Emissions from fuel combustion activities.

$$f_e = \frac{Specific\ fuel\ consumption\ \left(\frac{\text{g}}{\text{kWh}}\right) * \ rated\ power\ (\text{kW})}{fuel\ density\ \left(\frac{\text{kg}}{\text{l}}\right)}$$ Equation 7.1

where f_e = average fuel consumption ($l\ ha^{-1}$)

$$f_A = \frac{f_e}{q_A}$$ Equation 7.2

where f_A = fuel consumption ($l\ ha^{-1}$); q_A = work rate ($h\ ha^{-1}$)

$$Mean\ diesel\ use\ \left(\frac{l}{ha}\right) = \ f_A * \ operations$$ Equation 7.3

$$Diesel\ consumption\ \left(\frac{\text{l}}{\text{ha}}\right) = mean\ diesel\ use * passes$$ Equation 7.4

Table 7.2 – Data and sources included the calculation of diesel consumption.

Parameter	**Source**
Engine power (kW)	Williams *et al*. (2006)
Number of passes per season (n)	Williams *et al*. (2006)
Work rates ($h\ ha^{-1}$)	Williams *et al*. (2006)
Specific fuel consumption ($g\ kWh^{-1}$)	Handler and Nadlinger (2012)
Fuel density ($kg\ l^{-1}$)	(BEIS, 2020a)

After the nitrous oxide and methane emissions were obtained ($kg\ ha^{-1}$), they were multiplied by the corresponding Global Warming Potential (GWP) (Myhre *et al.*, 2013) to convert them into kg CO_2 eq ha^{-1}.

7.2.4 Carbon stock change estimation

Annual emissions and removals of CO_2 (carbon stock changes) can be estimated as the sum of changes in all land-use categories. The present study will account for carbon stock changes that occur in one land-use category, cropland, with no stratum, considering the crops are cultivated homogeneously on a unit of land (1 ha). No land-use changes are included in the study, assuming the land was previous cropland which remains cropland.

Carbon stock changes are derived from the variations occurring in each carbon pool, which are summed. In the case of arable crops, dead organic matter consists of litter plus residual roots because no deadwood is present. In a long-term arable rotation, the supply of crop residues and tillage intensity can be regarded as approximately constant. In a long-term perennial cropping system, such as Sida or Silphium, tillage is limited to the establishment year and weeding in the first few years. Crop residues in perennial systems will vary depending on the species and time of the harvest. The present study restricted the analysis to the biomass (above and below ground), soil and litter pools.

7.2.4.1 Soil pool

Carbon dioxide fluxes emerging from the soil pool can be positive (emissions) or negative (removals). Changes in organic soils were considered to be out of scope, because their estimation requires comprehensive hydrogeochemical analysis (IPCC, 2006d). Carbon stock changes in mineral soils were calculated following the IPCC guidelines (for further details see Appendix F, F.1.2 Carbon stock change in mineral soil pool).

The calculation of the emissions from the mineral soil pool was done by classifying the crops into arable and energy crops. The factors and reference SOC levels (SOC_{ref}) for the calculation of SOC stock at the beginning (SOC_{0-T}) and the end of the inventory period (SOC_0) are summarised in Table 7.3. These parameters were extracted from Chapter 2 and Chapter 5 of the IPCC guidelines (IPCC, 2019b, 2019c). The inventory period chosen

Table 7.3 – Factors included in the calculation of carbon stocks in mineral soils.

Factor	SOC_{0-T}		SOC_0	
	Arable	Energy	Arable	Energy
F_{LU}	0.70	0.70	0.70	0.72
F_{MG}	1.0	1.0	1.0	1.04
F_I	1.0	1.0	1.0	1.11
SOC_{ref}	76.0	76.0	76.0	76.0

where: F_{LU} = stock change factor for land-use systems for a particular land-use (-); F_{MG} = stock change factor for management regime (-); F_I = stock change factor for input of organic matter (-); SOC_{ref} = reference carbon stock (t C ha^{-1}).

was 16 years, to match with the rotation of the energy crops. The SOC stock of energy crops at the beginning of the inventory (SOC_{0-T}) period was set to be equal to the SOC stock of arable crops at the end of the inventory period (SOC_0).

7.2.4.2 Biomass pool

The net accumulation of carbon in the biomass pool for arable crops is zero, because the increase in biomass stocks for arable crops in a year are considered to be equal to the losses from harvest and mortality in the same year (IPCC, 2019c). Therefore, changes in the carbon stock pool of biomass were only calculated for perennial (energy) crops, using the IPCCC guidelines (Appendix F, F.1.3 Carbon stock change in biomass pool).

Whenever the IPCC guidelines provided specific data on the studied crops, that data was used as a model input. This was the case for SRC regarding the maximum above ground biomass carbon stock at harvest (12.69 t C ha^{-1}), above ground biomass accumulation rate (3.1725 t C ha^{-1} y^{-1}), and mean biomass carbon stock (6.35 t C ha^{-1}). The ratios of below ground to above ground biomass (R) were calculated/extracted from literature sources and own data, corresponding to 0.13 (Heinsoo and Tali, 2018), 0.39 (Mann *et al.*, 2013), 2.35 (own data) and 0.52 (Schoo *et al.*, 2017b) for SRC, Miscanthus, Sida and Silphium respectively. Yield data (Table 7.4) of energy crops until they reached maturity was extracted from Chapter 6 ECONOMICS OF *SIDA HERMAPHRODITA* (L.) RUSBY AND *SILPHIUM PERFOLIATUM* L. IN EUROPE. The whole data set of calculations is included in Appendix F, F.2.3 Stock changes in biomass pool (above and below ground). The carbon fraction (CF) of the biomass was extracted from the 2019 Refinement of the IPCC

Table 7.4 – Yield profiles of energy crops (t DM ha^{-1} y^{-1}).

Year	Miscanthus	Sida	Silphium
1	0.60	2.05	0.00
2	3.93	8.27	9.93
3	11.10	10.93	14.70
4	12.54	11.62	15.73
5	12.54	11.62	16.30

guidelines (IPCC, 2019a), being 0.5, 0.37 and 0.47 t DM for dead wood, litter, and herbaceous biomass respectively.

Root biomass data was extracted/calculated from literature sources and own data, corresponding to 1.40 (Matthews, 2001), 1.50 (Clifton-brown *et al.*, 2007), 1.71 (own data) and 0.53 (Schoo *et al.*, 2017b) t DM ha^{-1} y^{-1} for SRC, Miscanthus, Sida and Silphium respectively.

7.2.4.3 Litter pool

Following the IPCC guidelines, the stock-difference method was used for the estimation of changes in the litter pool for energy crops (Appendix F, F.1.4 Carbon stock change in litter pool). The emissions were calculated from the establishment year until the crops reach maturity, using the yields provided above (Table 7.4). Litter data for SRC and Miscanthus was extracted from the literature, respectively 1.85 t DM ha^{-1} y^{-1} (Hangs *et al.*, 2014) and 29-42% of the production (Lewandowski *et al.*, 2000). In the case of Sida and Silphium, it was assumed that the same proportion from the production as Miscanthus was yielded (0.36%). The carbon fraction (CF) of litter was fixed at 0.37. The litter stock at time 2 was estimated to be 0 for Silphium due to the fact that it is harvested for green biomass, not having time to produce litter. The complete set of calculations is included in Appendix F, F.2.4 Stock changes in litter pool.

7.2.5 N_2O emissions

The non-CO_2 emissions included in this study as a result of the agricultural activity are derived from the nitrification and denitrification process Figure 7.2. In particular, from additions of N from fertilisers and crop residues and through N mineralisation which

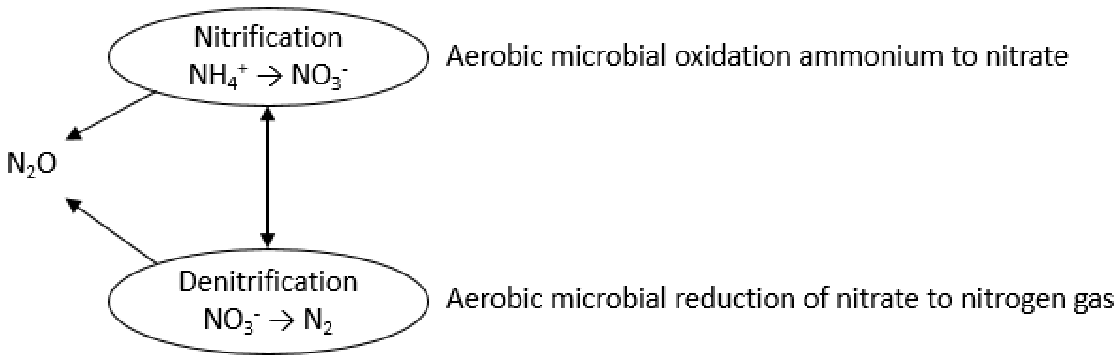

Figure 7.2 – Simplified diagram of the nitrification and denitrification process occurred during agricultural activities, origin of N_2O emissions.

occurs after cultivation of mineral soils (IPCC, 2006e). There are two types of N_2O emissions, direct and indirect. Direct N_2O emissions in crop production originate from N applications (fertilisers) and crop residues. Indirect N_2O emissions originate from volatilisation of ammonia and nitrogen oxides, combustion of fossil fuels, and from nitrate leaching and run off from managed soils (IPCC, 2006e). Converting N_2O-N emissions to N_2O emissions was done using by multiplying by 44/28.

7.2.5.1 Direct N_2O emissions

Direct N_2O emissions derived from the application of N fertilisers were calculated following the advised methodology (for further details see Appendix F, F.1.5 Direct N_2O emissions). Crops yields ($Crop_{(T)}$) and synthetic nitrogen fertiliser doses (F_{SN}) for arable crops were obtained from the John Nix Pocket Book for Farm Management (ABC Ltd, 2019b); from the Agricultural Budgeting and Costing book (ABC Ltd, 2019a) for SRC and Miscanthus; and from Chapter 6 for Sida and Silphium.

Annual above ground crop residues ($AGR_{(T)}$) for wheat, and oats and OSR, were obtained from DEFRA (2019); from Torma *et al.* (2018) for sugar beet and forage maize; litter data of mature energy crops reference in the previous section was used for SRC, Miscanthus, Sida and Silphium. It was considered that the residues of all crops were not removed

($Frac_{remove(T)}$ = 0) and that all the cropped area was renewed annually for all crops ($Frac_{renew(T)}$ = 1.0) but for SRC ($Frac_{renew(T)}$ = 0.25).

The ratio of below-ground residue to harvested yield ($RS_{(T)}$), the ratio of above-ground residues dry matter to harvested yield ($R_{AG(T)}$), dry matter content of arable crops, and nitrogen content of above and below ground residues ($N_{AG(T)}$, $N_{BG(T)}$) were extracted from the corresponding volume of the guidelines (IPCC, 2019d). Because no land use change was contemplated in the study, the annual amount of N in mineral soils that is mineralised in association with land use changes (F_{SOM}) was considered to be 0. A summary of the data applied in the model for the different crops is presented in Table 7.5, with all calculations shown in Appendix F, F.2.5 Direct N_2O emissions.

Table 7.5 – Activity data and coefficients used to derive above and below ground N_2O emissions from crop residues.

Crop	**$Crop_{(T)}$** (kg ha^{-1})	**F_{SN}** (kg ha^{-1})	**$AGR_{(T)}$** (kg DM y^{-1})	**$R_{AG(T)}$** (-)	**$RS_{(T)}$** (-)	**DRY** (%)	**$Frac_{remove(T)}$** (-)	**$Frac_{renew(T)}$** (-)	**$N_{AG(T)}$** (-)	**$N_{BG(T)}$** (-)
Wheat	7,390	190	3,900	1.3	0.23	0.89	0.0	1.0	0.006	0.009
Oats	5,610	130	3,500	1.3	0.25	0.89	0.0	1.0	0.007	0.008
OSR	3,150	190	2,600	0.3	0.54	0.90	0.0	1.0	0.015	0.012
Sugar beet	16,940	156	500	0.4	0.20	0.22	0.0	1.0	0.019	0.014
Forage maize	10,440	150	3,310	1.0	0.22	0.87	0.0	1.0	0.006	0.007
SRC	25,000	90	1,850	0.3	0.8	-	0.0	0.3	0.015	0.012
Miscanthus	12,500	84	4,450	0.3	0.8	-	0.0	1.0	0.015	0.012
Sida	11,600	100	4,120	0.3	0.8	-	0.0	1.0	0.015	0.012
Silphium	16,300	120	5,790	0.3	0.8	-	0.0	1.0	0.015	0.012

7.2.5.2 Indirect N_2O emissions

Indirect N_2O emissions included in this study come from N volatilisation (NH_3, NO_x) and atmospheric deposition (NH_3, NO_x, NH_4^+, NO_3^-) on soil and water surfaces, the application of synthetic fertilisers (F_{SN}), the nitrogen in crop residues (F_{CR}), and N mineralisation linked to soil organic matter loss as a result of management of mineral soils (Figure 7.3). Indirect N_2O emissions were calculated following the corresponding guidelines (for further details refer to Appendix F, F.1.6 Indirect N_2O emissions).

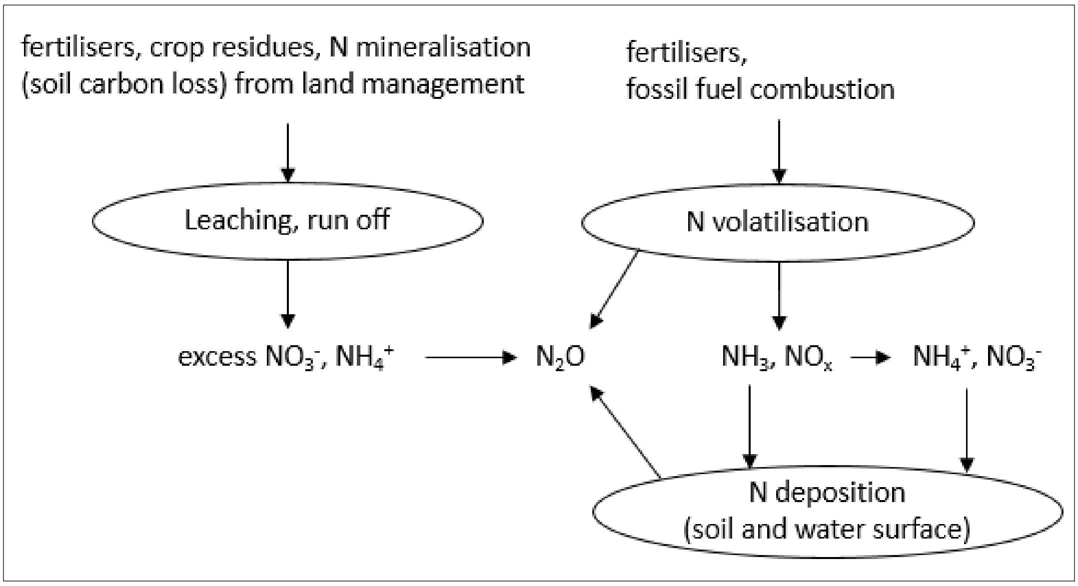

Figure 7.3 – Simplified process diagram of the origin and transformation of indirect N_2O emissions in agriculture.

The parameters used for the calculation of nitrous oxide emissions derived from atmospheric deposition and from leaching/run off were extracted from the IPCC guidelines (IPCC, 2019d). The fraction of synthetic N fertiliser that volatilises as NH_3 and NO_x ($Frac_{GASF}$) and the emission factor for N_2O emission from atmospheric deposition of N on soils and water surfaces (EF_4) were set respectively at 0.11 and 0.014 for all crops. The fraction of all N additions to managed soils that is lost through leaching and runoff ($Frac_{LEACH-H}$), and the emission factor for N_2O emission from N leaching and runoff were set respectively at 0.24 and 0.011. The amount of N in crop residues (above and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually (F_{CR}), was fixed at 0 to avoid double-counting (already accounted for in the emissions derived from litter). All calculations are included in Appendix F, F.2.6 Indirect N_2O emissions.

7.3 Results & Discussion

The amount of CO_2, CH_4 and N_2O derived from diesel consumption during agricultural operations was estimated annually for all crops. For energy crops, years were differentiated by establishment, recurring no harvest/harvest for SRC or simply recurring in the case of Miscanthus, Sida and Silphium. Results are shown in Table 7.6.

Table 7.6 – Annual emissions (kg CO_2 eq ha^{-1} y^{-1}) derived from diesel consumption during agricultural operations in the current study.

Crop and year	CO_2	CH_4	N_2O
Wheat	493	1.7	1745
Oats	493	1.7	1745
OSR	254	0.9	899
Sugar beet	1236	4.3	4376
Forage maize	494	1.7	1749
SRC (establishment)	423	1.5	1497
SRC (recurring no harvest)	82	0.3	290
SRC (recurring harvest years)	232	0.8	822
Miscanthus (establishment)	423	1.5	1497
Miscanthus (recurring)	129	0.5	455
Sida (establishment)	495	1.7	1751
Sida (recurring)	176	0.6	624
Silphium (establishment)	382	1.3	1354
Silphium (recurring)	176	0.6	624

Because the whole crops are removed every harvest, the estimates of carbon stock change for SRC, Miscanthus, Sida, and Silphium, in above-ground biomass pool during their rotation resulted in 0. Below-ground biomass produced by SRC, Miscanthus, Sida and Silphium resulted to fix 2890, 3590, 9850, 1370 kg CO_2 ha^{-1} annually. Growing Miscanthus, Sida, and Silphium retains approximately 2,280 kg CO_2 ha^{-1} in the soil per year. Carbon dioxide emissions derived from litter production of energy crops are summarised in Table 7.7. Annual direct and indirect N_2O emissions from managed soils are summarised in Table 7.8. The results from the 16 years simulation under different systems were obtained in tonnes and converted into CO_2 eq ha^{-1} are summarised in Figure 7.4.

Table 7.7 – Carbon stock changes in litter pool for energy crops (kg CO_2 ha^{-1} y^{-1}) obtained in the current study.

Period	**Carbon stock change (kg CO_2 ha^{-1} y^{-1})**
SRC (year 1)	2510
SRC (year 2)	2510
SRC (year 3)	2510
SRC (year 4)	2510
Miscanthus (year 1)	289
Miscanthus (year 2)	1890
Miscanthus (year 3)	5346
Miscanthus (year 4 and onwards)	6040
Sida (year 1)	986
Sida (year 2)	3983
Sida (year 3)	5263
Sida (year 4 and onwards)	5595
Silphium (year 1)	0
Silphium (year 2)	0
Silphium (year 3)	0
Silphium (year 4)	0
Silphium (year 5 and onwards)	0

Table 7.8 – Annual direct and indirect N_2O emissions from managed soils (kg CO_2 eq ha^{-1} y^{-1}) obtained in the current study.

Crop	**Direct N_2O emissions**	**Indirect N_2O emissions**
wheat	1627	122
oats	1180	83
OSR	1672	122
sugar beet	1518	100
forage maize	1322	96
SRC	1281	58
Miscanthus	2008	54
Sida	2007	64
Silphium	2685	77

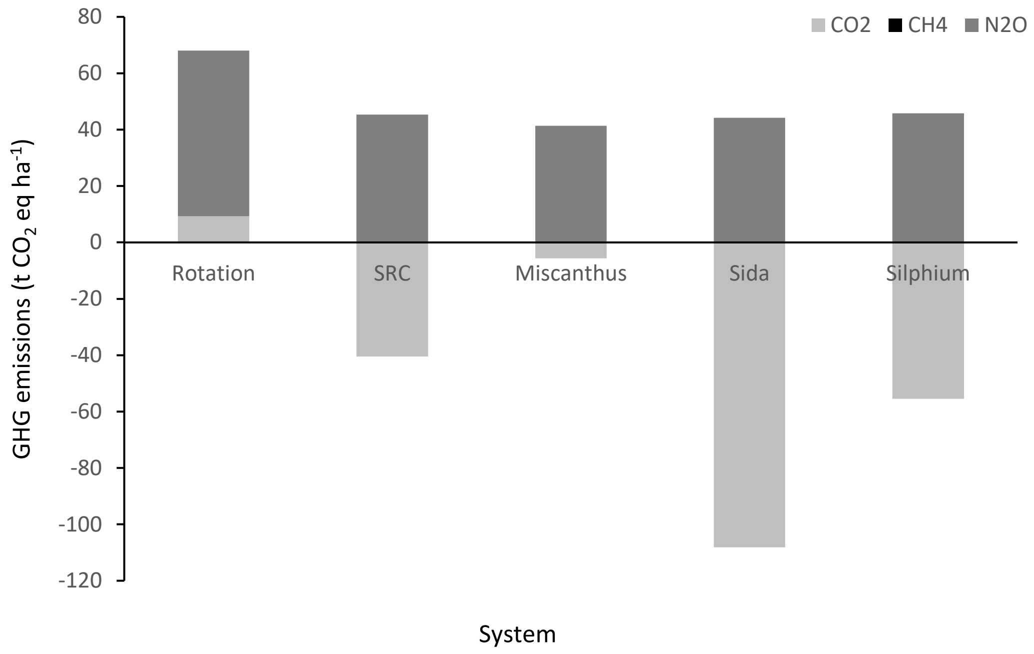

Figure 7.4 – GHG emissions balance from the 16 years rotation contemplated in the current study for the analysed agricultural systems.

Carbon dioxide emissions from the arable rotation were 9.4 t CO_2 ha^{-1} over the 16 years, equivalent to 0.6 t CO_2 ha^{-1} y^{-1}. All four perennial systems remove carbon dioxide from the atmosphere, fixing a total of 40.4, 5.6, 108.1 and 55.5 t CO_2 ha^{-1} over 16 years, equivalent to 2.5, 0.4, 6.8 and 3.5 t of CO_2 ha^{-1} y^{-1}. Methane emissions during the 16 years of cultivation from all five systems are very limited, ranging between 0.03 t CO_2 eq ha^{-1} (arable rotation), 0.02 t CO_2 eq ha^{-1} (SRC) and 0.01 t CO_2 eq ha^{-1} (Miscanthus, Sida, Silphium). Nitrous oxide emissions from all studied systems in order from highest to lowest were: 58.6 t CO_2 eq ha^{-1} from the arable rotation; 45.8 t CO_2 eq ha^{-1} from Silphium; 45.4 t CO_2 eq ha^{-1} from SRC; 44.2 t CO_2 eq ha^{-1} from Sida; 41.3 t CO_2 eq ha^{-1} from Miscanthus. Overall emissions in terms of CO_2 eq ha^{-1} y^{-1} were positive for the arable rotation, SRC and Miscanthus (4.2, 0.3, 2.2 t CO_2 eq ha^{-1} y^{-1}), whilst negative for Sida and Silphium (-4.0 and -0.6 t CO_2 eq ha^{-1} y^{-1}).

Don *et al.* (2012) reviewed the GHG emissions associated of perennial systems compared with arable systems obtained by various authors. They organised crops into low, medium and high nitrous oxide emissions, classifying Miscanthus, other perennial grasses, willow, and poplar into the first category; and maize, OSR, wheat, and root crops, into the third category.

During a four-years experiment, Hellebrand *et al.* (2010) recorded the nitrous oxide emissions of SRC and annual crops under different fertilisation regimes in Germany, observing significantly lower emissions from SRC compared to annual crops in all cases. For the doses of 0/75/150 kg N ha^{-1} they recorded nitrous oxide emissions of 0.50-0.57/0.94-1.14/1.15-1.99 kg NO_2-N ha^{-1} y^{-1}. We can compare those results with the results from the current study, where we calculated that 3.2 kg NO_2-N ha^{-1} y^{-1} were produced by the SRC system (considering a fertilisation rate of 90 kg N ha^{-1}). The results from the current study are slightly higher that the experimental results obtained by Hellebrand *et al.* (2010), indicating that our model might be overestimating the calculated GHG emissions.

In their 2.5 year field experiment in Lincolnshire (UK), Drewer *et al.* (2012) demonstrated that the cultivation of Miscanthus and SRC (with 0 fertilisation) produced about five times less nitrous oxide emissions than arable rotations, observing no significant differences between SRC and Miscanthus. In terms of kg CO_2 eq, they estimated that SRC and Miscanthus produce respectively 8 and 152 kg CO_2 eq ha^{-1} y^{-1} of nitrous oxide emissions (with no fertilisation), compared to 339-1,330 kg CO_2 eq ha^{-1} y^{-1} from the arable rotations. Comparing the results obtained by Drewer *et al.* (2012) with the results from the current study, our estimations of the N_2O emissions from of SRC and Miscanthus are significantly higher (2,835 and 2,582 kg CO_2 eq ha^{-1} y^{-1} for SRC and Miscanthus respectively) but we need to remember that our results assume annual fertilisation for optimum harvest. Our estimation of 3,660 t CO_2 eq ha^{-1} y^{-1} of nitrous oxide from the arable rotation is much higher than their upper range, confirming our previous suspicion of the model is overestimating results.

It is reasonable to expect the real GHG emissions from Sida and Silphium to be similar to the real emissions from SRC and Miscanthus, in the range of -5 to -14 kg CO_2 eq ha^{-1} y^{-1} of methane, and 8-152 kg CO_2 eq ha^{-1} y^{-1} of nitrous oxide (Drewer *et al*., 2012).

7.3.1 Life cycle emissions

Due to the limitation on resources, the current model does not account for life cycle emissions, including emissions derived from the manufacturing of inputs such as fertilisers, and emissions derived from the processing of the materials for energy production. However, we considered it necessary to reflect on available data and to make an estimation of overall life cycle emissions for Sida and Silphium. Emissions from bioenergy have been calculated and are published by the UK government online (BEIS, 2020b). DEFRA and BEIS give the emissions from biofuels in the range from 0.01545 kg CO_2 eq kWh^{-1} for wood-based fuels, 0.01619 kg CO_2 eq kWh^{-1} for grass/straw for combustion, and 0.00021 kg CO_2 eq kWh^{-1} for biogas fuels (UK Government, 2021). It is therefore sensible at this stage to assume that similar emissions are produced by Sida and Silphium, i.e. 0.0155 kg CO_2 eq kWh^{-1} from Sida when it is grown and processed for the production of solid fuel for combustion and 0.00021 kg CO_2 eq kWh^{-1} from Sida and Silphium grown and processed for the production of green biomass for anaerobic digestion. Comparing these values with alternative fossil fuels, such as natural gas (0.204 kg CO_2 eq kWh^{-1}), mineral diesel (0.26891 kg CO_2 eq kWh^{-1}) and coal for electricity generation (0.333 kg CO_2 eq kWh^{-1}), we can clearly see how much more emissions the fossil fuel-based options produce per kWh.

Studies covering the GHG emissions from Sida/Silphium are extremely rare. Using the software GaBi 9.2, Jablonowski *et al.* (2020) carried out a life cycle assessment of Sida, including different processing options. According to their results, life cycle emissions from Sida vary between 1.22-1.35 PE (Person Equivalents).

We compared GHG fluxes from common agricultural crops with Sida and Silphium per unit area. If take up of these crops is relatively small, and are about equivalent to the annual changes in crop areas, there should not be any problems of current arable crops being displaced. Should that occur, it could lead to land use change elsewhere to meet the demands for current crops (Smith *et al*., 2019). In a scenario in which livestock production decreases, land should be released and this would not create such problems (Williams *et al*., 2018).

7.4 Conclusions

The GHG emissions model of the establishment and cultivation of Sida and Silphium suggests that their emissions are akin to the emissions from other perennial systems. SRC, Miscanthus, Sida, and Silphium can capture 2.5, 0.4, 6.8, and 3.5 t of CO_2 ha^{-1} y^{-1}; producing marginal amounts of methane and potentially low amounts of nitrogen oxides when fertilisation is minimised/supressed.

Experimental data of the greenhouse gas emissions associated with the establishment and cultivation of Sida and Silphium would assist to refine the results from the present study. Further experimental research is needed to provide this kind of experimental data from long-term field experiments.

One way of reducing nitrous oxide emissions would be by minimising/removing nitrogen fertilisation. This may not be feasible for an arable rotation, but it should be considered for perennial systems. In the current study we assumed an annual fertilisation regime, to maximise biomass production, but what if that was not the main aim of their cultivation? We propose re-defining the purpose of perennial plantations in general, and of Sida and Silphium in particular; they are crops that could be grown with the objective of removing carbon dioxide from the atmosphere. If that was the main purpose of growing perennial crops, a reward system should be implemented to pay farmers for offsetting carbon dioxide emissions, as well as providing a wide range of other ecosystem services. In this context, any revenues derived from the production of energy would be additional income.

In addition, to have a complete picture of the environmental footprint associated with the production of Sida and Silphium biomass, we recommend carrying out a Life Cycle Assessment (LCA) of their cultivation and energy processing, comparing them with arable and other energy crops.

Acknowledgements

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8 SYNTHESIS

The overall aim of this PhD was to determine the agronomic and economic performance of *Sida hermaphrodita* and *Silphium perfoliatum*. This aim was addressed through five objectives. This section reviews the original objectives of the thesis and synthesises the main research findings (Figure 8.1). It concludes by providing recommendations for future research.

8.1 Existing knowledge on Sida and Silphium

Objective 1: the first objective was to determine the existing knowledge on cultivation and energy production of Sida and Silphium. To meet this objective, a systematic literature review was completed, covering both the cultivation and energy production of both energy crops. This literature review describing the agronomy, uses, and environmental benefits of each crops was published as a peer-reviewed paper in the journal Agronomy (Cumplido-Marin *et al.*, 2020). The main findings are summarised below.

Main findings: in the introduction of the paper, Sida is identified as a herbaceous species suited to continental climates (Kurucz et al., 2014). It requires a minimum annual precipitation of about 500-600 mm (Jasinskas *et al*. 2014). It can grow up to 4 m high and yield 12-20 t DM ha^{-1} y^{-1} (Borkowska and Molas, 2012), remaining productive for 15-20 years (Pszczółkowska et al., 2012).

Silphium plants have tall stems that can reach 3 m (von Gehren *et al*., 2016), producing yields of 12-25 t DM ha^{-1} y^{-1} (Ustak and Munoz, 2018; Zilverberg *et al*., 2016) from the second year onwards, remaining productive for 15 years (Stanford, 1990). Water needs of Silphium are 400-500 mm per season (Grebe *et al*., 2012, cited by Gansberger *et al*., 2015).

Chapter	Subsection	Sida	Silphium
Literature review	**Agronomy**	500-600 mm per season 12-20 t DM ha^{-1} y^{-1} Productive for 15-20 years Establishment via seeds: 4.5 kg ha^{-1} (spring/autumn prior) Establishment via seedlings (greater success): 20K-40K seedlings ha^{-1} (spring) Mechanical weed control Vulnerable to *Sclerotinia sclerotiorum* N-P_2O_5-K_2O: 100-92-84	400-500 mm per season 12-25 t DM ha^{-1} y^{-1} Productive for 15 years Establishment via seeds (most economic): (spring/autumn prior): 2-2.5 kg ha^{-1} Establishment via seedlings (most effective): 40K seedlings ha^{-1} (spring) Mechanical weed control Vulnerable to *Sclerotinia sclerotiorum* and Giant *Euscoma* moth N-P_2O_5-K_2O: 120-92-90
	Energy production	Yield increase up to 4th year then plateau Combustion: - Harvest time: BBCH 98, 14-20% moisture - Stems: 15.0 (LHV) /19.4 (HHV) MJ kg^{-1} - Pellets: 16.5 (LHV) /19.5 (HHV) MJ kg^{-1} Biogas: - Harvest time: BBCH 55, 71 - CNR: 22:1-199:1 - Methane yields: 125-220 dm^3 kg ODM	Combustion is rare Biogas: - Harvest time: dry matter 26-28% - CNR: 75:1-124:1 - Methane yields: 227-315 dm^3 kg ODM
	Environmental benefits	Phytoremediation (Sida) and phyto-stabilization, pollination, reduction of chemical inputs, increase in biodiversity, soil health, and water management.	
Soil carbon assessment	**Bulk density**	0-5 cm layer: 1.41 g cm^{-3} (2017), 1.41 g cm^{-3} (2020) 10-15 cm layer: 1.72 g cm^{-3} (2017), 1.42 g cm^{-3} (2020) Mean: 1.56 g cm^{-3} (2017), 1.41 g cm^{-3} (2020)	
	Total carbon	0-5 cm layer: 2.70 % (2017), 1.97 % (2020) 10-15 cm layer: 1.96 % (2017), 2.19 % (2020) Mean: 2.33 % (2017), 2.08 % (2020)	
	Organic carbon	0-5 cm layer: 2.58 % (2017), 1.86 % (2020) 10-15 cm layer: 1.85 % (2017), 2.12 % (2020) Mean: 2.22 % (2017), 1.99 % (2020) Organic carbon stock: 65.0-67.6 t C ha^{-1} (2017), 55.2-58.5 t C ha^{-1} (2020)	

Agronomic performance*	**Growth**	Maximum height: - 250 cm (2018) - 200 cm (2019) - 200 cm (2020) Maximum diameter: - 17 mm (2018) - 14mm (2019) - 13mm (2020) Observed decreasing trend in maximum heights and diameters from 2nd year.	Maximum height: - 175 cm (2018) - seedlings 200 cm; seeds 165 cm (2019) - seedlings 180 cm; seeds 155 cm (2020) Maximum diameter: - seedlings 17 mm; seeds 15 mm (2018) - seedlings 15 mm; seeds 13 mm (2019) - seedlings 14 mm; seeds 12 mm (2020) Decreasing trend only observed in maximum diameters from 2nd year.
	Yields	Solid fuel (combustion): 1.7 (2018), 3.0 (2019), 2.6 (2020) Green biomass (biogas): 10.8 (2018), 5.8 (2019), 4.7 (2020) (t DM ha^{-1}) Highest yields recorded for solid fuel in 2019 and for green biomass in 2018. Significant effects of treatment, year, treatment x year on solid fuel yields and treatment, treatment x year on green biomass yields	Green biomass (biogas): 4.6 (2018), 6.7 (2019), 8.9 (2020) (t DM ha^{-1}) Highest yield recorded in 2020 (increasing over time). No significant effects observed.
Economic analysis (UK case)		NPV without BPS [a]: £ 1,591 ha^{-1} NPV with BPS: £ 1,075 ha^{-1} Least profitable option under the assumed conditions and case specific inputs of the present study.	NPV without BPS [a]: £ 3,031 ha^{-1} NPV with BPS: £ 5,697 ha^{-1} Most profitable option, can compete even with arable rotation under assumed conditions and case specific inputs of the present study.
GHG emissions evaluation:		N_2O: 44.2 t CO_2 eq ha^{-1} CH_4: 0.0 t CO_2 eq ha^{-1} CO_2: -108.1 t CO_2 eq ha^{-1} Overall GHG emissions: -63.9 t CO_2 eq ha^{-1} Equivalent annual GHG emissions: -4.0 t CO_2 eq ha^{-1} y^{-1}	N_2O: 45.8 t CO_2 eq ha^{-1} CH_4: 0.0 t CO_2 eq ha^{-1} CO_2: -55.5 t CO_2 eq ha^{-1} Overall GHG emissions: -9.7 t CO_2 eq ha^{-1} Equivalent annual GHG emissions: -0.6 t CO_2 eq ha^{-1} y^{-1}

*The plantation was established in the spring-summer of 2017, therefore 2018, 2019, 2020 correspond with the 2nd, 3rd, 4th year of growth.
[a]BPS: Basic Payment Scheme

Figure 8.1 – Synthesis of findings extracted from the main five chapters.

Establishment: Sida can be established using treated seeds, but greater success is obtained by establishing plantations from seedlings or rhizomes, despite the additional cost involved. Sowing Sida is done in early spring/November the year prior to establishment (Šiaudinis *et al*., 2015). A seed rate of 4.5 kg ha^{-1} (Stolarski *et al.,* 2014b) or 25 seeds m^{-2} (Molas and Kupczyk 2009; Borkowska and Molas 2012; Molas *et al.* 2019) are recommended. Planting densities of 20,000 (Stolarski *et al.*, 2017; Krzyżaniak *et al*., 2018) to 40,000 (Borkowska and Molas, 2013, 2012) seedlings/rhizomes per ha^{-1} are recommended.

Silphium can be established using seeds (most economic) or seedlings (most effective). Sowing is recommended in autumn (Gansberger *et al*., 2015) or April/May (Pan *et al.*, 2011; Jasinskas *et al.*, 2014; Šiaudinis *et al.*, 2015) at rates of 2.0-2.5 kg ha^{-1} (Gansberger, *et al*., 2015). Seedlings should be planted before June (Gansberger *et al*., 2015). Using vegetable or strawberry planters (Schäfer *et al*., 2015) at densities of 40,000 seedlings ha^{-1} (Franzaring *et al.,* 2015; Gansberger *et al*., 2015; Hartmann and Lunenberg, 2016; Schittenhelm *et al*., 2016; Schoo *et al.*, 2017a; Schoo *et al.*, 2017b).

Weeds, pests and diseases: mechanical weed control is a requirement after sowing, and for the first few years after establishing Sida. Sida is vulnerable to the fungus *Sclerotinia sclerotiorum*, which causes bleached and mouldy white stems (Remlein-Starosta *et al.*, 2016). Silphium is vulnerable to *Sclerotinia* spp. and the larvae of the giant Euscoma moth (Gansberger *et al*., 2015).

Nutrient management: fertiliser rates of 100 kg N ha^{-1}, 92 kg P_2O_5 ha^{-1}, and 84 kg K_2O ha^{-1} are applied on average for Sida. Organic fertilisers are encouraged, i.e. sewage sludge, sewage compost, and biodigestate (Barbosa *et al*., 2014; Czyzyk and Rajmund, 2014; Nabel *et al.*, 2014; Antonkiewicz *et al.*, 2018). Average fertiliser rates applied to Silphium are 120 kg N ha^{-1}, 92 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1}.

Combustion: both crops can potentially be used to produce solid fuel but for Silphium this is not common. Harvesting Sida is best in winter because moisture contents are low, typically 14-20% in February-March (Borkowska and Molas, 2013; Pszczółkowska *et al*., 2012). The dry matter yields from Sida increase during the first four years after establishment and then typically plateau (Borkowska and Molas, 2013, 2012; Pszczółkowska *et al*., 2012). The calorific value of Sida stems is 13.3 MJ kg^{-1} on average (LHV) (Stolarski *et al.*, 2014) and 17.5-18.4 MJ kg^{-1} (HHV) for Sida pellets (Šiaudinis *et al*., 2015). Ash and sulphur content are remarkably low in Sida (Slepetys *et al.,* 2012).

Methane production: the crops are harvested during summer at the right time to maximise biogas production. Green biomass is often ensiled to maximise the biogas production. The carbon nitrogen ratio in Sida varies from 22:1 (Oleszek *et al*., 2013) to 199:1 (Slepetys *et al*., 2012); for Silphium it ranges from 75:1 to 124:1 (Slepetys *et al.*, 2012).

Harvesting: Sida can be first harvested at BBCH 55 (Jablonowski *et al*., 2017) with the second harvest at BBCH 71 for biogas or at BBCH 98 for combustion (Jablonowski *et al*., 2017). Sida can produce yields of 8-14 t DM ha^{-1} (single harvest) or 15-20 t ha^{-1} (double-harvest, but this can reduce the life span of the crop (Oleszek *et al*., 2013).

Silphium should be harvested when the dry matter content is 26-28% (Hartmann and Lunenberg, 2016). Silphium yields vary from 12.0-25.0 t DM ha^{-1} (Ustak and Munoz, 2018; Zilverberg *et al*., 2016). Single or double harvests of Silphium are possible, potentially increasing yields with the latter (Šiaudinis *et al*., 2012). Methane yields vary between 125-220 dm^3 kg ODM for Sida (Jablonowski *et al*., 2017; Oleszek *et al*., 2013) and 227-315 dm^3 kg ODM for Silphium (Haag *et al.*, 2015; Schittenhelm *et al*., 2016).

Environmental benefits: numerous studies report the use of Sida for phytoremediation. Both Sida and Silphium provide pollen and nectar for pollinators, can increase biodiversity, improve soil structure and water management, increase soil carbon, and decrease chemical inputs.

Other uses: both Sida and Silphium can be used as animal feed. Sida can be used to produce biochars, and as a source of fibre to be used in the pulp and paper, alternative turf, and bio-resin industries. Silphium can be used to manufacture particle boards and to produce a great number of chemical substances valuable for the pharmaceutical and food industries.

In summary, the review highlighted that under appropriate environmental conditions, both crops can provide high biomass yields (for direct combustion or biogas) with relatively low levels of management. There are also research examples of the crops being used for fodder and pharmaceuticals, or as a means of phytoremediating contaminated soils. Potential research areas included methods to reduce high planting costs, the response of yields to drought, the vulnerability of Sida to *Sclerotinia sclerotiorum*, how the crops perform outside of Germany and Poland, and the economics of the two crops.

Contribution to knowledge: the research in relation to Objective 1 has synthesised existing knowledge, bringing together previously unrelated facts, and significantly revising older views on the cultivation and energy production of Sida and Silphium. This work has been published as an open access peer-reviewed journal paper.

8.2 Soil carbon

Objective 2: the second objective was to determine the impact of establishment of Sida and Silphium on soil carbon. This was addressed by a series of field measurements at an experimental site on the Cranfield University Farm, at Silsoe in Bedfordshire, that had previously been grassland. Measurements of bulk density, and organic and total carbon concentrations were taken at 0-5 cm and 10-15 cm in March 2017 prior to the establishment of the crops, and again in 2020, three years after planting.

Main findings: in 2017, prior to cultivation, the bulk density at 0-5 cm was 1.40 g cm^{-3}, lower than that at a depth of 10-15 cm, which was 1.72 g cm^{-3}. After three years of the establishment and cultivation of Sida and Silphium (in 2020), the mean bulk density at both 0-5 cm and 10-15 cm was 1.42 g cm^{-3}.

The land available to establish the plantation was covered by grass before the start of the experiment, a ground cover which is associated with high levels of soil carbon. Comparing the soil carbon concentration in 2017 to the soil carbon concentration in 2020, we observed a reduction in soil carbon levels between both data sets. This reduction is a consequence of the change in land-use from grassland to cropland, change that entailed an initial decrease in the soil carbon as indicated by the results.

Regarding the levels of total and organic soil carbon, both decreased from the start to the end of the experiment. In 2017, prior to cultivation, total carbon in the soil was 69.2 t ha^{-1} and soil organic carbon was 64.7-67.3 t ha^{-1} (at 0-20 cm). After three years of the establishment and cultivation of Sida and Silphium, in 2020, mean soil total carbon decreased to 56.8 t ha^{-1} and soil organic carbon decreased to 54.3-57.0 t ha^{-1}.

SOC was highest in the control area (grass) both prior to the establishment operations and after three years of establishment. The organic carbon concentration in this area was reduced after ploughing the field but recovered at a quicker pace than areas where Sida and Silphium were grown. We conclude that a period longer than three years is required to determine the organic carbon storage abilities of Sida and Silphium.

Contribution to knowledge: the research in relation to Objective 3 has applied existing knowledge to new situations in respect of using the fixed mass approach to calculate the SOC stocks in the soil underneath Sida and Silphium plantations. New knowledge has been developed comparing the changes in bulk density and soil carbon between a grass control and a Sida and Silphium plantation. Chapter 3 will be submitted to a peer-reviewed journal.

8.3 Survival, development and growth

Objective 3: the third objective was to determine the survival, development, and growth of Sida and Silphium, and the effects of using seedlings or transplants. To meet this objective, a field experimental site of Sida and Silphium was established at the Cranfield University farm in Silsoe. All Silphium plants were grown from seed in the greenhouse at the Cranfield campus and then transferred to Silsoe. All Sida plants were grown from seedlings imported from Germany, because all attempts to germinate seeds failed. By summer 2017, the plantation was fully established, and we started recording and measuring the survival, development, and growth of both crops. Monitoring Sida and Silphium was continued throughout the duration of the project, from 2017 to 2020.

Main findings: the experiment demonstrated that it was possible to establish a Sida crop under UK conditions using transplants. Having no annual fertilisation and zero maintenance, the mean yields (in the winter if used for combustion) using transplants varied from 1.7 t DM ha^{-1} in year 1, to 5.4 t DM ha^{-1} in year 2, to 3.7 t DM ha^{-1} in year 3. The mean yields from transplants, if harvested in the summer for biogas (with no annual fertilisation and zero maintenance), were higher: 10.8 t DM ha^{-1} in year 1, 8.1 t DM ha^{-1} in year 2, and 6.0 t DM ha^{-1} in year 3. The higher summer yields were due to the additional harvest of the leaves.

The establishment of Sida from seeds in the field was unsuccessful. Possible reasons for this include the poor germination rate of the seed, or poor field conditions for establishment. The observed reductions in Sida transplant yields with time from planting include the presence of *S. sclerotiorum*, a lack of fertilisation, and increasing weed competition.

Under UK weather and the specific growing conditions of this study (no annual fertilisation and zero maintenance), the experiment demonstrated that the establishment of Silphium via seeds or seedlings are both viable options. Silphium plants produced green biomass yields for biogas of 4.0-5.1 t DM ha^{-1} in year 1, 6.1-7.2 t DM ha^{-1} in year 2, 8.4-9.4 t DM ha^{-1} t DM ha^{-1} in year 3.

Contribution to knowledge: the research in relation to Objective 3 developed new knowledge and applied existing knowledge to new situations. This was done in relation to the establishment, growth, development, and biomass yields of Sida and Silphium in the UK, where they had not been grown or measured before. Chapter 4 will be submitted to a peer-reviewed journal.

8.4 Predicted profitability

Objective 4: the fourth objective was to determine the profitability of Sida and Silphium against other potential crops. To meet this objective, a financial model based on the Net Present Value (NPV) approach was developed using Excel. The model compared the economics of the establishment and cultivation of Sida and Silphium with an arable rotation, and other energy crops (SRC and Miscanthus), for a rotation of 16 years. The resulting economic model was further adapted to the three other participating countries of the SidaTim project (Italy, Germany, and Poland).

Main findings: based on stated assumptions and without subsidies, Silphium was the most profitable option in the UK, followed by Miscanthus, the arable rotation, and SRC, whilst the profitability of Sida was negative. In Italy, SRC was the most profitable and only option with a positive NPV. In Germany, Silphium was the most profitable, followed by Miscanthus, and SRC, whilst both Sida and the arable rotation had negative NPVs. In Poland, Silphium was again the most profitable option, followed by SRC, whilst Miscanthus, Sida, and the arable rotation had negative NPVs. When subsidies were included in the analysis, the profitability of all crops increased accordingly, turning most unprofitable options into profitable ones, except for the case of Sida in Italy and Poland,

and Miscanthus in Poland. The profitability of Miscanthus in Poland was extremely negative because of the high establishment costs. The profitability of the arable rotation varied between countries, reflecting the differences in productivity, prices and costs.

The analysis suggests that given the assumptions made regarding input prices and costs in the United Kingdom, Italy, Germany, and Poland, Silphium could on the whole provide a profitable and viable alternative to conventional arable and energy crops to strengthen and support the bioeconomy. For Sida to be a profitable and viable crop, yields need to be above 12 t DM ha^{-1} and would greatly benefit from establishment grants or improved reliability in seed technology. Whilst the sensitivity analysis of NPVs includes forage maize to facilitate comparisons, in practice the continuous production of forage maize is not possible; it needs to be grown in a rotation to reduce the build-up of pests, and to maintain soil health. Assuming a generalised and hypothetical rotation of the arable crops in equal proportions over time, the results showed that Silphium could provide a highly competitive alternative to an arable rotation and to other energy crops in the United Kingdom, Italy, Germany, and Poland. Sida was less profitable than other options.

Sensitivity analysis and the shift in values to hit NPV of the most profitable arable and energy crop suggested that, on the basis of the assumptions made, both Sida and Silphium were profitable (with subsidies), and that large decreases in prices and increases in costs would be needed for the crop to show a negative financial return. Sida was generally outperformed by other crops in each of the four countries. In the UK, Silphium was less profitable than the forage and the arable rotation but outperformed the SRC and Miscanthus under favourable conditions. In Italy and Germany, Silphium was highly profitable and performed at a level that made it attractive as an alternative to an arable rotation and other energy crops. In Poland, the results showed that Silphium was generally less profitable than forage maize, but it outperformed the arable rotations and most of the other energy crop options.

The current study is based on the assumption that energy crops produce a stable yield throughout their mature life. In reality, this may not be the case because perennial plantations can lose some of their productivity over the years, or may be damaged by wildfires, major pest or diseases, or by deer. With the occurrence of such events, profitability will also be reduced in line with the extent of the damage. The cost of replacing plants in the damaged areas and treatments should therefore be taken into consideration.

Contribution to knowledge: the research in relation to Objective 4 developed new knowledge and applied existing knowledge to new situations by developing a cost benefit analysis of Sida and Silphium. This was the first time the economics of Sida and Silphium were compared with other energy and arable crops in the UK, Italy, Poland, and Germany. Chapter 6 will be submitted to a peer-reviewed journal.

8.5 Greenhouse gas emissions

Objective 5: the fifth objective was to determine (the environmental economic performance of selected) potential environmental services. To meet this objective, a greenhouse gas emissions (GHG) model based on the IPCC guidelines for National Greenhouse Gas Inventories was developed using Excel. The GHG model compared the GHG emissions associated with the establishment and 16 years cultivation of Sida and Silphium with an arable rotation and other energy crops (SRC and Miscanthus).

Main findings: the GHG emissions model of the establishment and cultivation of Sida and Silphium suggests that their emissions are akin to the emissions from other perennial systems. Carbon dioxide emissions from the arable rotation were equivalent to 0.6 t CO_2 ha^{-1} y^{-1}. All four perennial systems removed CO_2 from the atmosphere, fixing 2.5, 0.4, 6.8 and 3.5 t of CO_2 ha^{-1} y^{-1} respectively for SRC, Miscanthus, Sida and Silphium. Methane emissions during the 16 years of cultivation from all five systems are very limited, ranging between 0.03 t CO_2 eq ha^{-1} and 0.01 t CO_2 eq ha^{-1}. Nitrous oxide emissions during the 16 rotation were highest from the arable rotation (58.6 t CO_2 eq ha^{-1}) and lowest from Miscanthus (41.3 t CO_2 eq ha^{-1}). The balance of emissions was positive for the arable rotation, SRC and Miscanthus (4.2, 0.3, 2.2 t CO_2 eq ha^{-1} y^{-1}) and negative for Sida and Silphium (-4.0 and -0.6 t CO_2 eq ha^{-1} y^{-1}).

Contribution to knowledge: the research in relation to Objective 5 has discovered new knowledge, applied existing knowledge to new situations, and developed a new theory or design. Here, the GHG balance associated with the inputs, and operations associated with growing Sida and Silphium to the farm gate were calculated in a UK case study, which had not previously been done. Chapter 7 will be developed and submitted to a peer-review journal.

8.6 Recommendations for future research

After the extensive literature review and the work carried out over a period of four years, there are a number of areas where we have identified that further research could benefit the adoption and promote deployment of Sida and Silphium. These include research areas linked to: i) time scale, ii) organic carbon, iii) growth in the UK, iv) farm level, v) animal feed, vi) alley cropping, vii) GHG emissions, viii) Life Cycle Assessment, ix) policy.

Time scale: Generally, research projects last for 2-3 years. Experiments lasting for longer are rare due to funding constraints, but they are crucial to providing evidence of the long-term productivity of perennial crops and their effect on the environment. Three specific long-term questions are:

- How do the levels of organic carbon under Sida and Silphium develop after the initial establishment period? Do they attain the levels found under grassland?
- How will the plants cope under the pressure of competing weeds and diseases (*S. sclerotiorum*) without any treatment?
- How will the yield of Sida and Silphium change with time in the UK, under no fertilisation compared to optimum fertilisation?

Organic carbon: The experimental results showed that establishing Sida and Silphium through the cultivation of previous grassland led to a decline in the SOC levels three years after the planting. The process of cultivation is also the potential reason why the bulk densities at 0-5 cm and 10-15 cm were different before cultivation in 2017, but similar to each other in 2020. Soil organic carbon levels depend on the balance between organic inputs and outputs, and it may take many years before a perennial crop produces sufficient biomass (in excess of that harvested), which exceeds the balance produced by a grass crop, to result in higher soil organic carbon level. If the purpose of Sida and Silphium is to minimise greenhouse gas emission, then it is important that any reductions in soil carbon during establishment are minimised. The study in this PhD was conducted on a previously grassland site, and one further recommendation for future research is to compare the changes of carbon content in the soil under an arable rotation with the soil under a mature Sida/Silphium plantation, with a space between sampling times of at least 5 years. Because the soil organic carbon content of arable land is generally lower than that of grassland, the carbon benefits of growing Sida and Silphium on a previously arable area is likely to be greater than that on a grassland area.

Growth in the UK: The relatively high yield of Sida obtained for biogas in the 2nd year in the current experiment (10.7-10.8 t DM ha^{-1}) suggests that the UK could present favourable conditions for the cultivation of Sida. However, the significant yield decrease in subsequent years associated with plant mortality and low inputs indicates that this species requires moderate to high levels of management to maintain high yields. To confirm the performance of Sida in the UK, the existing experiment should be continued with a higher level of nutrient input and weed control. There is also a need to control the level of *S. sclerotiorum*.

In the case of Silphium, the yields obtained in the current experiment indicate that this species has potential for the production of biogas in the UK, which could be maximised given appropriate fertilisation and maintenance. A continuation of the existing experiment would determine the longevity of Silphium yields, under UK conditions.

Farm level (other environmental benefits): Both Sida and Silphium produce pollen and nectar for an extended window during summer, supporting pollinators. This is an important function from a biodiversity perspective and a potential source of income in the form of honey.

Compared to arable crop production, Sida and Silphium could offer environmental benefits in terms of reducing soil erosion due to the reduction of cultivation, also allowing the reduced use of chemical inputs and therefore reducing nitrogen leaching. The potential environmental benefits suggest that it would be appropriate to establish small pilot areas of Sida and Silphium within actual pioneer farms, perhaps in field margins set aside to deliver environmental benefits.

Having compiled the potential environmental benefits of Sida and Silphium, there is scope for others to value such environmental benefits in a whole system economic analysis.

Animal feed: There is genuine interest by farmers to grow Sida and Silphium to produce animal feed. Methods to increase the level and diversity of UK-produced animal feed and to reduce expensive imports is of particular interest (Podger, 2021). Again it would be appropriate for interested farmers to establish small pilot areas of Sida and Silphium on actual farms, and investigate the potential of Sida and Silphium as a possible source of feed for animals.

Alley cropping: The UK government currently has an ambitious tree planting programme, seeking to expand tree cover by about 30,000 ha per year. Studies in Northern Ireland have investigated the effect of growing short rotation coppice with timber species *(Lunny et al.*, 2015). Theoretically, Sida and Silphium could also be grown in rows alongside newly planted trees, in an agroforestry system. This could be a way of farmers continuing to secure annual crop and income from an area of tree planting, whilst also enhancing biodiversity. Further research could investigate how well trees, Sida, and Silphium grow when managed as an integral system.

GHG emissions: Experimental data of the greenhouse gas emissions associated with the establishment and cultivation of Sida and Silphium would assist to refining the results from the present study. Further experimental research is needed to provide this kind of experimental data from long-term field experiments.

One way of reducing nitrous oxide emissions is to reduce application of nitrogen fertiliser. This may not be feasible for an arable rotation, but it is possible for perennial systems. In the current study we assumed an annual fertilisation regime, to maximise biomass production, but what if that was not the main aim of their cultivation? We propose re-defining the purpose of perennial plantations in general, and of Sida and Silphium in particular; they are crops that could be grown with the objective of removing carbon dioxide from the atmosphere. If that was the main purpose of growing perennial crops, a reward system should be implemented to pay farmers for offsetting carbon dioxide emissions, as well as providing a wide range of other ecosystem services. In this context, any revenues derived from the production of energy would be additional income.

Life Cycle Assessment: Here, a model was developed to calculate the GHG emissions associated with the establishment and cultivation of Sida and Silphium. Further research is needed to develop a full life cycle assessment of Sida and Silphium. Such a study would provide a more complete picture of the environmental footprint associated with the production of Sida and Silphium crops, which could then be compared with arable and other energy crops.

Policy: If farmers are to invest in novel crops such as Sida and Silphium to support the development of a bioeconomy and a bioenergy sector, they need to feel that there is a reliable and assured demand for the crop outputs. As outlined in Chapter 1, several factors are crucial; reliable information, suitable policies, low investment risk, facilitating infrastructure, a reliable market, and a comparable or greater profitability. Most countries are lacking one or several of these factors, hence the need for policy support. Energy markets are currently too unpredictable to allow for long-term and low risk investment. One way of guaranteeing and securing biomass prices externally could be through long-term contacts with energy providers. If direct funding is not possible, alternatives to promote competitiveness such as carbon taxes on fossil fuels, mandatory co-firing, or monetization of ecosystem services could be put into place (Witzel and Finger, 2016).

In conclusion, research in the above mentioned areas would contribute to increase the adoption and promoting the deployment of perennial bioenergy crops like Sida and Silphium, which would in turn increase the availability of locally produced biomass feedstocks, supporting rural economies and the development of the bioeconomy. It would also contribute to farmers income diversification, due to the additional products that can be generated from Sida and Silphium (see section 3.6 Alternative uses). Furthermore, it would increase in-farm biodiversity and bring additional environmental benefits as highlighted in section 3.7 Environmental benefits.

9 CONCLUSIONS

Sida and Silphium are two novel bioenergy crops with great potential in European countries, particularly in countries such as the UK with a humid and mild climate where growth is not limited by a continued draught throughout summer. In addition, as shown in the review of literature, there are a number of other possible financial uses and environmental benefits associated with Sida and Silphium, that could make them both valuable and useful crops within a European bioeconomy. The extent to which these benefits are realised will depend on a combination of effective policy support, secure access to markets, reliable profitability, and confidence in the agronomy of both crops.

The research presented here showed that from a practical perspective, there are certain management challenges to successfully establishing Sida and Silphium that need to be considered, such as mechanical weed control during establishment, avoiding areas where *Sclerotinia sclerotiorum* is present (if possible), and treating the soil against it prior to establishment if avoidance is not possible.

Sida and Silphium can grow without annual fertilisation but their yields are reduced. Biomass yields will be substantially increased if the correct fertilisation rates are used each year. It is possible to harvest both Sida and Silphium to produce solid fuel for combustion and green biomass for anaerobic digestion. However, Silphium tends to be grown almost exclusively to produce green biomass for biogas production. Both crops can be harvested twice, potentially maximising yields in the same year but weakening the plants and decreasing the yields in the long-term. Therefore single harvesting of Sida and Silphium are recommended. To produce solid fuel for combustion, Sida is better harvested at the end of winter, corresponding to late February or early March in the UK. To produce green biomass for anaerobic digestion the optimum time to harvest Sida is at the flowering stage (BBCH 51) and Silphium when the dry matter content is about 30%. However, considering the great number of flowers supporting pollinators, we recommend harvesting for green biomass at the end of the flowering period, allowing butterflies, bees, bumblebees and, multiple other species of flies and insects to benefit from their pollen and nectar.

Sida and Silphium have the potential to increase carbon in the soil, particularly when organic fertilisers are applied. The use of organic fertilisers should be promoted because they are more sustainable and can trigger this sort of benefit. However, long-term studies are needed to determine the effects of growing Sida and Silphium on soil organic carbon. Here, Sida and Silphium were established on land that had been previously under grass. However, a more relevant comparison would be to determine the soil carbon effect of Sida and Silphium on previously arable land to see how it would compare with maize and barley being used for biomass production, or with conventional arable rotations.

From an economic perspective, Sida is not currently a competitive option in the UK, due to the high cost of establishment associated with the production or purchase of the seedlings, that are needed to ensure successful stand establishment. The planting of seedlings is relatively costly. If the seed technology was developed to provide reliable establishment of Sida via sowing, this would cut down costs, raising the profitability of Sida. Silphium, because it can be established reliably from seed, is currently a viable and profitable option for the UK. The results of the economic modelling showed that was competitive with high-revenue arable crops and other energy crops.

The results from Poland, Italy, and Germany showed broadly similar results, with the Silphium providing competitive levels of profitability in comparison with existing arable and energy crop options, whilst Sida, due to high establishment costs, was less competitive in Germany than Silphium and other existing options, and unprofitable in Italy and Poland.

Both Sida and Silphium can sequester CO_2 and therefore can be used to help reduce concentrations of atmospheric CO_2. However, at least to begin with, some support is needed to help develop this potential. This could be in the form of a carbon strategy for farmers that would support them to use the carbon sequestering properties of Sida and Silphium.

The results from the current study can help both farmers with the selection of their crops and decisions regarding their agricultural business, as well as policy makers contributing to reforms to existing policies or strategies or towards drawing up new policies or strategies. Further research should be focussing on: long-term Sida and Silphium experimental trials; experimental trials under optimum levels of management and fertilisation to determine rotation yields of Sida and Silphium in the UK; measuring soil organic carbon differences between arable and mature Sida and Silphium plantations over a minimum of 5 years; valuation of ecosystem services and complete economic analysis at the farm level; the use of Sida and Silphium as alternative animal feed to imported soya protein; alley-cropping of Sida and Silphium within agroforestry set-ups; experimental GHG emissions data obtained during long-term cultivation of Sida and Silphium; complete life cycle assessment of the establishment and cultivation of Sida and Silphium; ways of assuring crop demand for farmers.

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APPENDICES

Appendix A - Preliminary soil test

	
Sample 1 (IMG_4828)	Sample 2 (IMG_4792)
	
Sample 3 (IMG_4793)	Sample 4 (IMG_4794)
	
Sample 5 (IMG_4795)	Sample 6 (IMG_4796)

Sample 7 (IMG_4797)

Sample 8 (IMG_4798)

Sample 9 (IMG_4799)

Sample 10 (IMG_4800)

Sample (IMG_4802)

Sample 10 (IMG_4803)

Sample 11 (IMG_4804)

Sample 12 (IMG_4805)

	
Sample 13 (IMG_4806)	Sample 14 (IMG_4808)
	
Sample 15 (IMG_4809)	Sample 16 (IMG_4810)
	
Sample 17 (IMG_4811)	Sample 18 (IMG_ 4812)
	
Sample 19 (IMG_4813)	Sample 20 (IMG_4814)

	
Sample 21 (IMG_4815)	Sample 22 (IMG_4816)
	
Sample 23 (IMG_4817)	Sample 24 (IMG_4818)
	
Sample 25 (IMG_4819)	Sample 26 (IMG_4820)
	
Sample 27 (IMG_4821)	Sample 28 (IMG_4822)

	
Sample 29 (IMG_4823)	Sample 30 (IMG_4824)

Figure A.1 - Pictures taken during preliminary soil test for each sample.

	
Ribbon 1 (IMG_4801)	Ribbon 2 (IMG_4807)

Figure A.2 – Ribbon made of soil.

Appendix B - Two Novel Energy Crops: *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. – State of Knowledge

B.1 Reviewed documents

B.1.1 List of documents reviewed for *Sida hermaphrodita*

Table B.1 – Documents reviewed for *Sida hermaphrodita* (L.) Rusby.

Author	Title	Year
Tilvikiene, V., Kadziuliene, Z., Liaudanskiene, I., Zvicevicius, E., Cerniauskiene, Z., Cipliene, A., Raila, A. J., Baltrusaitis, J.	The quality and energy potential of introduced energy crops in northern part of temperate climate zone	2020
Khanh-Quang, T., Werle, S., Trinh, T. T., Magdziarz, A. Sobek, S., Pogrzeba, M.	Fuel characterization and thermal degradation kinetics of biomass from phytoremediation plants	2020
Kisielewska, M., Rusanowska, P., Dudek, M., Nowicka, A., Krzywik, A., Dębowski, M., Kazimierowicz, J., Zieliński, M.	Evaluation of ultrasound pretreatment for enhanced anaerobic digestion of *Sida hermaphrodita*	2020
Magdziarz, A., Wilk, M., Wądrzyk, M.	Pyrolysis of hydrochar derived from biomass—Experimental investigation	2020
Śliz, M., Wilk, M.	A comprehensive investigation of hydrothermal carbonization: Energy potential of hydrochar derived from Virginia mallow	2020
Lewtak, K., Fiołka, M.J., Czaplewska, P., Macur, K., Kaczyński, Z., Buchwald, T., Szczuka, E., Rzymowska, J.	*Sida hermaphrodita* seeds as the source of anti—*Candida albicans* activity	2019
Purwin, C., Gugołek, A., Strychalski, J., Fijałkowska, M.	Productivity, nutrient digestibility, nitrogen retention, and meat quality in rabbits fed diets supplemented with *Sida hermaphrodita*	2019
Bernat, P., Nesme, J., Paraszkiewicz, K., Schloter, M., Płaza, G.	Characterization of extracellular biosurfactants expressed by a *Pseudomonas putida* strain isolated from the interior of healthy roots from *Sida hermaphrodita* grown in a heavy metal contaminated soil	2019
Feledyn-Szewczyk, B., Matyka, M., Staniak, M.	Comparison of the effect of perennial energy crops and agricultural crops on weed flora diversity	2019
Jankowski, K.J., Dubis, B., Sokólski, M.M., Załuski, D., Bórawski, P., Szempliński, W.	Biomass yield and energy balance of Virginia fanpetals in different production technologies in north-eastern Poland	2019
Szwaja, S., Magdziarz, A., Zajemska, M., Poskart, A.	A torrefaction of *Sida hermaphrodita* to improve fuel properties. Advanced analysis of torrefied products	2019
Siwek, H., Włodarczyk, M., Mozdzer, E., Bury, M., Kitczak, T.	Chemical composition and biogas formation potential of *Sida hermaphrodita* and *Silphium perfoliatum*	2019
Zieliński, M., Kisielewska, M., Dudek, M., Rusanowska, P., Nowicka, A., Krzemieniewski, M., Kazimierowicz, J., Dębowski, M.	Comparison of microwave thermohydrolysis and liquid hot water pretreatment of energy crop *Sida hermaphrodita* for enhanced methane production	2019
Stolarski, M.J., Krzyżaniak, M., Warmiński, K., Olba-Zięty, E., Penni, D., Bordiean, A.	Energy efficiency indices for lignocellulosic biomass production: Short rotation coppices versus grasses and other herbaceous crops	2019

Saletnik, B., Bajcar, M., Zaguła, G., Saletnik, A., Tarapatskyy, M., Puchalski, C.	Biochar as a stimulator for germination capacity in seeds of Virginia mallow (*Sida hermaphrodita* (L.) Rusby)	2019
Nowicka, A., Zieliński, M., Dębowski, M., Dudek, M., Rusanowska, P.	Progress in the production of biogas from Virginia mallow after alkaline-heat pretreatment	2019
Szwaja, S., Poskart, A., Zajemska, M.	A new approach for evaluating biochar quality from Virginia mallow biomass thermal processing	2019
von Gehren, P., Gansberger, M., Pichler, W., Weigl, M., Feldmeier, S., Wopienka, E., Bochmann, G.	A practical field trial to assess the potential of *Sida hermaphrodita* as a versatile, perennial bioenergy crop for Central Europe	2019
Zielinski, M., Rusanowska, P., Krzywik, A., Dudek, M., Nowicka, A., Ebowski, M.D.	Application of hydrodynamic cavitation for improving methane fermentation of *Sida hermaphrodita* silage	2019
Schonhoff, A., Zapp, P., Schreiber, A., Jablonowski, N.D.	Environmental evaluation and comparison of process chains for the production and use of *Sida hermaphrodita* as a solid biofuel	2019
Bury, M., Facciotto, G., Chiocchini, F., Cumplido-Marín, L., Graves, A., Kitczak, T., Martens, R., Morhart, C., Możdżer, E., Nahm, M., Paris, P., Siwek, H., Włodarczyk, M., Burgess, P., Kahle, H.-P.	Preliminary results regarding yields of Virginia mallow (*Sida hermaphrodita* (L.) Rusby) and cup plant (*Silphium perfoliatum* L.) in different condition of Europe	2019
Antoszkiewicz, Z., Fijałkowska, M., Mazur-Kuśnirek, M., Przemieniecki, S., Purwin, C.	Effect of a harvest date and cutting height on the concentrations of carotenoids and tocopherols in Virginia fanpetals (*Sida hermaphrodita*) herbage and silage	2019
Werle, S., Tran, K.-Q., Magdziarz, A., Sobek, S., Pogrzeba, M., Løvås, T.	Energy crops for sustainable phytoremediation—Fuel characterization	2019
Kawecki, B., Podgórski, J., Głowacka, A.	Methods for determining elastic modulus in natural plant stems	2019
Trinh, T.T., Werle, S., Tran, K.-Q., Magdziarz, A., Sobek, S., Pogrzeba, M.	Energy crops for sustainable phytoremediation—Thermal decomposition kinetics	2019
Molas, R., Borkowska, H., Kupczyk, A., Osiak, J.	Virginia fanpetals (*Sida*) biomass can be used to produce high-quality bioenergy	2019
Streikus, D., Jasinskas, A., Šarauskis, E., Romaneckas, K., Marks, M.	Technological-technical and environmental evaluation of herbaceous plant usage for the production and burning of granulated biofuel	2019
Antonkiewicz, J., Kołodziej, B., Bielińska, E.J., Gleń-Karolczyk, K.	Research on the uptake and use of trace elements from municipal sewage sludge by multiflora rose and Virginia fanpetals	2019
Tilvikiene V., Kadziuliene Z., Liaudanskiene I., Zvicevicius E., Cerniauskiene Z., Cipliene A., Raila A.J., Baltrusaitis J.	The quality and energy potential of introduced energy crops in northern part of temperate climate zone	2019
Bilandžija, N., Krička, T., Matin, A., Leto, J., Grubor, M.	Effect of harvest season on the fuel properties of *Sida hermaphrodita* (L.) Rusby biomass as solid biofuel	2018
Pogrzeba, M., Krzyżak, J., Rusinowski, S., Werle, S., Hebner, A., Milandru, A.	Case study on phytoremediation driven energy crop production using *Sida hermaphrodita*	2018
Zachar, M., Lieskovský, M., Majlingová, A., Mitterová, I.	Comparison of thermal properties of the fast-growing tree species and energy crop species to be used as a renewable and energy-efficient resource	2018
Nabel, M., Schrey, S.D., Poorter, H., Koller, R., Nagel, K.A., Temperton, V.M., Dietrich, C.C., Briese, C., Jablonowski, N.D.	Coming late for dinner: Localized digestate depot fertilization for extensive cultivation of marginal soil with *Sida hermaphrodita*	2018
Nabel, M., Schrey, S.D., Temperton, V.M., Harrison, L., Jablonowski, N.D.	Legume intercropping with the bioenergy crop *Sida hermaphrodita* on marginal soil	2018

Kurucz, E., Fári, M.G., Antal, G., Gabnai, Z., Popp, J., Bai, A.	Opportunities for the production and economics of Virginia fanpetals (*Sida hermaphrodita*)	2018
Nahm, M., Morhart, C.	Virginia mallow (*Sida hermaphrodita* (L.) Rusby) as perennial multipurpose crop: biomass yields, energetic valorization, utilization potentials, and management perspectives	2018
Facciotto, G., Bury, M., Chiocchini, F., Marín, L.C., Czyż, H., Graves, A., Kitczak, T., Martens, R., Morhart, C., Paris, P., Nahm, M.	Performance of *Sida hermaphrodita* and *Silphium perfoliatum* in Europe: Preliminary results	2018
Stolarski, M. J., Śnieg, M., Krzyżaniak, M., Tworkowski, J., Szczukowski, S., Graban, Ł., Lajszner, W.	Short rotation coppices, grasses and other herbaceous crops: Biomass properties versus 26 genotypes and harvest time	2018
Krzyżaniak, M., Stolarski, M.J., Warmiński, K.	Life cycle assessment of Virginia mallow production with different fertilisation options	2018
Dobrowolski, J.W., Bedla, D., Czech, T., Gambuś, F., Górecka, K., Kiszczak, W., Kuźniar, T., Mazur, R., Nowak, A., Śliwka, M., Tursunov, O., Wagner, A., Wieczorek, J., Zabochnicka-Światek, M.	Integrated innovative biotechnology for optimization of environmental bioprocesses and a green economy	2018
Matyka, M., Kuś, J.	Influence of soil quality for yield and biometric features of *Sida hermaphrodita* (L.) Rusby	2018
Dudek, M., Rusanowska, P., Zieliński, M., Dębowski, M.	Influence of ultrasonic disintegration on efficiency of methane fermentation of *Sida hermaphrodita* silage	2018
Sienkiewicz, S., Wierzbowska, J., Kovacik, P., Krzebietke, S., Zarczynski, P.	Digestate as a substitute of fertilisers in the cultivation of Virginia fanpetals	2018
Zieliński, M., Dębowski, M., Kisielewska, M.	Effectiveness of biogas production from selected energy crops by anaerobic methane digestion supported by microwave radiation [Skuteczność wytwarzania biogazu z wybranych gatunków roślin energetycznych w procesie fermentacji metanowej wspomaganej promieniowaniem mikrofalowym]	2018
Rusanowska, P., Zieliński, M., Dudek, M., Dębowski, M.	Mechanical pretreatment of lignocellulosic biomass for methane fermentation in innovative reactor with cage mixing system	2018
Majlingová, A., Zachar, M., Lieskovský, M., Mitterová, I.	The analysis of mass loss and activation energy of selected fast-growing tree species and energy crops using the Arrhenius equation	2018
Antonkiewicz, J., Kolodziej, B., Bielinska, E.J., Glen-Karolczyk, K.	The use of macroelements from municipal sewage sludge by the multiflora rose and the Virginia fanpetals	2018
Kron, I., Porvaz, P., Kráľová-Hricindová, A., Tóth, Š., Sarvaš, J., Polák, M.	Green harvests of three perennial energy crops and their chemical composition	2017
Nabel, M., Schrey, S.D., Poorter, H., Koller, R., Jablonowski, N.D.	Effects of digestate fertilization on *Sida hermaphrodita*: Boosting biomass yields on marginal soils by increasing soil fertility	2017
Stolarski, M.J., Krzyżaniak, M., Warmiński, K., Tworkowski, J., Szczukowski, S.	Perennial herbaceous crops as a feedstock for energy and industrial purposes: Organic and mineral fertilisers versus biomass yield and efficient nitrogen utilization	2017
Nesme, J., Cania, B., Zadel, U., Schöler, A., Płaza, G.A., Schloter, M.	Complete genome sequences of two plant-associated *Pseudomonas putida* isolates with increased heavy-metal tolerance	2017
Krička, T., Matin, A., Bilandžija, N., Jurišić, V., Antonović, A., Voća, N., Grubor, M.	Biomass valorisation of *Arundo donax* L., *Miscanthus* × *giganteus* and *Sida hermaphrodita* for biofuel production	2017

Fijałkowska, M., Przemieniecki, S.W., Kurowski, T., Lipiński, K., Nogalski, Z., Purwin, C.	Ensiling suitability and microbiological quality of Virginia fanpetals biomass	2017
Dębowski, M., Zieliński, M., Kisielewska, M., Krzemieniewski, M.	Anaerobic co-digestion of the energy crop *Sida hermaphrodita* and microalgae biomass for enhanced biogas production	2017
Damm, T., Pattathil, S., Günl, M., Jablonowski, N.D., O'Neill, M., Grün, K.S., Grande, P.M., Leitner, W., Schurr, U., Usadel, B., Klose, H.	Insights into cell wall structure of *Sida hermaphrodita* and its influence on recalcitrance	2017
Zajac, G., Szyszlak-Barglowicz, J., Slowik, T., Wasilewski, J., Kuranc, A.	Emission characteristics of biomass combustion in a domestic heating boiler fed with wood and Virginia mallow pellets	2017
Werle, S., Bisorca, D., Katelbach-Woźniak, A., Pogrzeba, M., Krzyżak, J., Ratman-Kłosińska, I., Burnete, D.	Phytoremediation as an effective method to remove heavy metals from contaminated area—TG/FT-IR analysis results of the gasification of heavy metal contaminated energy crops	2017
Antonkiewicz, J., Kołodziej, B., Bielińska, E.J.	Phytoextraction of heavy metals from municipal sewage sludge by *Rosa multiflora* and *Sida hermaphrodita*	2017
Jablonowski, N.D., Kollmann, T., Nabel, M., Damm, T., Klose, H., Müller, M., Bläsing, M., Seebold, S., Krafft, S., Kuperjans, I., Dahmen, M., Schurr, U.	Valorization of *Sida* (*Sida hermaphrodita*) biomass for multiple energy purposes	2017
Zieliński, M., Dębowski, M., Rusanowska, P.	Influence of microwave heating on biogas production from *Sida hermaphrodita* silage	2017
von Gehren, P., Gansberger, M.	Investigating the type of dormancy, imbibition and germination of *Sida hermaphrodita* seeds and its practical application in a sowing experiment	2017
Stolarski, M.J., Krzyżaniak, M., Warmiński, K., Tworkowski, J., Szczukowski, S., Olba–Zięty, E., Gołaszewski, J.	Energy efficiency of perennial herbaceous crops production depending on the type of digestate and mineral fertilisers	2017
Zieliński, M., Nowicka, A., Dębowski, M.	Hydrothermal depolymerization of Virginia fanpetals (*Sida hermaphrodita*) biomass with the use of microwave radiation as a potential method for substrate pre-treatment before the process of methane fermentation	2017
Smoliński, A., Howaniec, N.	Chemometric modelling of experimental data on co-gasification of bituminous coal and biomass to hydrogen-rich gas	2017
Uchman, W., Skorek-Osikowska, A., Werle, S.	Evaluation of the potential of the production of electricity and heat using energy crops with phytoremediation features	2017
Urbanovičová, O., Krištof, K., Findura, P., Jobbágy, J., Angelovič, M.	Physical and mechanical properties of briquettes produced from energy plants	2017
Šiaudinis, G., Skuodienė, R., Repšienė, R.	The investigation of three potential energy crops: Common mugwort, cup plant and Virginia mallow on Western Lithuania's Albeluvisol	2017
Werle, S., Ziółkowski, Ł., Bisorca, D., Pogrzeba, M., Krzyzak, J., Milandru, A.	Fixed-bed gasification process—The case of the heavy metal contaminated energy crops	2017
Madej, J., Hilber, I., Bucheli, T.D., Oleszczuk, P.	Biochars with low polycyclic aromatic hydrocarbon concentrations achievable by pyrolysis under high carrier gas flows irrespective of oxygen content or feedstock	2016
Jankowski, K.J., Dubis, B., Budzyński, W.S., Bórawski, P., Bułkowska, K.	Energy efficiency of crops grown for biogas production in a large-scale farm in Poland	2016

Remlein-Starosta, D., Krzymińska, J., Kowalska, J., Bocianowski, J.	Evaluation of yeast-like fungi to protect Virginia mallow (*Sida hermaphrodita*) against *Sclerotinia sclerotiorum*	2016
Nabel, M., Temperton, V.M., Poorter, H., Lücke, A., Jablonowski, N.D.	Energizing marginal soils—The establishment of the energy crop *Sida hermaphrodita* as dependent on digestate fertilization, NPK, and legume intercropping	2016
Pachura, P., Ociepa-Kubicka, A., Skowron-Grabowska, B.	Assessment of the availability of heavy metals to plants based on the translocation index and the bioaccumulation factor	2016
Bedlan, G., Plenk, A.	First report of *Periconia sidae* on *Sida hermaphrodita* in Europe [Erstnachweis von *Periconia sidae* an *Sida hermaphrodita* in Europa]	2016
Bedlan, G.	*Didymella sidae-hermaphroditae* sp. nov., A new pathogen on *Sida hermaphrodita* (L.) Rusby [*Didymella sidae-hermaphroditae* sp. nov., Ein neues pathogen an *Sida hermaphrodita* (L.) Rusby]	2016
Veste, M., Halke, C., Garbe, D., Freese, D.	Effect of nitrogen fertiliser and compost on photosynthesis and growth of Virginia fanpetals (*Sida hermaphrodita* Rusby) [Einfluss von Stickstoffdüngung und Kompost auf Photosynthese und Wachstum der Virginiamalve (*Sida hermaphrodita* Rusby)]	2016
Piotrowski, K., Romanowska-Duda, Z., Grzesik, M.	Cyanobacteria, Asahi SL and biojodis as stimulants improving growth and development of the *Sida hermaphrodita* L. Rusby plant under changing climate conditions [Cyanobacteria, Asahi SL i Biojodis jako biostymulatory poprawiające wzrost i rozwój ślazowca pensylwańskiego w zmieniających się warunkach klimatycznych]	2016
von Gehren, P., Gansberger, M., Pichler, W., Wopienka, E., Montgomery, L.F.R., Mayr, J.	*Sida hermaphrodita* L.—A promising energy crop for producing an intelligent, densified and versatile energy carrier for central Europe	2016
Prelac, M., Bilandžija, N., Zgorelec, Ž.	The phytoremediation potential of heavy metals from soil using Poaceae energy crops: A review [Potencijal fitoremedijacije teških metala iz tla pomoću Poaceae kultura za proizvodnju energije: Pregledni rad]	2016
Wierzbowska, J., Sienkiewicz, S., Krzebietke, S., Sternik, P.	Content of selected heavy metals in soil and in Virginia mallow (*Sida hermaphrodita*) fertilised with sewage sludge	2016
Tilvikiene, V., Liaudanskiene, I., Pociene, L., Kadziuliene, Z.	The biomass potential of non-traditional energy crops in Lithuania	2016
Goryachkovskaya, T., Slynko, N., Golubeva, E., Shekhovtsov, S.V., Nechiporenko, N., Veprev, S., Meshcheryakova, I., Starostin, K., Burmakina, N., Bryanskaya, A., Kolchanov, N., Shumny, V., Peltek, S.E.	"Soranovskii": A new *Miscanthus* cultivar developed in Russia	2016
Kocoń A., Jurga B.	The evaluation of growth and phytoextraction potential of *Miscanthus* × *giganteus* and *Sida hermaphrodita* on soil contaminated simultaneously with Cd, Cu, Ni, Pb, and Zn	2016
Poskart, A., Szwaja, S., Musiał, D.	Torrefaction of Virginia mallow as substitute fuel for domestic boilers [Karbonizat ślazowca pensylwańskiego jako paliwo do kotłów węglowych C.O.]	2016

Hanzhenko, O.	SEEMLA Sustainable exploitation of biomass for bioenergy from marginal lands in Europe: Catalogue for bioenergy crops and their suitability in the categories of MagLs	2016
Šiaudinis, G., Jasinskas, A., Šarauskis, E., Steponavičius, D., Karčauskiene, D., Liaudanskiene, I.	The assessment of Virginia mallow (*Sida hermaphrodita* Rusby) and cup plant (*Silphium perfoliatum* L.) productivity, physico-mechanical properties and energy expenses	2015
Franzaring, J., Holz, I., Kauf, Z., Fangmeier, A.	Responses of the novel bioenergy plant species *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. to CO_2 fertilization at different temperatures and water supply	2015
Michalska, K., Bizukojć, M., Ledakowicz, S.	Pretreatment of energy crops with sodium hydroxide and cellulolytic enzymes to increase biogas production	2015
Pokój, T., Bułkowska, K., Gusiatin, Z.M., Klimiuk, E., Jankowski, K.J.	Semi-continuous anaerobic digestion of different silage crops: VFAs formation, methane yield from fiber and non-fiber components and digestate composition	2015
Goryachkovskaya, T.N., Starostin, K.V., Meshcheryakova, I.A., Slynko, N.M., Peltek, S.E.	Technology of *Miscanthus* biomass saccharification with commercially available enzymes	2015
Bogusz, A., Oleszczuk, P., Dobrowolski, R.	Application of laboratory prepared and commercially available biochars to adsorption of cadmium, copper and zinc ions from water	2015
Gansberger, M., Weinghappel, M., von Gehren, P., Ratzenbock, A., Liebhard, P., Mayr, J.	Seed germination of *Silphium perfoliatum* L. and *Sida hermaphrodita* L., and technological measures for its improvement	2015
Stolarski, M. J., Tworkowski, J., Szczukowski, S., Kwiatkowski, J., Graban, L.	Cost-effectiveness and energy efficiency of the production of Pennsylvanian mallow biomass depending on the seed used [Opłacalność i efektywność energetyczna produkcji biomasy ślazowca pensylwańskiego w zależności od stosowanego materiału siewnego]	2014
Stolarski, M. J., Krzyzaniak, M., Śnieg. M., Słomińska, E., Piórkowski, M., Filipkowski, R.	Thermophysical and chemical properties of perennial energy crops depending on harvest period	2014
Nabel, M., Barbosa, D.B.P., Horsch, D., Jablonowski, N.D.	Energy crop (*Sida hermaphrodita*) fertilization using digestate under marginal soil conditions: A dose-response experiment	2014
Szyszlak-Bargłowicz, J.	Content of chosen macroelements in biomass of Virginia mallow (*Sida hermaphrodita* Rusby) [Zawartość wybranych makroelementów w biomasie ślazowca pensylwańskiego (*Sida hermaphrodita* Rusby)]	2014
Franzaring, J., Schmid, I., Bäuerle, L., Gensheimer, G., Fangmeier, A.	Investigations on plant functional traits, epidermal structures and the ecophysiology of the novel bioenergy species *Sida hermaphrodita* Rusby and *Silphium perfoliatum* L.	2014
Kurucz, E., Antal, G., Gábor, F.M., Popp, J.	Cost-effective mass propagation of Virginia fanpetals (*Sida hermaphrodita* (L.) Rusby) from seeds	2014
Barbosa, D.B.P., Nabel, M., Jablonowski, N.D.	Biogas-digestate as nutrient source for biomass production of *Sida hermaphrodita*, *Zea mays* L. and *Medicago sativa* L.	2014
Packa, D., Kwiatkowski, J., Graban, Ł., Lajszner, W.	Germination and dormancy of *Sida hermaphrodita* seeds	2014

Czyzyk, F., Rajmund, A.	Influence of agricultural utilization of sludge and compost from rural wastewater treatment plant on nitrogen passes in light soil	2014
Emmerling, C.	Impact of land-use change towards perennial energy crops on earthworm population	2014
Michalsk, K., Ledakowicz, S.	Alkaline hydrogen peroxide pretreatment of energy crops for biogas production	2014
Jasinskas, A., Sarauskis, E., Sakalauskas, A., Vaiciukevicius, E., Siaudinis, G., Cekanauskas, S.	Assessment of unconventional tall grasses cultivation and preparation for solid biofuel	2014
Stolarski, M. J., Krzyzaniak, M., Śnieg, M., Słomińska, E., Piórkowski, M., Filipkowski, R.	Thermophysical and chemical properties of perennial energy crops depending on harvest period	2014
Balezentiene, L., Streimikiene, D., Balezentis, T.	Fuzzy decision support methodology for sustainable energy crop selection	2013
Szyszlak-Bargłowicz, J., Słowik, T., Zajac, G., Piekarski, W.	Inline plantation of Virginia mallow (*Sida hermaphrodita* R.) as biological acoustic screen [Pasowe nasadzenia ślazowca pensylwańskiego (*Sida hermaphrodita* R.) jako biologiczny ekran akustyczny]	2013
Borkowska, H., Molas, R.	Yield comparison of four lignocellulosic perennial energy crop species	2013
Oleszek, M., Matyka, M., Lalak, J., Tys, J., Paprota, E.	Characterization of *Sida hermaphrodita* as a feedstock for anaerobic digestion process	2013
Kurucz, E., Fári, M.G.	Improvement of germination capacity of *Sida hermaphrodita* (L.) Rusby by seed priming techniques	2013
Krzywy-Gawrońska, E.	The effect of industrial wastes and municipal sewage sludge compost on the quality of Virginia fanpetals (*Sida hermaphrodita* Rusby) biomass Part 2. Heavy metals content, their uptake dynamics and bioaccumulation	2012
Michalska, K., Miazek, K., Krzystek, L., Ledakowicz, S.	Influence of pretreatment with Fenton's reagent on biogas production and methane yield from lignocellulosic biomass	2012
Dobrowolski, J.W., Śliwka, M., Mazur, R.	Laser biotechnology for more efficient bioremediation, protection of aquatic ecosystems and reclamation of contaminated areas	2012
Voigt, T.B., Lee, D.K., Kling, G.J.	Perennial herbaceous crops with potential for biofuel production in the temperate regions of the USA	2012
Kocoń, A., Matyka, M.	Phytoextractive potential of *Miscanthus giganteus* and *Sida hermaphrodita* growing under moderate pollution of soil with Zn and Pb	2012
Borkowska, H., Molas, R.	Two extremely different crops, *Salix* and *Sida*, as sources of renewable bioenergy	2012
Krzywy-Gawrońska, E.	The effect of industrial wastes and municipal sewage sludge compost on the quality of Virginia fanpetals (*Sida hermaphrodita* Rusby) biomass Part 1. Macroelements content and their uptake dynamics	2012
Pszczó£kowska, A., Romanowska-Duda, Z., Pszczó£Kowski, W., Grzesik, M., Wysokiñska, Z.	Biomass production of selected energy plants: Economic analysis and logistic strategies	2012
Slepetys, J., Kadziuliene, Z., Sarunaite, L., Tilvikiene, V., Kryzeviciene, A.	Biomass potential of plants grown for bioenergy production	2012

Ewa, O.	The effect of fertilization on yielding and heavy metals uptake by maize and Virginia fanpetals (*Sida hermaphrodita*)	2011
Smoliński, A., Howaniec, N., Stańczyk, K.	A comparative experimental study of biomass, lignite and hard coal steam gasification	2011
Howaniec, N., Smoliński, A.	Steam gasification of energy crops of high cultivation potential in Poland to hydrogen-rich gas	2011
Tarkowski, A., Truchliński, J.	Nutritional value of Virginia fanpetals (*Sida hermaphrodita* Rusby) protein in evaluation of nitrogen fertilization effect on environment	2011
Poiša, L., Adamovičs, A., Antipova, L., Šiaudinis, G., Karčauskiene, D., Platače, R., Žukauskaite, A., Maiakauskaite, S., Teirumnieka, E.	The chemical content of different energy crops	2011
Igliński, B., Iglińska, A., Kujawski, W., Buczkowski, R., Cichosz, M.	Bioenergy in Poland	2011
Burczy, H., Mirowski, T., Kalawa, W., Sajdak, W.	Study on biomass trade in Poland	2010
Wielgosz, E.	Effect of selected plant species on enzymatic activity of soil microorganisms [Wpływ zróżnicowanej obsady rooelinnej na aktywność enzymatyczna{ogonek} drobnoustrojów glebowych]	2010
Thompson-Black, M.J.	Assessment and Status Report Virginia mallow *Sida hermaphrodita* in Canada	2010
Borkowska, H., Molas, R., Kupczyk, A.	Virginia fanpetals (*Sida hermaphrodita* Rusby) cultivated on light soil; height of yield and biomass productivity	2009
Tarkowski, A.	The yield and chemical composition of milk of cows fed the ration with protein-fibrous-extruderate [Wydajność i skład chemiczny mleka krow żywionych dawka{ogonek} z ekstruderatem białkowo-włóknistym]	2008
Avula, B., Joshi, V., Wang, Y.-H., Jadhav, A.N., Khan, I.A.	Quantitative determination of ecdysteroids in *Sida rhombifolia* L. and various other *Sida* species using LC-UV, and their anatomical characterization	2008
Borkowska, H.	Virginia mallow and willow coppice yield on good wheat complex soil	2007
Krzaczek, P., Szyszlak, J., Zarajczyk, J.	Assessment of the influence of selected operating parameters of S071/B KRUK seeder on seeding *Sida hermaphrodita* Rusby seeds	2006
Borkowska, H., Wardzińska, K.	Some effects of *Sida hermaphrodita* R. cultivation on sewage sludge	2003
Aguilar, J.F., Fryxell, P.A., Jansen, R.K.	Phylogenetic relationships and classification of the *Sida* generic alliance (Malvaceae) based on nrDNA ITS evidence	2003
Borkowska, H., Jackowska, I., Piotrowski, J., Styk, B.	Suitability of cultivation of some perennial plant species on sewage sludge	2001
Ligai, L.V., Bandyukova, V.A.	Chemical study of *Sida hermaphrodita*	1990
Bandyukova, V.A., Ligai, L.V.	Study of the kinetics of the extraction of flavonoids from plant raw material I. Extraction of rutin from *Sida hermaphrodita*	1987
Spooner, D.M., Cusick, A.W., Hall, G.F., Baskin, J.M.	], Observations on the Distribution and Ecology of *Sida hermaphrodita* (L.) Rusby (Malvaceae)	1985

B.1.2 List of documents reviewed for *Silphium perfoliatum*

Table B.2 – Documents reviewed for *Silphium perfoliatum* L.

Author	Title	Year
von Cossel, M., Amarysti, C., Wilhelm, H., Priya, N., Winkler, B., Hoerner, L.	The replacement of maize (*Zea mays* L.) by cup plant (*Silphium perfoliatum* L.) as biogas substrate and its implications for the energy and material flows of a large biogas plant	2020
Styks, J., Wróbel, M., Fraczek, J., Knapczyk, A.	Effect of compaction pressure and moisture content on quality parameters of perennial biomass pellets	2020
Reinert, S., Hulke, B. S., Prasifka, J. R.	Pest potential of *Neotephritis finalis* (Loew) on *Silphium integrifolium* Michx., *Silphium perfoliatum* L., and interspecific hybrids	2020
Mueller, A.L., Berger, C. A., Schittenhelm, S., Stever-Schoo, B., Dauber, J.	Water availability affects nectar sugar production and insect visitation of the cup plant *Silphium perfoliatum* L. (Asteraceae)	2020
Kowalska, G., Pankiewicz, U., Kowalski, R.	Evaluation of chemical composition of some *Silphium* L. species as alternative raw materials	2020
Guo, Y., Shang, H., Zhao, J., Zhang, H., Chen, S.	Enzyme-assisted extraction of a cup plant (*Silphium perfoliatum* L.) polysaccharide and its antioxidant and hypoglycemic activities	2020
von Cossel, M., Steberl, K., Hartung, J., Pereira, L.A., Kiesel, A., Lewandowski, I.	Methane yield and species diversity dynamics of perennial wild plant mixtures established alone, under cover crop maize (*Zea mays* L.), and after spring barley (*Hordeum vulgare* L.)	2019
Siwek, H., Włodarczyk, M., Mozdzer, E., Bury, M., Kitczak, T.	Chemical composition and biogas formation potential of *Sida hermaphrodita* and *Silphium perfoliatum*	2019
Hryniewicz, M.	Determination of the normalized yield curve of the cup-plant (*Silphium perfoliatum*) according to the nitrogen dose [Wyznaczenie znormalizowanej krzywej plonowania rożnika przerośniętego (*Silphium perfoliatum*) względem dawki azotu]	2019
Chmelíková, L., Wolfrum, S.	Mitigating the biodiversity footprint of energy crops—A case study on arthropod diversity	2019
Oleszek, M., Kowalska, I., Oleszek, W.	Phytochemicals in bioenergy crops	2019
Wever, C., Höller, M., Becker, L., Biertümpfel, A., Köhler, J., van Inghelandt, D., Westhoff, P., Pude, R., Pestsova, E.	Towards high-biomass yielding bioenergy crop *Silphium perfoliatum* L.: phenotypic and genotypic evaluation of five cultivated populations	2019
Du, J., Zhang, L., Ali, A., Li, R., Xiao, R., Guo, D., Liu, X., Zhang, Z., Ren, C., Zhang, Z.	Research on thermal disposal of phytoremediation plant waste: Stability of potentially toxic metals (PTMs) and oxidation resistance of biochars	2019
Bury, M., Facciotto, G., Chiocchini, F., Cumplido-Marín, L., Graves, A., Kitczak, T., Martens, R., Morhart, C., Możdżer, E., Nahm, M., Paris, P., Siwek, H., Włodarczyk, M., Burgess, P., Kahle, H.-P.	Preliminary results regarding yields of Virginia mallow (*Sida hermaphrodita* (L.) Rusby) and cup plant (*Silphium perfoliatum* L.) in different condition of Europe	2019
Mueller, A.L., Biertümpfel, A., Friedritz, L., Power, E.F., Wright, G.A., Dauber, J.	Floral resources provided by the new energy crop, *Silphium perfoliatum* L. (Asteraceae)	2019
Šiaudinis, G., Karčauskienė, D., Aleinikovienė, J.	Assessment of a single application of sewage sludge on the biomass yield of *Silphium perfoliatum* and changes in naturally acid soil properties [Nuotekų dumblo vienkartinio panaudojimo įtaka	2019

	geltonžiedžių legėstų biomasės derliui ir natūraliai rūgštaus dirvožemio savybių kaitai]	
Ruf, T., Audu, V., Holzhauser, K., Emmerling, C.	Bioenergy from periodically waterlogged cropland in Europe: A first assessment of the potential of five perennial energy crops to provide biomass and their interactions with soil	2019
Ustak, S., Munoz, J.	Cup-plant potential for biogas production compared to reference maize in relation to the balance needs of nutrients and some microelements for their cultivation	2018
Ruf, T., Makselon, J., Udelhoven, T., Emmerling, C.	Soil quality indicator response to land-use change from annual to perennial bioenergy cropping systems in Germany	2018
Facciotto, G., Bury, M., Chiocchini, F., Marín, L.C., Czyż, H., Graves, A., Kitczak, T., Martens, R., Morhart, C., Paris, P., Nahm, M.	Performance of *Sida hermaphrodita* and *Silphium perfoliatum* in Europe: Preliminary results	2018
Šimkūnas, A., Denisov, V., Valašinaitė, S., Jankauskienė, R., Ivanauskaitė, A.	From an empirical to conceptual modeling view of energy crop productivity	2018
Schäfer, A., Leder, A., Graff, M., Damerow, L., Lammers, P.S.	Determination and sorting of cup plant seeds to optimize crop establishment	2018
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Shang, H.-M., Zhou, H.-Z., Li, R., Duan, M.-Y., Wu, H.-X., Lou, Y.-J.	Extraction optimization and influences of drying methods on antioxidant activities of polysaccharide from cup plant (*Silphium perfoliatum* L.)	2017
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B.2 Supplementary material

B.2.1 *Sida hermaphrodita* BBCH-code

BBCH-code – *Sida hermaphrodita*: presented in the "Supporting Information" of Jablonowski *et al*. (Jablonowski *et al*., 2017) (https://doi.org/10.1111/gcbb.12346).

B.2.2 *Silphium perfoliatum* BBCH-code

Table B.3 - BBCH— *Silphium perfoliatum* L.: A standard coding for the phenological growth stages of *Silphium perfoliatum* L..

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Silphium perfoliatum BBCH-code	
Germination, sprouting, bud development	
00	S: dry seed (achene) R: winter dormancy or resting period
01	S: beginning of seed imbibition R: beginning of bud swelling
02	S:seed imbibition complete R: end of bud swelling
05	S: radicle emerged from seed
06	S: elongation of radicle, formation of root hairs and/or lateral roots
07	S: hypocotyl with cotyledons merged from seed
08	R: hypocotyl with cotyledons growing towards soil surface
09	Emergence: cotyledons emerge through soil surface
1st year after sowing or planting	
1	**Leaf development (single shoot)**
10	S: cotyledons completely unfolded
11	S: one true leaf
12	S:two true leaves unfolded
13	S: three true leaves
14	S: four true leaves (second pair) unfolded (stages continuous till 18)
19	S: nine or more true leaves
2	**Formation of basal rosette**
21	10% of plants of neighbouring rows strike each other/leaves cover 10% of ground
22	20% of plants of neighbouring rows strike each other/leaves cover 20% of ground
23	30% of plants of neighbouring rows strike each other /leaves cover 30% of ground (stages continuous till 28)
29	90% or more of plants of neighbouring rows strike each other/leaves cover 90% of ground
2nd year after sowing or planting	

1	**Leaf development (single shoot)**	
11	1 pair of oppositely arranged leaves	
12	2 couples of oppositely arranged leaves	
13	3 couples of oppositely arranged leaves	
19	9 or more couples of oppositely arranged leaves	

3	**Stalk development**	
31	10% of final length	
32	20% of final length	
33	30% of final length (stages continuous till 38)	
39	Maximum stem length reached	

5	**Inflorescence emergence**	
51	501	Inflorescence just visible between youngest leaves
53	503	Inflorescence separating from youngest leaves, bracts distinguishable from foliage leaves
55	505	Inflorescence separated from youngest leaves
57	507	Inflorescence clearly separated from youngest leaves
59	509	Golden-yellow ray florets visible between the bracts
	521	Second order stem inflorescence visible
	525	Second order stem inflorescence separated from youngest
	529	First flower formed on secondary inflorescence
	5N1	N*th* order stem inflorescence visible
	5N5	N*th* order stem inflorescence separated from youngest
	5N9	First flower formed on n*th* inflorescence

6	**Flowering**	
61	601	Beginning of flowering: ray florets extended, disc florets visible in outer part of inflorescence
62	602	Disc florets in blooms (stages continuous till 64)
65	605	Full flowering: disc florets in middle part of inflorescence in bloom
67	607	Flowering declining: disc floret in inner part of inflorescence in bloom
69	609	End of flowering: most disc florets finished flowering, ray florets dry or fallen
	621	Ray florets extended and disk florets visible in outer part on secondary inflorescence
	625	Full flowering: disc florets in middle part of inflorescence in bloom on secondary inflorescence
	629	End of flowering: most disc florets have finished flowering, ray florets dry or fallen on secondary inflorescence
	6N1	Ray florets extended and disk florets visible in outer part on *nth* order inflorescence
	6N5	Full flowering: disc florets in middle part of inflorescence in bloom on *nth* order inflorescence
	6N9	End of flowering: most disc florets have finished flowering, ray florets dry or fallen on *nth* order inflorescence

7	**Development of seeds**	
71	701	Seed on the outer edge of the first head have reached the final size
79	709	Seed on the inner edge of the first head have reached the final size
	721	Seed on the outer edge of the secondary head have reached the final size
	729	Seed on the inner edge of the secondary head have reached the final size
	7N1	Seed on the outer edge of the *nth* order head have reached the final size
	7N9	Seed on the inner edge of the *nth* order head have reached the final size
Outer bracts of the head still green seeds of on outer edge ripe and grey		

8	**Ripening or maturity of seed**	
81	801	Outer bracts of first head still green, seeds of on outer edge ripe and grey-brown
82	802	Outer bracts of first head begin to became grey-brown, 20% of seed grey-brown
89	809	Outer bracts of first head completely grey-brown, all seeds ripe and grey-brown
	821	Outer bracts of secondary head still green, seeds of on outer edge ripe and grey-brown
	822	Outer bracts of secondary head begin to became grey-brown, 20% of seed ripe and grey-brown
	829	Outer bracts of secondary heads completely grey-brown, all seeds ripe and grey-brown
	8N1	Outer bracts of *nth* order head still green, seeds of on outer edge ripe and grey-brown
	8N2	Outer bracts of *nth* order head begin to became grey-brown, 20% of seed ripe and grey-brown
	8N9	Outer bracts of *nth* order head completely grey-brown, all seeds ripe and grey-brown

9	**Senescence, beginning of dormancy**
91	Shoot development completed, foliage still green
93	Basal leaf completely dead, caulicle leaves discoloured
95	Majority of leaves are dead
97	All leaves dead
98	Above ground parts dead
99	Plant dead and dry (dry matter more than 80%)

Additional descriptions: S: plant from seed; R: plant from rhizome; C: crop carpet
If the description is valid for all, no additional description is given.

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Appendix C - Effect of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. on soil carbon dynamics

C.1 Soil texture

Table C.1 - Results and calculations from the particle size distribution analysis carried out to characterise the soil.

Sample number		**1**		**2**		**3**
Bottle number		PSD 17		PSD 4		PSD 7
500ml cylinder number		4C		6B		10C
Sieve tower number		6		7		2
Drying tin number		1C		11B		8C
Factor, F (g)		7.7632		8.1668		8.2455
Sieve + sample (g)		88.1946		93.2293		91.5812
Sieve (g)		87.5976		92.579		91.0097
Mass of sample (g)		0.597		0.6503		0.5715
0.6mm - 2mm (%)		**7.69**		**7.96**		**6.93**
Sieve + sample (g)		85.6827		89.5783		87.8938
Sieve (g)		82.3153		86.1796		84.3739
Mass of sample (g)		3.3674		3.3987		3.5199
0.212mm - 0.6mm (%)		**43.38**		**41.62**		**42.69**
Sieve + sample (g)		89.9897		86.7594		88.6133
Sieve (g)		87.6708		84.2415		86.4011
Mass of sample (g)		2.3189		2.5179		2.2122
0.063mm - 0.212mm (%)		**29.87**		**30.83**		**26.83**
Total mass of sand (S)		6.2833		6.5669		6.3036
Total Sand %		**80.94**		**80.41**		**76.45**
Bottle + sample (g)		115.3076		84.947		80.1351
Bottle (g)	18;	115.1712	21E;	84.8046	20D;	79.9756
Mass of sample (g)		0.1364		0.1424		0.1595
0.002mm - 0.063mm (Silt + Clay) (%)		**1.5**		**1.3**		**5.5**
Bottle + sample (g)		81.5144		80.1222		80.1037
Bottle (g)	8D;	81.384	12D;	79.9851	24C;	79.9669
Mass of sample (g)		0.1304		0.1371		0.1368
< 0.002mm (Clay) (%)		**17.52**		**18.29**		**18.04**

C.2 Available nitrogen, phosphorus and potassium analyses

Prior to the establishment of the plantation, the content of available N, P, and K in the soil was obtained in April 2017. The methodology followed for each analysis was in accord with the SOPs provided by Cranfield University. Theses analyses were repeated in March 2020, after 3 years of cultivation.

The available nitrogen followed NAR-SAS / SOP 30, "Determination of ammonium-N, nitrate-N and nitrite-N extracted by potassium chloride" (Cranfield University, 2017). Fresh soil was sieved and the dry matter and water content were determined on a dry-mass basis. To prepare the extracts, 100 ml of 2 mol/l potassium chloride solution was added to each 20 g < 5.6 mm fresh soil sample, then shacked for 2 h at 30 rev, filtered, and kept refrigerated. Then, a blank extraction was carried out. Using an auto-analyser, the amount of nitrate-N and ammonium-N was obtained from the potassium chloride extracts.

The available phosphorus analysis followed NAR-SAS / SOP 15, "Phosphorus soluble in sodium hydrogen carbonate solution", based on British Standard 7755: Section 3.6:1995 (BSI, 1995b). To prepare the extracts, 100 ml of sodium hydrogen carbonate (0.5 mol l^{-1}) were added to each 5 g sample of air-dried soil, shacked for 30 min, and filtered immediately, retaining the filtrate. Then, a blank extraction was carried out.

To prepare the standard graph, 1ml of 1.5 mol l^{-1} sulphuric acid, 20 ml of 0.15% m/v ammonium molybdate and 5 ml of ascorbic acid solution were added to each 5ml phosphorus working standard, swirling in between. The mixture was then allowed to develop colour for 30 min. The absorbance was measured at 880 nm using a spectrophotometer. The graph relating the absorbance to the phosphorus mass was constructed.

To determine the extractable phosphorus, 1 ml of 1.5 mol/l sulphuric acid, 20 ml of 0.15% m/v ammonium molybdate, and 5ml of ascorbic acid solution were added to each 5 ml soil extract, swirling in between. The mixture was then allowed to develop colour for 30 min. The absorbance was measured at 880 nm using a spectrophotometer.

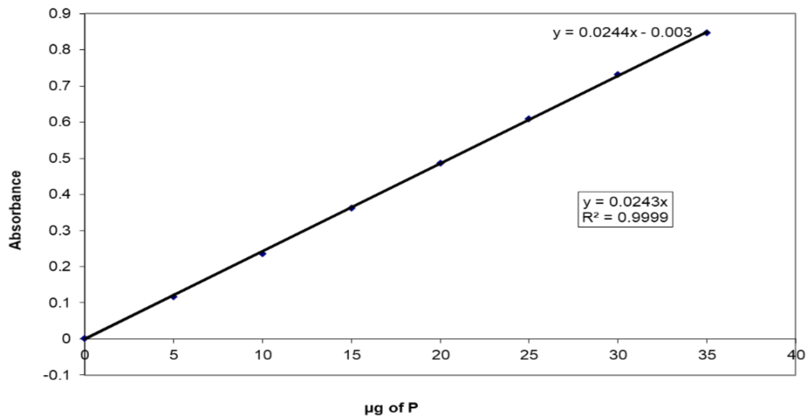
To obtain the amount of soluble phosphorus the following calculations were made. First, the value of phosphorus corresponding to the absorbance was estimated using the absorbance graph. Then the value of the blank was subtracted from the value of each sample, multiplied by a dilution factor of 20, and divided by the sample mass.

The available potassium analysis followed NAR-SAS/SOP 16, “Magnesium and potassium soluble in ammonium nitrate solution”, based on annexes D, E and G of British Standard 3882:1994 (BSI, 1994). To prepare the extracts, 50 ml of 1 mol l^{-1} ammonium nitrate solution were added to each 10 g sample of air-dried soil, shacked for 30 min, and filtered immediately, retaining the filtrate. Then, a blank extraction was carried out. Using the extracts, the calibration curves for potassium were prepared, diluting each 5 ml of extract to 25 ml using 1 mol l^{-1} of ammonium nitrate. The concentration of potassium in the extracts was measured and the amount of potassium was calculated.

Table C.2 - Results from the available nitrate-N and ammonium-N analyses.

Year		**Nitrate-N**		**Ammonium-N**	
	Sample ID	mg/l	mg/kg	mg/l	mg/kg
2017	W1	7.90	39.50	2.30	11.50
	W2	7.90	39.50	2.20	11.00
	W3	7.90	39.50	2.10	10.50
	Average		**39.50**		**11.00**
2020	14a	0.159	4.45	0.214	3.10
	20a	0.315	7.88	0.387	9.68
	21a	0.411	10.28	0.468	11.70
	26a	0.297	7.43	0.381	9.53
	27a	0.196	4.90	0.237	5.93
	31a	0.184	4.60	0.302	7.55
	32a	0.615	15.38	0.621	15.53
	33a	0.241	6.03	0.327	8.18
	Average		**7.60**		**8.90**

2017



2020

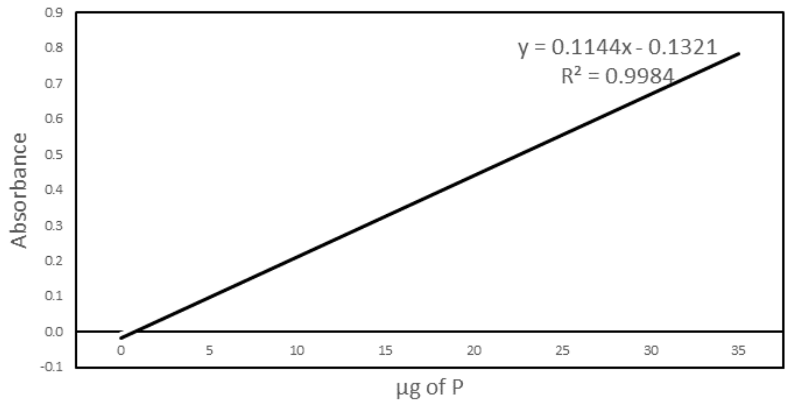


Figure C.1 - Phosphorus absorbance graphs.

Table C.3 - Parameters and results from the available phosphorus analyses.

Year	Blank (Abs.)	Blank (µg P)	Factor	µg of P	Absorbance	Sample ID	Mass of sample (g)	Absorbance	µg P eq.	Dilution factor	Available P (mg/kg)
2017	0.004	0.16	0.0243	0	0.001	W1	5.0	0.593	24.40	1	96.95
				5	0.117	W2	5.0	0.592	24.36	1	96.79
				10	0.236	W3	5.0	0.590	24.28	1	96.46
				15	0.362	**Average**					**96.74**
				20	0.486						
				25	0.609						
				30	0.731						
				35	0.848						
2020	0.004	-0.027	0.1144	0	-0.007	3a	4.99	0.559	4.886	2	39.3
				5	0.081	1a	5.03	0.509	4.449	2	35.8
				10	0.228	2a	5.02	0.523	4.572	2	36.8
				15	0.313	14a	5.07	0.538	4.703	2	37.8
				20	0.435	8a	5.08	0.515	4.502	2	36.2
				25	0.552	7	5.05	0.538	4.703	2	37.8
				30	0.671	12a	5.06	0.555	4.851	2	39.0
				35	0.788	15a	5.03	0.484	4.231	2	34.1
						17a	5.06	0.545	4.764	2	38.3
						Average					**37.25**

Table C.4 - Parameters and results from the available potassium analyses.

Year	mg/l K	K mean (mg/l)	Available K (mg/kg)
2017	Blank	0.33	
	S1	71.16	354.16
	S2	65.63	326.51
	S3	69.51	345.91
	Average		**342.19**
2020	Blank	0.13	
	33a	84.70	422.84
	26a	75.45	376.59
	32a	83.92	418.94
	27a	80.32	400.94
	31a	90.38	451.24
	25a	76.06	379.64
	21a	77.60	387.34
	20a	77.13	384.99
	19a	75.12	374.94
	Average		**399.71**

C.3 Bulk Density

Table C.5 - Bulk density obtained in 2017.

Area	Depth (cm)	Soil Core 1	2	3	4	5	6
1	0-5	1.34	1.33	1.29	1.43	1.39	1.43
	10-15	1.71	1.68	1.72	1.75	1.71	1.74
2	0-5	1.18	1.18	1.23	1.34	1.32	1.61
	10-15	1.73	1.63	1.70	1.64	1.80	1.68
3	0-5	1.36	1.42	1.31	1.44	1.38	1.45
	10-15	1.70	1.76	1.62	1.73	1.69	1.64
4	0-5	1.38	1.50	1.47	1.48	1.50	1.29
	10-15	1.67	1.87	1.72	1.77	1.67	1.71
5	0-5	1.41	1.38	1.54	1.61	1.53	1.57
	10-15	1.72	1.75	1.78	1.76	1.76	1.75

Table C.6 - Bulk density obtained in 2020.

Area	Depth (cm)	Soil Core 1	2	3	4	5	6
1	0-5	1.55	1.47	1.37	1.48	1.49	1.36
	10-15	0.94	1.60	1.63	1.54	1.58	1.57
2	0-5	1.20	1.36	1.38	1.28	1.32	1.35
	10-15	1.33	1.41	1.26	1.30	1.58	1.44
3	0-5	1.37	1.32	1.32	1.32	1.41	1.45
	10-15	1.38	1.26	1.34	1.39	1.43	1.49
4	0-5	1.45	1.55	1.55	1.46	1.44	1.57
	10-15	1.51	1.38	1.49	1.22	1.46	1.64
5	0-5	1.42	1.47	1.46	1.56	1.53	1.37
	10-15	1.60	1.15	1.12	1.54	1.52	1.39

C.4 Soil Carbon

Table C.7 - Organic carbon concentration (%) obtained in 2017.

Area	Depth (cm)	Soil Core 1	2	3	4	5	6	Mean	Std. Dev	Std. Error
1	0-5	2.24	3.00	2.79	2.82	2.48	2.26	2.60	0.32	0.13
	10-15	2.04	1.71	1.75	1.85	2.10	1.87	1.89	0.16	0.06
2	0-5	2.78	3.02	2.69	3.34	2.31	2.25	2.73	0.42	0.17
	10-15	1.82	2.33	1.73	1.96	1.42	1.67	1.82	0.31	0.13
3	0-5	2.71	2.66	3.35	1.90	2.90	2.62	2.69	0.47	0.19
	10-15	1.67	1.73	1.91	1.59	2.22	1.74	1.81	0.23	0.09
4	0-5	3.18	2.66	2.17	2.38	2.46	2.34	2.53	0.35	0.14
	10-15	2.17	1.52	1.78	1.84	1.67	1.79	1.79	0.21	0.09
5	0-5	2.19	2.97	1.79	2.48	2.23	2.36	2.34	0.39	0.16
	10-15	1.70	2.13	2.47	1.83	1.78	1.67	1.93	0.31	0.13

Table C.8 - Total carbon concentration (%) obtained in 2017.

Area	Depth (cm)	Soil Core 1	2	3	4	5	6	Mean	Std. Dev	Std. Error
1	0-5	2.27	3.10	2.94	2.89	2.64	2.27	2.68	0.35	0.14
	10-15	2.12	1.78	1.88	1.89	2.27	1.87	1.97	0.19	0.08
2	0-5	2.88	3.30	2.93	3.34	2.45	2.33	2.87	0.42	0.17
	10-15	2.11	2.50	1.73	2.05	1.42	1.68	1.92	0.38	0.16
3	0-5	2.76	2.90	3.43	1.91	3.07	2.76	2.81	0.50	0.21
	10-15	1.79	1.85	1.97	1.63	2.46	1.84	1.92	0.29	0.12
4	0-5	3.18	2.75	2.18	2.49	2.67	2.34	2.60	0.36	0.14
	10-15	2.23	2.34	1.90	1.91	1.78	1.82	2.00	0.23	0.09
5	0-5	2.67	3.03	1.84	2.73	2.32	2.46	2.51	0.41	0.17
	10-15	1.70	2.22	2.62	1.85	1.86	1.74	2.00	0.36	0.15

Table C.9 - Soil Organic Carbon stock results from 2017 (Mg C/ha), following Ellert *et al*. (2008) methodology.

Area	Soil Core						Mean	Std. Dev	Std. Error
	1	2	3	4	5	6			
1	64.03	68.42	66.09	69.45	68.45	61.81	66.38	2.98	1.22
2	62.40	73.61	60.45	73.48	51.53	56.21	62.95	9.02	3.68
3	63.14	63.84	74.73	51.04	74.35	63.73	65.14	8.75	3.57
4	78.86	62.70	59.16	63.16	61.92	60.81	64.43	7.21	2.94
5	59.97	78.10	66.55	67.59	62.44	62.95	66.27	6.44	2.63

Table C.10 - Organic carbon concentration (%) obtained in 2020.

Area	Depth (cm)	Soil Core						Mean	Std. Dev	Std. Error
		1	2	3	4	5	6			
1	0-5	1.99	1.46	1.62	1.63	1.68	2.07	1.74	0.24	0.10
	10-15	4.61	1.53	1.52	1.26	1.94	1.92	2.13	1.24	0.51
2	0-5	2.67	1.97	1.75	2.23	2.49	1.65	2.13	0.41	0.17
	10-15	2.05	1.63	2.33	2.55	1.65	1.63	1.97	0.40	0.16
3	0-5	1.90	2.03	2.01	1.94	1.99	1.84	1.95	0.07	0.03
	10-15	1.85	2.32	2.17	2.21	2.21	1.92	2.11	0.19	0.08
4	0-5	1.37	1.82	1.87	1.71	1.86	1.67	1.72	0.19	0.08
	10-15	1.71	1.52	1.72	2.90	1.57	1.81	1.87	0.52	0.21
5	0-5	1.72	1.83	1.66	1.56	1.70	2.02	1.75	0.16	0.07
	10-15	2.14	3.55	4.14	1.63	1.76	1.82	2.51	1.07	0.44

Table C.11 - Total carbon concentration (%) obtained in 2020.

Area	Depth (cm)	Soil Core 1	2	3	4	5	6	Mean	Std. Dev	Std. Error
1	0-5	2.18	2.02	1.70	1.74	1.72	2.08	1.91	0.21	0.09
	10-15	4.78	1.56	1.55	1.30	1.94	1.97	2.18	1.30	0.53
2	0-5	2.70	1.98	1.84	2.27	2.55	1.71	2.17	0.40	0.16
	10-15	2.10	1.79	2.61	2.65	1.65	1.69	2.08	0.45	0.18
3	0-5	1.92	2.13	2.02	2.01	1.99	1.85	1.99	0.10	0.04
	10-15	1.91	2.32	2.37	2.26	2.40	1.92	2.20	0.22	0.09
4	0-5	2.09	1.95	1.94	1.72	1.88	1.68	1.88	0.15	0.06
	10-15	1.79	1.68	1.76	2.95	1.58	1.82	1.93	0.51	0.21
5	0-5	1.72	1.83	2.12	1.83	1.76	2.10	1.89	0.17	0.07
	10-15	2.19	3.56	4.16	1.66	1.78	1.88	2.54	1.06	0.43

Table C.12 - Soil Organic Carbon stock results from 2020 (Mg C/ha), following Ellert *et al*. (2008) methodology.

Area	Soil Core 1	2	3	4	5	6	Mean	Std. Dev	Std. Error
1	101.17	45.94	48.09	44.31	55.77	61.05	59.39	21.43	8.75
2	64.34	49.88	56.69	66.64	57.01	45.43	56.66	8.13	3.32
3	50.08	58.08	55.76	55.28	55.84	49.96	54.17	3.36	1.37
4	49.93	53.22	57.32	75.56	54.53	55.75	57.72	9.09	3.71
5	58.63	81.90	88.84	48.12	52.14	57.67	64.55	16.72	6.82

C.5 Statistical Analyses

C.5.1 Bulk density (BD)

BD 2017

Anova:

```
                                  Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(Area)                    4 0.1111  0.0278   4.507 0.00346 **
as.factor(Depth)                   1 1.4949  1.4949 242.671 < 2e-16 ***
as.factor(Area):as.factor(Depth)   4 0.0353  0.0088   1.434 0.23643
Residuals                         50 0.3080  0.0062
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure C.2 – Results obtained from the ANOVA test of BD in 2017.

LSD test:

Study: BD ~ Area

```
LSD t Test for BD
P value adjustment method: holm

Mean Square Error:  0.0062

Area,  means and individual ( 95 %) CI

            BD       std  r      LCL      UCL      Min      Max
Area1 1.542764 0.1891409 12 1.497109 1.588419 1.286988 1.745760
Area2 1.502114 0.2326584 12 1.456458 1.547769 1.177489 1.797810
Area3 1.542552 0.1624485 12 1.496896 1.588207 1.306544 1.764910
Area4 1.584577 0.1735488 12 1.538922 1.630232 1.288617 1.867787
Area5 1.628546 0.1438592 12 1.582891 1.674201 1.376522 1.777336

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.936964

Minimum Significant Difference: 0.09441019

Treatments with the same letter are not significantly different.

            BD groups
Area5 1.628546      a
Area4 1.584577     ab
Area1 1.542764     ab
Area3 1.542552     ab
Area2 1.502114      b
```

Study: BD ~ Depth

```
LSD t Test for BD
P value adjustment method: holm
```

```
Mean Square Error:  0.0062

Depth,  means and individual ( 95 %) CI

            BD        std  r      LCL      UCL      Min      Max
0-5   1.402268 0.11298254 30 1.373393 1.431143 1.177489 1.608556
10-15 1.717953 0.05388771 30 1.689078 1.746827 1.621085 1.867787

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.008559

Minimum Significant Difference: 0.04083521

Treatments with the same letter are not significantly different.

            BD groups
10-15 1.717953      a
0-5   1.402268      b
```

Study: BD ~ Area:Depth

```
LSD t Test for BD
P value adjustment method: holm

Mean Square Error:  0.0062

Area:Depth,  means and individual ( 95 %) CI

                  BD        std r      LCL      UCL      Min      Max
Area1:0-5   1.366285 0.05787960 6 1.301719 1.430851 1.286988 1.429183
Area1:10-15 1.719243 0.02461066 6 1.654677 1.783809 1.680367 1.745760
Area2:0-5   1.309227 0.16090156 6 1.244661 1.373793 1.177489 1.607334
Area2:10-15 1.695000 0.06247996 6 1.630434 1.759567 1.627502 1.797810
Area3:0-5   1.395179 0.05501153 6 1.330613 1.459745 1.306544 1.452712
Area3:10-15 1.689924 0.05390374 6 1.625358 1.754491 1.621085 1.764910
Area4:0-5   1.435566 0.08500777 6 1.371000 1.500132 1.288617 1.500076
Area4:10-15 1.733588 0.07579910 6 1.669022 1.798154 1.666412 1.867787
Area5:0-5   1.505084 0.09234352 6 1.440518 1.569651 1.376522 1.608556
Area5:10-15 1.752007 0.02049625 6 1.687441 1.816574 1.716425 1.777336

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 3.46087

Minimum Significant Difference: 0.1573332

Treatments with the same letter are not significantly different.

                  BD groups
Area5:10-15 1.752007      a
Area4:10-15 1.733588      a
Area1:10-15 1.719243      a
Area2:10-15 1.695000      a
Area3:10-15 1.689924      a
Area5:0-5   1.505084      b
Area4:0-5   1.435566     bc
```

```
Area3:0-5   1.395179     bc
Area1:0-5   1.366285     bc
Area2:0-5   1.309227      c
```

BD 2020

Anova:

```
                                  Df Sum Sq Mean Sq F value Pr(>F)  
as.factor(Area)                    4 0.1476 0.03691   2.140 0.0895 .
as.factor(Depth)                   1 0.0003 0.00031   0.018 0.8931  
as.factor(Area):as.factor(Depth)   4 0.0469 0.01173   0.680 0.6088  
Residuals                         50 0.8623 0.01725                 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure C.3 – Results obtained from the ANOVA test of BD in 2020.

LSD test:

Study: BD ~ Area

```
LSD t Test for BD
P value adjustment method: holm

Mean Square Error:  0.01725

Area,  means and individual ( 95 %) CI

            BD        std  r      LCL      UCL      Min      Max
Area1 1.466310 0.18592752 12 1.390157 1.542463 0.940769 1.629947
Area2 1.351201 0.09792006 12 1.275048 1.427354 1.196435 1.579119
Area3 1.373686 0.06443067 12 1.297533 1.449840 1.263866 1.485205
Area4 1.476751 0.10635473 12 1.400597 1.552904 1.217010 1.636262
Area5 1.427858 0.15186328 12 1.351705 1.504012 1.122791 1.595213

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.936964

Minimum Significant Difference: 0.1574772

Treatments with the same letter are not significantly different.

            BD groups
Area4 1.476751      a
Area1 1.466310      a
Area5 1.427858      a
Area3 1.373686      a
Area2 1.351201      a
```

C.5.2 Organic carbon (OC)

OC 2017

Anova:

```
                                   Df Sum Sq Mean Sq F value   Pr(>F)    
as.factor(Area)                     4  0.183   0.046   0.422    0.792    
as.factor(Depth)                    1  7.974   7.974  73.449 2.21e-11 ***
as.factor(Area):as.factor(Depth)    4  0.474   0.118   1.091    0.371    
Residuals                          50  5.428   0.109                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure C.4 – Results obtained from the ANOVA test of OC in 2017.

LSD test:

Study: OC ~ Depth

```
LSD t Test for OC
P value adjustment method: holm

Mean Square Error:  0.109

Depth,  means and individual ( 95 %) CI

            OC       std  r      LCL      UCL      Min      Max
0-5   2.577159 0.3916336 30 2.456089 2.698229 1.785448 3.346546
10-15 1.848044 0.2376114 30 1.726974 1.969114 1.416338 2.465224

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.008559

Minimum Significant Difference: 0.1712191

Treatments with the same letter are not significantly different.

            OC groups
0-5   2.577159      a
10-15 1.848044      b
```

Study: OC ~ Area:Depth

```
LSD t Test for OC
P value adjustment method: holm

Mean Square Error:  0.109

Area:Depth,  means and individual ( 95 %) CI

                  OC       std r      LCL      UCL      Min      Max
Area1:0-5   2.598279 0.3166664 6 2.327558 2.869000 2.235968 2.997745
Area1:10-15 1.886385 0.1567310 6 1.615664 2.157106 1.705130 2.100093
Area2:0-5   2.731507 0.4186972 6 2.460786 3.002228 2.246581 3.341313
Area2:10-15 1.820148 0.3062560 6 1.549427 2.090869 1.416338 2.327582
Area3:0-5   2.687932 0.4695733 6 2.417211 2.958653 1.901546 3.346546
```

```
Area3:10-15 1.812029 0.2261337 6 1.541308 2.082751 1.590069 2.219488
Area4:0-5   2.532125 0.3543866 6 2.261403 2.802846 2.169164 3.176690
Area4:10-15 1.794246 0.2147244 6 1.523525 2.064968 1.518049 2.165081
Area5:0-5   2.335953 0.3896331 6 2.065232 2.606675 1.785448 2.970193
Area5:10-15 1.927411 0.3107676 6 1.656690 2.198132 1.669320 2.465224

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 3.46087

Minimum Significant Difference: 0.659687

Treatments with the same letter are not significantly different.

                  OC groups
Area2:0-5   2.731507      a
Area3:0-5   2.687932      a
Area1:0-5   2.598279      a
Area4:0-5   2.532125     ab
Area5:0-5   2.335953    abc
Area5:10-15 1.927411     bc
Area1:10-15 1.886385      c
Area2:10-15 1.820148      c
Area3:10-15 1.812029      c
Area4:10-15 1.794246      c
```

OC 2020

Anova:

```
                                   Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Area)                     4  0.786  0.1964   0.571 0.6848
as.factor(Depth)                    1  1.034  1.0339   3.007 0.0891 .
as.factor(Area):as.factor(Depth)    4  1.368  0.3420   0.995 0.4192
Residuals                          50 17.192  0.3438
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure C.5 – Results obtained from the ANOVA test of OC in 2020.

LSD test:

Study: OC ~ Depth

```
LSD t Test for OC
P value adjustment method: holm

Mean Square Error:  0.3438

Depth,  means and individual ( 95 %) CI

            OC       std  r      LCL      UCL      Min      Max
0-5   1.856434 0.2754936 30 1.641415 2.071453 1.371515 2.669869
10-15 2.118978 0.7689014 30 1.903959 2.333997 1.262667 4.613857

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.008559
```

```
Minimum Significant Difference: 0.3040828

Treatments with the same letter are not significantly different.

            OC groups
10-15 2.118978      a
0-5   1.856434      a
```

C.5.3 Total carbon (TC)

TC 2017

Anova:

```
                                    Df Sum Sq Mean Sq F value   Pr(>F)    
as.factor(Area)                      4  0.145   0.036   0.280    0.889    
as.factor(Depth)                     1  8.086   8.086  62.517 2.32e-10 ***
as.factor(Area):as.factor(Depth)     4  0.416   0.104   0.804    0.528    
Residuals                           50  6.467   0.129                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure C.6 – Results obtained from the ANOVA test of TC in 2017.

LSD test:

Study: TC ~ Depth

```
LSD t Test for TC
P value adjustment method: holm

Mean Square Error:  0.129

Depth,  means and individual ( 95 %) CI

            TC       std  r      LCL      UCL      Min      Max
0-5   2.695173 0.4054818 30 2.563463 2.826883 1.844448 3.430100
10-15 1.960983 0.2791479 30 1.829273 2.092694 1.424137 2.621769

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 2.008559

Minimum Significant Difference: 0.1862661

Treatments with the same letter are not significantly different.

            TC groups
0-5   2.695173      a
10-15 1.960983      b
```

Study: TC ~ Area:Depth

```
LSD t Test for TC
P value adjustment method: holm

Mean Square Error:  0.129

Area:Depth,  means and individual ( 95 %) CI

                  TC       std r      LCL      UCL      Min      Max
Area1:0-5   2.683734 0.3549010 6 2.389221 2.978246 2.265662 3.103954
Area1:10-15 1.968580 0.1896550 6 1.674068 2.263093 1.775066 2.274528
Area2:0-5   2.872628 0.4203070 6 2.578116 3.167141 2.325784 3.341701
Area2:10-15 1.916316 0.3829873 6 1.621803 2.210828 1.424137 2.503601
Area3:0-5   2.807291 0.5049881 6 2.512779 3.101804 1.910994 3.430100
Area3:10-15 1.923281 0.2860770 6 1.628768 2.217794 1.627838 2.462958
Area4:0-5   2.602912 0.3550388 6 2.308400 2.897425 2.175368 3.184682
Area4:10-15 1.998828 0.2318690 6 1.704315 2.293340 1.783293 2.343417
Area5:0-5   2.509301 0.4064843 6 2.214789 2.803814 1.844448 3.028901
Area5:10-15 1.997913 0.3552189 6 1.703400 2.292425 1.702717 2.621769

Alpha: 0.05 ; DF Error: 50
Critical Value of t: 3.46087

Minimum Significant Difference: 0.7176613

Treatments with the same letter are not significantly different.

                  TC groups
Area2:0-5   2.872628      a
Area3:0-5   2.807291      a
Area1:0-5   2.683734     ab
Area4:0-5   2.602912    abc
Area5:0-5   2.509301    abc
Area4:10-15 1.998828     bc
Area5:10-15 1.997913     bc
Area1:10-15 1.968580      c
Area3:10-15 1.923281      c
Area2:10-15 1.916316      c
```

TC 2020

Anova:

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
as.factor(Area)	4	0.637	0.1592	0.446	0.775
as.factor(Depth)	1	0.715	0.7152	2.002	0.163
as.factor(Area):as.factor(Depth)	4	0.927	0.2318	0.649	0.630
Residuals	50	17.866	0.3573		

Figure C.7 – Results obtained from the ANOVA test of TC in 2017.

Appendix D - Agronomic performance of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in the UK

D.1 Weight of seeds

After visual examination, it was evident that Sida1 seeds were coated with a blue substance. The total weight of each bag and the 100 seeds weight from each bag with three repetitions were obtained. Using those results, the number of total seeds received and the 1000 seed weight were calculated, all calculations and results included in Table D.1. We received a total of 41,653 Sida1 seeds, 28,928 Sida2 seeds, and 25,251 Silphium seeds.

The 1000 seeds weight is often used in literature to establish a baseline. The results obtained in the initial weighing are in line with the results from other research experiments. According to Krzaczek *et al*. (2006), the 1000 seed weight of Sida seeds is 3.4 g and according to Schäfer *et al.* (2015), the 1000 seed weigh of Silphium seeds is 16-20 g.

Table D.1 - Results obtained from initial weighing of seeds.

Description	**Parameter**	**Weight (g)**	**Number of seeds**
Sida 1 (blue seeds)	Total weight (g)	245.75	41,653
	100 seeds weight	0.60, 0.59, 0.58; average = 0.59	
	1000 seeds weight	5.90	
Sida 2 (normal seeds)	Total weight (g)	106.07	28,928
	100 seeds weight	0.35, 0.37, 0.38; average = 0.37	
	1000 seeds weight	3.67	
Silphium (N.L. Chrestensen)	Total weight (g)	51.45	3,377
	100 seeds weight	1.54, 1.52, 1.51; average = 1.52	
	1000 seeds weight	15.23	
Silphium (N.L. Chrestensen)	Total weight (g)	358.72	21,873
	100 seeds weight	1.65, 1.69, 1.64; 1.58; average = 1.64	
	1000 seeds weight	16.40	

D.2 Germination experiment

High-density sown seeds in propagators produced identical outcome to seed trays. The results obtained in the germination experiment (table below) are in line with the results from other research experiments. According to Krzaczek *et al*. (2006), the germination percentage of Sida seeds is 33% and according to von Gehren *et al*. (2016), the germination of Silphium is about 80%.

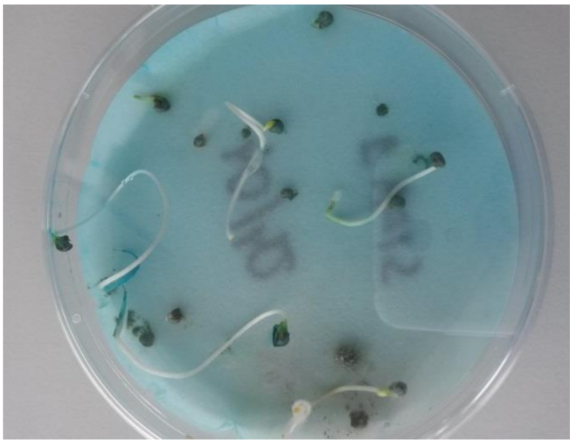
Table D.2 - Germination percentages (%) recorded of seeds sown between 28 February and 10 April.

	Treatment			
Species	**Greenhouse**	**Lab. A**	**Lab. B**	**Lab. C**
***Sida*1**	32.78	31.76	-	-
***Sida*2**	0.74	0	1.85	0.87
Silphium	81.40	-	-	-

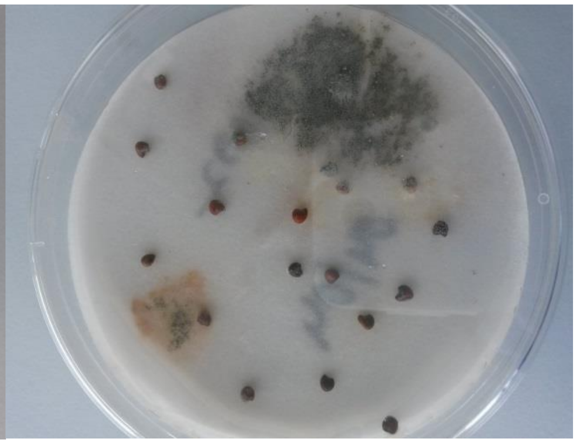
The three scarification methods described were selected as they had demonstrated increased germination capacity in previous studies. Despite previous recorded successes, none of the methods increased the germination rate of Sida seeds in the current experiment. Germination was measured after 3, 6, and 9 days from sowing. Seeds began to grow a white mycelium over them, finished by being completely covered in the mycelium. This mycelium also spread to the culture medium, turning it to grey/orange colour in some areas (Figure D.1).

There are various potential reasons for the low Sida germination percentage. One reason could be the non-optimal storage conditions between receipt in April 2016 and February 2017. Although the seeds were kept in a dark and dry environment, they were exposed to relatively high temperatures during 2016. The supplier of the seed also confirmed that the viability of the seed may have declined over the 10 months, and this may have been avoided by preserving the seeds at a low temperature.

Even though the selected scarification methods did not overcome the low germination rate, further research is recommended to consider other methods and factors. The National Reforestation, Nurseries, and Genetic Resources of the US, recommends soaking Sida seeds in water at 76°C for 24h followed by natural cooling (RNGR, 2017). Sida seeds might benefit from vernalisation and might be more successfully sown in autumn or scarified if planted in spring (Hanzhenko, 2016).



Sida1 seeds Treatment A



Sida2 seeds Treatment A

Sida2 seeds Treatment B

Sida2 seeds Treatment C

Figure D.1 - Representative images of the three laboratory treatments.

This germination experiment exposed the germination capacity of Sida seeds after they had been stored at room temperature for ten months. The cause behind the low germination percentage of *Sida* and the effective long-term storage of seeds collected from previous years should be further investigated as it has implications for farmers and other stakeholders in the biomass sector. The results presented in this document are restricted to the acquired seed material for this project specifically and should not be generalised.

D.3 Climate data

Table D.3 - Climate data from Woburn station for the years 2017-2020 (Met Office, 2020b).

	Daily max. T	Daily min. T	Daily mean T	Total rainfall	Effective rainfall	Rainy days
	°C	°C	°C	mm	mm	days
2017						
Jan	6.8	-0.1	3.4	59.6	52.9	20.0
Feb	9.1	3.4	6.3	43.2	39.3	19.0
Mar	13.0	5.0	9.0	41.8	38.0	16.0
Apr	14.1	3.8	8.9	11.2	10.1	11.0
May	18.2	8.3	13.3	63.0	56.7	13.0
Jun	22.0	11.8	16.9	35.4	30.0	10.0
Jul	22.4	12.7	17.5	87.0	77.5	15.0
Aug	20.7	11.4	16.1	69.2	59.9	15.0
Sep	17.9	9.6	13.7	66.2	60.9	23.0
Oct	16.0	9.3	12.7	30.0	26.7	13.0
Nov	10.1	3.3	6.7	45.2	39.7	22.0
Dec	7.7	2.2	5.0	78.6	70.2	22.0

	Daily max. T	Daily min. T	Daily mean T	Total rainfall	Effective rainfall	Rainy days
	°C	°C	°C	mm	mm	days
2018						
Jan	8.5	2.7	5.6	na	na	na
Feb	5.9	-0.6	2.7	29.0	26.4	15.0
Mar	8.7	1.8	5.3	67.6	61.5	25.0
Apr	14.1	6.7	10.4	77.4	70.0	19.0
May	19.1	6.9	13.0	66.8	60.2	12.0
Jun	21.9	10.2	16.1	3.2	2.7	5.0
Jul	26.5	12.6	19.5	13.6	12.1	5.0
Aug	22.8	12.5	17.6	49.8	43.1	12.0
Sep	19.5	9.2	14.4	30.4	28.0	8.0
Oct	15.3	6.5	10.9	65.0	57.9	15.0
Nov	11.3	5.0	8.2	34.8	30.6	18.0
Dec	9.8	4.2	7.0	55.0	49.1	18.0

	Daily max. T	Daily min. T	Daily mean T	Total rainfall	Effective rainfall	Rainy days
	°C	°C	°C	mm	mm	days
2019						
Jan	6.8	0.8	3.8	24.2	21.5	12.0
Feb	11.8	1.6	6.7	34.4	31.3	13.0
Mar	11.9	4.5	8.2	40.8	37.1	17.0
Apr	14.7	2.0	8.4	15.2	13.8	10.0
May	16.8	5.6	11.2	33.0	29.7	12.0
Jun	19.5	10.2	14.9	75.4	63.9	16.0
Jul	23.5	12.3	17.9	30.6	27.3	13.0
Aug	23.6	12.5	18.1	35.0	30.3	11.0
Sep	20.0	9.5	14.8	63.6	58.5	16.0
Oct	14.0	6.7	10.3	91.8	81.7	22.0
Nov	9.1	3.2	6.1	85.4	75.0	25.0
Dec	9.0	2.9	6.0	82.4	73.5	24.0

	Daily max. T	Daily min. T	Daily mean T	Total rainfall	Effective rainfall	Rainy days
	°C	°C	°C	mm	mm	days
2020						
Jan	9.2	4.1	6.7	59.8	53.1	18.0
Feb	10.1	3.1	6.6	74.2	67.5	25.0
Mar	10.9	2.3	6.6	29.0	26.4	15.0
Apr	16.7	3.8	10.3	40.2	36.4	6.0
May	19.1	5.3	12.2	6.0	5.4	5.0
Jun	20.9	10.4	15.6	69.0	58.5	16.0
Jul	21.6	11.7	16.6	56.4	50.3	13.0
Aug	23.3	13.6	18.4	86.6	74.9	15.0
Sep	19.8	9.2	14.5	36.8	33.9	8.0

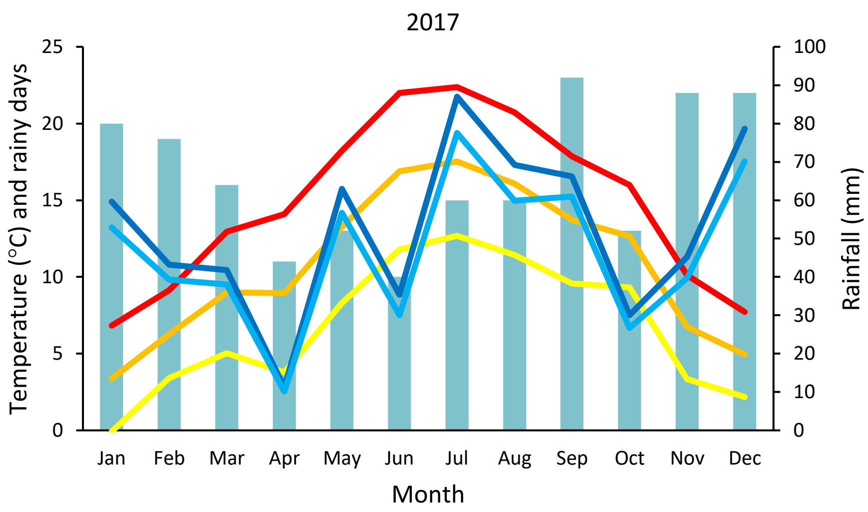


Figure D.2 - Average daily temperatures and rainfall for the years 2017-2020.

D.4 Pictures of Sida affected by *Sclerotinia sclerotiorum*

19/01/2018

16/02/2018

16/02/2018

16/02/2018

22/08/2019

19/02/2020

26/08/2020

Figure D.3 – Pictures of *Sida hermaphrodita* (L.) Rusby affected by *S. sclerotiorum.*

D.5 Growth records of plots adjacent to poplar trees

Table D.4 - Height and diameter of plots directly adjacent to poplar trees.

Height (cm)							
Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**
01/07/19							
16' Silphium E (fence)	137	136	147	169	162	147	139
16' Silphium W (fence)	121	82	77	110	115	87	130
16' Sida W (fence)	174	167	187	183	211	206	198
16' Sida E (fence)	15	241	255	251	244	242	265
20/08/19							
16' Silphium E (fence)	157	140	129	199	164	158	134
16' Silphium W (fence)	129	65*	72	112	105*	112	72*
16' Sida W (fence)	183	188	206	192	218	210	198
16' Sida E (fence)	260	305	270	288	296	292	

Diameter (mm)							
Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**
01/07/19							
16' Silphium E (fence)	12	10	11	15	13	13	12
16' Silphium W (fence)	9	6	8	8	6	11	10
16' Sida W (fence)	14	12	12	11	14	13	12
16' Sida E (fence)	13	14	18	13	17	18	20
20/08/19							
16' Silphium E (fence)	15.7	11.3	12.7	19.7	20.7	14.7	13.5
16' Silphium W (fence)	16.2	6.7*	15.6	9.9	9.12*	12.6	8.6*
16' Sida W (fence)	16.3	13.5	14.9	14.1	16.8	16.9	13
16' Sida E (fence)	16.4	20.7	15.4	20.1	20.5	25.7	

D.6 Plant density records 2017-2020

Table D.5 - Plant density records 2017-2020.

	DATE	**25/10/2017**		**28/06/2018**		**03/07/2019**		**10-17/09/2020**	
Plot	**Treatment**	**Count (n plants)**	**Density (%)**	**Count (n plants)**	**Density (%)**	**Count (n plants)**	**Density (%)**	**Count (n plants)**	**Density (%)**
A1	Sida2 seedlings							70	43.8
A2	Sida2 seeds	369	230.6	170	106.3	-	50	67	41.9
A3	Sida1 seedlings							72	45.0
A4	Sida1 seeds	4	2.5	0.0	0.0	0.0	0.0	0	0.0
B1	Sida1 seeds	124	77.5	85	53.1	-	30	63	39.4
B2	Sida2 seedlings							96	60.0
B3	Sida2 seeds	356	222.5	181	113.1	-	75	78	48.8
B4	Sida1 seedlings							70	43.8
C1	Silphium seedlings							122	76.3
C2	Silphium seeds	-	-	-	93	-	90	94	58.8
C3	Silphium seedlings							83	51.9
C4	Silphium seeds	-	-	-	55	-	50	64	40.0
D1	Silphium seeds	-	-	-	90	-	90	115	71.9
D2	Silphium seedlings							97	60.6
D3	Silphium seeds	-	-	-	95	-	90	91	56.9
D4	Silphium seedlings							113	70.6
E1	Sida1 seedlings							91	56.9
E2	Sida1 seeds	4	2.5	2	1.3	0.0	0.0	0	0.0
E3	Sida2 seedlings							87	54.4
E4	Sida2 seeds	71	44.5	32	20.0		50	17	10.6
F1	Sida2 seeds	197	123.1	74	46.3	-	25	30	18.8
F2	Sida1 seedlings							72	45.0
F3	Sida1 seeds	4	2.5	3	1.9	0.0	0.0	0	0.0
F4	Sida2 seedlings							94	58.8

D.7 Leaves-stalks biomass

Table D.6 - *Sida hermaphrodita* (L.) Rusby biomass records from July 2018 (Sanchez Muñoz, 2018).

	A2 (S1)	A4 (S2)	B1 (S1)	B3 (S2)	E2 (S2)	E4 (S1)	F1 (S2)	F3 (S1)	Avg. S1	Avg. S2	Global Avg.
FML (g)	311	222	252	354	249	162	179	168	226	251	237
FMS (g)	720	529	591	823	625	396	455	480	555	608	577
FMT (g)	1031	751	843	1176	874	559	634	647	781	859	814
SW (kg)	10.3	7.5	8.4	11.8	8.7	5.6	6.3	6.5	7.7	8.6	8.1
DML (g)	80	58	81	94	67	48	57	52	66	69	67
DMS (g)	224	166	215	273	209	144	174	178	194	206	198
DMT (g)	304	225	296	368	276	192	230	229	260	275	265
WCL (g)	232	163	171	259	182	114	122	116	160	182	170
WCS (g)	495	363	376	549	416	253	281	302	361	403	380
WCT (g)	727	526	547	809	598	367	404	418	522	584	549
DML (%)	0.26	0.26	0.32	0.27	0.27	0.30	0.32	0.31	0.29	0.28	0.29
DMS (%)	0.31	0.31	0.36	0.33	0.33	0.36	0.38	0.37	0.35	0.34	0.35
DMT (%)	0.29	0.30	0.35	0.31	0.32	0.34	0.36	0.35	0.33	0.32	0.33
HW (kg)	34.0	34.5	34.5	37.0	32.5	27.3	26.5	28.5	31.1	32.6	31.8
TW (kg)	44.3	42.0	42.9	48.8	41.2	32.8	32.8	35.0	38.8	41.2	40.0
FMY (t/ha)	36.9	35.0	35.8	40.6	34.4	27.4	27.4	29.1	32.3	34.3	33.3

FML = Fresh matter leaves
FMS = Fresh matter stalks
FMT = Fresh matter total (leaves + stalks)
SW = Sampling weight
DML = Dry matter leaves
DMS = Dry matter stalks
DMT = Dry matter total (leaves + stalks)
WCL = Water content leaves
WCS = Water content stalks
WCT = Water content total
HW = Harvesting weight
TW = Total weight (SW + HW)
FMY = Fresh matter yield

D.8 Statistical analyses

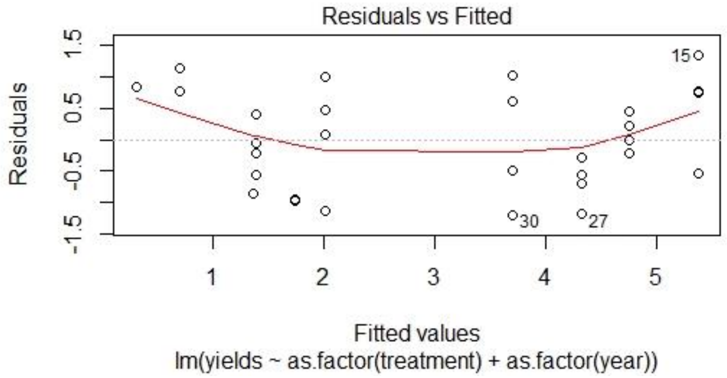
Table D.7 - Descriptive statistics of full yield dataset.

number of values (nbr.val) = 104.00
number of null values (nbr.null) = 18.00
number of missing values (nbr.na) = 0.00
minimal value (min) = 0.00
maximum value (max) = 12.74
range = 12.74
sum of all non-missing values (sum) = 478.93
median = 4.58
mean = 4.61
standard error on the mean (SE.mean) = 0.35
confidence interval on the mean (CI.mean) = 0.95-0.70
Variance (var) = 12.92
standard deviation (std.dev) = 3.59
coefficient of variation (coef.var) = 0.78

Table D.8 - Independence of data tests on clean (entries of yield equal to 0 kg DM ha^{-1} removed) yield data set.

Residuals:

Combustion



Biogas:

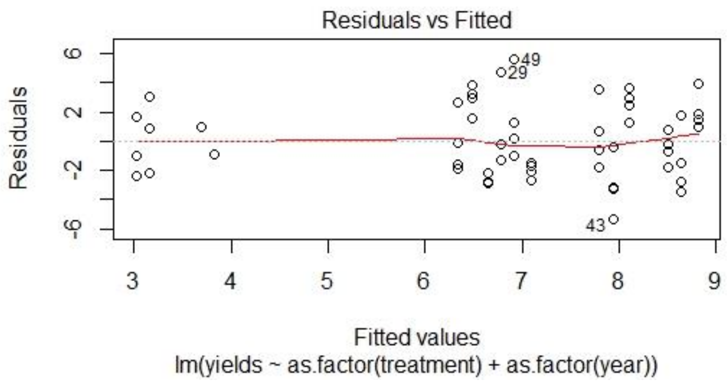
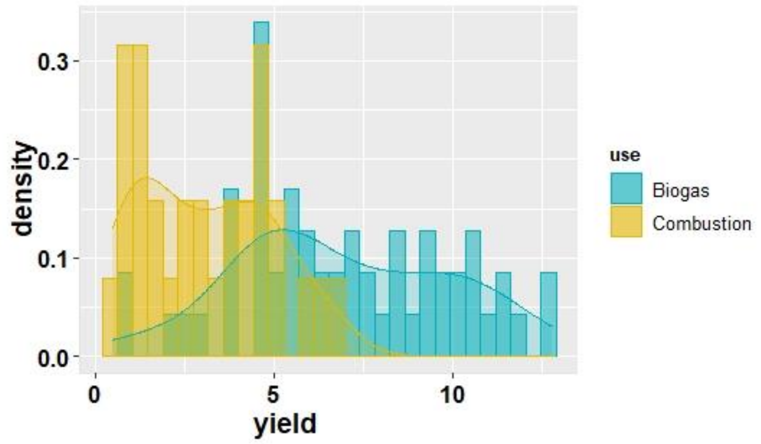
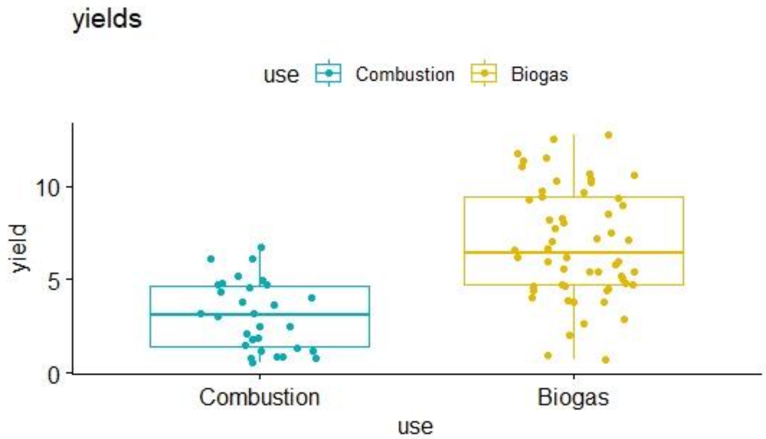


Table D.9 - Histogram, box-plot, QQ plots: normality tests on clean (entries of yield equal to 0 kg DM ha^{-1} removed) yield data set.

Histogram:



Boxplot:



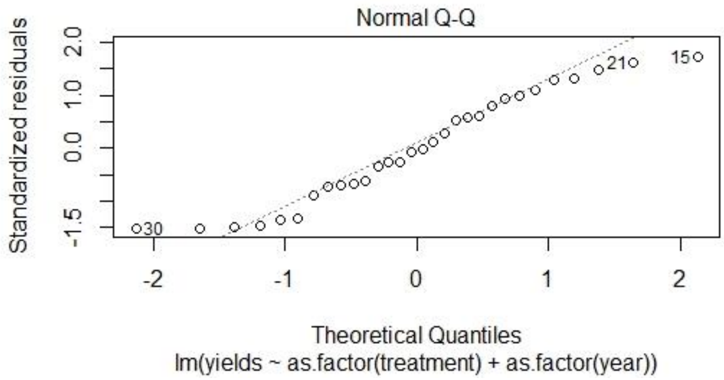
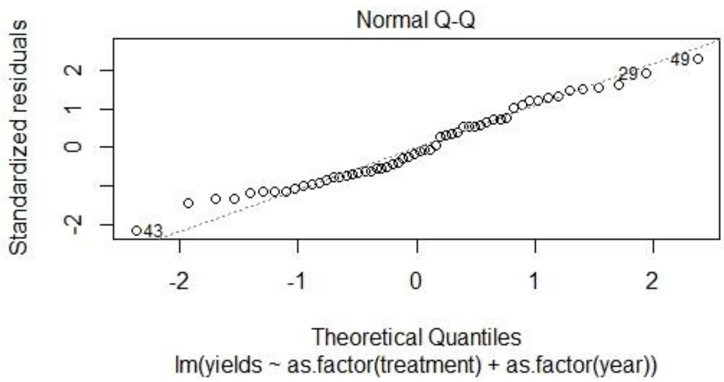
QQplot
Combustion:

Biogas:


Table D.10 - Shapiro-Wilk tests.

Combustion

`Shapiro-Wilk normality test`
 	
`data: yields`
`W = 0.93953, p-value = 0.08833`

Biogas

`Shapiro-Wilk normality test`
 	
`data: yields`
`W = 0.97453, p-value = 0.281`

Since p-value > 0.05, we accept the null hypothesis of normality.

Table D.11 - Homogeneity of variance tests on clean (entries of yield equal to 0 kg DM ha^{-1} removed) yield data set.

Bartlett test:

Combustion

```
Bartlett test of homogeneity of variances

data:  yields by as.factor(crop)
Bartlett's K-squared = 5.0712, df = 3, p-value = 0.1667
```

Biogas

```
Bartlett test of homogeneity of variances

data:  yields by as.factor(crop)
Bartlett's K-squared = 1.6916, df = 5, p-value = 0.89
```

Since p-value > 0.05, we accept the null hypothesis of homogeneity of variance.

As a result from all the previous tests, we concluded that the assumptions of independence of data, normality, and homogeneity of variance held.

Table D.12 - ANOVA tests.

Combustion 2018:

```
Df Sum Sq Mean Sq F value Pr(>F)
as.factor(crop)  1  1.362  1.3622   2.802  0.145
Residuals        6  2.917  0.4862
```

Combustion 2019:

```
Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(crop)  3  50.67  16.890    55.9 2.95e-05 ***
Residuals        7   2.12   0.302
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Combustion 2020:

```
Df Sum Sq Mean Sq F value Pr(>F)
as.factor(crop)  3 10.485   3.495   6.904 0.0169 *
Residuals        7  3.544   0.506
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Biogas 2018:

```
Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(crop)  3 157.68   52.56   68.47 8.09e-08 ***
Residuals       12   9.21    0.77
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Biogas 2019:

```
Df Sum Sq Mean Sq F value Pr(>F)
as.factor(crop)  5  76.06  15.212   3.228 0.0381 *
Residuals       14  65.97   4.712
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Biogas 2020:

```
Df Sum Sq Mean Sq F value Pr(>F)
as.factor(crop)  5  95.57  19.115   3.833 0.0213 *
Residuals       14  69.82   4.987
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Note: the different treatments are referred in the ANOVA tests as “crops” to avoid confusion.

Table D.13 - POST-HOC tests.

Combustion 2018:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  0.4862

crop,  means and individual ( 95 %) CI

            yield       std r       LCL      UCL       Min      Max
Sida1 sd 2.117580 0.9039087 4 1.2644878 2.970672 0.8805847 3.004633
Sida2 sd 1.292287 0.3942569 4 0.4391952 2.145379 0.8465298 1.796789

Alpha: 0.05 ; DF Error: 6
Critical Value of t: 2.446912

Minimum Significant Difference: 1.206454

Treatments with the same letter are not significantly different.

            yield groups
Sida1 sd 2.117580      a
Sida2 sd 1.292287      a
```

Combustion 2019:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  0.302

crop,  means and individual ( 95 %) CI

             yield        std r        LCL      UCL       Min       Max
Sida1 s  0.5111111         NA 1 -0.7883570 1.810579 0.5111111 0.5111111
Sida1 sd 5.9416667 0.78851713 4  5.2919326 6.591401 4.8333333 6.7000000
Sida2 s  0.7888889 0.01571348 2 -0.1299738 1.707752 0.7777778 0.8000000
Sida2 sd 4.8583333 0.28851471 4  4.2085993 5.508067 4.5333333 5.2000000

Alpha: 0.05 ; DF Error: 7
Critical Value of t: 3.635807

Groups according to probability of means differences and alpha level( 0.05 )

Treatments with the same letter are not significantly different.

             yield groups
Sida1 sd 5.9416667      a
Sida2 sd 4.8583333      a
Sida2 s  0.7888889      b
Sida1 s  0.5111111      b
```

Combustion 2020:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  0.506

crop,  means and individual ( 95 %) CI

            yield       std r        LCL      UCL      Min      Max
Sida1 s  1.156126        NA 1 -0.5259183 2.838170 1.156126 1.156126
Sida1 sd 3.639389 0.3779798 4  2.7983668 4.480411 3.137422 4.041156
Sida2 s  1.653041 0.2585235 2  0.4636559 2.842426 1.470237 1.835844
Sida2 sd 3.684300 1.0079946 4  2.8432779 4.525322 2.507233 4.708600

Alpha: 0.05 ; DF Error: 7
Critical Value of t: 3.635807

Groups according to probability of means differences and alpha level( 0.05 )

Treatments with the same letter are not significantly different.

            yield groups
Sida2 sd 3.684300      a
```

```
Sida1 sd 3.639389      a
Sida2 s  1.653041      a
Sida1 s  1.156126      a
```

Biogas 2018:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  0.77

crop,  means and individual ( 95 %) CI

                yield       std r      LCL       UCL      Min       Max
Sida1 sd    10.698280 1.0005500 4 9.742330 11.654231 9.392457 11.773260
Sida2 sd    10.849718 1.3134848 4 9.893768 11.805668 9.761492 12.744211
Silphium s   3.983333 0.3086543 4 3.027383  4.939284 3.800000  4.444444
Silphium sd  5.111111 0.4988877 4 4.155161  6.067061 4.444444  5.555556

Alpha: 0.05 ; DF Error: 12
Critical Value of t: 3.152681

Minimum Significant Difference: 1.956187

Treatments with the same letter are not significantly different.

                yield groups
Sida2 sd    10.849718      a
Sida1 sd    10.698280      a
Silphium sd  5.111111      b
Silphium s   3.983333      b
```

Biogas 2019:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  4.712

crop,  means and individual ( 95 %) CI

               yield      std r         LCL       UCL      Min       Max
Sida1 s     4.633533       NA 1 -0.02218537  9.289252 4.633533  4.633533
Sida1 sd    8.248073 2.329507 4  5.92021364 10.575932 5.954691 11.374827
Sida2 s     2.472227 2.053622 3 -0.21575372  5.160207 0.679010  4.712577
Sida2 sd    7.986351 1.074244 4  5.65849123 10.314210 6.666084  9.247083
Silphium s  6.107936 2.065864 4  3.78007641  8.435795 4.490203  9.002303
Silphium sd 7.248180 2.886121 4  4.92032069  9.576040 5.434047 11.498904

Alpha: 0.05 ; DF Error: 14
Critical Value of t: 3.529593

Groups according to probability of means differences and alpha level( 0.05 )

Treatments with the same letter are not significantly different.

               yield groups
Sida1 sd    8.248073      a
Sida2 sd    7.986351      a
Silphium sd 7.248180      a
Silphium s  6.107936      a
Sida1 s     4.633533      a
Sida2 s     2.472227      a
```

Biogas 2020:

```
Study: yield ~ crop

LSD t Test for yield
P value adjustment method: holm

Mean Square Error:  4.987

crop,  means and individual ( 95 %) CI

               yield       std r        LCL       UCL       Min
Sida1 s     2.886611        NA 1 -1.9030395  7.676261 2.8866106
Sida1 sd    4.886742 2.0046240 4  2.4919171  7.281567 2.6321665
Sida2 s     3.715376 2.6455660 3  0.9500703  6.480682 0.9364489
Sida2 sd    7.120362 2.3259828 4  4.7255367  9.515187 5.1517585
Silphium s  9.369639 0.9550224 4  6.9748138 11.764464 8.0387421
Silphium sd 8.429813 2.8753603 4  6.0349875 10.824638 5.9290419
                  Max
```

```
Sida1 s       2.886611
Sida1 sd      7.513977
Sida2 s       6.203563
Sida2 sd     10.385552
Silphium s  10.294157
Silphium sd 12.506228

Alpha: 0.05 ; DF Error: 14
Critical Value of t: 3.529593

Groups according to probability of means differences and alpha level( 0.05 )

Treatments with the same letter are not significantly different.

               yield groups
Silphium s  9.369639      a
Silphium sd 8.429813      a
Sida2 sd    7.120362      a
Sida1 sd    4.886742      a
Sida2 s     3.715376      a
Sida1 s     2.886611      a
```

D.9 SidaTim European joint project yield results

Table D.14 - Winter yields of *Sida hermaphrodita* (L.) Rusby to produce solid fuel for combustion.

Country		**Poland**	**Germany**	**Italy**		**UK**
Code		**Lipn**	**Wer**	**Cas**	**Mont**	**Sil**
1 year old	Sida1 s	0.7	0.6	0.4	-	-
	Sida1 sl	1.5	1.3	4.3	3.2	2.1
	Sida2 s	0.5	0.5	0.7	-	-
	Sida2 sl	1.1	1.4	2.0	3.5	1.3
2 year old	Sida1 s	9.6	6.4	2.9	-	0.5
	Sida1 sl	10.2	7.8	7.1	10.6	5.9
	Sida2 s	7.8	8.3	6.0	-	0.8
	Sida2 sl	9.3	9.5	8.2	10.6	4.9
3 year old	Sida1 s	9.6		3.2	-	1.2
	Sida1 sl	10.7	8.9	5.8		3.6
	Sida2 s	7.6		4.7	-	1.7
	Sida2 sl	10.3	6.7	6.5		3.7

Red text: corresponds to yields obtained from Sida seeds in the UK, which failed establishment.

Table D.15 - Summer yields of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. to produce green biomass for anaerobic digestion.

Country		Poland	Germany	Italy		UK
Code		**Lip**	**Wer**	**Cas**	**Mon**	**Sil**
0 year old	Sida1 s	4.6	4.5	2.1	-	
	Sida1 sl	4.5	4.5	6.8	4.4	
	Sida2 s	2.9	2.9	2.8	-	
	Sida2 sl	4.2	4.2	2.8	3.9	
	Silphium s	-	-	-		
	Silphium sl	-	-	-		
1 year old	Sida1 s	13.8	7.8	4.0		
	Sida1 sl	15.1	9.2	13.6	15.1	
	Sida2 s	9.2	9.0	5.1		
	Sida2 sl	14.8	9.0	8.8	15.0	
	Silphium s	24.7	13.7	11.5		
	Silphium sl	26.6	14.6	16.4	15.7	
2 year old	Sida1 s	7.2		3.9		-
	Sida1 sl	6.7	19.5	7.5	14.9	10.7
	Sida2 s	4.8		3.2		-
	Sida2 sl	8.5	16.4	5.6	15.3	10.8
	Silphium s	15.4		13.8		4.0
	Silphium sl	14.3	18.0	15.1	19.5	5.1
3 year old	Sida1 s	-	-	-	-	1.2
	Sida1 sl	-	-	-	-	8.2
	Sida2 s	-	-	-	-	1.9
	Sida2 sl	-	-	-	-	8.0
	Silphium s	-	-	-	-	6.1
	Silphium sl	-	-	-	-	7.2
4 year old	Sida1 s	-	-	-	-	0.7
	Sida1 sl	-	-	-	-	4.9
	Sida2 s	-	-	-	-	2.8
	Sida2 sl	-	-	-	-	7.1
	Silphium s	-	-	-	-	9.4
	Silphium sl	-	-	-	-	8.4

* 1 year old (2017): one cut for Sida before senescence in early Autumn in PL, GE and IT; Sida was not cut for biogas in the first year in the UK
2 year old (2018): two cuts for both for Sida and Silphium in all countries.
3 year old (2019): two cuts for both Sida and Silphium in PL, GE and IT; one cut for both Sida and Silphium in the UK.
4 year old (2020): project finished in PL, GE and IT; one cut for both Sida and Silphium in the UK.
Red text: corresponds to yields obtained from Sida seeds in the UK, which failed establishment.

Appendix E - Economics of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. in Europe

E.1 Inputs for arable crops

Note: The tables in Appendix E show the inputs and outputs for the economic model developed during the PhD to calculate the economic performance for Sida and Silphium. The model is a cost benefit analysis model that uses the Net Present Value as the key criterion of evaluation. It was developed in a Microsoft Excel spreadsheet, and allows both crops to be compared with arable and energy crops in the UK, Italy, Poland and Germany. The model is available upon request from myself or my supervisors.

Table E.1 – Input data for milling winter wheat, winter oats, winter OSR, sugar beet was obtained by default from ABC Ltd (2019b) in the UK. Default 4% discount rate.

a) Data for the UK								
			Wheat	**Oats**	**OSR**	**Sugar beet**	**Forage maize**	**Reference**
Production	Main crop	(t ha^{-1})	8.3	6.3	3.5	78.0	12.0 [i]	[i] (ABC Ltd, 2019a)
	Straw	(t ha^{-1})	3.9 [ii]	3.5 [ii]	2.6 [ii]	-	-	[ii] (DEFRA, 2019)
Prices	Main crop	(£ t^{-1})	162.0	140.0	335.0	27.16	107.1[iii]	[iii] (BASF SE, 2018)
	Straw price	(£ t^{-1})	65.0	70.0	37.5 [i]	-	-	[i] (ABC Ltd, 2019a)
	SFP	(£ ha^{-1})	220.0	220.0	220.0	220.0	220.0	
Variable costs	Seed cost	(£ ha^{-1})	89.8	64.0	55.0	207.0	166.3 [i]	[i] (ABC Ltd, 2019a)
	Nitrogen price	(£ kg^{-1})	0.7	0.7	0.7	0.7	0.7	
	Nitrogen rate	(kg ha^{-1})	250.0	130.0	190.0	156.0	150.0 [iv]	[iv] (AHDB, 2019)
	Phosphate price	(£ kg^{-1})	0.6	0.6	0.6	0.6	0.6	
	Phosphate rate	(kg ha^{-1})	146.5	112.1	112.1	148.7	115.0 [iv]	[iv] (AHDB, 2019)
	Potash price	(£ kg^{-1})	0.5	0.5	0.5	0.5	0.5	
	Potash rate	(kg ha^{-1})	112.2	85.4	95.1	319.5	235.0[v]	[iv](AHDB, 2019)
	Spray cost	(£ ha^{-1})	260.0	135.0	230.0	246.0	85.0[i]	[i](ABC Ltd, 2019a)
	Straw variable costs	(£ t^{-1})	3.5	3.5	3.5 [v]	-	-	[v] assumed same as wheat and oats
Fixed costs (machine costs) *	Cultivation	(£ ha^{-1})	118.8	118.8	46.2	111.5	118.8	

	Fertiliser application	(£ ha^{-1})	64.3	32.1	16.1	16.1	64.3
	Drilling	(£ ha^{-1})	27.0	27.0	57.5	57.2	45.0
	Spraying	(£ ha^{-1})	60.1	39.9	20.2	30.2	30.2
	Harvesting	(£ ha^{-1})	232.6	232.6	125.7	277.9	175.0
	Baling	(£ ha^{-1})	58.1	58.1	52.3	-	-
	Drying	(£ ha^{-1})	-	-	7.8	-	-
Fixed costs (labour) *	Labour cost	(£ h^{-1})	12.8	12.8	12.8	12.8	12.8
	Labour input (grain)	(h)	17.1	15.9	18.3	27.2	9.3
	Labour input (straw)	(h)	4.8	4.8	4.8	-	-

* Fixed costs (machine costs) and labour input calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise:

- Cultivation cost:
  - Wheat: ploughing (heavy land) at £57.5 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at £52.4 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at £8.9 ha^{-1} and 1.1 h ha^{-1}
  - Oats: ploughing (heavy land) at £57.5 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at £52.4 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at £8.9 ha^{-1} and 1.1 h ha^{-1}
  - OSR: cultivation at £37.3 ha^{-1} and 1.6 h ha^{-1}; ring rolling (seedbeds) at £8.9 ha^{-1} and 1.6 h ha^{-1}
  - Sugar beet: ploughing (heavy land) at £57.5 1.4 h ha^{-1}; cultivating at £37.3 and 3.2 h ha^{-1}; rolling (flat) at £16.7 and 0.8 h ha^{-1}
  - Forage maize: ploughing (heavy land) at £57.5 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at £52.4 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at £8.9 ha^{-1} and 1.1 h ha^{-1} (assumed same operations and times as wheat)
- Fertiliser application cost:
  - Wheat: x4 extra for variable rate application at £16.1 ha^{-1} and 0.3 h ha^{-1}
  - Oats: x2 extra for variable rate application at £16.1 ha^{-1} and 0.3 h ha^{-1}
  - OSR: x1 extra for variable rate application at £16.1 ha^{-1} and 1.6 h ha^{-1}
  - Sugar beet: x1 extra for variable rate application at £16.1 ha^{-1} and 0.7 h ha^{-1}

  - Forage maize: x4 extra for variable rate application at £16.1 ha^{-1} and 0.3 h ha^{-1} (assumed same procedure and times as wheat)
- Drilling cost:
  - Wheat: cereal drilling - conventional at £27.0 ha^{-1} and 1.1 h ha^{-1}
  - Oats: cereal drilling - conventional at £27.0 ha^{-1} and 1.1 h ha^{-1}
  - OSR: rape drilling with flatlift/subsoiler at £57.5 ha^{-1} and 1.6 h ha^{-1}
  - Sugar beet: sugar beet drilling at £57.2 ha^{-1} and 1.0 h ha^{-1}
  - Forage maize: maize precision drilling at £45.0 ha^{-1} (ABC Ltd, 2019a) and 1.1 h ha^{-1} (assumed same times as wheat)
- Spray application cost:
  - Wheat: x4 spraying (200 l/ha & 24m boom) at £10.1 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at £19.8 ha^{-1} and 1.0 h ha^{-1}
  - Oats: x2 spraying (based on 200 l/ha & 24m boom) at £10.1 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at £19.8 ha^{-1} and 1.0 h ha^{-1}
  - OSR: x2 spraying (based on 200 l/ha & 24m boom) at £10.1 ha^{-1} and 0.6 h ha^{-1}
  - Sugar beet: x3 spraying (based on 200 l/ha & 24m boom) at £10.1 ha^{-1} and 0.9 h ha^{-1}
  - Forage maize: x3 spraying (based on 200 l/ha & 24m boom) at £10.1 ha^{-1} and 0.3 h ha^{-1} (assumed same operations and times as wheat)
- Harvesting cost:
  - Wheat: combining cereals at £90.1 ha^{-1} and 1.5 h ha^{-1}; cart at £35.6 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at £35.6 ha^{-1} and 0.7 h ha^{-1}
  - Oats: combining cereals at £90.1 ha^{-1} and 1.5 h ha^{-1}; cart at £35.6 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at £35.6 ha^{-1} and 0.7 h ha^{-1}
  - OSR: OSR harvesting (direct combining) at £90.1 ha^{-1} and 2.4 h ha^{-1}; later barn work at £35.6 ha^{-1} and 2.1 ha ha^{-1}
  - Sugar beet: sugar beet harvesting (harvesting only) at £242.2 ha^{-1} and 14.0 h ha^{-1}; cart at £35.6 ha^{-1} and 3.4 h ha^{-1}
  - Forage maize: full harvesting operation including carting and clamping at £175.0 ha^{-1} (ABC Ltd, 2019a) and 1.5 h ha^{-1} (assumed same times as wheat)
- Baling cost:

  Number of bales for wheat and oats = 10 bales ha^{-1} obtained considering on average 3,500 kg of straw per ha^{-1} and weight of 350 kg per bale; number of bales for OSR = 7 bales ha^{-1} obtained considering on average 2,600 kg of straw per ha^{-1} and weight of 350 kg per bale

- Wheat: x10 baling (per bale) - round 150 cm at £2.2 ha^{-1} and 1.3 h ha^{-1}; cart at £35.6 ha^{-1} and 3.5 h ha^{-1}
- Oats: x10 baling (per bale) - round 150 cm at £2.2 ha^{-1} and 1.3 h ha^{-1}; cart at £35.6 ha^{-1} and 3.5 h ha^{-1}
- OSR: x7 baling (per bale) - round 150 cm at £2.2 ha^{-1} and 1.3 h ha^{-1}; cart at £35.6 ha^{-1} and 3.5 h ha^{-1}

- Drying cost: OSR: x2.6 drying (per tonne) at £7.8 ha^{-1} and 1.4 h ha^{-1}

Table E.2 – Input data for milling winter wheat, soya, winter OSR, sunflower and forage maize in Italy. Default 3% discount rate.

b) Data for Italy *								
			Wheat	**Soya**	**OSR**	**Sunflower**	**Forage maize ***	**Reference**
Production	Main crop	(t ha^{-1})	5.5 [i]	3.1 [i]	2.6 [i]	2.1 [i]	9.4 [i]	[i] (CREA, 2017)
	Straw	(t ha^{-1})	3.9 [ii]	-	2.6 [ii]	-	-	[ii] (DEFRA, 2019)
Prices	Main crop	(€ t^{-1})	210.0 [i]	310.8 [i]	197.0 [i]	235.6 [i]	94.3 [iii]	[i] (CREA, 2017) [iii] (Facciotto and Coaloa, 2019)
	Straw price	(€ t^{-1})	73.5	-	42.4 [iv]	-	-	[iv] (ABC Ltd, 2019a)
	PAC	(€ ha^{-1})	330.0 [iii]	330.0 [iii]	330.0 [iii]	330.0 [iii]	330.0 [iii]	[iii] (Facciotto and Coaloa, 2019)
Variable costs	Seed cost *	(€ ha^{-1})	132.0	29.0	1.5	2.9	187.9	
	Nitrogen price	(€ kg^{-1})	0.7	0.7	0.7	0.7	0.7	
	Nitrogen rate *	(kg ha^{-1})	108.0	0.0	114.0	92.0	150.0	
	Phosphate price	(€ kg^{-1})	0.7	0.7	0.7	0.7	0.7	
	Phosphate rate *	(kg ha^{-1})	210.5	210.5	109.8	157.9	115.0	
	Potash price	(€ kg^{-1})	0.5	0.5	0.5	0.5	0.5	
	Potash rate	(kg ha^{-1})	75.0 [iii]	175.0 [iii]	75.0 [iii]	75.0 [iii]	175.0 [iii]	[iii] (Facciotto and Coaloa, 2019)
	Spray cost	(€ ha^{-1})	189.3	29.9	104.0	31.9	96.1 [iv]	[iv] (ABC Ltd, 2019a)
	Straw variable costs	(€ t^{-1})	4.0	-	4.0 [v]	-	-	[v] assumed same as wheat
Fixed costs (machine costs) *	Cultivation	(€ ha^{-1})	134.3	124.2	52.2	134.3	134.3	
	Fertiliser application	(€ ha^{-1})	79.9	20.0	20.0	39.9	79.9	
	Drilling	(€ ha^{-1})	30.6	30.6	65.0	30.6	50.9	
	Spraying	(€ ha^{-1})	56.5	11.4	22.8	22.8	45.6	
	Harvesting	(€ ha^{-1})	262.9	262.9	142.1	394.5	197.8	
	Baling	(€ ha^{-1})	65.7	-	59.1	-	-	
	Drying	(€ ha^{-1})	-	-	8.8	-	-	
Fixed costs (labour) *	Labour cost	(€ h^{-1})	14.5	14.5	14.5	14.5	14.5	
	Labour input (grain)	(h)	16.8	6.8	18.3	10.8	14.2	
	Labour input (straw)	(h)	4.8	-	4.8	-	-	

* Exchange rate 1.13 €/£, discount rate 3% (Facciotto and Coaloa, 2019)

* Maize data was used when forage maize data was not available

* Variable costs extracted from various sources:

- Seed cost:
    - Wheat: €55 per 100 kg at 240 kg ha^{-1} (Semences de France, 2019)
    - Soya: €40 per 25 kg (Semences de France, 2019) at 18.125 kg ha^{-1} (Facciotto and Coaloa, 2019)
    - OSR: €0.38 per kg at 4.0 kg ha^{-1} (Facciotto and Coaloa, 2019)
    - Sunflower: €291 per tonne (Camera di Commercio Industria Artigianato e Agricoltura di Bologna, 2018) at 10.0 kg ha^{-1} (Facciotto and Coaloa, 2019)
    - Forage maize: £4.75 kg^{-1} at 35.0 kg ha^{-1} (ABC Ltd, 2019a)
- Nitrogen and phosphate rate:
    - Wheat: Pelliconi (2015a)
    - Soya: Pelliconi (2015b)
    - OSR: Rinaldi (2014a)
    - Sunflower: Rinaldi (2014b)
    - Forage maize: (AHDB, 2019)
- Spray cost:
    - Wheat: €59.0-67.2 per application (Pelliconi, 2015a) and 3 applications per ha (Facciotto and Coaloa, 2019)
    - Soya: €29.9 per application (Pelliconi, 2015b) and 1 applications per ha (Facciotto and Coaloa, 2019)
    - OSR: €18.7-45.1 per application (Rinaldi, 2014a) and 1 applications per ha (Facciotto and Coaloa, 2019)
    - Sunflower: €104.0 (Rinaldi, 2014b) and 1 applications per ha (Facciotto and Coaloa, 2019)
    - Forage maize: £85.0 ha^{-1} and 2 applications per ha (Facciotto and Coaloa, 2019)

* Fixed costs (machine costs) and labour input calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise (times for soya same as peas/field beans, times for sunflower same as spring cereals):

- Cultivation cost:

  - Wheat: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.1 h ha^{-1}
  - Soya: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 1.0 h ha^{-1}.
  - OSR: cultivating at €42.2 ha^{-1} and 1.6 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.6 h ha^{-1}
  - Sunflower: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 1.0 h ha^{-1}; ring rolling (seedbeds) at €10.0 and 0.8 h ha^{-1}
  - Forage maize: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.1 h ha^{-1} (assumed same operations and times as wheat)
- Fertiliser application cost:
  - Wheat: x4 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1}
  - Soya: x1 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1}
  - OSR: x1 extra for variable rate application at €20.0ha^{-1} and 1.6 h ha^{-1}
  - Sunflower: x2 extra for variable rate application at €20.0 ha^{-1} and 0.7 h ha^{-1}
  - Forage maize: x4 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1} (assumed same procedure and times as wheat)
- Drilling cost:
  - Wheat: cereal drilling - conventional at €30.6 ha^{-1} and 1.1 h ha^{-1}
  - Soya: cereal drilling - conventional at €30.6 ha^{-1} and 0.6 h ha^{-1}
  - OSR: rape drilling with flatlift/subsoiler at €65.0 ha^{-1} and 1.2 h ha^{-1}
  - Sunflower: cereal drilling - conventional at €30.6 ha^{-1} and 1.2 h ha^{-1}
  - Forage maize: maize precision drilling at €50.9 ha^{-1} (ABC Ltd, 2019a) and 1.1 h ha^{-1} (assumed same times as wheat)
- Spray application cost:
  - Wheat: x3 spraying (200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at €22.3 ha^{-1} and 1.0 h ha^{-1}
  - Soya: x1 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1}

  - OSR: x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.6 h ha^{-1}
  - Sunflower: x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.7 h ha^{-1}
  - Forage maize: x4 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} (assumed same operations and times as wheat)
- Harvesting cost:
  - Wheat: combining cereals at €101.8 ha^{-1} and 1.5 h ha^{-1}; cart at €40.3 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at €40.3 ha^{-1} and 0.7 h ha^{-1}
  - Soya: combining peas/beans at €101.8 ha^{-1} and 1.5 h ha^{-1}; cart at €40.3 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at €40.3 ha^{-1} and 0.7 h ha^{-1}
  - OSR: OSR harvesting - direct combining at €101.8 ha^{-1} and 2.4 h ha^{-1}; later barn work at €40.3 ha^{-1} and 2.1 ha ha^{-1}
  - Sunflower: sunflower harvesting (harvesting only) at €273.7 ha^{-1} and 2.0 h ha^{-1}; cart at €40.3 ha^{-1} and 0.4 h ha^{-1}; x2 later barn work at €40.3 ha^{-1} and 0.6 h ha^{-1}
  - Forage maize: full harvesting operation including carting and clamping at €197.8 ha^{-1} (ABC Ltd, 2019a) and 1.5 h ha^{-1} (assumed same times as wheat)
- Baling cost:

  Number of bales for wheat = 10 bales ha^{-1} obtained considering on average 3,500 kg of straw per ha^{-1} and weight of 350 kg per bale; number of bales for OSR = 7 bales ha^{-1} obtained considering on average 2,600 kg of straw per ha^{-1} and weight of 350 kg per bale
  - Wheat: x10 baling (per bale) - round 150 cm at €2.5 ha^{-1} and 1.3 h ha^{-1}; cart at €40.3 ha^{-1} and 3.5 h ha^{-1}
  - OSR: x7 baling (per bale) - round 150 cm at €2.5 ha^{-1} and 1.3 h ha^{-1}; cart at €40.3 ha^{-1} and 3.5 h ha^{-1}
- Drying cost: OSR: x2.6 drying (per tonne) at €8.8 ha^{-1} and 1.4 h ha^{-1}

Table E.3 – Input data for milling winter wheat, winter oats, winter OSR, sugar beet was obtained by default from ABC Ltd (2019b) in Germany. Default 4% discount rate.

c) Data for Germany *

			Wheat	**Oats**	**OSR**	**Sugar beet**	**Forage maize ***	**Reference**
Production	Main crop	(t ha^{-1})	7.5 [i]	4.1 [i]	3.3 [i]	63.1 [i]	8.1 [i]	[i] (Statista.com, 2020b)
	Straw	(t ha^{-1})	3.9 [ii]	3.5 [ii]	2.6 [ii]	-	-	[ii] (DEFRA, 2019)
Prices	Main crop	(€ t^{-1})	193.7 [i]	154.8 [i]	345.1 [i]	26.0 [i]	182.8 [i]	[i] (Statista.com, 2020b)
	Straw price	(€ t^{-1})	73.5	79.1	42.4 [iii]	-	-	[iii] (ABC Ltd, 2019a)
	PAC	(€ ha^{-1})	176.0 [iv]	176.0 [iv]	176.0 [iv]	176.0 [iv]	176.0 [iv]	[iv] (Morhart, 2020)
Variable costs	Seed cost *	(€ ha^{-1})	105.4	83.2	62.2	233.9	187.9	
	Nitrogen price	(€ kg^{-1})	0.6 [v]	0.6 [v]	0.6 [v]	0.6 [v]	0.6 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Nitrogen rate	(kg ha^{-1})	200.0 [v]	120.0 [v]	200.0 [v]	180.0 [v]	200.0 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Phosphate price	(€ kg^{-1})	1.0 [v]	1.0 [v]	1.0 [v]	1.0 [v]	1.0 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Phosphate rate	(kg ha^{-1})	86.0 [v]	68.0 [v]	92.0 [v]	91.0 [v]	96.0 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Potash price	(€ kg^{-1})	0.3 [v]	0.3 [v]	0.3 [v]	0.3 [v]	0.3 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Potash rate	(kg ha^{-1})	149.0 [v]	208.0 [v]	209.0 [v]	344.0 [v]	238.0 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Spray cost	(€ ha^{-1})	283.6	152.6	259.9	278.0	96.1 [iii]	[iii] (ABC Ltd, 2019a)
	Straw variable costs	(€ t^{-1})	4.0	4.0	4.0 [vi]	-	-	[vi] assumed same as wheat
Fixed costs (machine costs) *	Cultivation	(€ ha^{-1})	134.3	134.3	52.2	126.0	134.3	
	Fertiliser application	(€ ha^{-1})	79.9	39.9	20.0	39.9	79.9	
	Drilling	(€ ha^{-1})	30.6	30.6	65.0	64.6	50.9	
	Spraying	(€ ha^{-1})	67.9	45.1	22.8	34.2	34.2	
	Harvesting	(€ ha^{-1})	262.9	262.9	142.1	314.0	197.8	
	Baling	(€ ha^{-1})	65.7	65.7	59.1	-	-	
	Drying	(€ ha^{-1})	-	-	8.8	-	-	
Fixed costs (labour) *	Labour cost	(€ h^{-1})	15.0 [v]	15.0 [v]	15.0 [v]	15.0 [v]	15.0 [v]	[v] (Chamber of Agriculture North Rhine-Westphalia, 2020)
	Labour input (grain)	(h)	17.1	15.9	17.9	27.9	9.3	
	Labour input (straw)	(h)	4.8	4.8	4.8	-	-	

* Exchange rate 1.13 €/£

* Maize data was used when forage maize data was not available

* Variable costs extracted from various sources:

- Seed cost:
    - Wheat: €0.68 per kg (Baywa.de, 2020) at 155 kg ha^{-1}
    - Oats: €0.64 per kg (Baywa.de, 2020) at 130 kg ha^{-1}
    - Forage maize: £4.75 per kg at 35 kg ha^{-1} (ABC Ltd, 2019a)

* Fixed costs (machine costs) and labour input calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise (times for soya same as peas/field beans, times for sunflower same as spring cereals):

- Cultivation cost:
    - Wheat: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.1 h ha^{-1}
    - Oats: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 1.0 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.1 h ha^{-1}
    - OSR: cultivating at €42.2 ha^{-1} and 1.6 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.6 h ha^{-1}
    - Sugar beet: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; cultivating at €42.2 ha^{-1} and 3.2 h ha^{-1}; rolling (flat) at €18.8 and 0.8 h ha^{-1}
    - Forage maize: ploughing (heavy land) at €65.0 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at €59.2 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at €10.0 ha^{-1} and 1.1 h ha^{-1} (assumed same operations and times as wheat)
- Fertiliser application cost:
    - Wheat: x4 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1}
    - Oats: x2 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1}
    - OSR: x1 extra for variable rate application at €20.0ha^{-1} and 1.6 h ha^{-1}
    - Sugar beet: x2 extra for variable rate application at €20.0 ha^{-1} and 0.7 h ha^{-1}

  - Forage maize: x4 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1} (assumed same procedure and times as wheat)
- Drilling cost:
  - Wheat: cereal drilling - conventional at €30.6 ha^{-1} and 1.1 h ha^{-1}
  - Oats: cereal drilling - conventional at €30.6 ha^{-1} and 1.1 h ha^{-1}
  - OSR: rape drilling with flatlift/subsoiler at €65.0 ha^{-1} and 1.2 h ha^{-1}
  - Sugar beet: sugar beet drilling at €64.6 ha^{-1} and 1.0 h ha^{-1}
  - Forage maize: maize precision drilling at €50.9 ha^{-1} (ABC Ltd, 2019a) and 1.1 h ha^{-1} (assumed same times as wheat)
- Spray application cost:
  - Wheat: x4 spraying (200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at €22.3 ha^{-1} and 1.0 h ha^{-1}
  - Oats: x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at €22.3 ha^{-1} and 1.0 h ha^{-1}
  - OSR: x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.6 h ha^{-1}
  - Sugar beet: x3 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.9 h ha^{-1}
  - Forage maize: x3 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} (assumed same operations and times as wheat)
- Harvesting cost:
  - Wheat: combining cereals at €101.8 ha^{-1} and 1.5 h ha^{-1}; cart at €40.3 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at €40.3 ha^{-1} and 0.7 h ha^{-1}
  - Oats: combining cereals at €101.8 ha^{-1} and 1.5 h ha^{-1}; cart at €40.3 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at €40.3 ha^{-1} and 0.7 h ha^{-1}
  - OSR: OSR harvesting - direct combining at €101.8 ha^{-1} and 2.4 h ha^{-1}; later barn work at €40.3 ha^{-1} and 2.1 ha ha^{-1}
  - Sugar beet: sugar beet harvesting (harvesting only) at €273.7 ha^{-1} and 14.0 h ha^{-1}; cart at €40.3 ha^{-1} and 3.4 h ha^{-1}
  - Forage maize: full harvesting operation including carting and clamping at €197.8 ha^{-1} (ABC Ltd, 2019a) and 1.5 h ha^{-1} (assumed same times as wheat)
- Baling cost:

  Number of bales for wheat and oats = 10 bales ha^{-1} obtained considering on average 3,500 kg of straw per ha^{-1} and weight of 350 kg per bale; number of bales for OSR = 7 bales ha^{-1} obtained considering on average 2,600 kg of straw per ha^{-1} and weight of 350 kg per bale

- Wheat: x10 baling (per bale) - round 150 cm at €2.5 ha^{-1} and 1.3 h ha^{-1}; cart at €40.3 ha^{-1} and 3.5 h ha^{-1}
- Oats: x10 baling (per bale) - round 150 cm at £2.5 ha^{-1} and 1.3 h ha^{-1}; cart at €40.3 ha^{-1} and 3.5 h ha^{-1}
- OSR: x7 baling (per bale) - round 150 cm at €2.5 ha^{-1} and 1.3 h ha^{-1}; cart at €40.3 ha^{-1} and 3.5 h ha^{-1}

- Drying cost: OSR: x2.6 drying (per tonne) at €8.8 ha^{-1} and 1.4 h ha^{-1}

Table E.4 – Input data for milling winter wheat, winter oats, winter OSR, sugar beet was obtained by default from ABC Ltd (2019b) in Poland. Default 4% discount rate.

d) Data for Poland *								
			Wheat	**Barley**	**OSR**	**Sugar beet**	**Forage maize ***	**Reference**
Production	Main crop	(t ha^{-1})	4.6 [i]	2.5 [i]	3.5	56.8 [i]	12.0 [ii]	[i] (Bury, 2020) [ii] (ABC Ltd, 2019a)
	Straw	(t ha^{-1})	4.9 [i]	3.5 [i]	5.6 [i]	-	-	[i] (Bury, 2020)
Prices	Main crop	(PLN t^{-1})	867.0 [i]	721.0 [i]	1,645.0 [i]	120.0 [i]	724.0 [i]	[i] (Bury, 2020)
	Straw price	(PLN t^{-1})	140.0 [i]	120.0 [i]	120.0 [i]	-	-	[i] (Bury, 2020)
	PAC	(PLN ha^{-1})	471.6 [i]	471.6 [i]	471.6 [i]	471.6 [i]	471.6 [i]	[i] (Bury, 2020)
Variable costs	Seed cost *	(PLN ha^{-1})	378.0	306.0	542.6	1,690.0	583.4	
	Nitrogen price	(PLN kg^{-1})	3.4 [i]	3.4 [i]	3.4 [i]	3.4 [i]	3.4 [i]	[i] (Bury, 2020)
	Nitrogen rate	(kg ha^{-1})	200.0 [i]	120.0 [i]	200.0 [i]	180.0 [i]	200.0 [i]	[i] (Bury, 2020)
	Phosphate price	(PLN kg^{-1})	4.5 [i]	4.5 [i]	4.5 [i]	4.5 [i]	4.5 [i]	[i] (Bury, 2020)
	Phosphate rate	(kg ha^{-1})	86.0 [i]	68.0 [i]	92.0 [i]	91.0 [i]	96.0 [i]	[i] (Bury, 2020)
	Potash price	(PLN kg^{-1})	2.7 [i]	2.7 [i]	2.7 [i]	2.7 [i]	2.7 [i]	[i] (Bury, 2020)
	Potash rate	(kg ha^{-1})	149.0 [i]	208.0 [i]	209.0 [i]	344.0 [i]	238.0 [i]	[i] (Bury, 2020)
	Lime price	(PLN kg^{-1})	1.9 [i]	1.9 [i]	1.9 [i]	1.9 [i]	1.9 [i]	[i] (Bury, 2020)
	Lime rate	(kg ha^{-1})	50.0 [i]	50.0 [i]	50.0 [i]	50.0 [i]	50.0 [i]	[i] (Bury, 2020)
	Spray cost	(PLN ha^{-1})	148.8 [i]	99.2 [i]	248.0 [i]	99.2 [i]	148.8 [i]	[i] (Bury, 2020)
	Straw variable costs	(PLN t^{-1})	62.9 [i]	62.9 [i]	62.9 [i]	-	-	[i] (Bury, 2020)
Fixed costs (machine costs) *	Cultivation	(PLN ha^{-1})	582.3	582.3	226.4	546.5	582.3	
	Fertiliser application	(PLN ha^{-1})	1,259.8	944.8	314.9	629.9	1,259.8	
	Drilling	(PLN ha^{-1})	132.5	132.5	281.7	280.1	220.5	
	Spraying	(PLN ha^{-1})	245.0	195.7	247.0	98.8	148.2	
	Harvesting	(PLN ha^{-1})	1,139.8	1,139.8	616.1	1,631.5	847.5	
	Baling	(PLN ha^{-1})	328.9	273.8	351.0	-	-	
	Drying	(PLN ha^{-1})	-	-	82.32	-	-	
Fixed costs (labour) *	Labour cost	(PLN h^{-1})	17.0 [i]	17.0 [i]	17.0 [i]	17.0 [i]	17.0 [i]	[i] (Bury, 2020)
	Labour input (grain)	(h)	16.8	15.2	20.1	27.0	9.3	
	Labour input (straw)	(h)	4.8	4.8	4.8	-	-	

* Exchange rate 4.90 PLN/£

* Maize data was used when forage maize data was not available; winter cereals data used when barley data was not available

* Variable costs extracted from various sources:

- Seed cost:
    - Wheat: PLN1.9 per kg at 200 kg ha^{-1} (Bury, 2020)
    - Barley: PLN1.7 per kg at 180.0 kg ha^{-1} (Bury, 2020)
    - OSR: PLN180.9 per kg at 3.0 kg ha^{-1} (Bury, 2020)
    - Sugar beet: : PLN1,300.0 per kg at 1.3 kg ha^{-1} (Bury, 2020)
    - Forage maize: : PLN24.3 per kg at 24.0 kg ha^{-1} (Bury, 2020)

* Fixed costs (machine costs) and labour input calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise (times for soya same as peas/field beans, times for sunflower same as spring cereals):

- Cultivation cost:
    - Wheat: ploughing (heavy land) at PLN281.9 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at PLN256.8 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at PLN43.6 ha^{-1} and 1.1 h ha^{-1}
    - Barley: ploughing (heavy land) at PLN281.9 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at PLN256.8 ha^{-1} and 1.1 h ha^{-1}; ring rolling (seedbeds) at PLN43.6 ha^{-1} and 1.1 h ha^{-1}
    - OSR: cultivating at PLN182.9 ha^{-1} and 1.6 h ha^{-1}; ring rolling (seedbeds) at PLN43.6 ha^{-1} and 1.6 h ha^{-1}
    - Sugar beet: ploughing (heavy land) at PLN281.9 ha^{-1} and 1.4 h ha^{-1}; cultivating at PLN182.9 ha^{-1} and 3.2 h ha^{-1}; rolling (flat) at PLN81.7 and 0.8 h ha^{-1}
    - Forage maize: ploughing (heavy land) at PLN281.9 ha^{-1} and 1.4 h ha^{-1}; power harrowing (deep/on ploughing) at PLN256.8 ha^{-1} and 2.1 h ha^{-1}; ring rolling (seedbeds) at PLN43.6 ha^{-1} and 1.1 h ha^{-1} (assumed same operations and times as wheat)
- Fertiliser application cost:
    - Wheat: x4 extra for variable rate application at PLN314.9 ha^{-1} and 0.3 h ha^{-1}
    - Barley: x3 extra for variable rate application at PLN314.9 ha^{-1} and 0.3 h ha^{-1}
    - OSR: x1 extra for variable rate application at PLN314.9 ha^{-1} and 1.6 h ha^{-1}

  - Sugar beet: x2 extra for variable rate application at PLN314.9 ha^{-1} and 0.7 h ha^{-1}
  - Forage maize: x4 extra for variable rate application at PLN314.9 ha^{-1} and 0.3 h ha^{-1} (assumed same procedure and times as wheat)
- Drilling cost:
  - Wheat: cereal drilling - conventional at PLN132.5 ha^{-1} and 1.1 h ha^{-1}
  - Barley: cereal drilling - conventional at PLN132.5 ha^{-1} and 1.1 h ha^{-1}
  - OSR: rape drilling with flatlift/subsoiler at PLN281.7 ha^{-1} and 1.6 h ha^{-1}
  - Sugar beet: sugar beet drilling at PLN280.1 ha^{-1} and 1.0 h ha^{-1}
  - Forage maize: maize precision drilling at PLN228.1 ha^{-1} (ABC Ltd, 2019a) and 1.1 h ha^{-1} (assumed same times as wheat)
- Spray application cost:
  - Wheat: x3 (Bury, 2020) spraying (200 l/ha & 24m boom) at PLN49.4.4 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at PLN96.9 ha^{-1} and 1.0 h ha^{-1}
  - Barley: x2 (Bury, 2020) spraying (based on 200 l/ha & 24m boom) at PLN49.4.4 ha^{-1} and 0.3 h ha^{-1} plus 1x Avadex spraying at PLN96.9 ha^{-1} and 1.0 h ha^{-1}
  - OSR: x5 (Bury, 2020) spraying (based on 200 l/ha & 24m boom) at PLN49.4.4 ha^{-1} and 0.6 h ha^{-1}
  - Sugar beet: x2 (Bury, 2020) spraying (based on 200 l/ha & 24m boom) at PLN49.4.4 ha^{-1} and 0.9 h ha^{-1}
  - Forage maize: x3 spraying (based on 200 l/ha & 24m boom) at PLN49.4.4 ha^{-1} and 0.3 h ha^{-1} (assumed same operations and times as wheat)
- Harvesting cost:
  - Wheat: combining cereals at PLN441.5 ha^{-1} and 1.5 h ha^{-1}; cart at PLN174.6 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at PLN174.6 ha^{-1} and 0.7 h ha^{-1}
  - Barley: combining cereals at PLN441.5 ha^{-1} and 1.5 h ha^{-1}; cart at PLN174.6 ha^{-1} and 1.0 h ha^{-1}; x3 later barn work at PLN174.6 ha^{-1} and 0.7 h ha^{-1}
  - OSR: OSR harvesting - direct combining at PLN441.5 ha^{-1} and 2.4 h ha^{-1}; later barn work at PLN174.6 ha^{-1} and 2.1 ha ha^{-1}
  - Sugar beet: sugar beet harvesting (harvesting only) at PLN1,186.9 ha^{-1} and 14.0 h ha^{-1}; cart at PLN174.6 ha^{-1} and 3.4 h ha^{-1}
  - Forage maize: full harvesting operation including carting and clamping at PLN867.5 ha^{-1} (ABC Ltd, 2019a) and 1.5 h ha^{-1} (assumed same times as wheat)
- Baling cost:

Number of bales for wheat = 14 bales ha^{-1} obtained considering on average 4,900 kg of straw per ha^{-1} and weight of 350 kg per bale; barley = 9 bales ha^{-1} obtained considering on average 3,000 kg of straw per ha^{-1} and weight of 350 kg per bale; number of bales for OSR = 16 bales ha^{-1} obtained considering on average 5,600 kg of straw per ha^{-1} and weight of 350 kg per bale

- Wheat: x14 baling (per bale) - round 150 cm at PLN11.0 ha^{-1} and 1.3 h ha^{-1}; cart at PLN174.6 ha^{-1} and 3.5 h ha^{-1}
- Barley: x9 baling (per bale) - round 150 cm at PLN11.0 ha^{-1} and 1.3 h ha^{-1}; cart at PLN174.6 ha^{-1} and 3.5 h ha^{-1}
- OSR: x16 baling (per bale) - round 150 cm at PLN11.0 ha^{-1} and 1.3 h ha^{-1}; cart at PLN174.6 ha^{-1} and 3.5 h ha^{-1}

- Drying cost: OSR: x5.6 drying (per tonne) at PLN82.3 ha^{-1} and 1.4 h ha^{-1}

E.2 Inputs for energy crops

Table E.5 – Input data for SRC and Miscanthus in the UK, obtained by default from ABC Ltd (2019a) unless otherwise indicated. Default 4% discount rate.

a) Data for the UK							**Reference**
			SRC	**Miscanthus**	**Sida**	**Silphium**	
Description	Rotation	(years)	16	16	16	16	
	Year of first harvest	(years)	4	1	1	2	
	Interval between harvest	(years)	3	1	1	1	
Production	Yield per harvest	(odt ha^{-1})	30.0	12.5 [i]	11.6 [ii]	16.3 [ii]	[i] (Witzel and Finger, 2016) [ii] See section **Error! Reference source not found.**
Prices	Biomass	(£ t^{-1})	55.0	55.0	55.0	55.0	
	Single Farm Payment	(£ ha^{-1})	220.0 [iii]	220.0 [iii]	220.0 [iii]	220.0 [iii]	[iii] (ABC Ltd, 2019b)
Establishment costs	Planting material *	(£ ha^{-1})	750.0	1,190.0	4,361.0	1,312.8	
	Planting *	(£ ha^{-1})	300.0	350.0	126.3	45.0	
	Ground preparation	(£ ha^{-1})	200.0	180.0	180.0 [iv]	180.0 [iv]	[iv] Assumed same as Miscanthus
	Fertilisers *	(£ ha^{-1})	126.3	117.7	162.0	177.7	
	Fertiliser application *	(£ ha^{-1})	16.1	16.1	16.1	16.1	
	Sprays	(£ ha^{-1})	200.0	120.0	120.0 [v]	120.0 [v]	[v] Assumed same as Miscanthus
	Spray application *	(£ ha^{-1})	40.3	40.3	20.2	20.2	
	Mechanical weeding *	(£ ha^{-1})	-	-	120.8	120.8	
	Cutback end first year	(£ ha^{-1})	50.0	20.0 [iii]	20.0 [vi]	20.0 [vi]	[iii] (ABC Ltd, 2019b) [vi] Assumed same as Miscanthus
Recurring costs	Mechanical weeding *	(£ ha^{-1})	-	-	161.0	161.0	
	Fertilisers *	(£ ha^{-1})	126.3	117.7	162.0	177.7	
	Fertiliser application *	(£ ha^{-1})	16.1	16.1	16.1	16.1	
	Sprays *	(£ ha^{-1})	100.0 [vii]	60.0 [vii]	-	-	[vii] Assumed half cost of sprays (establishment)
	Spray application *	(£ ha^{-1})	40.3	40.3	-	-	
	Harvesting	(£ ha^{-1})	450.0	-	100.0 [viii]	-	[viii] Assumed same as forage maize harvesting only
	Mowing and baling	(£ ha^{-1})	-	240.7 [i]	-	-	[i] (Witzel and Finger, 2016)
	Harvesting and clamping	(£ ha^{-1})	-	-	-	175.0 [ix]	[ix] Assumed same as forage maize full harvesting operation
Decommissioning costs	Decommissioning	(£ ha^{-1})	170.0 [x]	170.0 [x]	170.0 [x]	170.0 [x]	[x] (P&L Cook and Partners, 2007)

* Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (2019b) unless indicated otherwise:

- Ground preparation cost: SRC and Miscanthus 5.0 h ha^{-1} and Silphium 6.0 h ha^{-1}
- Planting material cost: considering Sida at €350 per 1,000 seedlings (Helling-Jughans, 2017) and 14,000 seedlings per ha (Energiepflanzen.com, 2020a); Silphium at €295 per 500 g seeds and 2.5 kg seeds per ha (Energiepflanzen.com, 2020b).
- Planting cost: Sida same cost as potato planting at £126.29 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize (ABC Ltd, 2019a).
- Fertiliser cost (establishment): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020).
- Fertiliser application cost (establishment): all crops x1 extra for variable rate application at £16.07 ha^{-1} and 1.2 h ha^{-1} (assumed same time as wheat).
- Spray application cost (establishment): considering x4 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus and x2 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at £40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at £40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser cost (recurring): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020), only applied on harvest years.
- Fertiliser application cost (recurring): all crops x1 extra for variable rate application at £16.07 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat), only applied on harvest years.
- Spray application cost (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at £10.08 ha^{-1} 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

Table E.6 – Input data for SRC and Miscanthus in Italy, obtained by default from ABC Ltd (2019a) unless otherwise indicated. Default 3% discount rate.

b) Data for Italy							**Reference**
			SRC	**Miscanthus**	**Sida**	**Silphium**	
Description	Rotation	(years)	10	16	16	16	
	Year of first harvest	(years)	2 [i]	1	1	2	[i] (Facciotto and Coaloa, 2019)
	Interval between harvest	(years)	2 [i]	1	1	1	[i] (Facciotto and Coaloa, 2019)
Production	Yield per harvest	(odt ha^{-1})	26.0 [ii]	12.5 [iii]	10.0 [i]	15.0 [i]	[ii] (Bacenetti et al., 2016) [iii] (Witzel and Finger, 2016) [i] (Facciotto and Coaloa, 2019)
Prices	Biomass *	(€ t^{-1})	43.8	43.8	43.8	43.8	
	PAC	(€ ha^{-1})	330.0 [i]	330.0 [i]	330.0 [i]	330.0 [i]	[i] (Facciotto and Coaloa, 2019)
Establishment costs	Planting material *	(€ ha^{-1})	1,008.0	1,344.7	4,900.0	2,000.0	
	Planting *	(€ ha^{-1})	400.0 [i]	395.5	142.7	50.9	[i] (Facciotto and Coaloa, 2019)
	Ground preparation	(€ ha^{-1})	130.0 [i]	203.4	203.4 [iv]	203.4 [iv]	[i] (Facciotto and Coaloa, 2019) [iv] Assumed same as Miscanthus
	Fertilisers *	(€ ha^{-1})	142.8	133.0	183.0	200.8	
	Fertiliser application *	(€ ha^{-1})	20.0	20.0	20.0	20.0	
	Sprays	(€ ha^{-1})	130.0 [i]	135.6	135.6 [iv]	135.6 [iv]	[i] (Facciotto and Coaloa, 2019) [iv] Assumed same as Miscanthus
	Spray application *	(€ ha^{-1})	45.5	45.5	25.7	25.7	
	Mechanical weeding *	(€ ha^{-1})	-	-	136.4	136.4	
	Cutback end first year	(€ ha^{-1})	56.5	22.6 [v]	22.6 [iv]	22.6 [iv]	[v] (ABC Ltd, 2019b) [iv] Assumed same as Miscanthus
Recurring costs	Mechanical weeding *	(€ ha^{-1})	-	-	181.9	181.9	
	Fertilisers *	(€ ha^{-1})	142.8	133.0	183.0	200.8	
	Fertiliser application *	(€ ha^{-1})	20.0	20.0	20.0	20.0	
	Sprays	(€ ha^{-1})	65.0 [vi]	67.8 [vi]	-	-	[vi] Assumed half cost of sprays (establishment)
	Spray application *	(€ ha^{-1})	45.5	45.5	-	-	
	Harvesting	(€ ha^{-1})	475.0 [i]	-	113.0 [vii]	-	[i] (Facciotto and Coaloa, 2019) [vii] Assumed same as forage maize harvesting only (ABC Ltd, 2019a)
	Mowing and baling	(€ ha^{-1})	-	270.5 [iii]	-	-	[iii] (Witzel and Finger, 2016)
	Harvesting and clamping	(€ ha^{-1})	-	-	-	197.8 [viii]	[viii] Assumed same as forage maize full harvesting operation (ABC Ltd, 2019a)
Decommissioning costs	Decommissioning	(€ ha^{-1})	500.0 [i]	192.1 [ix]	192.1 [ix]	192.1 [ix]	[i] (Facciotto and Coaloa, 2019) [ix] (P&L Cook and Partners, 2007)

* Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise:

- Ground preparation cost: SRC and Miscanthus 5.0 h ha^{-1} and Sida and Silphium 6.0 h ha^{-1}
- Biomass price: considering €15-20 per tonne FM with average moisture 40% (Facciotto and Coaloa, 2019)
- Planting material cost: considering SRC at 0.180 € $unit^{-1}$ and 5,600 units ha^{-1} (Facciotto and Coaloa, 2019); Sida at €350 per 1,000 seedlings (Helling-Jughans, 2017) and 14,000 seedlings per ha (Energiepflanzen.com, 2020a); Silphium at €500 per kg of seeds and 4 kg seeds per ha (SeedFuture, 2019).
- Planting cost: Sida same cost as potato planting at €142.7 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize (ABC Ltd, 2019a).
- Fertiliser cost (establishment): calculated using cost of N, P_2O_5, K_2O (€ kg^{-1}) of 0.74, 0.72, 0.51 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020).
- Fertiliser application cost (establishment): all crops x1 extra for variable rate application at €20.0 ha^{-1} and 1.2 h ha^{-1} (assumed same time as wheat).
- Spray application cost (establishment): considering x4 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus and x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at €45.5 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at €45.5 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser cost (recurring): calculated using cost of N, P_2O_5, K_2O (€ kg^{-1}) of 0.74, 0.72, 0.51 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020), only applied on harvest years.
- Fertiliser application cost (recurring): all crops x1 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat), only applied on harvest years.
- Spray application cost (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

Table E.7 – Input data for SRC and Miscanthus in Germany, obtained by default from ABC Ltd (2019a) unless otherwise indicated. Default 4% discount rate.

c) Data for Germany							**Reference**
			SRC	**Miscanthus**	**Sida**	**Silphium**	
Description	Rotation	(years)	16	16	16	16	
	Year of first harvest	(years)	4	1	1	2	
	Interval between harvest	(years)	3	1	1	1	
Production	Yield per harvest	(odt ha^{-1})	30.0	12.5 [i]	11.6 [ii]	16.3 [ii]	[i] (Witzel and Finger, 2016) [ii] See section **Error! Reference source not found.**
Prices	Biomass	(€ t^{-1})	72.0 [iii]	72.0 [iii]	72.0 [iii]	72.0 [iii]	[iii] (Morhart, 2020)
	PAC	(€ ha^{-1})	176.0 [iii]	176.0 [iii]	176.0 [iii]	176.0 [iii]	[iii] (Morhart, 2020)
Establishment costs	Planting material *	(€ ha^{-1})	1,500.0	1,344.7	4,900.0	1,475.0	
	Planting *	(€ ha^{-1})	339.0	395.5	142.7	50.9	
	Ground preparation	(€ ha^{-1})	226.0	203.4	203.4 [iv]	203.4 [iv]	[iv] Assumed same as Miscanthus
	Fertilisers *	(€ ha^{-1})	130.8	102.8	176.6	190.6	
	Fertiliser application *	(€ ha^{-1})	20.0	20.0	20.0	20.0	
	Sprays	(€ ha^{-1})	226.0	135.6	135.6 [iv]	135.6 [iv]	[iv] Assumed same as Miscanthus
	Spray application *	(€ ha^{-1})	45.6	45.6	22.8	22.8	
	Mechanical weeding *	(€ ha^{-1})	-	-	136.4	136.4	
	Cutback end first year	(€ ha^{-1})	56.5	22.6 [v]	22.6 [iv]	22.6 [iv]	[v] (ABC Ltd, 2019b) [iv] Assumed same as Miscanthus
Recurring costs	Mechanical weeding *	(€ ha^{-1})	-	-	181.9	181.9	
	Fertilisers *	(€ ha^{-1})	130.8	102.8	176.6	190.6	
	Fertiliser application *	(€ ha^{-1})	20.0	20.0	20.0	20.0	
	Sprays	(€ ha^{-1})	113.0 [vi]	67.8 [vi]	-	-	[vi] Assumed half cost of sprays (establishment)
	Spray application *	(€ ha^{-1})	45.6	45.6	-	-	
	Harvesting	(€ ha^{-1})	508.5	-	113.0 [vii]	-	[vii] Assumed same as forage maize harvesting only (ABC Ltd, 2019a)
	Mowing and baling	(€ ha^{-1})	-	270.5 [iii]	-	-	[i] (Witzel and Finger, 2016)
	Harvesting and clamping	(€ ha^{-1})	-	-	-	197.8 [viii]	[viii] Assumed same as forage maize full harvesting operation (ABC Ltd, 2019a)
Decommissioning costs	Decommissioning	(€ ha^{-1})	192.1 [ix]	192.1 [ix]	192.1 [ix]	192.1 [ix]	[ix] (P&L Cook and Partners, 2007)

* Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise:

- Ground preparation cost: SRC and Miscanthus 5.0 h ha^{-1} and Sida and Silphium 6.0 h ha^{-1}
- Planting material cost: considering SRC at 0.10 € $unit^{-1}$ (Morhart, 2020) and 15,000 units ha^{-1}; Sida at €350 per 1,000 seedlings (Helling-Jughans, 2017) and 14,000 seedlings per ha (Energiepflanzen.com, 2020a); Silphium at €590 per kg of seeds and 2.5 kg seeds per ha (Energiepflanzen.com, 2020b)
- Planting cost: Sida same cost as potato planting at €142.7 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize (ABC Ltd, 2019a).
- Fertiliser cost (establishment): calculated using cost of N, P_2O_5, K_2O (€ kg^{-1}) of 0.60, 0.97, 0.32 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020).
- Fertiliser application cost (establishment): all crops x1 extra for variable rate application at €20.0 ha^{-1} and 1.2 h ha^{-1} (assumed same time as wheat).
- Spray application cost (establishment): considering x4 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus; x2 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at €45.5 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at €45.5 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser cost (recurring): calculated using cost of N, P_2O_5, K_2O (€ kg^{-1}) of 0.60, 0.97, 0.32 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB (2019); Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al*., (2020), only applied on harvest years.
- Fertiliser application cost (recurring): all crops x1 extra for variable rate application at €20.0 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat), only applied on harvest years.
- Spray application cost (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at €11.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

Table E.8 – Input data for SRC and Miscanthus in Poland, obtained by default from ABC Ltd (2019a) unless otherwise indicated. Default 4% discount rate.

d) Data for Poland							**Reference**
			SRC	**Miscanthus**	**Sida**	**Silphium**	
Description	Rotation	(years)	16	16	16	16	
	Year of first harvest	(years)	4	1	1	2	
	Interval between harvest	(years)	3	1	1	1	
Production	Yield per harvest	(odt ha^{-1})	25.0 [i]	12.5 [ii]	11.6 [iii]	16.3 [iii]	[i] (Bury, 2020) [ii] (Witzel and Finger, 2016) [iii] See section **Error! Reference source not found.**
Prices	Biomass	(PLN t^{-1})	269.5 [iv]	269.5 [iv]	269.5 [iv]	269.5 [iv]	
	PAC	(PLN ha^{-1})	471.6 [i]	471.6 [i]	471.6 [i]	471.6 [i]	[i] (Bury, 2020)
Establishment costs	Planting material *	(PLN ha^{-1})	3,675.0	63,000.0	24,010.0	7,227.5	
	Planting *	(PLN ha^{-1})	450.0	450.0	450.0	220.5	
	Ground preparation	(PLN ha^{-1})	812.0	812.0	812.0	812.0	
	Fertilisers *	(PLN ha^{-1})	988.8	1023.2	1023.2	1023.2	
	Fertiliser application	(PLN ha^{-1})	327.0 [i]	327.0 [i]	327.0 [i]	327.0 [i]	[i] (Bury, 2020)
	Sprays	(PLN ha^{-1})	980.0	588.0	588.0 [iv]	588.0 [iv]	[iv] Assumed same as Miscanthus
	Spray application *	(€ ha^{-1})	197.6	197.6	98.8	98.8	
	Mechanical weeding *	(PLN ha^{-1})	-	-	591.7	591.7	
	Cutback end first year	(PLN ha^{-1})	245.0	98.0 [v]	98.0 [iv]	98.0 [iv]	[v] (ABC Ltd, 2019b) [iv] Assumed same as Miscanthus
Recurring costs	Mechanical weeding *	(PLN ha^{-1})	-	-	788.9	788.9	
	Fertilisers *	(PLN ha^{-1})	988.8	1023.2	1023.2	1023.2	
	Fertiliser application *	(PLN ha^{-1})	327.0 [i]	327.0 [i]	327.0 [i]	327.0 [i]	
	Sprays	(PLN ha^{-1})	490.0 [vi]	294.0 [vi]	-	-	[vi] Assumed half cost of sprays (establishment)
	Spray application *	(PLN ha^{-1})	197.6	197.6	-	-	
	Harvesting	(PLN ha^{-1})	805.0 [i]	-	490.0 [vii]	-	[i] (Bury, 2020) [vii] Assumed same as forage maize harvesting only (ABC Ltd, 2019a)
	Mowing and baling	(PLN ha^{-1})	-	650.0 [i]	-	-	[i] (Bury, 2020)
	Harvesting and clamping	(PLN ha^{-1})	-	-	-	857.5 [viii]	[viii] Assumed same as forage maize full harvesting operation (ABC Ltd, 2019a)
Decommissioning costs	Decommissioning	(PLN ha^{-1})	2,100.0 [i]	500.0 [i]	500.0 [i]	500.0 [i]	[i] (Bury, 2020)

* Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd (ABC Ltd, 2019b) unless indicated otherwise:

- Planting material cost: considering SRC at PLN0.245 unit^{-1} (Bury, 2020) and 15,000 units ha^{-1}; Miscanthus at PLN4.5 unit^{-1} (Bury, 2020) and 14,000 unit ha^{-1}; Sida at €350 per 1,000 seedlings (Helling-Jughans, 2017) and 14,000 seedlings per ha (Energiepflanzen.com, 2020a); Silphium at €590 per kg of seeds and 2.5 kg seeds per ha (Energiepflanzen.com, 2020b)
- Planting cost: SRC PLN812.0 ha^{-1} at 1.0 h ha^{-1}; Miscanthus PLN812.0 ha^{-1} at 1.0 h ha^{-1}; Sida same cost as potato planting at PLN812.0 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize (ABC Ltd, 2019a).
- Ground preparation cost: SRC PLN812.0 ha^{-1} at 5.0 h ha^{-1}; Miscanthus PLN812.0 ha^{-1} at 5.0 h ha^{-1}; Sida PLN812.0 ha^{-1} and 6.0 h ha^{-1}; Silphium PLN812.0 ha^{-1} and 6.0 h ha^{-1}
- Fertiliser cost (establishment): calculated using cost of N, P_2O_5, K_2O (PLN kg^{-1}) of 3.44, 4.47, 2.68 and fertilising rates for SRC – 90 (AHDB, 2019), 80, 120 (Bury, 2020) and Miscanthus – 100, 80, 120 (Bury, 2020); Sida – 100, 80, 120 (Bury, 2020) and Silphium – 120, 80, 120 (Bury, 2020).
- Fertiliser application costs (establishment): PLN327.0 (Bury, 2020) and 1.2 h ha^{-1} (assumed same time as wheat)
- Spray application cost (establishment): x4 spraying (based on 200 l/ha & 24m boom) at PLN49.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus; x2 spraying (based on 200 l/ha & 24m boom) at PLN49.4 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at PLN197.2 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at PLN197.3 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser cost (recurring): calculated using cost of N, P_2O_5, K_2O (PLN kg^{-1}) of 3.44, 4.47, 2.68 and fertilising rates for SRC – 90 (AHDB, 2019), 80, 120 (Bury, 2020) and Miscanthus – 100, 80, 120 (Bury, 2020); Sida – 100, 80, 120 (Bury, 2020) and Silphium – 120, 80, 120 (Bury, 2020), only applied on harvest years.
- Fertiliser application cost (recurring): PLN327.0 (Bury, 2020) and 0.3 h ha^{-1} (assumed same time as wheat)
- Spray application cost (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at PLN49.4 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

E.2.1 Yield profiles

a) Miscanthus

Miscanthus average DM yield was extracted from Witzel and Finger (2016). Using data from ADAS (2003) the average yield from year 1 to 3 was obtained and the yield profile and yield indexes were calculated:

Table E.9 – Average DM yield of Miscanthus from years 1 to 3.

Site	**Year**		
	1	**2**	**3**
Buckfast Abbey			14.9
Arthur Rickwood			16.8
Rosemaund			13.6
Brigets	0.8	7.9	15.2
High Mowthorpe	0.5	1.7	4.6
Gleadthorpe	0.6	2.2	4.6
Boxworth	0.5	3.9	8
Average	**0.60**	**3.93**	**11.10**

Table E.10 – Miscanthus yield profile.

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Annual yield	0.60	3.93	11.10	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54	12.54
Yield index	0.05	0.31	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

b) Sida

Average DM yields for Sida were extracted from the literature and the total average was calculated as 11.6 t DM ha^{-1}, data that was analysed for outliers using a box plot diagram. Using data from the literature the average yield from year 1 to 3 was obtained (Figure E.1) and the yield profile and yield indexes were calculated.

Author	Average
Borkowska (2007)	17.5
Borkowska and Molas (2013)	13.0
Borkowska *et al*. (2009)	8.4
Jankowski *et al*. (2019)	4.75
Matyka and Kus (2018)	14.0
Krzyzaniak *et al*. (2018)	4.32
Szwaja *et al*. (2019)	10.0
Tilvikiene *et al*. (2020)	12.0
Feledyn-Szewczyk *et al*. (2019)	17.7
Feledyn-Szewczyk *et al*. (2019)	14.5
Total average	**11.6**

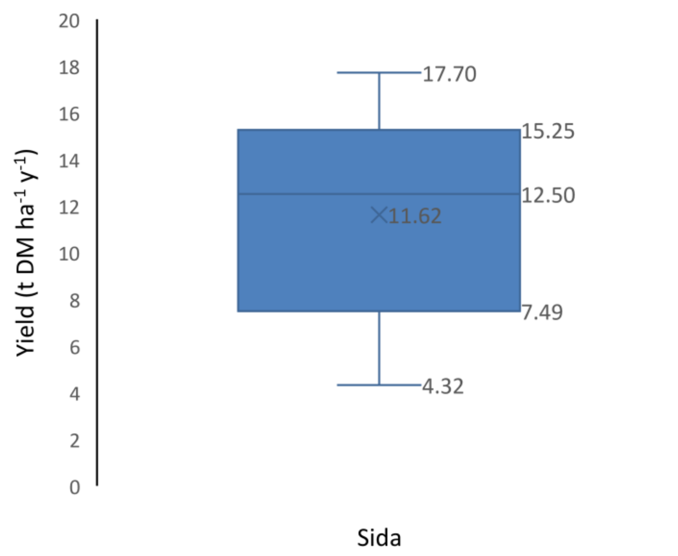


Figure E.1 - Total average DM yield (left) and box plot diagram of average yields (right) from *Sida hermaphrodita* (L.) Rusby.

Table E.11 – Average DM yield of *Sida hermaphrodita* (L.) Rusby from years 1 to 3.

Author	**Year**		
	1	**2**	**3**
Borkowska et al., 2009	2.79	8.36	11.08
von Gehren et al., 2019 (combustion)	1.55	8.4	13.75
von Gehren., 2019 (biogas)	1.8	8.05	7.95
Average	**2.05**	**8.27**	**10.93**

Table E.12 – *Sida hermaphrodita* (L.) Rusby yield profile.

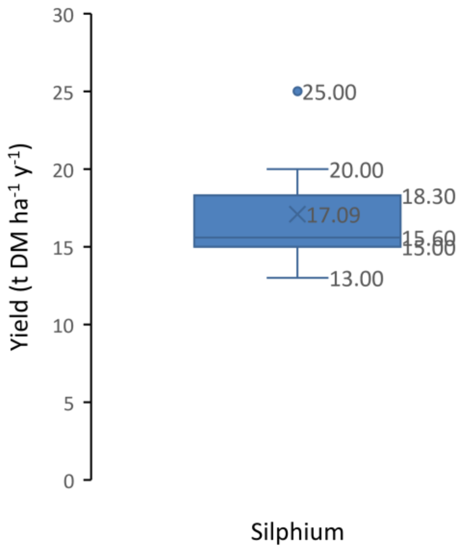
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Yield profile	2.05	8.27	10.93	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62
Yield indexes	0.18	0.71	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

c) Silphium

Average DM yields for Silphium were extracted from the literature and the total average was calculated as 17.1 t DM ha^{-1}, data that was analysed for outliers using a box plot diagram, removing one data from the set, and obtaining a final average of 16.3 t DM ha^{-1}. Using data from the literature the average yield of from year 1 to 3 was obtained and the yield profile and yield indexes were calculated.

Author	Average
Ustak et al., 2018	15.0
Jasinskas et al., 2014	13.0
von Cossel et al., 2020	15.0
Siaudinis et al., 2012	15.6
Frolich et al., 2016	15.0
Wever et al., 2019	15.5
Conrad 2015	17.6
Pichard 2012	18.0
Ruidisch et al., 2015	18.3
Vetter et al., 2010	20.0
Zizelberg et al., 2016	25.0
Total average	**17.1**

(a)



(b)

Author	Average
Ustak et al., 2018	15.0
Jasinskas et al., 2014	13.0
von Cossel et al., 2020	15.0
Siaudinis et al., 2012	15.6
Frolich et al., 2016	15.0
Wever et al., 2019	15.5
Conrad 2015	17.6
Pichard 2012	18.0
Ruidisch et al., 2015	18.3
Vetter et al., 2010	20.0
Total average	**16.3**

(c)

Figure E.2 - Total average DM yield (a), box plot diagram of average yields (b), total average DM yield with outliers removed (c) of *Silphium perfoliatum* L..

Table E.13 – Average DM yield of *Silphium perfoliatum* L. from years 1 to 3.

Author	Year			
	1	**2**	**3**	**4**
Siaudinis et al., 2015	0.0	7.0	13.1	13.5
Siaudinis et al., 2019	0.0	5.5	12.9	12
von Cossel et al., 2019	0.0	17.3	18.1	21.7
Average	0.0	9.93	14.70	15.73

Table E.14 – *Silphium perfoliatum* L. yield profile.

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Annual yield	0.00	9.93	14.70	15.73	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30	16.30
Yield index	0.00	0.61	0.90	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

E.3 Cash Flows

E.3.1 United Kingdom

Table E.15 – Cash flow of the arable rotation in the UK.

ARABLE ROTATION															
Year	**Crop**	**Yield**	**Price**	**SFP**	**Variable Costs**	**Fixed Costs**	**Total Costs**	**Crop revenue without SFP**	**Crop revenue with SFP**	**Net margin without SFP**	**Net margin with SFP**	**Discounted Net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative net margin without SFP**	**Discounted cumulative net margin with SFP**
		(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	Wheat	8.25	162.00	220.00	684.46	841.32	1525.78	1336.50	1556.50	-189.28	30.72	64.22	284.22	64.22	284.22
2	Sugar beet	78.00	27.16	220.00	793.84	841.03	1634.87	2118.48	2338.48	483.61	703.61	465.01	676.55	529.23	960.77
3	Maize	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	188.87	392.28	718.10	1353.04
4	OSR	3.50	335.00	220.00	541.76	621.47	1163.23	1172.50	1392.50	9.27	229.27	94.92	290.49	813.02	1643.54
5	Oats	6.30	140.00	220.00	418.55	773.66	1192.21	882.00	1102.00	-310.21	-90.21	-55.74	132.32	757.28	1775.85
6	Wheat	8.25	162.00	220.00	684.46	841.32	1525.78	1336.50	1556.50	-189.28	30.72	52.78	233.60	810.06	2009.46
7	Sugar beet	78.00	27.16	220.00	793.84	841.03	1634.87	2118.48	2338.48	483.61	703.61	382.21	556.08	1192.26	2565.54
8	Maize	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	155.24	322.42	1347.50	2887.96
9	OSR	3.50	335.00	220.00	541.76	621.47	1163.23	1172.50	1392.50	9.27	229.27	78.01	238.77	1425.52	3126.72
10	Oats	6.30	140.00	220.00	418.55	773.66	1192.21	882.00	1102.00	-310.21	-90.21	-45.81	108.75	1379.70	3235.48
11	Wheat	8.25	162.00	220.00	684.46	841.32	1525.78	1336.50	1556.50	-189.28	30.72	43.38	192.01	1423.09	3427.48
12	Sugar beet	78.00	27.16	220.00	793.84	841.03	1634.87	2118.48	2338.48	483.61	703.61	314.15	457.05	1737.23	3884.54
13	Maize	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	127.60	265.01	1864.83	4149.54
14	OSR	3.50	335.00	220.00	541.76	621.47	1163.23	1172.50	1392.50	9.27	229.27	64.12	196.25	1928.95	4345.79
15	Oats	6.30	140.00	220.00	418.55	773.66	1192.21	882.00	1102.00	-310.21	-90.21	-37.66	89.39	1891.29	4435.18
16	Wheat	8.25	162.00	220.00	684.46	841.32	1525.78	1336.50	1556.50	-189.28	30.72	35.66	157.81	1926.95	4592.99

Table E.16 – Cash flow of SRC in the UK.

SRC															
Year	**Yield**	**Price**	**SFP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without SFP**	**Crop revenue with SFP**	**Net margin without SFP**	**Net margin with SFP**	**Discounted net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative Net margin without SFP**	**Discounted cumulative Net margin with SFP**
	(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	0.00	55.00	220.00	1642.41	0.00		1642.41	0.00	220.00	-1642.41	-1422.41	-1642.41	-1422.41	-1642.41	-1422.41
2	0.00	55.00	220.00		140.30		140.30	0.00	220.00	-140.30	79.70	-134.90	76.63	-1777.31	-1345.77
3	0.00	55.00	220.00		140.30		140.30	0.00	220.00	-140.30	79.70	-129.72	73.69	-1907.02	-1272.08
4	30.00	55.00	220.00		592.41		592.41	1650.00	1870.00	1057.60	1277.60	940.20	1135.78	-966.83	-136.31
5	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	188.06	-966.83	51.75
6	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	180.82	-966.83	232.57
7	30.00	55.00	220.00		592.41		592.41	1650.00	1870.00	1057.60	1277.60	835.83	1009.70	-130.99	1242.28
8	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	167.18	-130.99	1409.46
9	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	160.75	-130.99	1570.21
10	30.00	55.00	220.00		592.41		592.41	1650.00	1870.00	1057.60	1277.60	743.05	897.62	612.06	2467.83
11	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	148.62	612.06	2616.46
12	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	142.91	612.06	2759.36
13	30.00	55.00	220.00		592.41		592.41	1650.00	1870.00	1057.60	1277.60	660.57	797.98	1272.63	3557.35
14	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	132.13	1272.63	3689.47
15	0.00	55.00	220.00		0.00		0.00	0.00	220.00	0.00	220.00	0.00	127.04	1272.63	3816.52
16	30.00	55.00	220.00		592.41	170.00	762.41	1650.00	1870.00	887.60	1107.60	492.85	615.01	1765.48	4431.52

Table E.17 – Cash flow of Miscanthus in the UK.

MISCANTHUS

Year	Yield	Price	SFP	Establishment Costs	Recurring Costs	Decommissioning Costs	Total Costs	Crop revenue without SFP	Crop revenue with SFP	Net margin without SFP	Net margin with SFP	Discounted net margin without SFP	Discounted net margin with SFP	Discounted cumulative net margin without SFP	Discounted cumulative net margin with SFP
	(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	0.60	55.00	220.00	1993.81	0.00		1993.81	33.00	253.00	-1960.81	-1740.81	-1960.81	-1740.81	-1960.81	-1740.81
2	3.93	55.00	220.00		334.11		334.11	215.88	435.88	-118.24	101.76	-113.69	97.85	-2074.50	-1642.96
3	11.10	55.00	220.00		334.11		334.11	610.50	830.50	276.39	496.39	255.54	458.94	-1818.97	-1184.02
4	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	405.28	600.86	-1413.68	-583.16
5	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	389.69	577.75	-1023.99	-5.41
6	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	374.71	555.53	-649.28	550.12
7	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	360.29	534.16	-288.99	1084.28
8	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	346.44	513.62	57.45	1597.90
9	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	333.11	493.86	390.56	2091.77
10	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	320.30	474.87	710.87	2566.64
11	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	307.98	456.61	1018.85	3023.24
12	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	296.14	439.04	1314.98	3462.29
13	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	284.75	422.16	1599.73	3884.45
14	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	273.79	405.92	1873.52	4290.37
15	12.54	55.00	220.00		233.81		233.81	689.70	909.70	455.89	675.89	263.26	390.31	2136.79	4680.67
16	12.54	55.00	220.00		233.81	170.00	403.81	689.70	909.70	285.89	505.89	158.74	280.90	2295.53	4961.58

Table E.18 – Cash flow of forage maize in the UK.

FORAGE MAIZE														
Year	**Yield**	**Price**	**SFP**	**Variable Costs**	**Fixed Costs**	**Total Costs**	**Crop revenue without SFP**	**Crop revenue with SFP**	**Net margin without SFP**	**Net margin with SFP**	**Discounted net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative net margin without SFP**	**Discounted cumulative net margin with SFP**
	(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	204.29	424.29	204.29	424.29
2	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	196.43	407.97	400.71	832.25
3	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	188.87	392.28	589.59	1224.53
4	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	181.61	377.19	771.19	1601.71
5	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	174.62	362.68	945.82	1964.40
6	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	167.91	348.73	1113.73	2313.13
7	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	161.45	335.32	1275.17	2648.45
8	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	155.24	322.42	1430.41	2970.87
9	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	149.27	310.02	1579.68	3280.89
10	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	143.53	298.10	1723.21	3578.98
11	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	138.01	286.63	1861.22	3865.62
12	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	132.70	275.61	1993.92	4141.22
13	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	127.60	265.01	2121.51	4406.23
14	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	122.69	254.81	2244.20	4661.05
15	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	117.97	245.01	2362.17	4906.06
16	12.00	107.10	220.00	528.52	552.40	1080.92	1285.20	1505.20	204.29	424.29	113.43	235.59	2475.60	5141.65

Table E.19 – Cash flow of *Sida hermaphrodita* (L.) Rusby in the UK.

SIDA															
Year	**Yield**	**Price**	**SFP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without SFP**	**Crop revenue with SFP**	**Net margin without SFP**	**Net margin with SFP**	**Discounted net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative net margin without SFP**	**Discounted cumulative net margin with SFP**
	(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	2.05	55.00	220.00	5106.09	0.00		5106.09	112.57	332.57	-4993.53	-4773.53	-4993.53	-4773.53	-4993.53	-4773.53
2	8.27	55.00	220.00		439.04		439.04	454.85	674.85	15.81	235.81	15.20	226.74	-4978.33	-4546.79
3	10.93	55.00	220.00		439.04		439.04	600.97	820.97	161.92	381.92	149.71	353.11	-4828.62	-4193.68
4	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	320.83	516.41	-4507.78	-3677.26
5	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	308.49	496.55	-4199.29	-3180.71
6	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	296.63	477.45	-3902.66	-2703.26
7	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	285.22	459.09	-3617.44	-2244.17
8	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	274.25	441.43	-3343.20	-1802.74
9	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	263.70	424.45	-3079.49	-1378.29
10	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	253.56	408.13	-2825.94	-970.16
11	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	243.81	392.43	-2582.13	-577.73
12	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	234.43	377.34	-2347.70	-200.40
13	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	225.41	362.82	-2122.29	162.43
14	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	216.74	348.87	-1905.54	511.30
15	11.62	55.00	220.00		278.04		278.04	638.94	858.94	360.89	580.89	208.41	335.45	-1697.14	846.75
16	11.62	55.00	220.00		278.04	170.00	448.04	638.94	858.94	190.89	410.89	106.00	228.15	-1591.14	1074.90

Table E.20 – Cash flow of *Silphium perfoliatum* L. in the UK.

SILPHIUM															
Year	**Yield**	**Price**	**SFP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without SFP**	**Crop revenue with SFP**	**Net margin without SFP**	**Net margin with SFP**	**Discounted net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative net margin without SFP**	**Discounted cumulative net margin with SFP**
	(t ha^{-1})	(£ t^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})	(£ ha^{-1})
1	0.00	55.00	220.00	1992.28	0.00		1992.28	0.00	220.00	-1992.28	-1772.28	-1992.28	-1772.28	-1992.28	-1772.28
2	9.93	55.00	220.00		529.78		529.78	546.33	766.33	16.55	236.55	15.91	227.45	-1976.37	-1544.83
3	14.70	55.00	220.00		529.78		529.78	808.50	1028.50	278.72	498.72	257.69	461.09	-1718.68	-1083.74
4	15.73	55.00	220.00		368.78		368.78	865.33	1085.33	496.55	716.55	441.43	637.01	-1277.24	-446.72
5	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	451.10	639.15	-826.15	192.43
6	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	433.75	614.57	-392.40	807.00
7	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	417.06	590.93	24.66	1397.93
8	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	401.02	568.20	425.68	1966.13
9	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	385.60	546.35	811.28	2512.48
10	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	370.77	525.34	1182.05	3037.82
11	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	356.51	505.13	1538.56	3542.95
12	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	342.80	485.70	1881.35	4028.66
13	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	329.61	467.02	2210.96	4495.68
14	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	316.93	449.06	2527.90	4944.74
15	16.30	55.00	220.00		368.78		368.78	896.50	1116.50	527.72	747.72	304.74	431.79	2832.64	5376.53
16	16.30	55.00	220.00		368.78	170.00	538.78	896.50	1116.50	357.72	577.72	198.63	320.79	3031.27	5697.31

E.3.2 Italy

Table E.21 – Cash flow of the arable rotation in Italy.

ARABLE ROTATION															
Year	**Crop**	**Yield**	**Price**	**CAP**	**Variable Costs**	**Fixed Costs**	**Total Costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
		($t\ ha^{-1}$)	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	Wheat	5.50	210.00	330.00	622.35	943.00	1565.35	1441.46	1771.46	-123.89	206.11	-123.89	206.11	-123.89	206.11
2	Sunflower	2.10	235.55	330.00	255.08	778.68	1033.76	494.66	824.66	-539.10	-209.10	-523.40	-203.01	-647.30	3.09
3	Forage maize	9.40	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-350.55	-39.49	-997.84	-36.40
4	OSR	2.60	196.99	330.00	327.77	704.91	1032.69	622.35	952.35	-410.34	-80.34	-375.52	-73.52	-1373.36	-109.92
5	Soya	3.10	310.75	330.00	300.33	547.62	847.95	963.33	1293.33	115.37	445.37	102.51	395.71	-1270.85	285.79
6	Wheat	5.50	210.00	330.00	622.35	943.00	1565.35	1441.46	1771.46	-123.89	206.11	-106.87	177.79	-1377.73	463.58
7	Sunflower	2.10	235.55	330.00	255.08	778.68	1033.76	494.66	824.66	-539.10	-209.10	-451.49	-175.12	-1829.22	288.46
8	Forage maize	9.40	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-302.38	-34.06	-2131.60	254.39
9	OSR	2.60	196.99	330.00	327.77	704.91	1032.69	622.35	952.35	-410.34	-80.34	-323.93	-63.42	-2455.53	190.97
10	Soya	3.10	310.75	330.00	300.33	547.62	847.95	963.33	1293.33	115.37	445.37	88.42	341.34	-2367.10	532.31
11	Wheat	5.50	210.00	330.00	622.35	943.00	1565.35	1441.46	1771.46	-123.89	206.11	-92.19	153.36	-2459.29	685.68
12	Sunflower	2.10	235.55	330.00	255.08	778.68	1033.76	494.66	824.66	-539.10	-209.10	-389.46	-151.06	-2848.75	534.62
13	Forage maize	9.40	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-260.84	-29.38	-3109.59	505.23
14	OSR	2.60	196.99	330.00	327.77	704.91	1032.69	622.35	952.35	-410.34	-80.34	-279.42	-54.71	-3389.01	450.52
15	Soya	3.10	310.75	330.00	300.33	547.62	847.95	963.33	1293.33	115.37	445.37	76.27	294.44	-3312.74	744.97
16	Wheat	5.50	210.00	330.00	622.35	943.00	1565.35	1441.46	1771.46	-123.89	206.11	-79.52	132.29	-3392.26	877.26

Table E.22 – Cash flow of SRC in Italy.

SRC															
Year	Yield	Price	CAP	Establishment costs	Recurring costs	Decommissioning costs	Total Costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	0.00	43.75	330.00	1887.23	0.00		1887.23	0.00	330.00	-1887.23	-1557.23	-1887.23	-1557.23	-1887.23	-1557.23
2	26.00	43.75	330.00		748.27		748.27	1137.50	1467.50	389.23	719.23	377.89	698.28	-1509.34	-858.95
3	0.00	43.75	330.00		110.54		110.54	0.00	330.00	-110.54	219.46	-104.19	206.86	-1613.54	-652.09
4	26.00	43.75	330.00		637.73		637.73	1137.50	1467.50	499.77	829.77	457.36	759.35	-1156.18	107.26
5	0.00	43.75	330.00		0.00		0.00	0.00	330.00	0.00	330.00	0.00	293.20	-1156.18	400.46
6	26.00	43.75	330.00		637.73		637.73	1137.50	1467.50	499.77	829.77	431.10	715.76	-725.08	1116.23
7	0.00	43.75	330.00		0.00		0.00	0.00	330.00	0.00	330.00	0.00	276.37	-725.08	1392.60
8	26.00	43.75	330.00		637.73		637.73	1137.50	1467.50	499.77	829.77	406.36	674.68	-318.72	2067.27
9	0.00	43.75	330.00		0.00		0.00	0.00	330.00	0.00	330.00	0.00	260.51	-318.72	2327.78
10	26.00	43.75	330.00		637.73		637.73	1137.50	1467.50	499.77	829.77	383.03	635.95	64.31	2963.73
11	0.00	43.75			0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	64.31	2963.73
12	26.00	43.75			637.73		637.73	1137.50	1137.50	499.77	499.77	361.04	361.04	425.35	3324.77
13	0.00	43.75			0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	425.35	3324.77
14	26.00	43.75			637.73		637.73	1137.50	1137.50	499.77	499.77	340.32	340.32	765.67	3665.08
15	0.00	43.75			0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	765.67	3665.08
16	26.00	43.75			637.73	500.00	1137.73	1137.50	1137.50	-0.23	-0.23	-0.15	-0.15	765.52	3664.94

Table E.23 – Cash flow of Miscanthus in Italy.

MISCANTHUS															
Year	Yield	Price	SFP	Establishment costs	Recurring costs	Decommissioning costs	Total Costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha-1)	(€ t-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)	(€ ha-1)
1	0.60	43.75	330.00	2254.82	0.00		2254.82	26.25	356.25	-2228.57	-1898.57	-2228.57	-1898.57	-2228.57	-1898.57
2	3.93	43.75	330.00		536.86		536.86	171.72	501.72	-365.14	-35.14	-354.51	-34.12	-2583.08	-1932.69
3	11.10	43.75	330.00		536.86		536.86	485.63	815.63	-51.24	278.76	-48.30	262.76	-2631.38	-1669.93
4	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	114.49	416.48	-2516.89	-1253.45
5	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	111.15	404.35	-2405.74	-849.10
6	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	107.91	392.57	-2297.83	-456.52
7	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	104.77	381.14	-2193.06	-75.38
8	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	101.72	370.04	-2091.34	294.66
9	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	98.76	359.26	-1992.58	653.92
10	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	95.88	348.80	-1896.70	1002.72
11	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	93.09	338.64	-1803.61	1341.35
12	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	90.38	328.78	-1713.24	1670.13
13	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	87.74	319.20	-1625.49	1989.33
14	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	85.19	309.90	-1540.30	2299.23
15	12.54	43.75	330.00		423.52		423.52	548.63	878.63	125.10	455.10	82.71	300.88	-1457.60	2600.11
16	12.54	43.75	330.00		423.52	192.10	615.62	548.63	878.63	-67.00	263.00	-43.00	168.81	-1500.60	2768.92

Table E.24 – Cash flow of forage maize in Italy.

FORAGE MAIZE

Year	Yield	Price	CAP	Variable costs	Fixed costs	Total Costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	($t\ ha^{-1}$)	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-371.90	-41.90	-371.90	-41.90
2	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-361.06	-40.68	-732.96	-82.57
3	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-350.55	-39.49	-1083.51	-122.06
4	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-340.34	-38.34	-1423.84	-160.40
5	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-330.42	-37.22	-1754.27	-197.62
6	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-320.80	-36.14	-2075.07	-233.76
7	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-311.46	-35.09	-2386.52	-268.85
8	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-302.38	-34.06	-2688.91	-302.92
9	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-293.58	-33.07	-2982.49	-335.99
10	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-285.03	-32.11	-3267.51	-368.10
11	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-276.73	-31.17	-3544.24	-399.27
12	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-268.67	-30.27	-3812.90	-429.54
13	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-260.84	-29.38	-4073.74	-458.92
14	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-253.24	-28.53	-4326.99	-487.45
15	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-245.87	-27.70	-4572.85	-515.15
16	9.4	94.29	330.00	566.71	691.47	1258.18	886.29	1216.29	-371.90	-41.90	-238.71	-26.89	-4811.56	-542.04

Table E.25 – Cash flow of *Sida hermaphrodita* (L.) Rusby in Italy.

SIDA															
Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	1.76	43.75	330.00	5743.76	113.00		5856.76	77.08	407.08	-5779.68	-5449.68	-5779.68	-5449.68	-5779.68	-5449.68
2	7.12	43.75	330.00		497.93		497.93	311.45	641.45	-186.48	143.52	-181.05	139.34	-5960.73	-5310.34
3	9.41	43.75	330.00		497.93		497.93	411.50	741.50	-86.43	243.57	-81.47	229.59	-6042.20	-5080.76
4	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	111.19	413.18	-5931.01	-4667.57
5	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	107.95	401.15	-5823.07	-4266.42
6	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	104.80	389.47	-5718.26	-3876.96
7	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	101.75	378.12	-5616.51	-3498.84
8	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	98.79	367.11	-5517.72	-3131.73
9	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	95.91	356.42	-5421.81	-2775.31
10	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	93.12	346.03	-5328.69	-2429.28
11	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	90.41	335.96	-5238.29	-2093.32
12	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	87.77	326.17	-5150.52	-1767.15
13	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	85.22	316.67	-5065.30	-1450.48
14	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	82.73	307.45	-4982.57	-1143.03
15	10.00	43.75	330.00		316.00		316.00	437.50	767.50	121.50	451.50	80.32	298.49	-4902.24	-844.54
16	10.00	43.75	330.00		203.00	192.10	395.10	437.50	767.50	42.40	372.40	27.21	239.03	-4875.03	-605.51

Table E.26 – Cash flow of *Silphium perfoliatum* L. in Italy.

SILPHIUM															
Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	0.00	43.75	330.00	2769.69	0.00		2769.69	0.00	330.00	-2769.69	-2439.69	-2769.69	-2439.69	-2769.69	-2439.69
2	9.14	43.75	330.00		600.47		600.47	399.92	729.92	-200.55	129.45	-194.70	125.68	-2964.39	-2314.00
3	13.53	43.75	330.00		600.47		600.47	591.83	921.83	-8.64	321.36	-8.14	302.92	-2972.53	-2011.09
4	14.48	43.75	330.00		418.54		418.54	633.44	963.44	214.90	544.90	196.66	498.66	-2775.87	-1512.43
5	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	211.20	504.40	-2564.67	-1008.03
6	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	205.05	489.71	-2359.62	-518.31
7	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	199.08	475.45	-2160.54	-42.87
8	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	193.28	461.60	-1967.26	418.73
9	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	187.65	448.16	-1779.61	866.89
10	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	182.19	435.10	-1597.42	1301.99
11	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	176.88	422.43	-1420.54	1724.42
12	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	171.73	410.13	-1248.82	2134.55
13	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	166.73	398.18	-1082.09	2532.73
14	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	161.87	386.58	-920.22	2919.31
15	15.00	43.75	330.00		418.54		418.54	656.25	986.25	237.71	567.71	157.15	375.32	-763.07	3294.64
16	15.00	43.75	330.00		418.54	192.10	610.64	656.25	986.25	45.61	375.61	29.28	241.09	-733.79	3535.73

E.3.3 Germany

Table E.27 – Cash flow of the arable rotation in Germany.

ARABLE ROATION															
Year	**Crop**	**Yield**	**Price**	**CAP**	**Variable Costs**	**Fixed Costs**	**Total Costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted Net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
		($t\ ha^{-1}$)	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	Wheat	7.45	193.70	175.95	671.93	969.47	1641.40	1729.52	1905.47	88.12	264.07	88.12	264.07	88.12	264.07
2	Sugar beet	63.10	26.00	175.95	819.30	996.95	1816.26	1640.60	1816.55	-175.66	0.29	-168.90	0.28	-80.78	264.35
3	Forage maize	8.14	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	256.47	419.14	175.68	683.49
4	OSR	3.30	345.10	175.95	619.75	710.24	1329.98	1249.01	1424.96	-80.98	94.97	-71.99	84.43	103.70	767.92
5	Oats	4.11	154.80	175.95	468.64	888.76	1357.40	913.08	1089.03	-444.32	-268.37	-379.81	-229.40	-276.11	538.52
6	Wheat	7.45	193.70	175.95	671.93	969.47	1641.40	1729.52	1905.47	88.12	264.07	72.43	217.04	-203.68	755.56
7	Sugar beet	63.10	26.00	175.95	819.30	996.95	1816.26	1640.60	1816.55	-175.66	0.29	-138.83	0.23	-342.51	755.79
8	Forage maize	8.14	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	210.80	344.50	-131.71	1100.30
9	OSR	3.30	345.10	175.95	619.75	710.24	1329.98	1249.01	1424.96	-80.98	94.97	-59.17	69.40	-190.88	1169.70
10	Oats	4.11	154.80	175.95	468.64	888.76	1357.40	913.08	1089.03	-444.32	-268.37	-312.17	-188.55	-503.05	981.14
11	Wheat	7.45	193.70	175.95	671.93	969.47	1641.40	1729.52	1905.47	88.12	264.07	59.53	178.40	-443.53	1159.54
12	Sugar beet	63.10	26.00	175.95	819.30	996.95	1816.26	1640.60	1816.55	-175.66	0.29	-114.10	0.19	-557.63	1159.73
13	Forage maize	8.14	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	173.26	283.16	-384.37	1442.88
14	OSR	3.30	345.10	175.95	619.75	710.24	1329.98	1249.01	1424.96	-80.98	94.97	-48.63	57.04	-433.00	1499.92
15	Oats	4.11	154.80	175.95	468.64	888.76	1357.40	913.08	1089.03	-444.32	-268.37	-256.58	-154.98	-689.59	1344.95
16	Wheat	7.45	193.70	175.95	671.93	969.47	1641.40	1729.52	1905.47	88.12	264.07	48.93	146.63	-640.66	1491.57

Table E.28 – Cash flow of SRC in Germany.

SRC															
Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total Costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	0.00	72.00	175.95	2498.30	0.00		2498.30	0.00	175.95	-2498.30	-2322.35	-2498.30	-2322.35	-2498.30	-2322.35
2	0.00	72.00	175.95		158.56		158.56	0.00	175.95	-158.56	17.39	-152.46	16.72	-2650.76	-2305.63
3	0.00	72.00	175.95		158.56		158.56	0.00	175.95	-158.56	17.39	-146.60	16.08	-2797.36	-2289.55
4	30.00	72.00	175.95		704.86		704.86	2160.00	2335.95	1455.14	1631.09	1293.62	1450.03	-1503.74	-839.52
5	0.00	72.00	175.95		45.56		45.56	0.00	175.95	-45.56	130.39	-38.95	111.46	-1542.69	-728.06
6	0.00	72.00	175.95		45.56		45.56	0.00	175.95	-45.56	130.39	-37.45	107.17	-1580.14	-620.89
7	30.00	72.00	175.95		704.86		704.86	2160.00	2335.95	1455.14	1631.09	1150.02	1289.08	-430.12	668.19
8	0.00	72.00	175.95		45.56		45.56	0.00	175.95	-45.56	130.39	-34.62	99.08	-464.74	767.27
9	0.00	72.00	175.95		45.56		45.56	0.00	175.95	-45.56	130.39	-33.29	95.27	-498.03	862.54
10	30.00	72.00	175.95		704.86		704.86	2160.00	2335.95	1455.14	1631.09	1022.36	1145.98	524.33	2008.53
11	0.00	72.00	175.95		0.00		0.00	0.00	175.95	0.00	175.95	0.00	118.87	524.33	2127.39
12	0.00	72.00	175.95		0.00		0.00	0.00	175.95	0.00	175.95	0.00	114.29	524.33	2241.69
13	30.00	72.00	175.95		659.30		659.30	2160.00	2335.95	1500.70	1676.65	937.33	1047.23	1461.67	3288.92
14	0.00	72.00	175.95		0.00		0.00	0.00	175.95	0.00	175.95	0.00	105.67	1461.67	3394.59
15	0.00	72.00	175.95		0.00		0.00	0.00	175.95	0.00	175.95	0.00	101.61	1461.67	3496.20
16	30.00	72.00	175.95		659.30	192.10	851.40	2160.00	2335.95	1308.60	1484.55	726.62	824.32	2188.29	4320.52

Table E.29 – Cash flow of Miscanthus in Germany.

MISCANTHUS

Year	Yield	Price	CAP	Establishment costs	Recurring costs	Decommissioning costs	Total costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(£ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	0.60	72.00	175.95	2224.61	0.00		2224.61	43.20	219.15	-2181.41	-2005.46	-2181.41	-2005.46	-2181.41	-2005.46
2	3.93	72.00	175.95		506.67		506.67	282.60	458.55	-224.07	-48.12	-215.45	-46.27	-2396.86	-2051.73
3	11.10	72.00	175.95		506.67		506.67	799.20	975.15	292.53	468.48	270.46	433.13	-2126.41	-1618.60
4	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	453.01	609.42	-1673.40	-1009.17
5	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	435.58	585.98	-1237.82	-423.19
6	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	418.83	563.45	-818.99	140.26
7	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	402.72	541.78	-416.27	682.03
8	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	387.23	520.94	-29.04	1202.97
9	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	372.34	500.90	343.30	1703.87
10	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	358.02	481.64	701.31	2185.51
11	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	344.25	463.11	1045.56	2648.62
12	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	331.01	445.30	1376.57	3093.92
13	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	318.28	428.17	1694.84	3522.10
14	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	306.03	411.71	2000.88	3933.80
15	12.54	72.00	175.95		393.31		393.31	902.88	1078.83	509.57	685.52	294.26	395.87	2295.14	4329.67
16	12.54	72.00	175.95		393.31	192.10	585.41	902.88	1078.83	317.47	493.42	176.28	273.98	2471.42	4603.65

Table E.30 – Cash flow of forage maize in Germany.

FORAGE MAIZE														
Year	**Yield**	**Price**	**CAP**	**Variable costs**	**Fixed costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted Net margin without CAP**	**Discounted Net margin with CAP**	**Discounted Cumulative Net margin without CAP**	**Discounted Cumulative Net margin with CAP**
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	277.39	453.34	277.39	453.34
2	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	266.73	435.91	544.12	889.25
3	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	256.47	419.14	800.59	1308.40
4	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	246.60	403.02	1047.19	1711.42
5	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	237.12	387.52	1284.31	2098.94
6	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	228.00	372.62	1512.31	2471.56
7	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	219.23	358.29	1731.54	2829.84
8	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	210.80	344.50	1942.33	3174.35
9	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	202.69	331.25	2145.02	3505.60
10	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	194.89	318.51	2339.92	3824.12
11	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	187.40	306.26	2527.32	4130.38
12	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	180.19	294.48	2707.51	4424.86
13	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	173.26	283.16	2880.77	4708.02
14	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	166.60	272.27	3047.36	4980.29
15	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	160.19	261.80	3207.55	5242.08
16	8.1	182.80	175.95	574.23	636.37	1210.60	1487.99	1663.94	277.39	453.34	154.03	251.73	3361.58	5493.81

Table E.31 – Cash flow of *Sida hermaphrodita* (L.) Rusby in Germany.

SIDA															
Year	**Yield**	**Price**	**PAC**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	2.05	72.00	175.95	5737.33	113.00		5850.33	147.36	147.36	-5702.97	-5527.02	-5702.97	-5527.02	-5702.97	-5527.02
2	8.27	72.00	175.95		491.51		491.51	595.44	595.44	103.93	279.88	99.93	269.12	-5603.04	-5257.91
3	10.93	72.00	175.95		491.51		491.51	786.72	786.72	295.21	471.16	272.94	435.62	-5330.10	-4822.29
4	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	468.36	624.78	-4861.74	-4197.51
5	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	450.35	600.75	-4411.39	-3596.76
6	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	433.03	577.65	-3978.36	-3019.11
7	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	416.37	555.43	-3561.99	-2463.68
8	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	400.36	534.07	-3161.63	-1929.62
9	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	384.96	513.53	-2776.67	-1416.09
10	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	370.15	493.77	-2406.51	-922.32
11	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	355.92	474.78	-2050.59	-447.53
12	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	342.23	456.52	-1708.37	8.99
13	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	329.07	438.96	-1379.30	447.95
14	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	316.41	422.08	-1062.89	870.03
15	11.62	72.00	175.95		309.58		309.58	836.42	836.42	526.85	702.80	304.24	405.85	-758.65	1275.88
16	11.62	72.00	175.95		196.58	192.10	388.68	836.42	836.42	447.75	623.70	248.62	346.32	-510.03	1622.20

Table E.32 – Cash flow of *Silphium perfoliatum* L. in Germany.

SILPHIUM															
Year	Yield	Price	CAP	Establishment costs	Recurring costs	Decommissioning costs	Total costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha^{-1})	(€ t^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
1	0.00	72.00	175.95	2234.48	0.00		2234.48	0.00	175.95	-2234.48	-2058.53	-2234.48	-2058.53	-2234.48	-2058.53
2	9.93	72.00	175.95		590.26		590.26	715.20	891.15	124.94	300.89	120.13	289.31	-2114.35	-1769.22
3	14.70	72.00	175.95		590.26		590.26	1058.40	1234.35	468.14	644.09	432.82	595.49	-1681.53	-1173.73
4	15.73	72.00	175.95		408.33		408.33	1132.80	1308.75	724.47	900.42	644.05	800.47	-1037.49	-373.26
5	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	654.15	804.55	-383.34	431.29
6	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	628.99	773.61	245.66	1204.90
7	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	604.80	743.86	850.46	1948.76
8	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	581.54	715.25	1432.00	2664.01
9	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	559.17	687.74	1991.17	3351.74
10	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	537.67	661.29	2528.83	4013.03
11	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	516.99	635.85	3045.82	4648.88
12	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	497.10	611.40	3542.92	5260.28
13	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	477.98	587.88	4020.90	5848.16
14	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	459.60	565.27	4480.50	6413.43
15	16.30	72.00	175.95		408.33		408.33	1173.60	1349.55	765.27	941.22	441.92	543.53	4922.42	6956.95
16	16.30	72.00	175.95		408.33	192.10	600.43	1173.60	1349.55	573.17	749.12	318.26	415.96	5240.68	7372.91

E.3.4 Poland

Table E.33 – Cash flow of the arable rotation in Poland.

ARABLE ROTATION															
Year	**Crop**	**Yield**	**Price**	**CAP**	**Variable costs**	**Fixed costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without SFP**	**Discounted net margin with SFP**	**Discounted cumulative net margin without SFP**	**Discounted cumulative net margin with SFP**
		($t\ ha^{-1}$)	($PLN\ t^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)	($PLN\ ha^{-1}$)
1	Wheat	4.60	867.00	471.64	2731.33	4055.61	6786.94	4674.20	5145.84	-2112.74	-1641.10	-2112.74	-1641.10	-2112.74	-1641.10
2	Sugar beet	56.80	120.00	471.64	3648.31	3375.81	7024.12	6816.00	7287.64	-208.12	263.52	-200.11	253.39	-2312.85	-1387.71
3	Forage maize	12.00	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2761.89	3197.95	449.04	1810.24
4	OSR	3.50	1645.00	471.64	3562.04	2542.67	6104.71	6429.50	6901.14	324.79	796.43	288.74	708.03	737.79	2518.27
5	Barley	2.50	721.00	471.64	1959.48	3608.95	5568.43	2162.50	2634.14	-3405.93	-2934.29	-2911.40	-2508.24	-2173.62	10.03
6	Wheat	4.60	867.00	471.64	2731.33	4055.61	6786.94	4674.20	5145.84	-2112.74	-1641.10	-1736.51	-1348.86	-3910.13	-1338.83
7	Sugar beet	56.80	120.00	471.64	3648.31	3375.81	7024.12	6816.00	7287.64	-208.12	263.52	-164.48	208.26	-4074.61	-1130.57
8	Forage maize	12.00	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2270.08	2628.48	-1804.53	1497.92
9	OSR	3.50	1645.00	471.64	3562.04	2542.67	6104.71	6429.50	6901.14	324.79	796.43	237.32	581.95	-1567.21	2079.86
10	Barley	2.50	721.00	471.64	1959.48	3608.95	5568.43	2162.50	2634.14	-3405.93	-2934.29	-2392.96	-2061.59	-3960.17	18.27
11	Wheat	4.60	867.00	471.64	2731.33	4055.61	6786.94	4674.20	5145.84	-2112.74	-1641.10	-1427.29	-1108.67	-5387.46	-1090.39
12	Sugar beet	56.80	120.00	471.64	3648.31	3375.81	7024.12	6816.00	7287.64	-208.12	263.52	-135.19	171.18	-5522.65	-919.22
13	Forage maize	12.00	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1865.84	2160.42	-3656.81	1241.21
14	OSR	3.50	1645.00	471.64	3562.04	2542.67	6104.71	6429.50	6901.14	324.79	796.43	195.06	478.32	-3461.75	1719.52
15	Barley	2.50	721.00	471.64	1959.48	3608.95	5568.43	2162.50	2634.14	-3405.93	-2934.29	-1966.84	-1694.48	-5428.59	25.05
16	Wheat	4.60	867.00	471.64	2731.33	4055.61	6786.94	4674.20	5145.84	-2112.74	-1641.10	-1173.13	-911.24	-6601.71	-886.20

Table E.34 – Cash flow of SRC in Poland.

SRC																
Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discount. net margin without CAP**	**Discount. net margin with CAP**	**Discount. cumulative net margin without CAP**	**Discount. cumulative net margin with CAP**
	(t ha^{-1})	(PLN t^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})
1	0.00	269.50	471.64	7477.80	0.00		7477.80	0.00	471.64	-7477.80	-7006.16	-7477.80	-7006.16	-7477.80	-7006.16
2	0.00	269.50	471.64		687.57		687.57	0.00	471.64	-687.57	-215.93	-661.12	-207.62	-8138.92	-7213.78
3	0.00	269.50	471.64		687.57		687.57	0.00	471.64	-687.57	-215.93	-635.70	-199.64	-8774.62	-7413.42
4	25.00	269.50	471.64		2318.37		2318.37	6737.50	7209.14	4419.13	4890.77	3928.59	4347.88	-4846.03	-3065.54
5	0.00	269.50	471.64		197.57		197.57	0.00	471.64	-197.57	274.07	-168.88	234.28	-5014.91	-2831.26
6	0.00	269.50	471.64		197.57		197.57	0.00	471.64	-197.57	274.07	-162.39	225.27	-5177.29	-2606.00
7	25.00	269.50	471.64		2318.37		2318.37	6737.50	7209.14	4419.13	4890.77	3492.50	3865.25	-1684.79	1259.25
8	0.00	269.50	471.64		197.57		197.57	0.00	471.64	-197.57	274.07	-150.14	208.27	-1834.93	1467.52
9	0.00	269.50	471.64		197.57		197.57	0.00	471.64	-197.57	274.07	-144.36	200.26	-1979.29	1667.79
10	25.00	269.50	471.64		2318.37		2318.37	6737.50	7209.14	4419.13	4890.77	3104.82	3436.19	1125.54	5103.98
11	0.00	269.50	471.64		0.00		0.00	0.00	471.64	0.00	471.64	0.00	318.62	1125.54	5422.60
12	0.00	269.50	471.64		0.00		0.00	0.00	471.64	0.00	471.64	0.00	306.37	1125.54	5728.97
13	25.00	269.50	471.64		2120.80		2120.80	6737.50	7209.14	4616.70	5088.34	2883.58	3178.16	4009.11	8907.13
14	0.00	269.50	471.64		0.00		0.00	0.00	471.64	0.00	471.64	0.00	283.25	4009.11	9190.38
15	0.00	269.50	471.64		0.00		0.00	0.00	471.64	0.00	471.64	0.00	272.36	4009.11	9462.75
16	25.00	269.50	471.64		2120.80	2100.00	4220.80	6737.50	7209.14	2516.70	2988.34	1397.43	1659.32	5406.55	11122.06

Table E.35 – Cash flow of Miscanthus in Poland.

MISCANTHUS															
Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discount. Net margin without CAP**	**Discount. Net margin with CAP**	**Discount. Cumulati. Net margin without CAP**	**Discount. Cumulati. Net margin with CAP**
	(t ha^{-1})	(PLN t^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(£ ha^{-1})
1	0.60	269.50	471.64	66298.20	0.00		66298.20	161.70	633.34	-66136.50	-65664.86	-66136.50	-65664.86	-66136.50	-65664.86
2	3.93	269.50	471.64		2491.77		2491.77	1057.79	1529.43	-1433.98	-962.34	-1378.83	-925.33	-67515.33	-66590.19
3	11.10	269.50	471.64		2491.77		2491.77	2991.45	3463.09	499.68	971.32	461.98	898.04	-67053.34	-65692.15
4	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1226.22	1645.51	-65827.12	-64046.64
5	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1179.06	1582.22	-64648.07	-62464.42
6	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1133.71	1521.36	-63514.36	-60943.06
7	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1090.10	1462.85	-62424.25	-59480.21
8	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1048.18	1406.59	-61376.08	-58073.63
9	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	1007.86	1352.49	-60368.21	-56721.14
10	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	969.10	1300.47	-59399.11	-55420.67
11	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	931.83	1250.45	-58467.29	-54170.23
12	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	895.99	1202.35	-57571.30	-52967.87
13	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	861.53	1156.11	-56709.78	-51811.76
14	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	828.39	1111.64	-55881.39	-50700.12
15	12.54	269.50	471.64		2000.20		2000.20	3379.53	3851.17	1379.33	1850.97	796.53	1068.89	-55084.86	-49631.23
16	12.54	269.50	471.64		2000.20	500.00	2500.20	3379.53	3851.17	879.33	1350.97	488.26	750.15	-54596.60	-48881.08

Table E.36 – Cash flow of forage maize in Poland.

FORAGE MAIZE

Year	Yield	Price	CAP	Variable costs	Fixed costs	Total costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha^{-1})	(PLN t^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})
1	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2987.27	3458.91	2987.27	3458.91
2	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2872.37	3325.87	5859.64	6784.78
3	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2761.89	3197.95	8621.53	9982.73
4	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2655.67	3074.95	11277.20	13057.68
5	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2553.53	2956.69	13830.73	16014.37
6	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2455.31	2842.97	16286.04	18857.34
7	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2360.88	2733.62	18646.92	21590.96
8	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2270.08	2628.48	20917.00	24219.45
9	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2182.77	2527.39	23099.76	26746.83
10	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2098.81	2430.18	25198.57	29177.01
11	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	2018.09	2336.71	27216.66	31513.73
12	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1940.47	2246.84	29157.14	33760.57
13	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1865.84	2160.42	31022.97	35920.99
14	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1794.07	2077.33	32817.05	37998.32
15	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1725.07	1997.43	34542.12	39995.75
16	12.0	724.00	471.64	2474.37	3226.36	5700.73	8688.00	9159.64	2987.27	3458.91	1658.72	1920.61	36200.84	41916.36

Table E.37 – Cash flow of *Sida hermaphrodita* (L.) Rusby in Poland.

SIDA

Year	**Yield**	**Price**	**CAP**	**Establishment costs**	**Recurring costs**	**Decommissioning costs**	**Total costs**	**Crop revenue without CAP**	**Crop revenue with CAP**	**Net margin without CAP**	**Net margin with CAP**	**Discounted net margin without CAP**	**Discounted net margin with CAP**	**Discounted cumulative net margin without CAP**	**Discounted cumulative net margin with CAP**
	(t ha^{-1})	(PLN t^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})
1	2.05	269.50	471.64	27899.88	490.00		28389.88	551.58	1023.22	-27838.30	-27366.66	-27838.30	-27366.66	-27838.30	-27366.66
2	8.27	269.50	471.64		2629.10		2629.10	2228.77	2700.41	-400.34	71.30	-384.94	68.56	-28223.24	-27298.10
3	10.93	269.50	471.64		2629.10		2629.10	2944.74	3416.38	315.64	787.28	291.82	727.88	-27931.41	-26570.21
4	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	1147.32	1566.61	-26784.09	-25003.61
5	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	1103.19	1506.35	-25680.90	-23497.25
6	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	1060.76	1448.42	-24620.13	-22048.83
7	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	1019.97	1392.71	-23600.17	-20656.12
8	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	980.74	1339.14	-22619.43	-19316.98
9	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	943.02	1287.64	-21676.41	-18029.34
10	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	906.75	1238.11	-20769.67	-16791.23
11	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	871.87	1190.49	-19897.80	-15600.74
12	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	838.34	1144.71	-19059.46	-14456.03
13	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	806.09	1100.68	-18253.37	-13355.35
14	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	775.09	1058.34	-17478.28	-12297.01
15	11.62	269.50	471.64		1840.20		1840.20	3130.78	3602.42	1290.58	1762.22	745.28	1017.64	-16733.00	-11279.37
16	11.62	269.50	471.64		1350.20	500.00	1850.20	3130.78	3602.42	1280.58	1752.22	711.06	972.95	-16021.94	-10306.42

Table E.38 – Cash flow of *Silphium perfoliatum* L. in Poland.

SILPHIUM

Year	Yield	Price	CAP	Establishment costs	Recurring costs	Decommissioning costs	Total costs	Crop revenue without CAP	Crop revenue with CAP	Net margin without CAP	Net margin with CAP	Discounted net margin without CAP	Discounted net margin with CAP	Discounted cumulative net margin without CAP	Discounted cumulative net margin with CAP
	(t ha^{-1})	(PLN t^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})	(PLN ha^{-1})
1	0.00	269.50	471.64	10887.88	0.00		10887.88	0.00	471.64	-10887.88	-10416.24	-10887.88	-10416.24	-10887.88	-10416.24
2	9.93	269.50	471.64		2996.60		2996.60	2677.03	3148.67	-319.57	152.07	-307.28	146.22	-11195.15	-10270.01
3	14.70	269.50	471.64		2996.60		2996.60	3961.65	4433.29	965.05	1436.69	892.24	1328.30	-10302.91	-8941.71
4	15.73	269.50	471.64		2207.70		2207.70	4240.13	4711.77	2032.43	2504.07	1806.83	2226.11	-8496.08	-6715.60
5	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1867.88	2271.04	-6628.21	-4444.56
6	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1796.03	2183.69	-4832.17	-2260.87
7	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1726.96	2099.70	-3105.22	-161.18
8	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1660.53	2018.94	-1444.68	1857.77
9	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1596.67	1941.29	151.99	3799.06
10	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1535.26	1866.63	1687.24	5665.68
11	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1476.21	1794.83	3163.45	7460.51
12	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1419.43	1725.80	4582.88	9186.31
13	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1364.84	1659.42	5947.72	10845.74
14	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1312.34	1595.60	7260.07	12441.34
15	16.30	269.50	471.64		2207.70		2207.70	4392.85	4864.49	2185.15	2656.79	1261.87	1534.23	8521.94	13975.57
16	16.30	269.50	471.64		2207.70	500.00	2707.70	4392.85	4864.49	1685.15	2156.79	935.70	1197.59	9457.64	15173.16

E.4 Sensitivity analyses

Table E.39 – Results of the sensitivity analysis in the UK.

a) Results for the UK (£ ha⁻¹)						
		Relative changes (%) in inputs parameters				
	Crop	**-100%**	**-50%**	**0%**	**50%**	**100%**
Prices	SRC	-1445	1493	4432	7370	10308
	Miscanthus	-2211	1375	4962	8548	12134
	Forage maize	-10433	-2646	5142	12929	20716
	Sida	-5929	-2427	1075	4577	8079
	Silphium	-3825	1016	5697	10458	15219
	Rotation	-13542	-4474	4593	13660	22728
Yield	SRC	-1445	1493	4432	7370	10308
	Miscanthus	-2211	1375	4962	8548	12134
	Forage maize	-10433	-2646	5142	12929	20716
	Sida	-5929	-2427	1075	4577	8079
	Silphium	-3825	936	5697	10458	15219
	Rotation	-13542	-4474	4593	13660	22728
Costs	SRC	8543	6487	4432	2376	320
	Miscanthus	9839	7400	4962	2523	85
	Forage maize	18241	11691	5142	-1408	-7957
	Sida	9670	5373	1075	-3223	-7521
	Silphium	12160	8943	5697	2452	-793
	Rotation	20801	12697	4593	-3511	-11615
Discount rate	SRC	6715	5446	4432	3613	2945
	Miscanthus	7474	6082	4962	4051	3305
	Forage maize	6789	5876	5142	4545	4056
	Sida	3226	2035	1075	295	-345
	Silphium	8482	6939	5697	4689	3863
	Rotation	5965	5207	4593	4090	3675

Table E.40 – Results of the sensitivity analysis in Italy.

b) Results for Italy (€ ha^{-1})						
		Relative changes (%) in inputs parameters				
	Crop	**-100%**	**-50%**	**0%**	**50%**	**100%**
Prices	SRC	297	3817	7336	10855	14374
	Miscanthus	-3339	-353	2,633	5,619	8,605
	Forage maize	-11686	-6107	-527	5052	10631
	Sida	-5752	-3249	-747	1756	4259
	Silphium	-3924	-281	3362	7004	10647
	Rotation	-10668	-5488	-309	4870	10049
Yield	SRC	297	3817	7336	10855	14374
	Miscanthus	-3339	-353	2633	5619	8605
	Forage maize	-11686	-6107	-527	5052	10631
	Sida	-5752	-3,249	-747	1756	4259
	Silphium	-3924	-281	3362	7004	10647
	Rotation	-10668	-5488	-309	4870	10049
Costs	SRC	13686	10511	7336	4161	986
	Miscanthus	10127	6380	2633	-1144	-4861
	Forage maize	15313	7393	-527	-8448	-16368
	Sida	9160	4207	-747	-5700	-10653
	Silphium	11440	7401	3362	-677	-4717
	Rotation	14513	7102	-309	-7720	-15132
Discount rate	SRC	9838	8480	7336	6367	5542
	Miscanthus	4069	3288	2633	2080	1611
	Forage maize	-670	-593	-527	-472	-426
	Sida	728	-74	-747	-1,313	-1793
	Silphium	5176	4190	3362	2663	2071
	Rotation	-310	-311	-309	-306	-302

Table E.41 – Results of the sensitivity analysis in Germany.

c) Results for Germany (€ ha^{-1})						
		Relative changes (%) in inputs parameters				
	Crop	**-100%**	**-50%**	**0%**	**50%**	**100%**
Prices	SRC	-3332	366	4065	7764	11463
	Miscanthus	-4681	-166	4349	8864	13379
	Forage maize	-12096	-3,398	5300	13998	22696
	Sida	-7475	-3,064	1347	5758	10170
	Silphium	-4975	-1,017	7010	13003	18996
	Rotation	-15332	-7,771	-211	7349	14910
Yield	SRC	-3332	366	4065	7764	11463
	Miscanthus	-4681	-166	4349	8864	13379
	Forage maize	-12096	-3398	5300	13998	22696
	Sida	-7475	-3064	1347	5758	10170
	Silphium	-4975	-1017	7010	13003	18996
	Rotation	-15332	-7771	-211	7349	14910
Costs	SRC	9454	6760	4065	1370	-1324
	Miscanthus	11087	7718	4349	981	-2388
	Forage maize	19453	12376	5300	-1776	-8853
	Sida	10879	6113	1347	-3419	-8185
	Silphium	14043	10526	7010	3494	-22
	Rotation	17178	8483	-211	-8905	-17600
Discount rate	SRC	6992	5352	4065	3045	2230
	Miscanthus	7135	5581	4349	3365	2570
	Forage maize	7254	6164	5300	4607	4046
	Sida	4281	2644	1347	310	-527
	Silphium	10889	8725	7010	5638	4530
	Rotation	-410	-296	-211	-148	-100

Table E.42 – Results of the sensitivity analysis in Poland.

d) Results for Poland (PLN ha^{-1})						
		Relative changes (%) in inputs parameters				
	Crop	**-100%**	**-50%**	**0%**	**50%**	**100%**
Prices	SRC	-12650	-1102	10425	21962	33499
	Miscanthus	-83326	-66427	-49527	-32627	-15727
	Forage maize	-61132	-10347	40437	91222	142007
	Sida	-43985	-27474	-10963	5549	22060
	Silphium	-30674	-8242	14189	36620	59052
	Rotation	-68009	-36569	-5129	26311	57751
Yield	SRC	-12650	-1102	10425	21962	33499
	Miscanthus	-83326	-66427	-49527	-32627	-15727
	Forage maize	-61132	-10347	40437	91222	142007
	Sida	-43985	-27474	-10963	5549	22060
	Silphium	-30674	-8242	14189	36620	59052
	Rotation	-68009	-36569	-5129	26311	57751
Costs	SRC	58588	19507	10425	1343	-7739
	Miscanthus	39314	-5106	-49527	-93947	-138367
	Forage maize	107083	73760	40437	7114	-26209
	Sida	38536	13787	-10963	-35712	-60462
	Silphium	50376	32283	14189	-3905	-21999
	Rotation	68394	31632	-5129	-41890	-78652
Discount rate	SRC	18294	13895	10425	7660	5438
	Miscanthus	-42093	-46245	-49527	-52145	-54251
	Forage maize	55342	47032	40437	35151	30872
	Sida	-3609	-7719	-10963	-15548	-15627
	Silphium	25058	18990	14189	10335	7266
	Rotation	-7651	-6205	-5129	-4321	-3711

Appendix F - Greenhouse gas emissions associated with the cultivation of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.

Note: The tables in Appendix F show the inputs and outputs for the GHG evaluation model developed during the PhD to calculate the GHG benefits for Sida and Silphium. The model is an inventory of the GHG emissions associated with the establishment and cultivation of Sida and Silphium over a 16-year rotation, compared to a theoretical arable rotation and other energy crops. It was developed in a Microsoft Excel spreadsheet and is available upon request from myself or my supervisors.

F.1 IPCC greenhouse gas emissions overall methodology calculations

F.1.1 Emissions from fuel combustion activities

Table F.1 – Formulas used to calculate fuel combustion activities.

$$Emissions = \sum_j (Fuel_j * EF_j)$$ *where: Emission = Emissions (kg); $Fuel_j$ = fuel consumed (as represented by fuel sold (TJ); EF_j = emission factor (kg TJ^{-1}); j = fuel type*	Equation F.1 (IPCC, 2006c)

F.1.2 Carbon stock change in mineral soil pool

Table F.2 – Formulas used to calculate carbon stock changes in mineral soil pool.

$$\Delta C_{SOILS} = \Delta C_{mineral}$$ *where: ΔC_{SOILS} = annual change in carbon stock in dead organic matter (t C y^{-1}); $\Delta C_{mineral}$ = annual change in carbon stock in mineral soils (t C y^{-1})*	Equation F.2 (IPCC, 2006d)
$$\Delta C_{mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$ *SOC_0 = soil organic carbon stock in the last year of inventory (t C); $SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory (t C); SOC_0 and $SOC_{(0-T)}$ calculated using SOC equation*	Equation F.3 (IPCC, 2006d)

(below); T = number of years over a single inventory time period (y); D = default time period for transition between equilibrium SOC values (y), commonly 20 years	
$SOC = \sum_{c,s,i}(SOC_{REF_{c,s,i}} * F_{LU_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}} * A_{c,s,i})$ *c = climate zones; s = soil types; i = set of management systems present in a country; SOC_{REF} = reference carbon stock (t C ha^{-1}), for a cold temperate moist climate region and low activity clay soil, SOC_{REF} = 85 t C ha^{-1}; F_{LU} = stock change factor for land-use systems for a particular land-use, dimensionless; F_{MG} = stock change factor for management regime, dimensionless; F_I = stock change factor for input of organic matter, dimensionless; A = land area (ha)*	Equation F.4 (IPCC, 2006d)

F.1.3 Carbon stock change in biomass pool

Table F.3 – Formulas used to calculate carbon stock changes in biomass pool.

$\Delta C_{CL} = \Delta C_B + \Delta C_{SO} + \Delta C_{LI}$ *where: ΔC_{CL} = carbon stock change in cropland; ΔC_B = carbon stock changes of biomass pool; ΔC_{SO} = carbon stock changes of soil pool; ΔC_{LI} = carbon stock changes of litter pool*	Equation F.5 (IPCC, 2006d)
$\Delta C_B = \Delta C_G - \Delta C_L$ *where: ΔC_B = annual change in carbon stocks in biomass pool; ΔC_G = annual increase in carbon stock due to biomass growth (t C y^{-1}); ΔC_L = annual decrease in carbon stock due to biomass loss (t C y^{-1})*	Equation F.6 (IPCC, 2006d)
$\Delta C_G = \sum_{i,j}(A_{i,j} * G_{total_{i,j}} * CF_{i,j})$ *where: ΔC_G = annual increase in carbon stock due to biomass growth (t C y^{-1}); $A_{i,j}$ = area of land (ha); $G_{total\ I,j}$ = mean annual biomass growth (t DM ha^{-1} y^{-1}); $CF_{I,j}$ = carbon fraction of dry matter (t DM t DM^{-1})*	Equation F.7 (IPCC, 2006d)
$G_{total} = \sum\{G_W * (1 + R)\}$ *where: G_{total} = average annual biomass growth, both above and below ground (t DM ha^{-1} y^{-1}); G_w = average annual above-ground biomass growth specific vegetation type (t DM ha^{-1} y^{-1}); R = ratio of below ground to above ground biomass (-)*	Equation F.8 (IPCC, 2006d)
$\Delta C_L = L_{disturbance}$ *where: ΔC_L = annual decrease in carbon stock due to biomass loss (t C y^{-1}); $L_{disturbance}$ = annual biomass carbon losses due to disturbances (t C y^{-1})*	Equation F.9 (IPCC, 2006d)
$L_{disturbance} = \{A_{disturbance} * B_W * (1 + R) * CF * fd\}$	Equation F.10 (IPCC, 2006d)

where: $L_{disturbance}$ = annual biomass carbon losses due to disturbances (t C y^{-1}); $A_{disturbance}$ = area affected by disturbances (ha y^{-1}); B_W = average above-ground biomass affected by disturbances (t DM ha^{-1}); R = ratio of below-ground biomass to above-ground biomass (-); CF = carbon fraction of dry matter (-); fd = fraction of biomass lost in disturbance, fd=1 if whole stand replaced	

F.1.4 Carbon stock change in litter pool

Table F.4 – Formulas used to calculate carbon stock changes in litter pool.

$\Delta C_{DOM} = \left[A * \frac{(DOM_{t2} - DOM_{t1})}{T}\right] * CF$ *where: ΔC_{DOM} = annual change in carbon stock in litter pool (t C y^{-1}); A = area (ha); DOM_{t2} = litter stock at time t2 (t DM ha^{-}); DOM_{t1} = litter stock at time t1 (t DM ha^{-1}); T = (t2 – t1) = period of time between second stock estimate and first stock estimate (y); CF = carbon fraction of dry matter (t C), litter = 0.37*	Equation F.11 (IPCC, 2019b)

F.1.5 Direct N_2O emissions

Table F.5 – Formulas used to calculate direct N_2O emissions.

$N_2O_{direct}N = N_2O - N_{Ninputs}$ *where: N_2O_{direct} N = annual direct N_2O–N emissions produced from managed soils (kg N_2O–N y^{-1})*	Equation F.12 (IPCC, 2006e)
$N_2O - N_{inputs} = (F_{SN} + F_{CR} + F_{SOM}) * EF_1$ *N_2O - N_{inputs} = annual direct N_2O–N emissions from N inputs to managed soils (kg N_2O–N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils (kg N y^{-1}); F_{SOM} = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management (kg N y^{-1}); EF_1 = emission factor for N_2O emissions from N inputs (kg N_2O N per kg N input) = 0.01*	Equation F.13 (IPCC, 2006e)
$F_{CR} = \sum_T \{[AGR_{(T)} * N_{AG(T)} * (1 - Frac_{remove(T)})] + [BGR_{(T)} * N_{BG(T)}]\}$ *where: $AGR_{(T)}$ = annual above-ground crop residue for crop T (kg DM y^{-1}); $N_{AG(T)}$ = N content of above-ground residues for crop T (kg N per kg DM); $Frac_{remove(T)}$ = fraction of above-ground*	Equation F.14 (IPCC, 2019d)

residues crop T removed annually, if not available assume no removal; $BGR_{(T)}$ = annual below-ground crop residue of crop t (kg DM y^{-1}); $N_{BG(T)}$ = N content of below-ground residues for crop T (kg N per kg DM)	
$BGR_T = \left(Crop_{(T)} + AG_{DM(T)}\right) * RS_{(T)} * Area_{(T)} * Frac_{renew(T)}$ *where: $Crop_{(T)}$ = harvested annual dry matter yield for crop T (kg DM ha^{-1}) = Fresh yield * DM (%); $AG_{DM(T)}$ = above-ground residue for crop T (kg DM ha^{-1}); $RS_{(T)}$ = ratio of below-ground residue to harvested yield of crop T (-); $Area_{(T)}$ = total annual area harvested of crop T (ha y^{-1}); $Frac_{renew(T)}$ = fraction of total area under crop T renewed annually. Annual crops $Frac_{renew}$ = 1*	Equation F.15 (IPCC, 2019d)
$AG_{DM(T)} = Crop_{(T)} * R_{AG(T)}$ *where: $R_{AG(T)}$ = ratio of above-ground residues dry matter ($AG_{DM(T)}$) to harvested yield*	Equation F.16 (IPCC, 2019d)
$F_{SOM} = \sum_{LU}[\left(\Delta C_{mineral,LU} * \frac{1}{R}\right) * 1000]$ *where: F_{SOM} = the net annual amount of N mineralised in mineral soils as a result of loss of soil carbon through change in land use or management (kg N); $\Delta C_{mineral,LU}$ = average annual loss of soil carbon for each land-use type (t C); R = C:N ratio of the soil organic matter. Default value of 10 (range from 8 to 15) for changes on Cropland Remaining Cropland*	Equation F.17 (IPCC, 2006e)

F.1.6 Indirect N_2O emissions

Table F.6 – Formulas used to calculate indirect N_2O emissions.

$N_2O_{(ATD)}N = \left[\left(F_{SN} * F_{racGASF}\right)\right] * EF_4$ *where: $N_2O_{(ATD)}$ N = annual amount of N_2O N produced from atmospheric deposition of N volatilised from managed soils (kg N_2O N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); $Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x (kg N volatilised per kg of N applied), default value = 0.10; EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N_2O N per kg NH_3 N + NOx N volatilised, default value = 0.010*	Equation F.18 (IPCC, 2006e)
$N_2O_{(L)}N = (F_{SN} + F_{CR} + F_{SOM}) * Frac_{LEACH-H} * EF_5$ *where: $N_2O_{(L)}N$ = annual N_2O–N from leaching and runoff of N additions to managed soils (kg N_2O–N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); F_{CR} = amount of N in crop residues (above and below ground), returned to soils annually (kg N y^{-1}); F_{SOM} = annual N mineralised in mineral*	Equation F.19 (IPCC, 2006e)

soils associated with loss of soil C from soil organic matter as a result of changes to management (kg N y^{-1}); $Frac_{LEACH-H}$ = N fraction added to/mineralised in managed soils lost through leaching and runoff (kg N per kg of N additions), default = 0.30; EF_5 = emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N per kg N leached and runoff), default = 0.0075	

F.2 Model calculations

F.2.1 Emissions from fuel combustion activities

Table F.7 – Diesel consumption during agricultural activity.

	Operation	Implement	Engine power	Average fuel consumption (f_e)	Work rate (q_A)	Fuel consumption (f_A)	Multiplier	Mean diesel use per ha	Passes per season	Diesel use per season
			(kW)	(l h^{-1})	(h ha^{-1})	(l ha^{-1})	(-)	(l ha^{-1})	(-)	(l ha^{-1})
Wheat										
Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.2	39.91
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.6	12.91
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	2	13.80	1.0	13.80
	Discing	Disc and pack	200	51.52	2.9	17.77	1	17.77	1.5	26.65
Drilling	Drilling	Drill	200	51.52	4.1	12.57	1	12.57	1.0	12.57
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.6	3.64
Harvesting	Combining cereals	Combine harvester	150	38.64	1.1	35.13	1	35.13	1.0	35.13
Baling	Baling	Baler	75	19.32	1.4	13.80	1	13.80	1.0	13.80
Carting	Carting	Carting trailer	75	19.32	4.2	4.60	1	4.60	2.0	9.20
								Wheat - diesel total (l ha^{-1})		189.95
Oats										
Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.2	39.91
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.6	12.91
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	2	13.80	1.0	13.80
	Discing	Disc and pack	200	51.52	2.9	17.77	1	17.77	1.5	26.65

Drilling	Drilling	Drill	200	51.52	4.1	12.57	1	12.57	1.0	12.57
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.6	3.64
Harvesting	Combining cereals	Combine harvester	150	38.64	1.1	35.13	1	35.13	1.0	35.13
Baling	Baling	Baler	75	19.32	1.4	13.80	1	13.80	1.0	13.80
Carting	Carting	Carting trailer	75	19.32	4.2	4.60	1	4.60	2.0	9.20
									Oats - diesel total (l ha^{-1})	189.95
OSR										
Cultivation	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.3	8.66
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Drilling	Drilling	Drill	200	51.52	4.1	12.57	1	12.57	1.0	12.57
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	4.8	29.12
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.9	5.46
Harvesting	OSR harvesting	Combine harvester	150	38.64	1.1	35.13	1	35.13	1.0	35.13
Carting	Carting	Carting trailer	75	19.32	3.5	5.52	1	5.52	1.0	5.52
									OSR - diesel total (l ha^{-1})	97.84
Sugar beet										
Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.3	43.23
	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.5	9.99
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Drilling	Drilling	Drill	200	51.52	1.3	39.63	1	39.63	1.0	39.63
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	11.8	71.60
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.6	3.64
Harvesting	Sugar beet harvesting	Sugar beet harvester	585	150.70	0.5	301.41	1	301.41	1.0	301.41
Carting	Carting	Carting trailer	75	19.32	12.9	1.50	1	1.50	1.0	1.50
									Sugar beet - diesel total (l ha^{-1})	476.40
Forage maize										

Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.3	43.23
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Seedbed prep and drilling	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.2	7.99
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.9	19.36
	Drilling	Drill	200	51.52	4.1	12.57	1	12.57	1.0	12.57
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	7.0	42.47
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Harvesting	Forage harvesting	Forage harvester	370	95.32	1.7	56.07	1	56.07	1.0	56.07
Carting	Carting	Carting trailer	75	19.32	10.2	1.89	1	1.89	2.0	3.79
									Forage maize - diesel total (l ha^{-1})	190.41
SRC (establishment year)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.3	43.23
	Subsoiling	Subsoiler	200	51.52	2.4	21.47	1	21.47	0.2	4.29
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.9	19.36
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Planting	Potato planting	Potato planter	200	51.52	1.3	39.63	1	39.63	1.0	39.63
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Mowing	Mowing	Mower	69	17.78	1.1	16.16	1	16.16	1.0	16.16
									SRC (establishment year - diesel total (l ha^{-1})	162.95
SRC (no harvest years)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
									SRC (no harvest years) - diesel total (l ha^{-1})	**31.55**
SRC (harvest years)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Harvesting	Forage harvesting	Forage harvester	370	95.32	1.7	56.07	1	56.07	1.0	56.07
Carting	Carting	Carting trailer	75	19.32	10.2	1.89	1	1.89	2.0	3.79

									SRC (harvest years) - diesel total (l ha⁻¹)	89.44
Miscanthus (establishment year)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Cultivation	Ploughing	Plough	142	36.58	1.1	33.26	1	33.26	1.3	43.23
	Subsoiling	Subsoiler	200	51.52	2.4	21.47	1	21.47	0.2	4.29
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.9	19.36
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Planting	Potato planting	Potato planter	200	51.52	1.3	39.63	1	39.63	1.0	39.63
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Mowing	Mowing	Mower	69	17.78	1.1	16.16	1	16.16	1.0	16.16
									Miscanthus (establishment year) - diesel total (l ha⁻¹)	162.95
Miscanthus (recurring)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Mowing	Mowing	Mower	69	17.78	1.1	16.16	1	16.16	1.0	16.16
Carting	Carting	Carting trailer	75	19.32	10.2	1.89	1	1.89	2.0	3.79
									Miscanthus (recurring) - diesel total (l ha⁻¹)	49.53
Sida (establishment year)										
	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Cultivation	Ploughing	Tractor 200 kW	200	51.52	1.1	46.84	1	46.84	1.3	60.89
	Subsoiling	Subsoiler	200	51.52	2.4	21.47	1	21.47	0.2	4.29
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.9	19.36
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Planting	Potato planting	Potato planter	200	51.52	1.3	39.63	1	39.63	1.0	39.63
Mechanical weeding	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.5	9.99
Mowing	Mowing	Mower	69	17.78	1.1	16.16	1	16.16	1.0	16.16
									Sida (establishment year) - diesel total (l ha⁻¹)	190.60

Sida (recurring)										
Mechanical weeding	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.5	9.99
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Harvesting	Forage harvesting	Forage harvester	370	95.32	1.7	56.07	1	56.07	1.0	56.07
Carting	Carting	Carting trailer	75	19.32	10.2	1.89	1	1.89	2.0	3.79
									Sida (recurring) - Diesel Total (l ha^{-1})	67.88
Silphium (establishment year)										
Spraying	Spraying	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	5.2	31.55
Cultivation	Ploughing	Tractor 200 kW	200	51.52	1.1	46.84	1	46.84	1.3	60.89
	Subsoiling	Subsoiler	200	51.52	2.4	21.47	1	21.47	0.2	4.29
	Power harrowing	Power harrow	167	43.02	2.0	21.51	1	21.51	0.9	19.36
	Rolling	Cambridge rolls	75	19.32	2.8	6.90	1	6.90	1.0	6.90
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Seedbed prep and sowing	Drilling	Drill	200	51.52	4.1	12.57	1	12.57	1.0	12.57
Mechanical weeding	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.5	9.99
									Silphium (establishment year) - Diesel Total (l ha^{-1})	147.37
Silphium (recurring)										
Mechanical weeding	Cultivating	Cultivator	75	19.32	2.9	6.66	1	6.66	1.5	9.99
Fertilising	Fertilising	Self pro. sprayer	179	46.11	7.6	6.07	1	6.07	0.3	1.82
Harvesting	Forage harvesting	Forage harvester	370	95.32	1.7	56.07	1	56.07	1.0	56.07
Carting	Carting	Carting trailer	75	19.32	10.2	1.89	1	1.89	2.0	3.79
									Silphium (recurring) - Diesel Total (l ha^{-1})	67.88

F.2.2 Stock changes in mineral soil pool

Table F.8 – Mineral Soil Organic C stock at the beginning of the inventory time period.

System	$A_{(0-T)}$ (ha)	SOC_{ref} (t C ha^{-1})	F_{LU} (-)	F_{MG} (-)	F_I (-)	$SOC_{(0-T)}$ (t C)
arable	1	76	0.70	1.00	1.00	53.20
energy	-	-	-	-	-	53.20

Table F.9 – Mineral Soil Organic C stock in the last year of the inventory time period.

System	$A_{(0)}$ (ha)	SOC_{ref} (t C ha^{-1})	F_{LU} (-)	F_{MG} (-)	F_I (-)	$SOC_{(0)}$ (t C)
arable	1	76	0.70	1.00	1.00	53.20
energy	1	76	0.72	1.04	1.11	63.17

Table F.10 – Carbon stock change in mineral soil pool.

System	$SOC_{(0)}$ (t C)	$SOC_{(0-T)}$ (t C)	**D** (y)	$\Delta C_{Mineral}$ (t C y^{-1})
arable	53.20	53.20	16	0.000
energy	63.17	53.20	16	0.623

F.2.3 Stock changes in biomass pool (above and below ground)

Table F.11 – Stock changes in above ground biomass pool calculations.

	G_w (t DM ha^{-1} y^{-1})	R (-)	G_{total} (t DM ha^{-1} y^{-1})	A (ha)	CF (-)	ΔC_G (t C y^{-1})	$A_{disturbance}$ (ha^{-1} y^{-1})	B_w (t DM ha^{-1})	R (-)	CF (-)	fd (-)	ΔC_L (t C y^{-1})	ΔC_B (t C y^{-1})
SRC (year 1)	3.17	0.13	3.58	1.00	0.50	1.79	0.00	3.17	0.13	0.50	1.00	0.00	1.79
SRC (year 2)	3.17	0.13	3.58	1.00	0.50	1.79	0.00	3.17	0.13	0.50	1.00	0.00	1.79
SRC (year 3)	3.17	0.13	3.58	1.00	0.50	1.79	0.00	3.17	0.13	0.50	1.00	0.00	1.79
SRC (year 4 and onwards)	3.17	0.13	3.58	1.00	0.50	1.79	1.00	12.69	0.13	0.50	1.00	7.15	-5.36
Miscanthus (year 1)	0.60	0.39	0.83	1.00	0.47	0.39	1.00	0.60	0.39	0.47	1.00	0.39	0.00
Miscanthus (year 2)	3.93	0.39	5.45	1.00	0.47	2.56	1.00	3.93	0.39	0.47	1.00	2.56	0.00
Miscanthus (year 3)	11.10	0.39	15.42	1.00	0.47	7.25	1.00	11.10	0.39	0.47	1.00	7.25	0.00
Miscanthus (year 4 and onwards)	12.54	0.39	17.42	1.00	0.47	8.19	1.00	12.54	0.39	0.47	1.00	8.19	0.00
Sida (year 1)	2.05	2.35	6.86	1.00	0.47	3.22	1.00	2.05	2.35	0.47	1.00	3.22	0.00
Sida (year 2)	8.27	2.35	27.70	1.00	0.47	13.02	1.00	8.27	2.35	0.47	1.00	13.02	0.00
Sida (year 3)	10.93	2.35	36.60	1.00	0.47	17.20	1.00	10.93	2.35	0.47	1.00	17.20	0.00
Sida (year 4 and onwards)	11.62	2.35	38.92	1.00	0.47	18.29	1.00	11.62	2.35	0.47	1.00	18.29	0.00
Silphium (year 1)	0.00	0.52	0.00	1.00	0.47	0.00	1.00	0.00	0.52	0.47	1.00	0.00	0.00
Silphium (year 2)	9.93	0.52	15.05	1.00	0.47	7.07	1.00	9.93	0.52	0.47	1.00	7.07	0.00
Silphium (year 3)	14.70	0.52	22.28	1.00	0.47	10.47	1.00	14.70	0.52	0.47	1.00	10.47	0.00
Silphium (year 4)	15.73	0.52	23.84	1.00	0.47	11.21	1.00	15.73	0.52	0.47	1.00	11.21	0.00
Silphium (year 5 and onwards)	16.30	0.52	24.70	1.00	0.47	11.61	1.00	16.30	0.52	0.47	1.00	11.61	0.00

Table F.12 – Stock changes in below ground biomass pool calculations.

	G_w (t DM ha^{-1} y^{-1})	R (-)	G_{total} (t DM ha^{-1} y^{-1})	A (ha)	CF (-)	ΔC_G (t C y^{-1})	$A_{disturbance}$ (ha^{-1} y^{-1})	B_w (t DM ha^{-1})	R (-)	CF (-)	fd (-)	ΔC_L t C y^{-1}	ΔC_B t C y^{-1}
SRC	1.40	0.13	1.58	1.00	0.50	0.79	0.00	0.00	0.13	0.50	1.00	0.00	0.79
Miscanthus	1.50	0.39	2.08	1.00	0.47	0.98	0.00	0.00	0.39	0.47	1.00	0.00	0.98
Sida	1.71	2.35	5.72	1.00	0.47	2.69	0.00	0.00	2.35	0.47	1.00	0.00	2.69
Silphium	0.53	0.52	0.80	1.00	0.47	0.37	0.00	0.00	0.52	0.47	1.00	0.00	0.37

F.2.4 Stock changes in litter pool

Table F.13 – Stock changes in litter pool calculations.

	A (ha)	DOM_{t1} (t DM ha^{-1})	DOM_{t2} (t DM ha^{-1})	T (y)	CF (-)	ΔC_{DOM} (t C yr^{-1})
SRC (year 1)	1	0.000	1.850	1	0.37	0.685
SRC (year 2)	1	1.850	3.700	1	0.37	0.685
SRC (year 3)	1	3.700	5.550	1	0.37	0.685
SRC (year 4)	1	5.550	7.400	1	0.37	0.685
Miscanthus (year 1)	1	0.000	0.213	1	0.37	0.079
Miscanthus (year 2)	1	0.000	1.393	1	0.37	0.516
Miscanthus (year 3)	1	0.000	3.941	1	0.37	1.458
Miscanthus (year 4)	1	0.000	4.452	1	0.37	1.647
Sida (year 1)	1	0.000	0.727	1	0.37	0.269
Sida (year 2)	1	0.000	2.936	1	0.37	1.086
Sida (year 3)	1	0.000	3.879	1	0.37	1.435
Sida (year 4)	1	0.000	4.124	1	0.37	1.526
Silphium (year 1)	1	0.000	0.000	1	0.37	0.000
Silphium (year 2)	1	0.000	0.000	1	0.37	0.000
Silphium (year 3)	1	0.000	0.000	1	0.37	0.000
Silphium (year 4)	1	0.000	0.000	1	0.37	0.000
Silphium (year 5)	1	0.000	0.000	1	0.37	0.000

F.2.5 Direct N_2O emissions

Table F.14 – Direct N_2O emissions calculations.

	F_{SN}	$AGR_{(T)}$	$N_{AG(T)}$	$Frac_{remove(T)}$	Yield Fresh	DRY	$Crop_{(T)}$	$R_{AG(T)}$	$AG_{DM(T)}$	$RS_{(T)}$	$Frac_{renew(T)}$	$BGR_{(T)}$	$N_{BG(T)}$	F_{CR}	F_{SOM}	EF_1	N2O-N inputs
	(kg ha^{-1})	(kg DM y^{-1})	(-)	(-)	(kg DM ha^{-1})	(%)	(kg ha^{-1})	(-)	(kg DM ha^{-1})	(-)	(-)	(kg DM y^{-1})	(-)	(kg N y^{-1})	(kg N y^{-1})	(-)	(kg N_2O N y^{-1})
Wheat	190	3900.00	0.006	0.00	8300	0.89	7387	1.3	9603.1	0.23	1.0	3907.7	0.009	58.57	0.00	0.0157	3.906
Oats	130	3500.00	0.007	0.00	6300	0.89	5607	1.3	7289.1	0.25	1.0	3224.0	0.008	50.29	0.00	0.0157	2.833
OSR	190	2600.00	0.015	0.00	3500	0.90	3150	0.3	945.0	0.54	1.0	2211.3	0.012	65.54	0.00	0.0157	4.016
Sugar beet	156	500.00	0.019	0.00	77000	0.22	16940	0.4	6776.0	0.20	1.0	4743.2	0.014	75.90	0.00	0.0157	3.644
Forage maize	150	3310.00	0.006	0.00	12000	0.87	10440	1.0	10440.0	0.22	1.0	4593.6	0.007	52.02	0.00	0.0157	3.175
SRC	90	1850.00	0.015	0.00	-	-	25000	0.3	7500.0	0.8	0.3	6500.0	0.012	105.75	0.00	0.0157	3.076
Miscanthus	84	4452.29	0.015	0.00	-	-	12500	0.3	3750.0	0.8	1.0	13000.0	0.012	222.78	0.00	0.0157	4.821
Sida	100	4124.04	0.015	0.00	-	-	11600	0.3	3480.0	0.8	1.0	12064.0	0.012	206.63	0.00	0.0157	4.818
Silphium	120	5786.50	0.015	0.00	-	-	16300	0.3	4890.0	0.8	1.0	16952.0	0.012	290.22	0.00	0.0157	6.446

F.2.6 Indirect N_2O emissions

Table F.15 – Indirect N_2O emissions calculations (I).

	F_{SN} (kg N y^{-1})	$Frac_{GASF}$ (-)	EF_4 (-)	$N_2O_{(ATD)}N$ kg N_2O N y^{-1}
Wheat	190	0.11	0.014	0.293
Oats	130	0.11	0.014	0.200
OSR	190	0.11	0.014	0.293
Sugar beet	156	0.11	0.014	0.240
Forage maize	150	0.11	0.014	0.231
SRC	90	0.11	0.014	0.139
Miscanthus	84	0.11	0.014	0.129
Sida	100	0.11	0.014	0.154
Silphium	120	0.11	0.014	0.185

Table F.16 – Indirect N_2O emissions calculations (II).

	F_{SN} (kg N y^{-1})	F_{CR} (kg N y^{-1})	F_{SOM} (kg N y^{-1})	$Frac_{LEACH-(H)}$ (-)	EF_5 (-)	$N_2O_{(L)}N$ (kg N_2O N y^{-1})
Wheat	190	58.6	0.0	0.24	0.011	0.656
Oats	130	75.9	0.0	0.24	0.011	0.544
OSR	190	222.8	0.0	0.24	0.011	1.090
Sugar beet	156	75.9	0.0	0.24	0.011	0.612
Forage maize	150	52.0	0.0	0.24	0.011	0.533
SRC	90	0.0	0.0	0.24	0.011	0.238
Miscanthus	84	0.0	0.0	0.24	0.011	0.222
Sida	100	0.0	0.0	0.24	0.011	0.264
Silphium	120	0.0	0.0	0.24	0.011	0.317