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# Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe

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ABSTRACT

Agroforestry, relative to conventional agriculture, contributes significantly to carbon sequestration, increases a range of regulating ecosystem services, and enhances biodiversity. Using a transdisciplinary approach, we combined scientific and technical knowledge to evaluate nine environmental pressures in terms of ecosystem services in European farmland and assessed the carbon storage potential of suitable agroforestry systems, proposed by regional experts. First, regions with potential environmental pressures were identified with respect to soil health (soil erosion by water and wind, low soil organic carbon), water quality (water pollution by nitrates, salinization by irrigation), areas affected by climate change (rising temperature), and by underprovision in biodiversity (pollination and pest control pressures, loss of soil biodiversity). The maps were overlaid to identify areas where several pressures accumulate. In total, 94.4% of farmlands suffer from at least one environmental pressure, pastures being less affected than arable lands. Regional hotspots were located in north-western France, Denmark, Central Spain, north and south-western Italy, Greece, and eastern Romania. The 10% of the area with the highest number of accumulated pressures were defined as Priority Areas, where the implementation of agroforestry could be particularly effective. In a second step, European agroforestry experts were asked to propose agroforestry practices suitable for the Priority Areas they were familiar with, and identified 64 different systems covering a wide range of practices. These ranged from hedgerows on field boundaries to fast growing

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coppices or scattered single tree systems. Third, for each proposed system, the carbon storage potential was assessed based on data from the literature and the results were scaled-up to the Priority Areas. As expected, given the wide range of agroforestry practices identified, the carbon sequestration potentials ranged between 0.09 and 7.29 t C $ha^{-1}$ $a^{-1}$. Implementing agroforestry on the Priority Areas could lead to a sequestration of 2.1 to 63.9 million t C $a^{-1}$ (7.78 and 234.85 million t $CO_{2eq}$ $a^{-1}$) depending on the type of agroforestry. This corresponds to between 1.4 and 43.4% of European agricultural greenhouse gas (GHG) emissions. Moreover, promoting agroforestry in the Priority Areas would contribute to mitigate the environmental pressures identified there. We conclude that the strategic and spatially targeted establishment of agroforestry systems could provide an effective means of meeting EU policy objectives on GHG emissions whilst providing a range of other important benefits.

## 1. Introduction

Increased market price volatility and the risks of changing climate are - according to the EU Agricultural Markets Briefs (September 2017) – the biggest challenges European farmers will face in near future (DG Agriculture and Rural Development, 2017). Facing the complex relationship between competitive farming and sustainable production, the current Common Agricultural Policy (CAP, the European framework for agricultural subsidies), supports farmers' income, market measures and rural development (European Commission, 2016). In spite of cross-compliance mechanism and the recently introduced greening measure that links environmental standards to subsidies, the agricultural sector is still one of the prime causes of pressure on natural resources and the environment (EEA, 2017a). To address these environmental problems, the European Commission has issued policies such as the Nitrate Directive (91/676/CEE) in 1991, the Water Framework Directive (Directive 2000/60/EC) in 2000 and the Biodiversity Strategy in 2010 (COM(2011) 244). Nonetheless, major environmental problems persist and are still linked to or caused by intensive agricultural production on the one hand, and by land abandonment on the other (Plieninger et al., 2016). Most recently and in line with the COP21 Paris Agreement (UNFCCC, 2015) the Effort Sharing 2021–2030 (REGULATION (EU) 2018/842) includes agricultural practices, aiming to reduce greenhouse gas (GHG) emissions or balance with an equal amount of GHG sequestration.

In this context, the future CAP for the next funding period after 2020 (CAP2020+) proposes three focal areas: a) "natural" farming, b) sustainable water management and use and c) dealing with climate change (European Commission, 2017a). This will require strategies to manage the above mentioned financial and environmental risks of production, ideas to expand the agricultural product range, and a focus on sustainable farming systems with climate adaptation and mitigation functions (Wezel et al., 2014). Agroforestry, the integrated management of woody elements on croplands or grasslands (European Commission, 2013a), may become part of those strategies because it provides multiple (annual and perennial) products while simultaneously moderating critical environmental emissions and impacts on soil, water, landscapes, and biodiversity (Torralba et al., 2016). In addition, it is highlighted as one of the agricultural practices with the greatest potential for climate change mitigation and adaptation (Aertsens et al., 2013; Hart et al., 2017). For example, agroforestry can enhance the sequestration of carbon in woody biomass and in the soil of cultivated fields (mitigation) (Kim et al., 2016), increase soil organic matter, improve water availability (adaptation to climate aridification) (Murphy, 2015), protect crops, pastures, and livestock from harsh-climate events (adaptation to global warming and increasing wind speed) (Sánchez and McCollin, 2015).

Against this background, our study aimed to evaluate the potential contribution of agroforestry towards achieving zero-GHG emissions agriculture in pursuit of the ambitious Paris Agreement COP21 and CAP targets. Using a transdisciplinary approach including scientific and practical knowledge, the study focused on three key questions: I. Where and to what extent is European agricultural land affected by (multiple) environmental pressures that could be reduced through agroforestry? II. Which regional types of agroforestry (combinations of various woody plants, crop / animal species and management practices) can be used to reduce these environmental pressures and provide multiple products? and – as an example of an ecosystem service that agroforestry can provide – III. What is the impact of the proposed systems on European climate change targets, in particular on carbon storage and GHG emissions?

## 2. Material and methods

The study was conducted in three main phases: First, the agricultural areas most seriously affected by environmental pressures ("Pressure Areas") were identified using various spatially explicit datasets on e.g. soil erosion, water pollution, and pollination pressures. In a second step, local agroforestry experts were consulted to propose suitable agroforestry practices for their regions suffering from environmental pressures. Finally, the annual carbon storage impact of the proposed systems was identified and evaluated in the light of European agricultural GHG emissions. In the next subsections, these three main phases are described more in detail, while we address advantages and limitations of the adopted approach, as well as possible improvements, in the Discussion section.

### 2.1. Identification of Priority Areas

#### 2.1.1. Conceptual approach

Bearing in mind that agroforestry is only one aspect of a diversified agriculture, our focus was on agricultural areas facing combined environmental pressures, in which agroforestry can mitigate several environmental pressures. Fig. 1 illustrates the conceptual background of the Priority Area approach.

The analysis uses the Corine Land Cover 2012 (EEA, 2016) to identify the area of European arable and pasture land. From this farmland layer, the areas of high nature value such as Natura 2000 (EEA, 2015a), High Nature Value Farmland (EEA, 2015b; Paracchini et al., 2008), and the existing agroforestry areas (den Herder et al., 2017) were subtracted. The remaining "Focus Areas" (block II in Fig. 1) were the starting point for the pressure analysis.

#### 2.1.2. Selection of indicators to assess environmental pressures

The indicator selection passed three stages as visualised in Fig. 2. First, indicators characterizing benefits provided by agroforestry systems were chosen. Torralba et al. (2016) summarized them into i) timber, food, and biomass production, ii) soil fertility and nutrient cycling, iii) erosion control, iv) biodiversity provision and Hart et al. (2017) completed the list with v) climate change mitigation. Given that continental spatial datasets covering most of the European countries and addressing the indicators in a consistent way were limited, the selection focussed in a second step on the CAP 2014–2020 context indicators. The CAP monitoring and evaluation framework is composed on a set of socio-economic, sectorial, and environmental indicators to reflect the impact and provide (annual) information of the performance

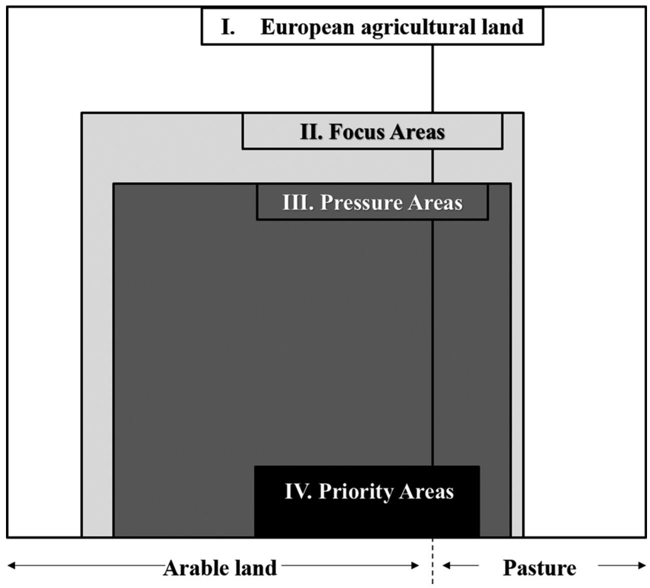


**Fig. 1.** Conceptual approach for the spatially explicit pressure analysis. European agricultural land: Arable and pasture land. Focus Areas: European agricultural land minus nature conservation areas, High Nature Value Farmland, and existing agroforestry land. Pressure Areas: Areas where at least one ecosystem service pressure was mapped. Priority Areas: Areas where environmental pressures accumulate (four out of eight in pasture and five out of nine in arable land).

of the strategy (European Commission, 2017b, 2014). Within this list four context environmental indicators were related to agroforestry benefits. These were i) water abstraction in agriculture (C.39) addressing pressures on available fresh water resources (indicator: e.g. irrigated area), ii) water quality (C.40) dealing with agricultural water pollution by nitrates and phosphates (indicator: e.g. Gross Nitrogen Balance), iii) soil organic matter (SOC) in arable land (C.41) as SOC influences soil structure, aggregate stability, nutrient availability, water retention and resilience (indicator: SOC content), and iv) soil erosion by water (C.42) the most widespread form of soil degradation (indicator: erosion) (European Commission, 2017b). Third, as indicators for climate change mitigation and biodiversity were not addressed within the CAP monitoring, we reviewed the literature and identified relevant datasets. In conclusion, only consistent spatial datasets, which were available with a wide European coverage, were included in the analysis.

Accordingly, environmental pressures related to: i) soil health (soil erosion by wind and water, soil organic carbon), ii) water quality and abstraction (water pollution by nitrates, irrigation), iii) climate change (rising temperature), and iv) biodiversity (pollination and pest control pressures, reduced soil biodiversity) were identified. Individual pressure maps were spatially aggregated and combined into the "Pressure Areas" map showing all regions where one or several environmental pressures occur. To identify the "Priority Areas" for intervention, the sum of pressures per spatial unit (pixel size = 100 m x 100 m) was expressed as an accumulation map or a "heatmap of environmental pressures".

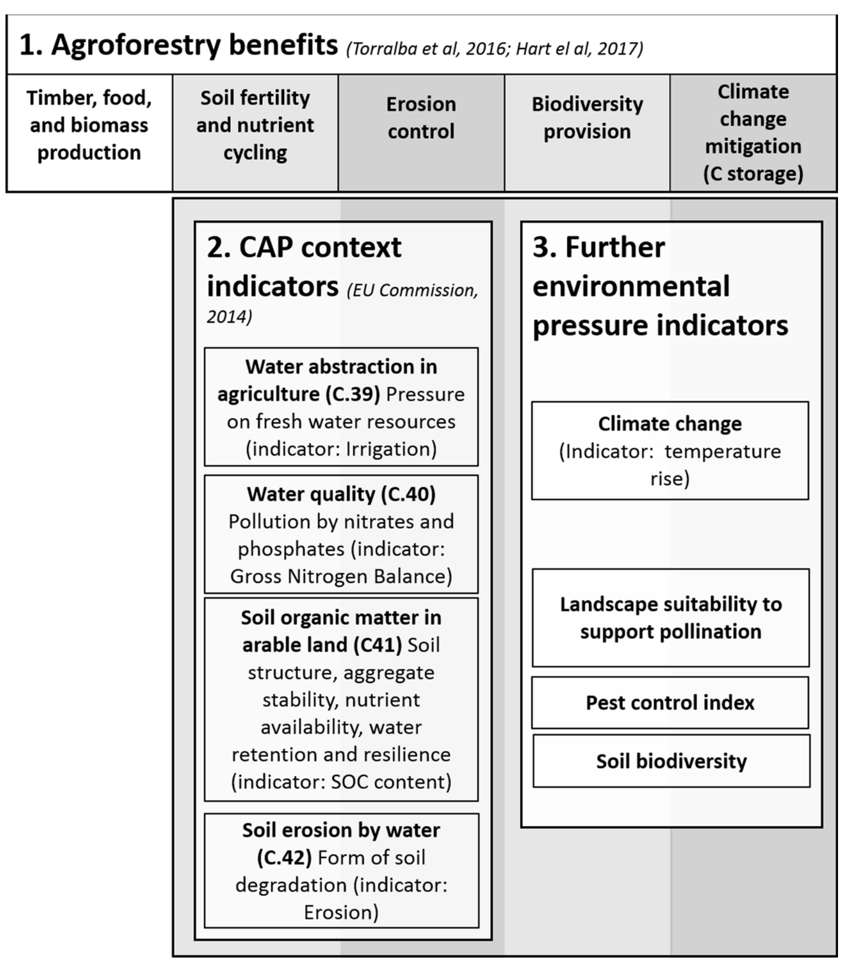


**Fig. 2.** Selection process of environmental pressure indicators. 1. Assessment of agroforestry benefits, 2. Evaluation of existing CAP context indicators, 3. Review of further environmental pressure indicators for climate change mitigation and biodiversity provision. (SOC: Soil organic carbon).

## 2.2. Pressure Area analysis

### 2.2.1. Soil health pressures

The European water erosion map (Panagos et al., 2015) and the Swiss soil erosion risk map (Prasuhn et al., 2013) together with the European wind erosion map (Borrelli et al., 2017) were used to locate areas with potentially critical loads of soil losses. According to Panagos et al. (2015) a critical threshold is reached if the soil loss is more than 5 t soil $ha^{-1}$ $a^{-1}$. The analysis of potential wind erosion was limited to arable land, which is more affected than grassland.

The Soil Organic Carbon (SOC) saturation capacity provided at European level by Lugato et al. (2014a), 2014b) expresses the ratio between actual and potential SOC stocks. Regions with a ratio of less than 0.5 were identified as Pressure Areas, meaning that these soils contain less than half of their SOC storage potential.

### 2.2.2. Water quality pressures

Irrigated fields regardless of whether they were pasture or arable land were included in the pressure analysis. Irrigation maps were provided by the JRC Water Portal (2017) and the Farm Structure Survey (FSS) (Eurostat, 2017a) and expressed the proportion of irrigated land on the total agricultural area. Regions with more than 25% of the agricultural area under irrigation were included as Pressure Area.

The nitrogen surplus, which can lead to both high levels of nitrate leaching and denitrification to gaseous nitrous oxide, was assessed for the European Union using the CAPRI model by Leip et al. (2014). For Switzerland data were obtained from modelled accumulated nitrogen losses (BAFU, 2015). According to the German Ministry of Environment (BMUB, 2017), there is a critical load if the annual nitrogen surplus exceeds 70 kg N $ha^{-1}$ $a^{-1}$ and this threshold was used to identify areas with high nitrogen surplus.

### 2.2.3. Pressures related to changing climate

Annual mean temperatures from the current climate (1970–2000 WorldClim; Hijmans et al., 2005) and the forecast for 2050 (HadGEM2-ES, Martin et al., 2011) were used to derive the predicted regional temperature increase up to 2050. According to Hart et al. (2012), agroforestry systems remain robust within an average temperature increase of up to 4 °C. Therefore, all areas with a predicted increase of temperature of more than 2 °C and less than 4 °C were qualified as Pressure Areas where agroforestry could potentially be beneficial.

### 2.2.4. Biodiversity pressures

Soil fauna, microorganisms and biological functions derived from the spatial analysis by Orgiazzi et al. (2016) were used to assess soil biodiversity. The areas identified with "high" and "moderate-high" levels of risk were defined as Pressure Areas.

The pollination assessment was based on the indicator of landscape suitability to support pollinators by Rega et al. (2017). The indicator is a dimensionless score; areas with "very low" and "low" suitability (corresponding to the first two quintiles of the values' distribution) were defined as Pressure Areas.

The pest control index (Rega et al., 2018) was used as input for the assessment of regions with potential pressures in natural pest control. Again, the indicator is a dimensionless score; areas with "very low" and "low" suitability to support natural pest control, corresponding to the first two quintiles of the values' distribution, were combined and defined as Pressure Areas.

### 2.2.5. Selection of Priority Areas

Using the thresholds previously mentioned (Table 1), the nine environmental pressures were spatially combined using GIS. In each spatial unit the number of pressures were added together by weighting each indicator equally. Implications, advantages and drawbacks of this methodological approach are addressed in the discussion section (4.1). In the resulting "heatmap", the 10% of the area with the highest number of pressures were defined as the Priority Area for the implementation of agroforestry. Based on Mücher et al. (2010) the Priority Areas were clustered into seven biogeographical regions: Atlantic; Continental lowlands, Continental hills; Mediterranean lowlands, Mediterranean hills, Mediterranean mountains; and Steppic.

The spatial analysis was performed in ArcGIS10.4 (ESRI, 2016). The

**Table 1**
Spatial datasets with their respective characteristics and the threshold applied to define Pressure Areas (EU28: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Ireland, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Spain, Slovakia, Slovenia, Sweden, and the United Kingdom; EU 27: is without Croatia; CH = value for Switzerland).

| Indicator | | Source | Coverage | Resolution | Threshold |
|---|---|---|---|---|---|
| Focus Area | CORINE - Agricultural land | EEA, 2016 | all Europe | 250 m | |
| | Agroforestry area | den Herder et al., 2017 | EU 28, CH | 100 m | |
| | High Nature Value Farmland | EEA, 2015b; Paracchini et al., 2008 | all Europe (without Greece) | 100 m | |
| | Natura 2000, Ramsar areas | EEA, 2015a | EU 28, CH | | |
| Soil Pressure Areas | Soil erosion by water | Panagos et al., 2015; Prasuhn et al., 2013 | EU 28, CH | 100 m | > 5 t soil $ha^{-1}$ $a^{-1}$ (Panagos et al., 2015) |
| | Soil erosion by wind | Borrelli et al., 2017 | EU 28, CH | 500 m | > 5 t soil $ha^{-1}a^{-1}$ (Panagos et al., 2015), limited to arable land |
| | Soil Organic Carbon (SOC) saturation capacity | Lugato et al., 2014a, 2014b | EU 28 | 250 m | < 0.5 Ratio between actual and potential SOC stock (Lugato et al., 2014a, 2014b) |
| Water related Pressure Areas | Irrigation | Eurostat, 2017a, 2017b, 2017c; JRC Water Portal, 2017 | all Europe | 100 m, 1000 m | > 25% irrigated land |
| | Nitrogen surplus | BAFU, 2015; Leip et al., 2014 | EU 27, CH (without Cyprus) | 1000 m (100 m CH) | > 70 kg N $ha^{-1}$ $a^{-1}$ (BMUB, 2017). |
| Climate Risk Areas | Climate change / Temperature rise | Hijmans et al., 2005 | all Europe | | 2 - 4 °C between 1990 and 2050 (Hart et al., 2012) |
| Biodiversity Pressure Areas | Soil biodiversity | Combination of soil fauna, soil microorganisms and soil biological function; Orgiazzi et al., 2016 | EU 27 | 500 m | Risk level "high", "moderate-high" (Orgiazzi et al., 2016) |
| | Landscape suitability to support pollination | Rega et al., 2017 | all Europe (without Cyprus) | 100 m | Classes "very low" and "low" (Rega et al., 2017) |
| | Pest control index | Rega et al., 2018 | all Europe (without Cyprus | 100 m | Classes "very low" and "low" (Rega et al., 2018) |

outcomes were processed in R (R Development Core Team, 2016) with packages plyr (Wickham, 2016), Hmisc (Harrell, 2018), and ggplot2 (Wickham et al., 2016).

### 2.3. Agroforestry recommendations

Potential agroforestry practices, which are: 1) of interest to farmers and the most likely to be adopted by them, 2) the most adapted to mitigate the prominent environmental issues in the region, 3) the most developed in the region and 4) the most suitable to face climate change, were compiled by local experts and the authors for each Priority Area. A total of 20 experts, mainly national delegates of the European Agroforestry Federation (EURAF) or associated researchers, were asked for their contribution.

We used a uniform emailing consisting of an explanation letter, maps of the Priority Area and a structured template. The template was divided into eight questions (see Table 3): i) type of agroforestry (e.g. silvopastoral, silvoarable; hedgerows, coppice, or single trees), ii) title and a short description of the system, iii) tree and hedgerow species, iv) number of trees per hectare or the percentage of woody cover per hectare, v) planting scheme (e.g. lines, scattered) and management system (e.g. year of harvesting / harvesting cycles), vi) crop species and products, vii) tree products, and viii) harvesting year. The outcomes were summarized by biogeographical region.

### 2.4. Assessment of carbon sequestration in biomass

The total biomass production (aboveground wood and root biomass) of the woody elements and the carbon storage potential of the proposed agroforestry systems were assessed based on literature data (see Supplementary material) and from (regional) test sites [units: t biomass $ha^{-1}$ $a^{-1}$; t C $ha^{-1}$ $a^{-1}$]. Herein the values represented an average potential per year of tree life and did not consider any dynamics of tree growth over time, or other impact factors such as water and nutrient availability, temperature, tree density, etc. Potential minimum and maximum values of carbon storage in biomass (both above- and belowground) of each agroforestry practice for each biogeographic region were extracted separately for pasture and arable land. These values were used for upscaling the results to the "Priority Area", assuming that in those regions, the total available farmland would be converted into agroforestry with one of the recommended agroforestry practices.

## 3. Results

### 3.1. Pressure assessment

In EU (EU28 minus Cyprus and Croatia) and Switzerland, the total area of European agricultural land is 1,544,022 $km^2$ (CLC, EEA, 2016). Subtracting existing agroforestry and nature protection areas, the analysis was then restricted to 1,414,803 $km^2$ as Focus Area. This area consisted of 1,071,179 $km^2$ of arable land (≙ 92% of total European arable land) and 343,624 $km^2$ of pasture (88% of total European pasture).

Fig. 3 gives an overview of the size of the individual "Pressure Areas" in relation to the Focus Area. Soil loss risks over 5 t soil $ha^{-1}$ $a^{-1}$ from water erosion were identified on 11.9% of the arable area and 9.5% of the pasture. Areas suffering from an annual loss greater than 5 t soil $ha^{-1}$ $a^{-1}$ by wind erosion were relatively small (1.5%), whereas a low SOC saturation capacity was present on 58.7% of arable lands and on 12.8% of pastures. In total, 8.4% of the arable areas and 1% of the pastures had irrigation levels greater than 25%. High nitrogen pollution risk was mapped on 20.6% of arable lands and on 34.5% of the pastures. Around 63.0% of arable lands and 53.6% of pastures were located in regions where temperature is expected to rise between 2 and 4 °C by 2050 according to the HadGEM2-ES forecast scenario. Pressures in biodiversity and resulting potential underprovision of ecosystem services are widely spread all over European agricultural land. In total, 66.4% of the arable lands and 36.8% of pastures in the Focus Area were predicted to have low or very low natural pest control potential, whilst 41.8% of the arable areas and 21.0% of pastures were predicted to be not suitable for supporting pollinators. Potential soil biodiversity pressures were mapped on 11.5% of arable lands and on 18.7% of pastures.

By combining the nine individual pressure maps, we created a heatmap for environmental pressures (Fig. 4a).

For the total Pressure Area, a lower proportion of pasture areas were identified than of arable lands. Only 4% of the arable lands in the Focus

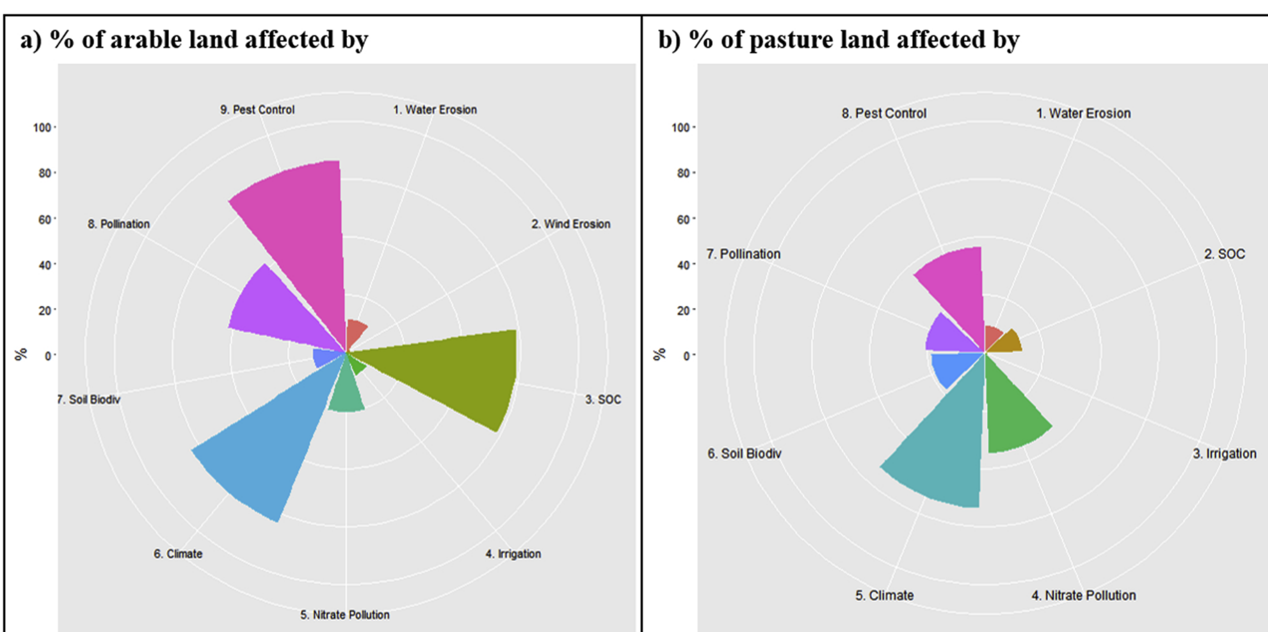


**Fig. 3.** The proportion of a) the arable land and b) the pasture affected by each of the environmental pressures across the selected Focus Areas. Wind erosion was only considered in arable areas. (SOC: Soil organic carbon).

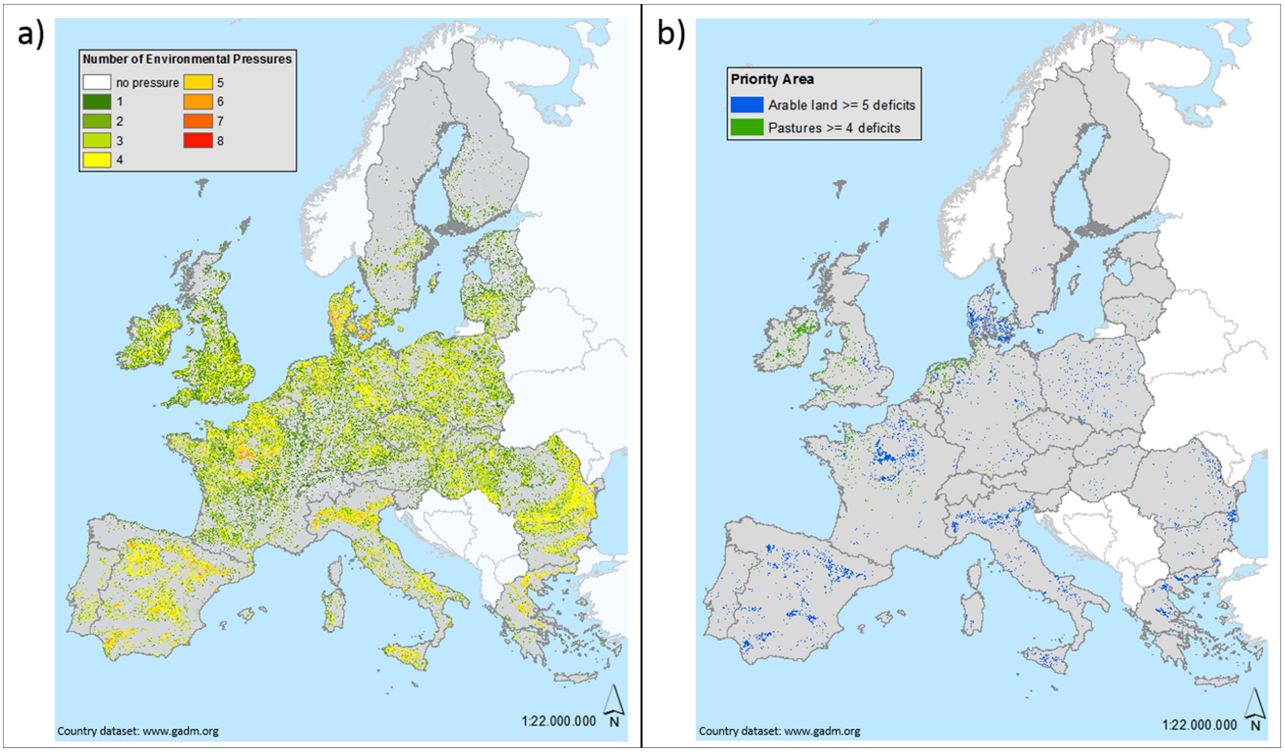


**Fig. 4.** a) Heatmap for the number of environmental pressures and b) Priority Areas (arable areas with more than five pressure indicators; and pasture areas with more than four pressure indicators).

**Table 2**
Summary of the Priority Areas by country divided into biogeographical regions based on the landscape classification by Mücher et al. (2010).

| Biogeographical Region | | Country | Arable land [km$^2$] | Pasture [km$^2$] | Total [km$^2$] | Share of total agricultural land [%] |
|---|---|---|---|---|---|---|
| Atlantic | | **Total** | **29,611** | **29,088** | **58,698** | **9.74** |
| | | Denmark | 498 | 3,223 | 3,721 | 20.19 |
| | | France | 16,156 | 6,151 | 22,308 | 10.7 |
| | | Germany | 6,366 | 102 | 6,468 | 9.78 |
| | | Ireland | 6 | 7,133 | 7,139 | 17.12 |
| | | Netherlands | 2,624 | 3,030 | 5,654 | 32.96 |
| | | UK | 2,600 | 8,719 | 11,319 | 8.43 |
| | | others | 1,361 | 730 | 2,090 | 1.8 |
| Continental | **Lowlands** | **Total** | **7,644** | **1,259** | **8,903** | **6.24** |
| | | Denmark | 3,607 | 21 | 3,628 | 38.82 |
| | | Germany | 1,660 | 809 | 2,469 | 5.22 |
| | | Poland | 1,296 | 106 | 1,402 | 3.76 |
| | | Others | 1,081 | 322 | 1,403 | 2.88 |
| | **Hills** | **Total** | **13,906** | **4,360** | **18,265** | **4.11** |
| | | Bulgaria | 2,116 | 537 | 2,654 | 7.03 |
| | | Germany | 1,905 | 1,473 | 3,377 | 3.88 |
| | | Poland | 6,379 | 439 | 6,818 | 5.73 |
| | | Romania | 2,054 | 1,078 | 3,132 | 4.87 |
| | | others | 1,452 | 833 | 2,285 | 1.68 |
| Mediterranean | **Lowlands** | **Total** | **12,399** | **156** | **12,555** | **22.52** |
| | | Greece | 3,020 | 42 | 3,063 | 38.28 |
| | | Italy | 7,990 | 39 | 8,029 | 21.15 |
| | | Spain | 1,220 | 50 | 1,270 | 22.36 |
| | | Others | 169 | 25 | 193 | 4.7 |
| | **Hills** | **Total** | **20,226** | **650** | **20,876** | **15.53** |
| | | Greece | 2,340 | 117 | 2,457 | 22.04 |
| | | Italy | 6,985 | 83 | 7,069 | 15.64 |
| | | Spain | 9,676 | 227 | 9,903 | 25.02 |
| | | Others | 1,225 | 223 | 1,448 | 3.77 |
| | **Mountains** | **Total** | **12,858** | **628** | **13,486** | **10.96** |
| | | Italy | 1,071 | 78 | 1,149 | 10.66 |
| | | Spain | 11,176 | 429 | 11,606 | 12.34 |
| | | Others | 611 | 120 | 732 | 4.02 |
| Steppic | | **Total** | **2,948** | **1,026** | **3,974** | **11.54** |
| Total | | | **99,592** | **37,166** | **136,758** | **8.87** |

**Table 3**
Agroforestry practices for arable lands and pastures in the European biogeographical regions (an extract of the practices with the lowest, medium, and the highest carbon sequestration potential are shown. See Supplementary material for the complete list and references). (SRC: Short rotation coppice)

| Biogeographical region | Agroforestry type | Title | Tree / hedgerow species | Trees [trees $ha^{-1}$], hedgerow [m $ha^{-1}$] or wood cover [% $ha^{-1}$] | Management system | Crop species and products | Tree products | Year of tree harvesting | Carbon sequestration [t C $ha^{-1}a^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|
| Atlantic pasture | Silvopastoral, coppice | Agroforestry for ruminants in France | Pear (*Pyrus* spp), honey locust (*Gleditsia triacanthos*), service tree (*Sorbus domestica*), white mulberry (*Morus alba*), Italian alder (*Alnus cordata*), goat willow (*Salix caprea*), field elm (*Ulmus minor*), black locust (*Robinia pseudoacacia*), grey alder (*Alnus incana*) | (single −2 m, double −6 m, triple −10 m), 4 m for trees, 1.3 m coppices x 20 m, (11% woody cover) | Single, double, or triple lines | Grazing, hay, silage | Fodder-trees, woodchips | 5–8 | 0.16-0.48 |
| Atlantic pasture | Silvopastoral, single trees | Traditional orchard | Fruit trees (apple – *Malus domcestica*, pear - Pyrus spp, plum - *Prunus domestica*) | 80 trees $ha^{-1}$ | Lines | Grazing, hay, silage | Fruits (woodchips) | 60 | 1.23 |
| Atlantic pasture | Silvopastoral, single trees | High stem timber trees | Poplar (*Populus* spp) | 400 trees $ha^{-1}$, After 15-20 years: 120-150 trees $ha^{-1}$ | Lines | Grazing, hay, silage | Timber | First cut: 15-20 harvest:25-30 | 2.78-6.35 |
| Atlantic arable | Silvoarable, hedgerows | Productive boundary hedgerow | Mixed hedgerow species: hawthorn (*Crataegus* spp), blackthorn (*Prunus spinosa*), field maple (*Acer campestre*), hazel (*Corylus avellane*) | 0.03% $ha^{-1}$ | Boundary hedgerow | Crop rotation with cereals (wheat, barley, oats), potatoes, squash, organic fertility building ley | Woodchips | Every 15 | 0.1-0.45 |
| Atlantic arable | Silvoarable, coppice | Alley cropping – Short Rotation Coppice (SRC) | Willow (*Salix viminalis*), hazel (*Corylus avellana*) | 1000-1300 trees $ha^{-1}$ (24% $ha^{-1}$) | Twin rows with 10-15 m wide crop alley | Cereals (wheat, barley, oats), potatoes, squash, organic fertility building ley | Woodchips | Every 2 for willow, every 5 for hazel | 0.36-1.05 |
| Atlantic arable | Silvoarable, single trees | High stem timber trees | Walnuts (*Juglans regia*), maples (*Acer* spp), wild cherry (*Prunus avium*), checker tree (*Sorbus torminalis*), service tree (*Sorbus domestica*), apple (*Malus domestica*), pear (*Pyrus* spp). | 28-110 trees $ha^{-1}$, (26-50 m between rows) | Lines | | Timber | 60 | Walnut: 0.32-2.75, cherry: 0.19-1.4 |
| Continental hills pasture | Silvopastoral, single trees | Wooded grassland | Fruit trees: cherry (*Prunus avium*), walnut (*Juglans regia*), apple (*Malus domestica*), etc. | 60 trees $ha^{-1}$ | Lines | Grazing, hay, silage | Fruits | 70-90 | Cherry: 0.41-0.76, apple: 0.93-1.43, walnut: 0.86-1.16 |
| Continental lowlands pasture | Silvopastoral, coppice | Agroforestry for free-range pig production | Poplar (*Populus* spp), willow (*Salix* spp), various fruit trees | 10-40% $ha^{-1}$ (2.5 × 3.5 m) | SRC lines | Grazing, hay, silage | Woodchips, fodder-trees | 5-8 | Poplar: 0.44-1.41 |
| Continental hills pasture | Silvopastoral, single trees | High nature and cultural value wood pastures and wooded grasslands | Sessile oak (*Quercus petraea*), beech (*Fagus sylvatica*), hornbeam (*Carpinus betulus*), wild fruit trees, mixed poplar (*Populus* spp.), willow (*Salix* spp.) | 50-300 trees $ha^{-1}$ (10-50% $ha^{-1}$) | Scattered | Grazing, hay, silage | Acorns, fruits, timber, (fodder-trees) | Trees not harvested | Oak: 0.71-2.83, beech: 0.59-2.34, hornbeam: 0.38-1.55 |
| Continental lowlands arable | Silvoarable, coppice | Alley cropping | Poplar (*Populus* spp); Mixed hedgerow species: willow (*Salix* spp), hornbeam (*Carpinus betulus*), common ash (*Fraxinus excelsior*), common birch (*Betula pendula*), black locust (*Robinia pseudoacacia*) | Rows A, B, and C: 10,000 trees $ha^{-1}$, Rows D, E, F, and G: 2222 trees $ha^{-1}$, (10% $ha^{-1}$). | Single and twin rows with 48, 96, and 144 m wide crop alleys. | Crop rotation (wheat, maize, oilseed rape, barley) | Woodchips | Rows A, B, and C: every 3-5. Rows D, E, F, and G: every 8–10 | 0.15 - 0.44 |
| Continental hills arable | Silvoarable, single trees | Orchard with vegetables or fruits (strawberries) | Fruit trees: cherry (*Prunus avium*), walnut (*Juglans regia*), apple (*Malus domestica*), etc | 60 trees $ha^{-1}$ | Lines | Vegetable, berries (strawberries) | Fruits, timber | 70-90 | Cherry: 0.41-0.76, apple: 0.93-1.43, walnut: 0.86 -1.16 |
| Continental hills arable | Silvoarable, single trees | Non-native, energy tree with Alfalfa | Pauwlonia (*Paulownia tomentosa*) | 126 trees $ha^{-1}$ (18 m x 5 m) | Lines | Triticale, alfalfa | Timber | 10-12 | 3.77 |

(*continued on next page*)

**Table 3** (*continued*)

| Biogeographical region | Agroforestry type | Title | Tree / hedgerow species | Trees [trees $ha^{-1}$], hedgerow [m $ha^{-1}$] or wood cover [% $ha^{-1}$] | Management system | Crop species and products | Tree products | Year of tree harvesting | Carbon sequestration [t C $ha^{-1}a^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|
| Mediterranean hills pasture | Silvopastoral, single trees | Dehesa | Holm oak (*Quercus ilex*) | 25-50 trees $ha^{-1}$ | Scattered | Grazing | Acorns, fodder-trees | Trees not harvested | 0.09–0.16 |
| Mediterranean hills pasture | Silvopastoral, single trees | Grazed cork oak plantation | Cork oak (*Quercus suber*) | 113 trees $ha^{-1}$, after 20 years: 50 trees $ha^{-1}$ | Lines | Grazing | Cork, timber | 80 | 0.34-1.29 |
| Mediterranean hills/ mountains pasture | Silvopastoral, single trees | Grazed fruit plantations | Olive (*Olea europaea*), almond (*Prunus dulcis*) | 250 trees $ha^{-1}$ | Lines | Grazing, legume rich mix (annual self seeding species) | Fruits, oil, nuts | Annual prunings, trees not harvested | Olive: 1.97, almond:1.36 |
| Mediterranean lowlands arable | Silvoarable, single trees | High stem timber trees | Pedunculate oak (*Quercus robur*) | 57 trees $ha^{-1}$ | Lines | Cereals | Timber | 35 | 0.11-0.26 |
| Mediterranean hills arable | Silvoarable, single trees | Fruit tree alley | Olive (*Olea europaea*) | 200-400 trees $ha^{-1}$ | Lines or scattered | Wild asparagus | Oil, forage | Annual prunings, trees not harvested | 1.57-3.14 |
| Mediterranean mountains arable | Silvoarable, single trees | High stem timber trees | Poplar (*Populus* spp) | 200 trees $ha^{-1}$ | Lines | Crop rotation wheat, oilseed rape, chickpeas | Timber | 15 | 5.76 - 7.29 |
| Steppic arable | Silvoarable, single trees | High stem forest trees | Poplar (*Populus* spp), willow (*Salix* spp.), black locust (*Robinia pseudoacacia*), pedunculate oak (*Quercus robur*), plain common and black walnut (*Juglans nigra*), common ash (*Fraxinus excelsior*), red oak (*Quercur subra*),), lime (*Tilia* sp.), | 60–70 trees $ha^{-1}$ | Lines | Vegetables | Timber | 70-90 | Poplar: 1.72-2.85, oak: 0.32-1.2, walnut: 1.31 |
| Steppic, arable | Silvoarable, single trees | Mixed timber and wild fruit species plantation | Grayish oak (*Quercus pedunculiflora*), field maple (*Acer campestre*), lime (*Tilia* sp.), hawthorn (*Crataegus* sp), *Rosa* sp, blackthorn (*Prunus spinosa*) | 100 trees $ha^{-1}$ | Lines | Vegetables | Fruits, fodder trees, timber | Harvesting depends on species estimated from 25-120. | Oak : 1.59, tilia:1.32 |
| Steppic, arable | Silvoarable, single trees | Poplar plantation | Poplar (*Populus* spp) | 100 trees $ha^{-1}$ | Lines | Sunflower, cabbage, corn, pepper and eggplant, water-melon and squash, cauliflower; wheat, beans | Timber | 35 | 2.88-4.76 |

Areas had no pressures, while in pasture it was around 12%. More than half of the pasture areas had less than three pressures, while 35% of arable area were affected by more than four pressures, and 9% had more than five pressures. Whilst we defined the Priority Areas as arable lands with more than five pressures, we set the threshold to only four pressures for pasture, as we evaluated only eight pasture pressure indicators (excluding soil erosion by wind). Together, they represent the worst 10% of the Pressure Area (Fig. 4b). These combined Priority Areas for arable and pasture land amounted to 136,758 $km^2$, which corresponds to about 8.9% of the total European agricultural land. Table 2 gives an overview of the Priority Areas according to country and biogeographical region.

### 3.2. Potential agroforestry practices

In total, 64 agroforestry practices were proposed by the authors and local experts. They cover a wide range of practices from hedgerow systems on field boundaries to fast growing coppices or scattered single tree systems. Table 3 lists, for each biogeographical region, the proposed system with the lowest, medium, and highest carbon sequestration potential. In line with the largest Pressure Areas, the highest number of agroforestry practices was proposed for Atlantic regions (14 silvopastoral and 9 silvoarable practices) followed by Mediterranean arable lands. The complete list can be found in Supplementary material.

### 3.3. Carbon storage potential

For each system the annual carbon storage potential of the woody elements (including roots) was identified using data from the literature and in each geographical region, the minimum and maximum storage potential were determined. The wide range of practices selected corresponded to a wide range of carbon storage potentials, between 0.09 and 7.29 t C $ha^{-1}$ $a^{-1}$. In Table 4 these data were upscaled to the entire Priority Area of each biogeographical region. Overall, implementing the proposed agroforestry practices in the Priority Areas could mitigate between 2.1 and 63.9 million t C $a^{-1}$ depending on the systems chosen, which is between 7.7 and 234.8 million t $CO_{2eq}$ $a^{-1}$.

In 2015, the 28 members of the European Union (EU28) together with Switzerland emitted 4,504.9 million t of greenhouse gases (million t $CO_{2eq}$), with agriculture contributing 12% (~540 million t $CO_{2eq}$; Eurostat, 2017b). Converting the conventionally used farmland in the Priority Area (which was about 8.9% of total agricultural land) to agroforestry could therefore capture between 1.4 and 43.4% of the European agricultural GHG emissions.

## 4. Discussion

This research investigated three questions: I) Where and to what extent is European agricultural land affected by (multiple) environmental pressures? II) Which regional types of agroforestry can be used to reduce environmental pressures? and III) What is the potential contribution of the proposed systems to the European zero-emission agriculture climate targets?

### 4.1. European environmental Pressure Areas

In response to the first question, several environmental pressures that can be mitigated by establishing agroforestry practices were selected. According to Alam et al. (2014) and Torralba et al. (2016) these include soil conservation, the improvement of water quality, nutrient retention, climate regulation, and enhanced biodiversity. We investigated nine environmental pressures and mapped their occurrence in European agricultural land, based on existing spatially explicit databases at a continental European scale. The best available data were used, although it should be noted that differences in scales (100–1000 m pixel size), time periods (2006–2017) and models (e.g. modelled soil losses in EU vs. soil erosion risk map in Switzerland) existed that might result in spatial inaccuracies (Schulp et al., 2014). However, as other authors have pointed out, this is an intrinsic limit of all pan-European, spatially explicit studies: “as fully harmonized data on the different aspects are not available, the possible bias from inconsistencies between the different data layers is unavoidable” (Malek and Verburg, 2017). All the datasets used, required some degree of modelling and the maps therefore show predicted rather than measured environmental pressures. Moreover, not all the existing environmental problems in agricultural areas could be addressed. Methane emissions, ammonia emissions, and zoonoses contamination, for example, were not included in the analysis presented here. In addition, biodiversity aspects in terms of quality and diversity (Zhang et al., 2007), the amenity value of the landscape, and natural hazards, such as avalanches, floods, droughts, and landslides (EEA, 2017b) were not considered.

Recommendations from the literature were used to define the thresholds for delimiting the Pressure Areas. The definition of thresholds is always arbitrary to some extent: different thresholds exist and modifying these or using different models would affect the size and spatial location of the Pressure Areas. For erosion, we used 5 t soil $ha^{-1}$ $a^{-1}$ as a threshold for erosion caused by water and erosion caused by wind, whereas for example, adopting a “tolerable” soil erosion rate of 0.3 to 1.4 t soil $ha^{-1}$ $a^{-1}$ as recommended by Verheijen et al. (2009) would strongly have increased the Pressure Area. The 5 t soil $ha^{-1}$ $a^{-1}$ threshold was uniformly used for the whole of Europe. However, soil erosion threshold values could also be defined by the nature of the soils in a particular area, depending for example, on soil quality and depth, with lower quality and shallower soils given lower thresholds to reflect their already precarious state and the relative importance of conserving what remains.

Surplus regions for nitrogen have also been defined in different

**Table 4**
Potential carbon sequestration in the whole Priority Area using minimum and maximum carbon storage potential of agroforestry practices proposed for each biogeographical region.

| Biogeographical region | Minimum carbon storage potential | | | | | Maximum carbon storage potential | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [t C $km^{-2}$ $a^{-1}$] | | Priority Area [t C $a^{-1}$] | | | [t C $km^{-2}$ $a^{-1}$] | | Priority Area [t C $a^{-1}$] | | |
| | Arable land | Pasture | Arable land | Pasture | Total | Arable land | Pasture | Arable land | Pasture | Total |
| **Atlantic** | 10 | 16 | 296,109 | 465,401 | 761,510 | 275 | 635 | 8,142,998 | 18,470,618 | 26,613,616 |
| **Continental lowlands** | 15 | 44 | 114,660 | 55,396 | 170,056 | 159 | 141 | 1,215,401 | 177,518 | 1,392,919 |
| **Continental hills** | 27 | 38 | 375,461 | 165,661 | 541,122 | 377 | 283 | 5,242,545 | 1,233,741 | 6,476,286 |
| **Mediterranean lowlands** | 11 | 9 | 136,390 | 1,400 | 137,790 | 600 | 197 | 7,439,447 | 30,654 | 7,470,101 |
| **Mediterranean hills** | 11 | 9 | 222,488 | 5,850 | 228,338 | 530 | 197 | 10,719,872 | 128,053 | 10,847,925 |
| **Mediterranean mountains** | 11 | 9 | 141,441 | 5,650 | 147,092 | 729 | 197 | 9,373,711 | 123,676 | 9,497,387 |
| **Steppic hills** | 32 | 38 | 94,322 | 39,003 | 133,325 | 476 | 283 | 1,403,039 | 290,467 | 1,693,506 |
| Total | | | **1,380,871** | **738,362** | **2,119,233** | | | **43,537,013** | **20,454,727** | **63,991,740** |

ways by the European states. The Nitrate Directive (91/676/CEE) limits the nitrate content in ground and drinking waters to 50 mg $NO_3$ $l^{-1}$, and uses this limit for national governments to identify Nitrate Vulnerable Zones (NVZ). In an earlier study on arable target regions for agroforestry implementation, based on soil erosion risk and NVZs, Reisner et al. (2007) identified 51.6% of the European arable land as Pressure Area. Yet the delimitation of NVZs was partly also a political process. In some countries they are limited to areas where the nitrate content in groundwater regularly exceeded the 50 mg $NO_3$ $l^{-1}$ threshold. In other countries, entire territories or regions were designated where special actions for nitrate reduction are compulsory for farmers (European Commission, 2013b). For example, almost the entire territory of Germany is labelled as NVZ. To allow for a spatially more differentiated analysis, we opted to locate areas with modelled annual nitrogen surplus above 70 kg N $ha^{-1}$. Together, they accounted for 22% of arable lands and 36% of pastures, which is substantially lower than the 51.6% of European arable land identified by Reisner et al. (2007) as Pressure Area for nitrate emissions.

The most prominent pressure in terms of area affected was the impact of rising temperature and climate change. This is in line with Olesen et al. (2012) and Schauberger et al. (2017) who modelled effects of climate change on crop development and yields. They found an earlier start to the growing and flowering period followed by enhanced transpiration in combination with water stress resulted in a reduction of maize yield of up to 6% for each day with temperatures over 30 °C. In fact, already during the summer of 2017 the potential impact of climate change was revealed by drought and heat waves, which impeded cereal production in various parts of Europe, mainly in southern and central Europe (JRC, 2017). However, by contrast, Knox et al. (2016) predicted positive effects of between 14–18% on the yields of wheat, maize, sugar beet, and potato by 2050 in Northern Europe.

To identify Priority Areas, we accumulated all indicators. This simple addition implied assigning the same weight to all the environmental pressures addressed, and not considering the magnitude of each pressure and its relevance for the local context. For instance, soil erosion could be more damaging for agricultural practices than pests in a particular region or vice versa. However, a more sophisticated approach incorporating these two aspects, would have introduced a further level of arbitrariness in the study, in relation to the assignment of different weights. The approach used here has the advantage of being straightforward and immediate to understand and interpret for decision-makers. Indeed, our methods and results are in line with other pan-European studies, e.g. Mouchet et al. (2017) and Maes et al. (2015), that both analysed the ecosystem service provision of European landscapes. Mouchet et al. (2017) aggregated bundles of ecosystem services and found a longitudinal gradient of decreasing land use intensity from France to Romania. Maes et al. (2015) assessed the quantity of green infrastructure that maintained regulating ecosystem services and showed that regions with intensive agricultural production (arable and livestock) generally had lower levels of regulating ecosystem services provision. Both studies referred to the sum of all assessed indicators. The similarity among the three studies for the spatial output gives confidence to the overall outcomes of this study.

### 4.2. Potential agroforestry practices and ecosystem service provision

To address the second research question, the collection of agroforestry practices, we hypothesized that agroforestry could mitigate the environmental pressures identified and that for each region, suitable practices could be proposed. Although agroforestry provides multiple ecosystem services (Torralba et al., 2016), there is a general lack of uptake by farmers (Rois-Díaz et al., 2018). Therefore, instead of trying to propagate the most suitable agroforestry for a particular pressure area and environmental pressure, we argue that the highest impact could be achieved by proposing an array of agroforestry practices that are locally adapted and attractive for farmers. This was how the experts selected the proposed practices. The suitable combination of tree and crop species is highly dependent on soil, water, and climate conditions at specific locations. For this reason, we have provided only a list of examples of agroforestry practices. The composition, implementation, and management of the agroforestry systems needs to be discussed with regional agroforestry experts and developed in partnership with the farmers themselves[1] .

For soil conservation, silvoarable alley cropping systems have been evaluated in earlier studies. Palma et al. (2007) and Reisner et al. (2007) estimated that their introduction on eight million hectares of arable land subject to water induced erosion risks would reduce soil erosion in those areas by 65%. Similar findings were provided by Ceballos and Schnabel (1998) and McIvor et al. (2014), who analysed how agroforestry can contribute to soil protection and preservation. Hedgerow systems lowered wind speed and consequently soil erosion by wind (Sánchez and McCollin, 2015). Regarding the reduction of nitrate leaching, Nair et al. (2007) and Jose (2009) showed that agroforestry reduced nutrient losses by 40 to 70%. The conversion of 12 million ha of European cropland in NVZ to agroforestry with high tree densities could reduce nitrogen leaching by up to 28% (Palma et al., 2007). Moreno et al. (2016); Birrer et al. (2007); Bailey et al. (2010); and Lecq et al. (2017) investigated the potential of agroforestry to provide multiple habitats for flora and fauna and enhance biodiversity. Flowering trees, such as orchards with fruit trees, were especially important in providing nesting and foraging habitats for pollinators (Sutter et al., 2017) and could enhance pest control (Simon et al., 2011). In general, findings from recent literature suggest that green infrastructure, such as agroforestry, enhances the overall provision of multiple ecosystem services (Kay et al., 2018a,b; Maes et al., 2015).

### 4.3. Carbon sequestration potential

Our third research question focussed on the most prominent pressure “climate change” in pursuit of a zero-emission scenario in European agriculture. To do this, we estimated the carbon storage potential of the proposed agroforestry systems in the above- and below-ground biomass of the woody elements. Whilst we are aware that agroforestry can also increase soil organic carbon (e.g. López-Díaz et al., 2017; Seitz et al., 2017; Upson and Burgess, 2013), soil carbon storage is difficult to quantify. E.g. Feliciano et al. (2018) reported inconsistent results for temperate agroforestry ranging from a decrease of -8 t C $ha^{-1}$ $a^{-1}$ to an increase of 8 t C $ha^{-1}$ $a^{-1}$. They affirmed that different climatic conditions and the previous land management had a higher impact on soil carbon storage than the established agroforestry system. At the scale of this study it was therefore not sufficiently reliable to account for (additional) soil carbon storage.

We found an overall average carbon sequestration potential of agroforestry of between 0.09 to 7.29 t C $ha^{-1}$ $a^{-1}$. The lower values were related to systems involving fewer woody elements per area (e.g. hedgerows on field boundaries, which typically make up less than 5% of the field). The higher values were mainly related to systems with higher densities of fast growing tree species and good soil conditions, which would also be associated with some reduction in food and feed production (see also Table 3). Previous studies (e.g. Palma et al., 2007; Reisner et al., 2007) estimated a sequestration range of between 0.77 and 3 t C $ha^{-1}$ $a^{-1}$ for alley cropping, and Aertsens et al. (2013) proposed an average sequestration of 2.75 t C $ha^{-1}$ $a^{-1}$. Our estimates ranged from 0.09 to 7.29 t C $ha^{-1}$ $a^{-1}$ for implementing different agroforestry systems across Europe. In comparison, European forest stands sequestered 167 million t C in 2015 on 160.93 million ha (1.04 t C $ha^{-1}$ $a^{-1}$) (FOREST EUROPE, 2015). This value is a continental average and also comprises trees grown at latitudes and altitudes where growth is relatively slow. In

[1] See also European Agroforestry Federation (EURAF) - http://www.eurafagroforestry.eu/

general, the competition between trees, e.g. for light and nutrients, is higher in forests than for trees in agroforestry systems.

### 4.4. Potential implementation and impact

The hotspots of environmental pressures were mainly located, as was expected, in intensively managed agricultural regions mostly correlated with a high level of production (Eurostat, 2018, 2017c). The implementation of agroforestry in these regions would have the greatest environmental benefits (Weissteiner et al., 2016). In spite of the rising awareness of the importance of improving the environment and the investment in supporting measures of the European and national Rural Development Programs of the EU Member States (Santiago-Freijanes et al., 2018), the impact on green infrastructure is mixed. For example in the UK, whilst the area of woodland is increasing, the area of hedgerows declined from 1998 to 2007 (Wood et al., 2018). Agroforestry, landscape features, agro-ecological systems, and green infrastructure are still in decline (Angelstam et al., 2017; EEA, 2018; Salomaa et al., 2017). This implies that the established incentives are insufficient or do not adequately address the problem and actors (e.g. Mosquera-Losada et al., 2018). In contrast, a promising trend can be observed in Switzerland, where since 1993 agroforestry trees and hedgerows in open landscapes are qualified as ecological focus areas. This measure and the related payments have allowed a consolidation of the area under agroforestry (BLW, 2017; Herzog et al., 2018).

There might be a trade-off between the introduction of agroforestry on arable and grassland, food production and the challenge of food security over the coming decades with a rising human population (Ray et al., 2013). For example, for a poplar silvoarable system in the UK, García de Jalón et al. (2018) predicted that crop yields would be 42% of those in arable systems, and that timber yields would be 85% of those in a widely-spaced forest system. Thus, the crop production and hence the production of food for human nutrition would be reduced. In the case of silvopastoral practices, Rivest et al. (2013) showed that trees did not compromise pasture yields, though the impact of future drought pressures on yield would strongly be related to the chosen species. In addition, no significant correlation between the number of semi-natural vegetation on agricultural output was found (García-Feced et al., 2015).

The potential reduction of agricultural yields after the introduction of trees is an argument that is often put forward by farmers, who see themselves foremost as producers of food and fodder. However, under Mediterranean conditions, Arenas-Corraliza et al. (2018) predict that crop production could be reinforced under silvoarable schemes compared to open fields if the recurrence of warm springs keeps increasing. In addition, farmers are increasingly being asked to provide environmental goods and services beyond food production and policy makers and researchers are seeking for ways to sustainably intensify agricultural production, which necessitates increasing productivity whilst at the same time reducing environmental damage and maintaining the functioning of agro-ecosystems in the long-term (Tilman et al., 2011; Tilman and Clark, 2014). In many cases, this will require a shift towards more complex and knowledge intensive agro-ecological approaches (Garibaldi et al., 2017). Trees on farmland have been identified for a long time as key elements in the design of sustainable agricultural systems (Edwards et al., 1993) and can contribute to multiple ecosystem services beyond carbon sequestration in combination with other types of semi-natural vegetation (Smith et al., 2017).

Agroforestry implementation in the Priority Areas, which made up 8.9% of total European farmland, would capture between 1.4 and 43.4% of European agricultural GHG emissions, depending on whether the focus is on increasing tree cover in hedgerows as field boundary or supporting within field silvoarable and silvopastoral systems. These values support the observation by Hart et al. (2017) and Aertsens et al. (2013) who championed agroforestry as the most promising tool for climate change mitigation and adaptation in agriculture. Consequently, agroforestry can contribute significantly to the ambitious climate targets of the EU for a zero-emission agriculture.

Finally, implications of this study are not restricted to the agricultural sector. Promoting agroforestry should be part of a more general land use policy aiming at the design of multifunctional agricultural landscapes. Scholars maintain that this will require coordinated actions at scales larger than individual farms and suggest that mechanisms for coordination and integration between spatial planning and agricultural measures will need to be put in place (e.g. Landis, 2017; Rega, 2014). This is also in line with the European Biodiversity Strategy and the Communication on Green Infrastructure (COM(2013) 249 fin. l), which advocates for the integration between green infrastructure and spatial planning to achieve the Strategy's Target 2 objectives – ecosystem services enhancement and ecosystem restoration. In this frame, agroforestry should be considered as a key component of green infrastructure and, in turn, green infrastructure can offer a suitable policy frame, beyond the CAP, to promote agroforestry.

## 5. Conclusion

We investigated the potential for implementing agroforestry in agricultural areas subject to multiple environmental pressures of agricultural land in Europe and its contribution to European climate and GHG emission reduction targets. We found around one quarter of European arable and pasture land to be affected by none or only one of nine analysed environmental pressures and not primarily in need of restoration through introduction of agroforestry. Pastures were less affected than arable lands. For the Pressure Areas, we propose a wide range of agroforestry practices, which could mitigate the environmental pressures. The collection confirms the huge potential of agroforestry (1) to be introduced and established in nearly every region in Europe and (2) to adapt to various contexts, ideas, and needs of farmers. The estimated potential carbon storage depends on the selected agroforestry practice. The evidence from this study, that agroforestry on 8.9% of European agricultural land could potentially store between 1.4 up to 43.4% of the total European agricultural GHG emissions, is encouraging and demonstrates that agroforestry could contribute strongly to prepare the ground for future zero-emission agriculture. Imposing e.g. carbon payments or penalties for nutrient or soil loss pollutions as presented would make agroforestry a more financially profitable system. Future analysis should regionalize the approach to individual countries making use of data of higher spatial and thematic resolution, and ultimately to the farm scale, accompanied by extension and advice.

In sum, agroforestry can play a major role to reach national, European and global climate targets, whilst additionally fostering environmental policy and promoting sustainable agriculture, particularly in areas of intensive agricultural management where environmental pressures accumulate. Future policy and legislation, e.g. the future Common Agricultural Policy (CAP2020+), should explicitly promote and strengthen agroforestry.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2019.02.025

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