CRANFIELD UNIVERSITY

Lucie Maskova

Alternative cropping practices for sustainable soil management and yield optimisation in asparagus

School of Water, Energy and Environment

PhD
Academic Year: 2018 - 2021

Supervisor: Dr Robert Simmons and Dr Lynda Deeks
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ABSTRACT

Asparagus (*Asparagus officinalis* L.) is a high value perennial crop with long economic production period ranging between 10-20 years. Field operations associated with conventional UK asparagus production such as re-ridging and intensive foot and vehicular trafficking of the wheelings however run a danger of causing a range of negative environmental impacts and pose a risk to long-term asparagus productivity. Nonetheless, majority of British growers continues to cultivate asparagus in the conventional way due to a lack of alternatives to the conventional practice.

The aim of this research is to critically evaluate the long-term efficacy of a set of potential best management practices (BMPs) targeted at preventing or remediating soil compaction in asparagus interrows, promoting root growth and increasing profitability of asparagus production. The research further aimed to quantify the impacts of annual re-ridging associated with the conventional production on soil compaction, root development, yields and on soil bio-chemical characteristics. The experimental field trial located in Herefordshire tested a range of potential BMPs inducing (i) companion cropping with either rye (*Secale cereale* L.) or mustard (*Sinapis alba* L.) which were re-ridged or non-ridged, (ii) interrow surface mulching with either straw mulch or compost which were re-ridged or non-ridged and (iii) a combination of tillage practices (ridging and shallow soil disturbance) applied to bare soil interrows. Treatments were applied annually from 2018-2020. This research showed that the field management practice currently adopted by the of British asparagus industry is unsustainable and poses high risks to both the soil environment and asparagus productivity. Key findings show that soil compaction, root growth, asparagus profitability and soil bio-chemistry in asparagus cropping systems can be effectively modified and managed by BMPs. Consequently, this research identified a set of BMPs to be considered for practical application.

Keywords: *companion crops, straw mulch, compost, yield, soil compaction, best management practice, tillage*

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BMP	Best management practice
PAS	Publicly available specification
CC	Companion crop
R	Re-ridging
NR	Non-ridging
SSD	Shallow soil disturbance
No-SSD	No shallow soil disturbance
PR	Penetration resistance
CRR	Crown and root rot
RMD	Root mass density
CZL	Crown zero line
IDW	Inverse distance weighing
CHO	Soluble carbohydrate
DMC	Dry matter content
MC	Moisture content
MBC	Microbial biomass carbon
CEC	Cation exchange capacity
SOM	Soil organic matter
IP	Impact points
DEFRA	Departments for Environment, Food and Rural Affairs
ELMS	Future Environmental Land Management scheme

1 Introduction

Asparagus (*Asparagus officinalis* L.) is a high value perennial crop with expected length of economic production ranging between 10-20 years (Elmer et al., 1996). The British asparagus industry is growing rapidly and value of which increased between 2009 and 2019 by more than 77% to approximately £26 million. In the period between 2009 to 2019, the asparagus cropped area in the UK increased by >50 % and value of marketed home production increased by 77 % (Defra, 2020; FAO, 2021). Conventional UK asparagus growing practices adopted by the majority of British growers are associated with on and offsite environmental impacts. Typically in the UK, asparagus is grown as a monoculture on raised beds with bare soil interrows. Row crop production systems in general promote a number of issues, including deep-seated compaction and soil erosion (Alakukku et al., 2003; Chamen et al., 2003; Håkansson, 1994; Niziolomski et al., 2020). In UK asparagus systems, the majority of tillage operations are undertaken between March to April, when soils are at or close to field capacity (Niziolomski et al., 2016). In addition, interrows are assoiciated with daily foot-trafficking duirng the harvest period April to June irrepsective of soil moisture condition. This repeated vehicle and foot trafficking causes compaction of all interrow wheelings. Asparagus fields are also left bare for the whole harvest period increasing the risk of runoff and erosion (Niziolomski et al., 2020).

Annual re-ridging of asparagus typically in early-March is the dominant practice adopted by UK asparagus growers and considered the UK conventional practice. Asparagus is grown on ridges for multiple reasons: to promote the growth of thicker spears meeting customer specifications, to ensure adequate soil depth above the crown, to raise asparagus beds for efficient manual harvest and to bury fern residue for control of *Stemphylium vesicarium*. Ridging also facilitates transport of excess rainfall away from the asparagus crown area, through the interrows and off the field to prevent waterlogging (Niziolomski et al., 2020). Subsoiling is sometimes used by UK asparagus growers to alleviate interrow compaction (Niziolomski et al., 2020, 2016). However, the current paradigm is that tillage operations pose a high risk of damage to asparagus root systems. Research undertaken in North America and New Zealand has demonstrated that root damage associated with tillage operations can have a major negative impact on asparagus yield and aboveground biomass (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). The size of the root system affects the crops ability to access and acquire soil resources determining crop productivity (Bengough, 2012; Lynch, 1995). The 'Root-Engine', which is an analogy for the root system used by Wilson, Cloughley and Sinton (2002), is particularly important in asparagus as physiological processes fully depend on the ability of the root system to deliver nutrients and carbohydrates for spear growth and fern development. Tillage also increases susceptibility to crown and root rot (CRR) caused by pathogens such as *Phytophthora asparagi* (Falloon and Grogan, 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2015), which are the major cause of 'asparagus decline syndrome'. Asparagus decline can reduce average economic productivity to only 5-10 years (Elmer et al., 1996), causing major economic losses. In the UK, asparagus decline was estimated to cause up to 60 % loss of stand and up to £16 million in revenue losses over a 10 year period (AHDB, 2017). Thus, conventional operations associated with tillage, harvest and agronomy of asparagus in the UK pose a risk to crop productivity, stand longevity and economic profitability.

Achieving sustainable agriculture is a global challenge as excessive pressure continues to be applied on soil systems due to a lack of viable alternatives to conventional soil management practices. Asparagus production is a part of a complex network of relationships between abiotic and biotic factors. Some of these factors such as weather cannot be manipulated however it is expected that the majority of production issues can be effectively managed though field management. This research evaluates the long-term efficacy of a range of potential BMPs on crop performance and soil characteristics in asparagus production systems as compared with conventional practice. BMPs are used to reduce negative environmental impacts of agriculture, for example in winter cereals or potatoes (Deasy et al., 2009; Gordon et al., 2011). In asparagus, management decisions made one year will have a significant impact on crop productivity the following year (Wilson et al., 2002b). This emphasises the importance of alternative management practices needing to be subject to thorough assessment prior to wider commercial application. Application of the BMPs investigated in this study to asparagus cropping systems is a novel strategy which had not been implemented or tested before. It is envisaged that the results of this research will provide a set of viable alternatives to conventional practice and identify research gaps limiting implementation of alternative cropping practices in asparagus production systems. This research also aims to provide a critical evaluation of the impact of conventional practice on asparagus productivity and on soils in asparagus systems, aspect which has rarely been addressed in the past (Putnam, 1972; Wilcox-Lee and Drost, 1991).

1.1 Research aims and objectives

Aim: The overall aim of this project is to critically evaluate a set of potential best management practices (BMPs) to prevent or ameliorate compaction of the interrows, sustain long-term profitable asparagus production and environmental protection in asparagus cropping systems. The following objectives were undertaken in order to achieve this aim:

> **Objective 1:** To critically evaluate the effectiveness of BMPs to remediate deep-seated soil compaction in asparagus interrows.
>
> **Objective 2:** To critically evaluate the impacts of BMPs on asparagus storage root development, storage root soluble carbohydrate levels, yield and yield quality, potential revenues and on soil bio-chemical indicators as compared with Conventional practice.
>
> **Objective 3:** To quantify the effect of tillage operations associated with Conventional practice on asparagus productivity indicators, soil compaction and on soil bio-chemical indicators in asparagus cropping systems.

Case study: This field trial was undertaken as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The trial occupied a total area of 4.5 ha and is located at Gatsford Farm, Ross-on-Wye, Herefordshire.

1.2 Thesis outline

This thesis has been written in a paper format. Therefore, contributions to scientific knowledge were written as individual academic journal articles (Chapters 2 to 5). Please note that due to the thesis format, introduction, methodology, results and discussion are presented within each chapter. Repetition of the experimental design description and methodology occurs between chapters. Chapter 2 has been published in *Soil and Tillage Research* (Mašková et al., 2021). Chapters 3, 4 and 5 will be submitted for review to their target journal after thesis submission. Chapters 6 synthesises the research outcomes and discusses the wider implications of the research and future research directions. Chapter 7 concludes the overall research and summarises key conclusions.

Chapter 1 provides background information to the research topic and the wider context.

Chapter 2 'Best Management Practices to Alleviate Deep-Seated Compaction in Asparagus (*Asparagus officinalis*) Interrows (UK)' has been accepted for publication in *Soil and Tillage Research* (Mašková et al., 2021). This chapter provides a critical review of the literature on soil compaction in various cropping systems and outlines possible impacts of soil compaction on asparagus. The chapter further evaluates progression of soil compaction throughout a three year experimental period and compares results from all potential BMPs to legacy compaction levels. Implications of BMPs and Conventional practice on interrow soil compaction are also highlighted in this chapter (Objectives 1 and 3).

Chapter 3 presents results on the ‘Impact of Best Management Practices on the ‘Root-Engine’ of Asparagus (*Asparagus officinalis*) (UK)’ and is intended for submission to *Soil and Tillage Research*. This Chapter describes the impacts of BMPs on asparagus root growth and discusses potential implications restricted root growth may have on asparagus productivity and stand longevity (Objectives 2 and 3).

Chapter 4 investigates the ‘Impacts of Long-Term Application of Best Management Practices on Yields and Root Carbohydrate Content in Asparagus (*Asparagus officinalis*) (UK). This Chapter was written as an academic article for *Field Crops Research* and presents a detailed analysis of the yield data obtained from the field trial between 2018 to 2020. Impacts of potential BMPs on yield quality metrics are also quantified. Impacts of BMP application on potential profits are also presented (Objectives 2 and 3).

Chapter 5 presents results on ‘Changes in Soil Microbial Communities and Soil Chemical Parameters Following Long-Term Application of Best Management Practices in Asparagus (*Asparagus officinalis*) (UK)’, has been written for the *Soil Biology and Biochemistry* and explores impacts of BMPs on soil biology and on selected chemical parameters. The chapter highlights significant implications of tillage on soil chemical indicators and on soil microbial communities in asparagus systems (Objectives 2 and 3).

Chapter 6 synthesises research outcomes in terms of their potential impact on the UK and global asparagus industry. This chapter recognises and discusses limitations of the current research and identifies gaps to be addressed by future research.

Chapter 7 concludes main outcomes of the study and identifies contribution to knowledge made by this research project. The chapter further summarises key conclusions related to the initial aim.

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2 Best Management Practices to Alleviate Deep-Seated Compaction in Asparagus Interrows

Abstract

Field operations associated with UK asparagus production (re-ridging and intensive foot and vehicular trafficking of the wheelings) can result in severe deep-seated compaction in interrows, impacting on crop health and productivity. In this project, we investigate the long-term efficacy of a range of Best Management Practices (BMPs) targeted at preventing or remediating soil compaction in asparagus (*Asparagus officinalis* L.) interrows as compared to Conventional practice. BMPs included (1) companion crops - Rye (*Secale cereale* L.), Mustard (*Sinapis alba* L.), (2) interrow surface mulch applications (straw mulch and PAS 100 compost in combination with shallow soil disturbance (SSD)), (3) modifications of the conventional tillage practice (re-ridging (R) or not ridging (NR) and applying SSD or not applying SSD) and (4) a zero-tillage option. In general, companion cropping had no effect on soil compaction or water infiltration rates as compared to the Conventional practice. Application and incorporation of straw mulch or PAS 100 compost however significantly reduced soil compaction of the interrows to >0.45 m beyond the working depth of the subsoiler (0.25 m). Composts and mulches in combination with SSD significantly reduce deep-seated compaction of the interrows within 3 years of annual application. Further, Conventional practice equivalent treatment (Bare soil No-SSD R) was associated with significantly higher PR values as compared to the zero-tillage (Bare soil No-SSD NR). These findings show that the extremely high levels of deep-seated compaction in interrows, associated with re-ridging, foot and vehicular traffic can be alleviated using surface mulches in combination with SSD.

2.1 Introduction

Achieving sustainable agriculture is a global challenge and excessive pressure continues to be applied to soil systems by a lack of viable alternatives to conventional soil management practices. This has led to soil degradation in the form of soil compaction, soil erosion, carbon-loss and loss of soil biodiversity (Bronick and Lal, 2005). Soil compaction in particular can severely restrict root development (Clark et al., 2003; Whalley et al., 2007) and compromise the ability of crop plants to access water and nutrients (White and Kirkegaard, 2010). Soil compaction can also increase susceptibility to disease and pest damage with direct impacts on yield, yield quality and production costs.

In the UK, the asparagus planted area increased from 1710 ha in 2010 to approximately 2392 ha in 2019 equating to a 40% increase in cropped area (Defra, 2020). However, over a typical 10-year commercial production cycle 'asparagus decline' caused by crown and root rot (CRR) and associated progressive loss of stand results in ca. £1.6M in lost revenue per annum. It is postulated that soil compaction of interrows contributes to 'asparagus decline' (AHDB, 2017). In 2019, global asparagus production was estimated to be >9.4 Million t with 88.8, 2.88 and 3.88% of production in China, Mexico and Peru, respectively. This was associated with an estimated global production area of >1.6 Million ha of which 90.5% was in mainland China (FAO, 2021). In over 90% of this global land bank asparagus is ridged. Regular interrow trafficking associated with asparagus and other row crop production systems in particular promote deep-seated compaction which is one of the most challenging problems growers can encounter (Alakukku et al., 2003; Chamen et al., 2003; Håkansson, 1994;

Niziolomski et al., 2020). Deep-seated compaction is considered extremely difficult and costly to remediate, with the damage often being permanent (Håkansson, 1994).

Field operations associated with ridged asparagus production systems [tillage operations such as ridging, spray operations, harvesting (foot-trafficking and/or hand harvesting using picking rigs)] can result in progressive and severe compaction of all interrows. In the UK, the majority of tillage operations in asparagus are undertaken in March-April, when soil is at or close to field capacity (Niziolomski et al., 2016). Such operations are undertaken to promote the growth of spears which meet customer specifications, for *Stemphyllium* control, to raise asparagus beds for efficient manual harvest and as a means of conveying excess rainfall offsite. However, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and crop productivity (Reijmerink, 1973; Wilcox-Lee and Drost, 1991). Re-ridging also increases the susceptibility to CRR caused by *Phytophthora megasperma* (Falloon and Grogan, 1991) (now known as P. asparagi) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2015) which leads to yield decline and direct economic losses to the grower. In contrast, zero-tillage options have been shown to significantly increase the marketable weight of asparagus spears as compared to tilled asparagus (Wilcox-Lee and Drost, 1991) due to higher soluble carbohydrate (CHO) levels in storage roots of non-tilled treatments. Tillage operations such as sub-soiling of interrows for runoff and erosion control (Niziolomski et al., 2020) pose a high risk of damage to asparagus root systems which can cause reductions to CHO storage capacity.

Asparagus is a perennial crop with expected economic production between 10-20 years (Elmer et al., 1996). With such a long lifespan, it is expected that decisions made in one year determine the next years' crop performance. A single year of mismanagement may also result in years of stunted growth and associated yield losses (Wilson et al., 2002a). Annual re-ridging of asparagus continues to be adopted by the majority of British growers, however, long-term effect of this practice and trafficking operations associated with harvest and agronomy on soil compaction in asparagus is unknown.

Best Management Practices (BMPs) have been used to prevent and/or ameliorate soil compaction in several crops such as winter cereals, potatoes and vines (Deasy et al., 2009; Gordon et al., 2011; Judit et al., 2011). However, there is a paucity of research focusing on how to effectively manage interrow compaction in asparagus. The objective of this research is to critically evaluate the efficacy of a range of BMPs to mitigate deep seated compaction in asparagus interrows as compared to Conventional practice. Impacts of interrow compaction on marketable asparagus yield are also quantified.

2.2 Materials and Methods

The trial took place as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The long-term field trial (4.5 ha) is located at Gatsford Farm, Ross-on-Wye, Herefordshire. Asparagus 'A' crowns of Gijnlim variety (which represents 70% of UK field grown asparagus) were planted on 20–21st of April 2016 on a flat surface at an anticipated depth of 0.14 m, at 0.16 m spacing between crowns. Beds were on 1.83 m wide centres. In spring 2017, all plots were re-ridged as a consequence of the shallowness of the crown (circa 0.06 m) instead of the intended 0.14 m. Conventional agrochemical treatments have been applied to all trial plots from 2016 to 2020.

2.2.1 Experimental Design

The trial investigated the efficacy of a range of potential BMPs (Table 2-1); (1) companion crops - Rye (*Secale cereale* L. var. Protector.) and Mustard (*Sinapis alba* L. var. Severka), (2) interrow surface mulch (Straw and PAS 100 compost) applications in combination with shallow soil disturbance (SSD), (3) modifications of the conventional tillage practice by not re-ridging (NR) and applying SSD and (4) a zero-tillage option. Rye is commonly used by North American asparagus growers as a strong weed suppressor which also provides soil protection through interception of rainfall kinetic energy. Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which are known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991). Furthermore, rye has been reported to have the ability to reduce the severity of *Fusarium* crown and root rot in asparagus (Matsubara et al., 2001). Mustard is known for its extensive tap-rooting system associated with bio-drilling and for its bio-fumigation potential, which has been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998). Two mulch products, straw mulch and PAS 100 certified quality compost (WRAP, 2011) were investigated. Both mulch options used in the experiment were subject to SSD so as to replicate the bio-drilling (Cresswell and Kirkegaard, 1995) and canopy effects associated with companion crops to test the ability of mulches to simulate companion crops. The experiment comprised 48 randomly distributed, 35 m long treatment plots. Each plot consists of 2 asparagus rows, central interrow and 2 guard interrows (separating the treatments). All treatments were replicated in quadruplicate. As appropriate, treatment plots were separated by tramlines to facilitate sprayer operations.

The tractor used for ridging and SSD operations was John Deere 6155R of 155 HP with Michelin 650/65 R38 rear tyres and Michelin 540/65 R28 front tyres. Tyre pressure was 82.74 kPa on the front tyres and 82.74 kPa on the rear tyres. SSD was applied in April 2018 and in March and June 2020 (Figure 2-1) using a winged tine operating to 0.25-0.3m depth to all mulch treatments (PAS 100 Compost or Straw) and to selected bare soil treatments (Table 2-1). Re-ridging was undertaken using a tractor mounted 1.83 m double disk ridger in March 2017, April 2018, March 2019 and March 2020. Companion crops were broadcast for the first time on the 10th August 2017 when the asparagus was at full fern stage at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard, respectively.

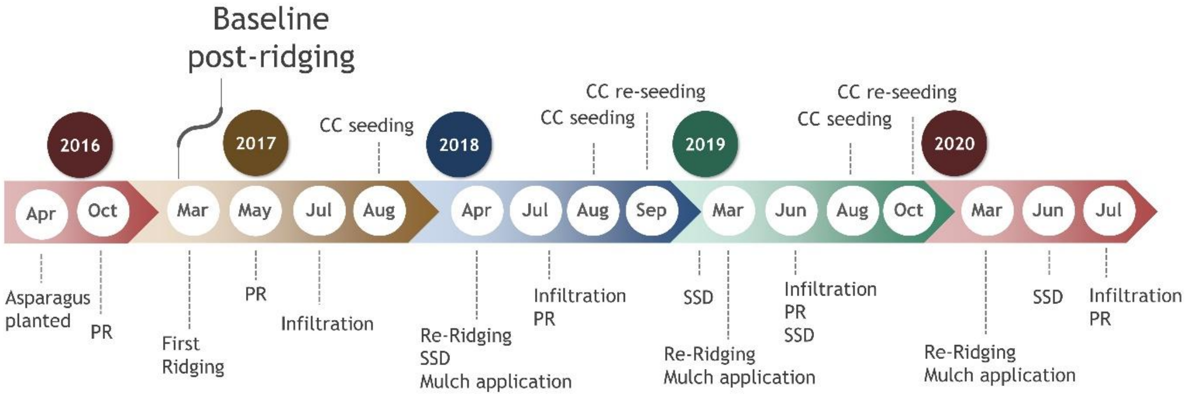

Figure 2-1. Timeline of the AHDB FV450/FV450a projects indicating when treatments were applied, and metrics measured. PR=penetration resistance, SSD = shallow soil disturbance, CC = companion crop.

In the first year, the emergence rate of the companion crops achieved sufficient ground cover of 70-75% (Morgan, 2005). However, in 2018 and 2019, due to predation, seeding rates were increased to 200 kg ha^{-1} and 25 kg ha^{-1} for rye and mustard, respectively and repeated in September 2018 and October 2019. Mulches were applied annually in April 2016, April 2018, March 2019 and March 2020 at rates of 25 t ha^{-1} and 6 t ha^{-1} for PAS 100 and straw mulch, respectively. Hereafter, the Bare soil No-SSD NR and Bare soil No-SSD R treatments will be also referred to as a 'zero-tillage' and 'Conventional practice', respectively (Table 2-1).

Table 2-1. Summary of the experimental Best Management Practice treatments applied to asparagus interrows.

Treatment	Interrow Cover	Annual re-ridging (R)	Sub-soiling (SSD)
[2]Bare soil No-SSD R	Bare soil	R	No SSD
[1]Bare soil No-SSD NR	Bare soil	NR	No SSD
Bare soil SSD R	Bare soil	R	SSD
Bare soil SSD NR	Bare soil	NR	SSD
Mustard R	Mustard	R	No SSD
Mustard NR	Mustard	NR	No SSD
Rye R	Rye	R	No SSD
Rye NR	Rye	NR	No SSD
Straw mulch SSD R	Straw mulch	R	SSD
Straw mulch SSD NR	Straw mulch	NR	SSD
PAS 100 SSD R	Compost	R	SSD
PAS 100 SSD NR	Compost	NR	SSD

NR = No annual re-ridging and R = annual re-ridging; SSD = shallow soil disturbance; [1]Zero-tillage, [2]Conventional practice.

2.2.2 Sampling Methodology

Penetrative Resistance (PR) was used as an indicator of soil compaction (Bengough et al., 2006). PR measurements were taken twice during the trial establishment period. Legacy compaction was measured, in October 2016 (n=6), 6 months after asparagus was planted on a flat bed. Baseline PR compaction measurements were taken in May 2017 (n=60) tangentially from the asparagus crown zero line (CZL) (at 0.10, 0.15, 0.20, 0.25, 0.30, 0.45, 0.60 and 0.90m distances from the crown) after the first ridging operation. Both legacy and baseline compaction levels are critical as they enable differences in PR to be linked to the BMP treatments applied. PR and infiltration rates were subsequently measured in July 2017, June 2018, June 2019, and July 2020 (n=12 per treatment per year).

All measurements were conducted in the compacted central asparagus interrow. Measurements were obtained from two randomly selected plots per treatment. PR was determined using a digital Eijkelkamp Penetrologger with a 1.0 cm^2 base area and 60° apex angle cone. PR was measured to 0.6m depth (where possible) at a recording interval of 0.01m. Each plot was sampled at 6 locations along the length of the plot (5, 10, 15, 20, 25 and 30m). In addition, in 2020, PR transects were taken tangentially from the asparagus CZL at 0.3 m intervals to the centre of asparagus interrow (0.9m from CZL). For each experimental plot, four PR transects were measured. Cumulative rainfall for a 2-day period immediately prior to the start of PR measurements was 22.2 mm in 2018, 700 mm in 2019 and 11.8 mm in 2020. Soil MC during trafficking and tillage events were not determined. The commercial grower followed Good Agricultural and Environmental Conditions (GAEC) recommendations (GAEC, 2021) which advises that field operations are undertaken when soil MC is below field capacity in order to minimise compaction risk. As such in 2018, 2019 and 2020 all trafficking, and tillage events associated with the experimental treatments were undertaken at least 2-3 days after rainfall events. In addition, when applied all trafficking and tillage events associated with the experimental treatments were performed on the same day within a 2 hr period. As such soil MC was considered to be uniform across treatments when trafficking and tillage events were applied.

Penetrative Resistance soil moisture normalisation models such as PENETR model by Canarache (1990) or covariance analysis for correcting cone index to soil moisture content by Christensen et al. (1989) were not applied to facilitate direct comparison between the 2018, 2019 and 2020 PR datasets. This was due to the complexity of data required by these models, which were not able to be recorded in the context of the experimental program. However, the annual PR measurements represent a quantification of the efficacy of the BMPs to mitigate against repeated intra and inter annual tillage and/or trafficking operations irrespective of the prevailing and contrasting climatic conditions during 2018-2020. The 2018, 2019 and 2020 PR measurements reflect a legacy effect of the intra and inter annual machinery passes associated with ridging and tillage operations as well as foot trafficking during the 3-month annual harvest periods applied to the treatments. Consequently, as PR data from each year had to be evaluated separately.

Infiltration rate was measured in triplicate per plot concurrently with PR in July 2017, June 2018, June 2019, and July 2020. All measurements were conducted in the compacted central asparagus interrow. Infiltration was measured following a modified USDA single ring infiltrometer method, using a 0.12m internal diameter PVC ring with falling head (Esparcia, 2014). Infiltration rate classes were adapted from the USDA Soil Quality Test Kit Guide (USDA, 1999).

Yields from all experimental plots were collected in 2018, 2019 and 2020. In 2018, harvest took place over a 28 day period between the 24th April to 21st May from 19 cuts. In 2019, the harvest extended to 53 cuts between the 20th April to 17th June and in 2020 from a total of 65 cuts between the 12th April to 22nd June.

2.2.3 Statistical analysis

Statistical analysis was undertaken using the TIBCO Statistica 13.3.0 analytics software. Infiltration data was checked for normality and analysed by the standard analysis of variance followed by *post-hoc* Fisher LSD analysis at 95% conf. level. For data which failed to meet requirements for normal distribution, a log-normal transformation was applied prior to analysis. Penetrative resistance in asparagus interrows was analysed using the repeated measures ANOVA. Penetrative resistance spatial distribution contour maps were generated using the inverse distance weighing interpolation method (IDW) in Esri ArcMap^{TM} (GIS software) version 10.7. Pearson correlation coefficients were calculated to determine the relationship between the 2018, 2019 and 2020 marketable asparagus yield and mean PR of the asparagus interrow.

2.3 Results

Soil analyses conducted in 2016 indicated that there were no significant differences in the soil parameters tested ($p \leq 0.05$) between plots (Appendix B). Soils at the trial site are Cambisols (IUSS Working Group WRB, 2007) of Eardiston series association (Cranfield University, 2020) with 77% sand, 11% silt and 12% clay composition. Other soil parameters showed soil pH of 6.34 (± 0.03), soil organic matter of 2.78% (±0.03), total soil C of 1.24% (±0.01) and total mineralizable N of 0.13% (±0.001).

2.3.1 Infiltration rates in asparagus interrows

The 2017 baseline mean infiltration rate was 99.8 mm hr^{-1} (Moderately Rapid), with 75% of the measurements being classified as moderate (15-50 mm hr^{-1}) and moderately rapid (50-150 mm hr^{-1}) (USDA, 1999).

In 2018, both R and SSD had a significant impact on infiltration rates measured on bare soil treatments, SSD significantly increased infiltration rates while re-ridging significantly decreased infiltration rates. In terms of significant differences between the whole set of treatments, infiltration rates of the Conventional practice were significantly lower as compared to Bare soil SSD NR, PAS 100 NR, PAS 100 R, Rye NR, Straw Mulch NR and Straw Mulch R (Table 2-2).

In 2019, SSD application was not undertaken. Consequently, no significant effect of SSD on infiltration rates in bare soil treatments was observed. Although re-ridging had no significant impact on bare soil treatments, it was associated with significantly lower infiltration rates where mustard was used as a companion crop. Furthermore, PAS 100 compost facilitated significantly higher infiltration rates as compared with straw mulch. Overall, the PAS 100 R/NR treatments were associated with significantly higher infiltration rates (234.2 and 217.7 mm hr^{-1}) as compared to the Conventional practice, Bare soil SSD R, Mustard R, Rye R/NR and straw mulch R treatments (Table 2-2).

In 2020 (Table 2-2), all treatments subject to SSD were classified as “Very Rapid” (>500 mm hr^{-1}) and as expected, had significantly higher infiltration rates as compared to all other treatments. No significant differences in infiltration rates were observed between SSD treatments. Re-ridging significantly decreased infiltration rates of Mustard R as compared to the Mustard NR. Overall, Conventional practice had significantly lower infiltration rates as compared to Mustard NR and Rye NR.

Table 2-2. Mean (n=6) infiltration rates (mm hr^{-1}) in the asparagus interrows for all Best Management Practice treatments as compared with Conventional practice for 2018, 2019 and 2020.

Treatment	Infiltration (mm hr^{-1})		
	2018	2019	2020
[1]Zero-tillage	161 ^{ab}	129 ^{abcd}	48.8 ^{ab}
[2]Conventional practice	94.6 ^{a}	51.5 ^{ab}	23.2 ^{a}
Bare Soil SSD NR	3984 ^{d}	59.5 ^{abc}	10145 ^{de}
Bare Soil SSD R	299 ^{ab}	24.4 ^{ab}	11942 ^{de}
Mustard NR	289 ^{ab}	136 ^{bcd}	230 ^{c}
Mustard R	175 ^{ab}	16.3 ^{a}	43.7 ^{ab}
PAS 100 NR (SSD)	3764 ^{d}	234 ^{d}	13513 ^{d}
PAS 100 R (SSD)	5724 ^{d}	218 ^{cd}	10064 ^{de}
Rye NR	578 ^{bc}	52.1 ^{a}	128 ^{bc}
Rye R	331 ^{ab}	22.5 ^{ab}	48.0 ^{abc}
Straw mulch NR (SSD)	4049 ^{cd}	100 ^{abc}	10334 ^{de}
Straw mulch R (SSD)	4437 ^{cd}	92.6 ^{a}	23146 ^{e}

For each year, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence *interval* (following log-normal transformation). Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD. [1]Bare Soil No-SSD NR, [2]Bare Soil No-SSD R. Moderately rapid (50-150 mm hr^{-1}); Rapid (150-500 mm hr^{-1}); very rapid (>500 mm hr^{-1}) (USDA, 1999). Note due to logistical challenges, in 2019, SSD was not applied.

2.3.2 Penetration resistance in asparagus interrows

Mean soil moisture content (MC) during 2016 pre-ridging PR measurements was 18% (±0.54) and 16% (±0.83) during the 2017 post-ridging PR measurement. Soil MC in the PR sampling period of 2018 was 15% (±0.34), 16% (±0.28) in 2019 and 15% (±0.19) in 2020 as measured in the topsoil (5-10 cm depth).

Mean profile PR values were significantly higher following the 2017 re-ridging as compared to the 2016 legacy compaction with mean PR in the interrows (0.90 m distance from the crown) of 2.56 MPa and 1.80 MPa, respectively. Spatial distribution patterns of pre and post-ridging PR are shown in Figure 2-2.

Pre-ridging, PR values of 2.3-2.7 MPa were measured at 0.30 m depth and below (Figure 2-2). Post-ridging, PR of the interrows (90 cm) increased to between 2.7-3.0 MPa. As shown in Table 2-3, PR values were significantly higher post-ridging (2017) as compared to pre-ridging (2016) at the 60 cm distance from the crown at 0-5, 10-15 and 20-30 cm depths and at the 90 cm distance from the crown at 5-30 cm depth, corresponding to the assumed zone of influence of the ridger.

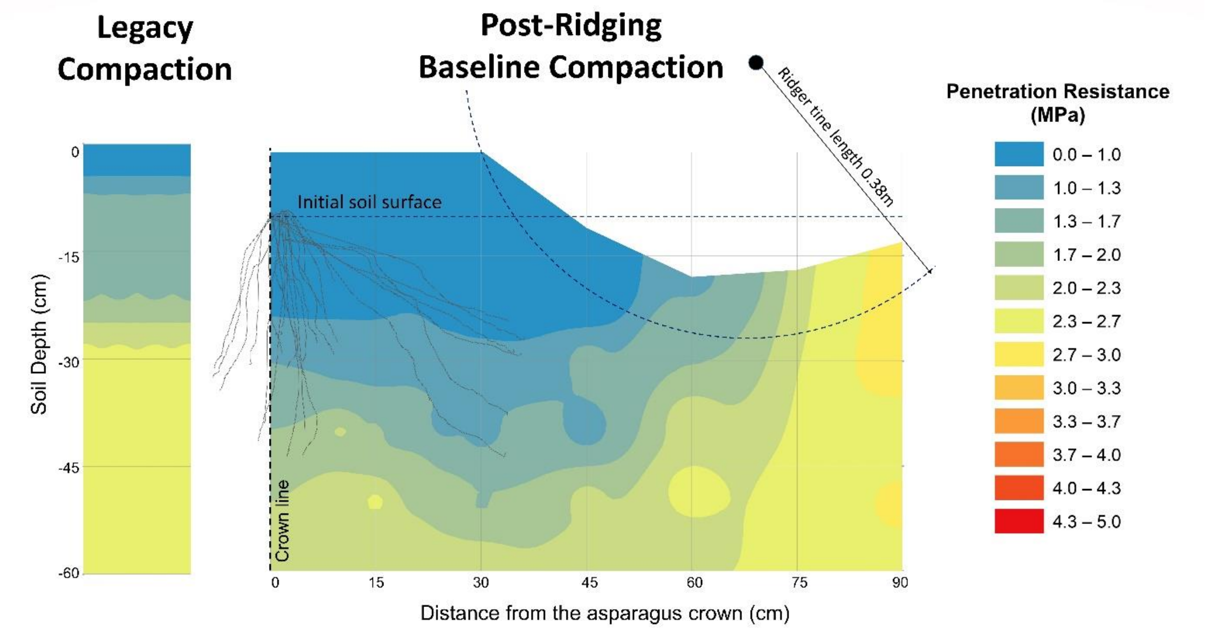

Figure 2-2. Contour diagrams based on Penetration Resistance (PR) determined at set positions from the crown line using the inverse distance weighing (IDW) interpolation. The left image is the 2016 legacy compaction (n=6) and the right, the 2017 post-ridging.

Table 2-3. Mean (n=60) PR (MPa) of the 2017 post-ridging baseline at specific soil depths (cm) and set distances from the crown line (cm) as compared with the mean (n=6) 2016 legacy compaction levels. 90cm distance from the crown line refers to the centre of the interrow.

PR depth (cm)	2016 legacy compaction	2017 Post-ridging				
		Distance from the crown line				
		25 cm	30 cm	45 cm	60 cm	90 cm
0-5	**0.31**	0.02 ns	0.04 ns	0.03 ns	0.45 ns	1.63 +
5-10	**0.95**	0.19 -	0.25 -	0.56 -	2.11 +	3.74 +
10-15	**1.35**	0.40 -	0.45 -	1.35 ns	1.86 +	3.04 +
15-20	**1.58**	0.63 -	0.80 -	1.55 ns	1.58 ns	2.62 +
20-25	**1.54**	0.92 -	0.98 -	1.16 ns	2.02 +	2.41 +
25-30	**1.70**	1.29 -	1.22 -	1.24 -	2.41 +	2.24 +
30-35	**2.25**	1.20 -	1.18 -	2.05 ns	2.51 ns	2.73 +
35-40	**2.46**	1.13 -	1.18 -	2.40 ns	2.45 ns	2.75 +
40-45	**2.32**	1.52 -	1.49 -	2.27 ns	2.12 ns	2.50 ns
45-50	**2.32**	2.06 ns	1.88 -	2.28 ns	2.04 ns	2.43 ns
50-55	**2.39**	2.13 ns	2.34 ns	2.44 ns	2.68 ns	2.32 ns
55-60	**2.50**	2.15 ns	2.37 ns	2.56 ns	2.73 +	2.25 ns

Values followed by +, - or ns are significantly higher, lower or not significantly different as compared to the 2016 legacy compaction value (highlighted in bold) following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

Figure 2-3 - Figure 2-5 show the evolution of soil compaction in the interrows from 2018 to 2020. Each year, differences between treatments were more pronounced than the year before. In 2018, the Conventional practice was associated with significantly higher PR values as compared to the zero-tillage treatment at 50-55 cm depth (Figure 2-3a). No major differences could be seen between the four companion crop treatments and the Conventional practice (Figure 2-3b). Early signs of differences could however be observed between straw mulches and the conventional treatment (Figure 2-3c). In 2019, the effect of SSD on PR in bare soil treatments could be seen, with Conventional practice having a higher PR than the bare soil SSD R to the subsoiler working depth of 0-25 cm (Figure 2-4a). All companion crop treatments had elevated levels of soil compaction at 0-10 cm depth, comparable to compaction of the conventional treatment (Figure 2-4b). Rye R had the lowest PR of any companion crop in the subsoil area at 40-60 cm depth. Mulches showed a significant decrease in PR as compared with the Conventional practice at the 0-25 cm depth (Figure 2-4c). Straw mulch NR further showed reduction in subsoil compaction to 30-60 cm depth as compared to the Conventional practice. In 2020, clear differences were observed between the bare soil treatments (Figure 2-5a). Bare soil SSD treatments had significantly lower PR levels at 0-30 cm depth. Companion crops exhibited similar PR levels to the Conventional practice equivalents while no further differences were observed between the different companion crops (Figure 2-5b). Finally, there was a noticeable reduction in PR levels for all mulch-SSD treatments as compared to the Conventional practice to 0-45 cm depth (Figure 2-5c and Table 2-4). Straw mulch NR continued to have significantly lower PR compared to the conventional throughout the whole measured depth.

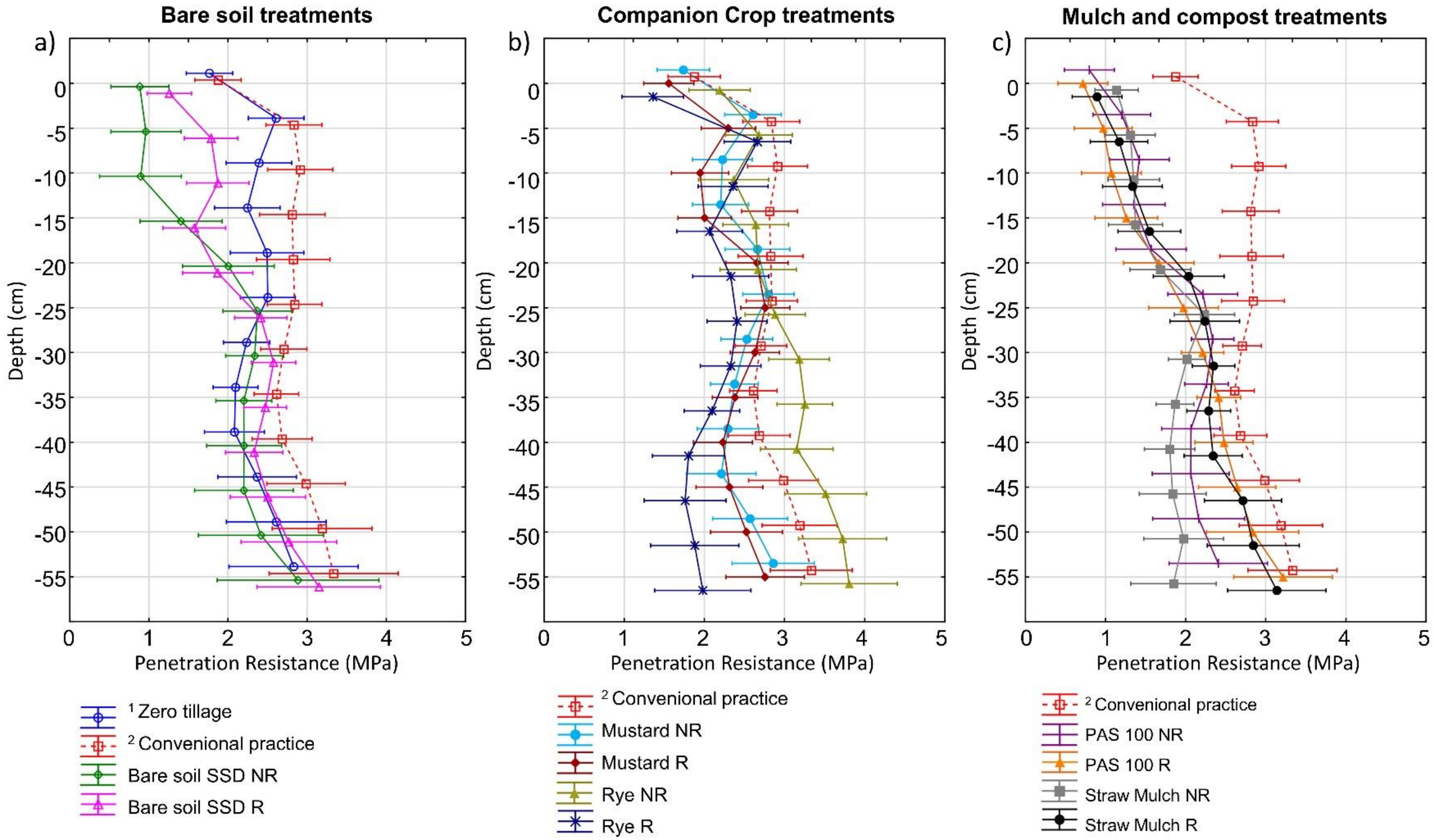

Figure 2-3. Mean (n=12) 2018 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals. Horizontal bars denote 0.95 confidence interval. [1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

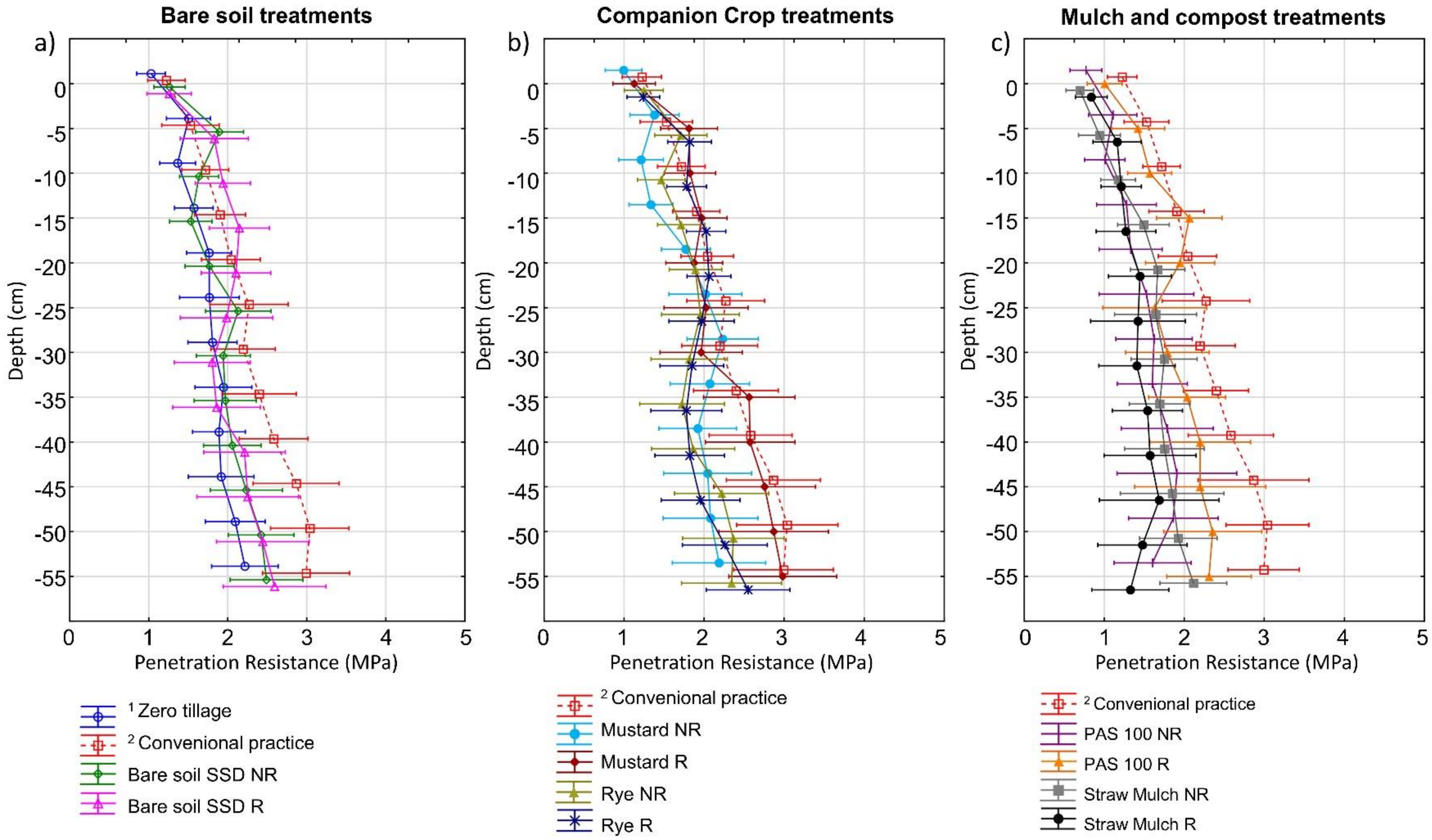

Figure 2-4. Mean (n=12) 2019 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals (n=12). Horizontal bars denote 0.95 confidence interval. [1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

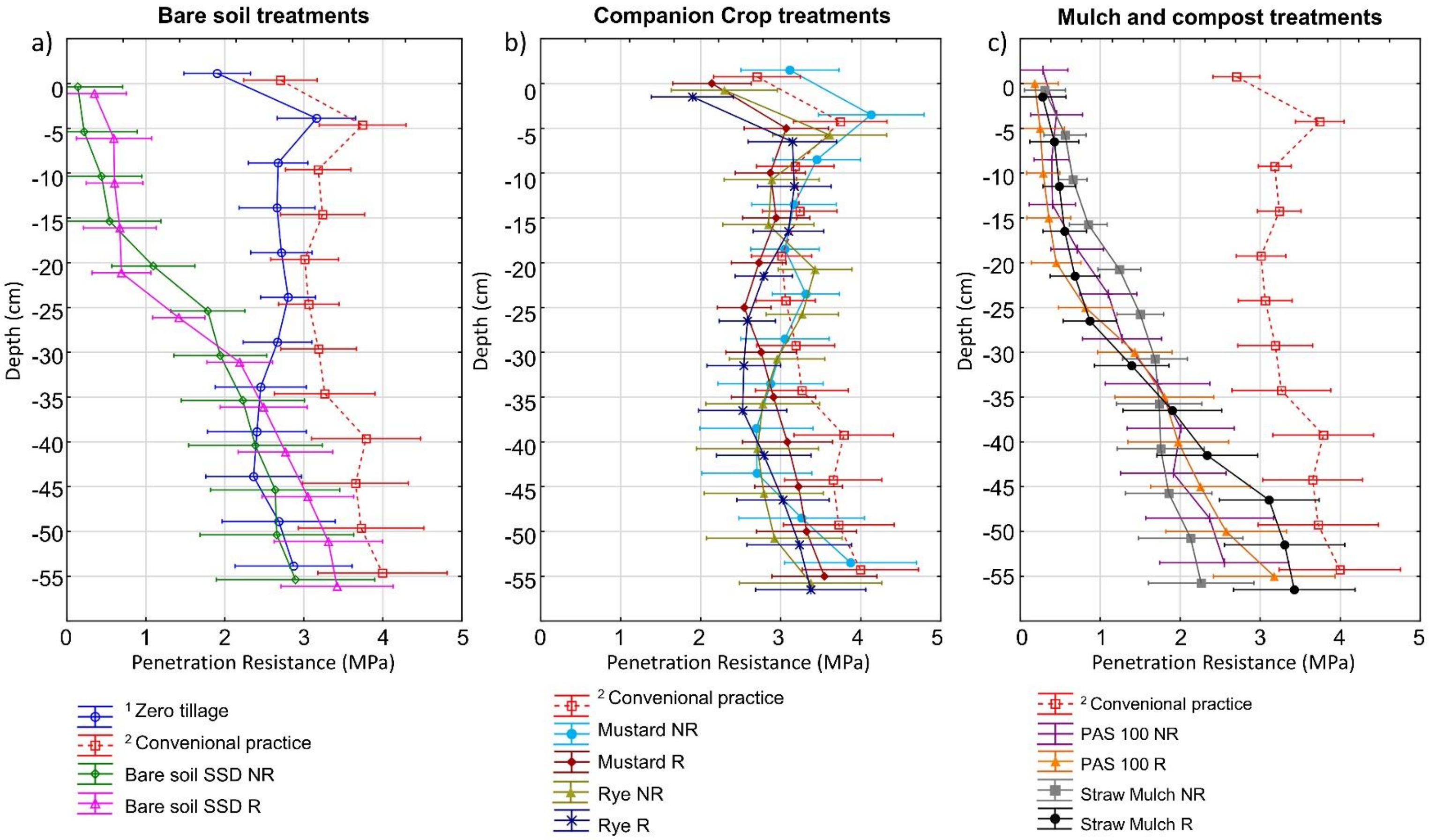

Figure 2-5. Mean (n=12) 2020 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals (n=12). Horizontal bars denote 0.95 confidence interval. ¹ Bare soil No-SSD NR; ² Bare soil No-SSD R.

Comparison of 2016 legacy compaction and 2020 PR results showed that Conventional practice had significantly higher compaction levels throughout the whole measured profile while Zero-tillage had similar compaction levels to the 2016 legacy compaction at 30-50 cm depth. Further, treatments subject to SSD saw significant decreases in PR as compared to the legacy compaction to 5-25 cm depth. Crucially, mulches though subject to SSD exhibited significant decrease in PR beyond the subsoiler working depth. Compared to the 2016 legacy compaction, PAS 100 compost saw reduction in PR from 5-40 cm depth while straw mulch NR achieved significantly lower PR values from 5-20 and 30-50 cm depths. Compared to the 2017 post-ridging baseline, in 2020, Conventional practice showed a significant increase in PR at 40-60 cm depth. All SSD treatments were associated with significantly lower PR to 0-35 cm depth although straw mulch NR significantly decreased PR values 10 cm deeper, to 0-45 cm depth.

In 2020, a negative response to re-ridging was observed in Bare soil No-SSD treatments, where the Conventional practice (Bare soil No-SSD R) had significantly higher PR at 35-60 cm depth as compared to the zero-tillage (Bare soil No-SSD NR) (Table 2-4). Furthermore, all SSD treatments (Bare soil SSD, PAS 100 and straw mulch) had significantly lower interrow compaction levels as compared to the Conventional practice to at least 0-45 cm depth. PR values of companion crop treatments were similar to the Conventional practice.

Table 2-4. Differences in the 2020 mean (n=12) PR (MPa) in the centre of the asparagus interrow (90 cm distance from the crown line) between treatments for 5 cm depth intervals.

PR Depth (cm)	Treatment											
	Bare soil no-SSD		Bare soil SSD		Mustard		PAS 100		Rye		Straw mulch	
	NR[1]	R[2]	NR	R	NR	R	NR	R	NR	R	NR	R
0-5	1.96 -	**2.91**	0.11 -	0.35 -	3.11 ns	2.11 -	0.18 -	0.17 -	2.29 ns	1.78 -	0.31 -	0.28 -
5-10	3.27 ns	**3.88**	0.16 -	0.60 -	4.13 ns	3.03 -	0.30 -	0.23 -	3.61 ns	3.00 -	0.56 -	0.43 -
10-15	2.72 ns	**3.27**	0.32 -	0.60 -	3.45 ns	2.83 ns	0.28 -	0.27 -	2.89 ns	2.98 ns	0.66 -	0.49 -
15-20	2.71 ns	**3.37**	0.44 -	0.67 -	3.17 ns	2.98 ns	0.26 -	0.33 -	2.85 ns	3.04 ns	0.85 -	0.56 -
20-25	2.75 ns	**3.11**	0.97 -	0.69 -	3.05 ns	2.78 ns	0.57 -	0.43 -	3.43 ns	2.65 ns	1.24 -	0.68 -
25-30	2.87 ns	**3.12**	1.67 -	1.42 -	3.31 ns	2.60 ns	1.01 -	0.80 -	3.27 ns	2.41 ns	1.50 -	0.87 -
30-35	2.75 ns	**3.27**	1.87 -	2.19 -	3.05 ns	2.82 ns	0.99 -	1.37 -	2.95 ns	2.52 ns	1.68 -	1.39 -
35-40	2.55 -	**3.31**	2.22 -	2.49 -	2.87 ns	2.98 ns	1.24 -	1.76 -	2.78 ns	2.60 ns	1.74 -	1.90 -
40-45	2.48 -	**3.88**	2.34 -	2.77 -	2.70 -	3.08 -	1.64 -	1.97 -	2.71 -	3.04 -	1.76 -	2.34 -
45-50	2.41 -	**3.72**	2.64 -	3.05 ns	2.70 -	3.18 ns	1.59 -	2.28 -	2.79 -	3.33 ns	1.86 -	3.11 ns
50-55	2.55 -	**3.80**	2.65 -	3.31 ns	3.26 ns	3.22 ns	1.65 -	2.58 -	2.92 -	3.36 ns	2.13 -	3.31 ns
55-60	2.60 -	**3.96**	2.80 -	3.42 ns	3.87 ns	3.54 ns	1.80 -	2.93 -	3.37 ns	3.39 ns	2.26 -	3.43 ns

[1] Zero-tillage, [2] Conventional practice. Values followed by - or ns are significantly lower or not significantly different as compared to the Conventional practice (highlighted in bold) following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

In 2020, PR was measured in the whole soil profile, from the crown zero line (CZL) to the interrow (Figure 2-6). Each diagram represents PR as measured tangentially from the asparagus CZL at 30 cm intervals to the centre of asparagus interrow (90 cm from the CZL). Very high PR values (3.3 – 5.0 MPa) were observed for the interrows of the Conventional practice (Bare soil No-SSD R), to within 30 cm of the CZL (Figure 2-6b). The zero-tillage treatment was associated with reduced PR at depth (45 – 60 cm) compared to all other bare soil treatments (Figure 2-6). The significantly lower PR associated with SSD was observed on both Bare soil SSD treatments to approximately 20 cm depth (right hand upper corner of Figure 2-6c and Figure 2-6d).

All mulch treatments demonstrated a zone of PR reduction at the centre of the interrow (at 90 cm from the CZL) which is a direct result of SSD (Figure 2-7a - Figure 2-7d). Further, straw mulch NR PR values in the interrow (90 cm distance from the CZL) did not exceed 2.3 MPa (Figure 2-7b). In comparison to treatments subject to SSD, all companion crops showed a zone of increased soil compaction in the interrows (>3.0 MPa), values of which were similar to PR of the Conventional practice in the same location (Figure 2-7e - Figure 2-7h). Mustard NR surface PR (Figure 2-7f) reach values of up to 5.0 MPa, which are comparable to deep-seated (45 – 60 cm depth) compaction of the Conventional practice (Figure 2-6b).

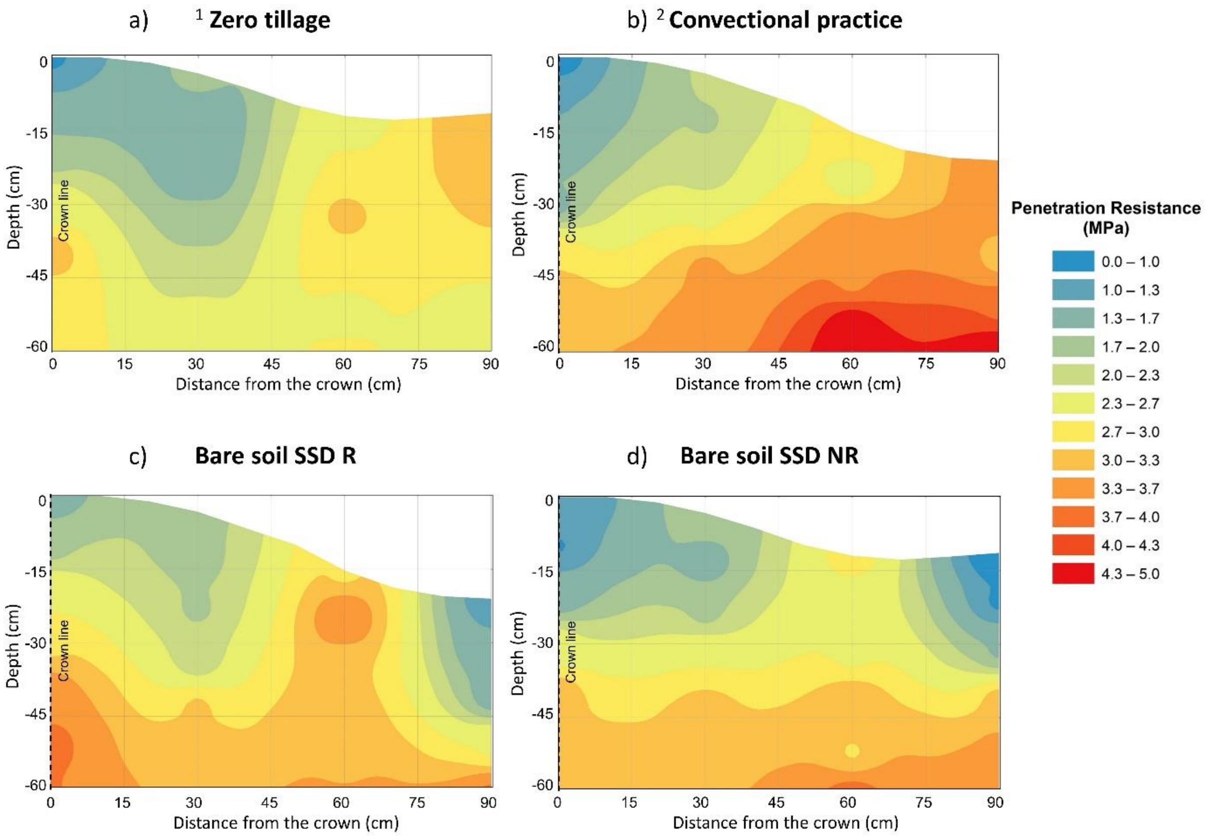

Figure 2-6. 2020 bare soil treatments contour diagrams based on Penetration Resistance (MPa) transects determined tangential to the crown line (n=4) using the inverse distance weighing (IDW) interpolation method. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

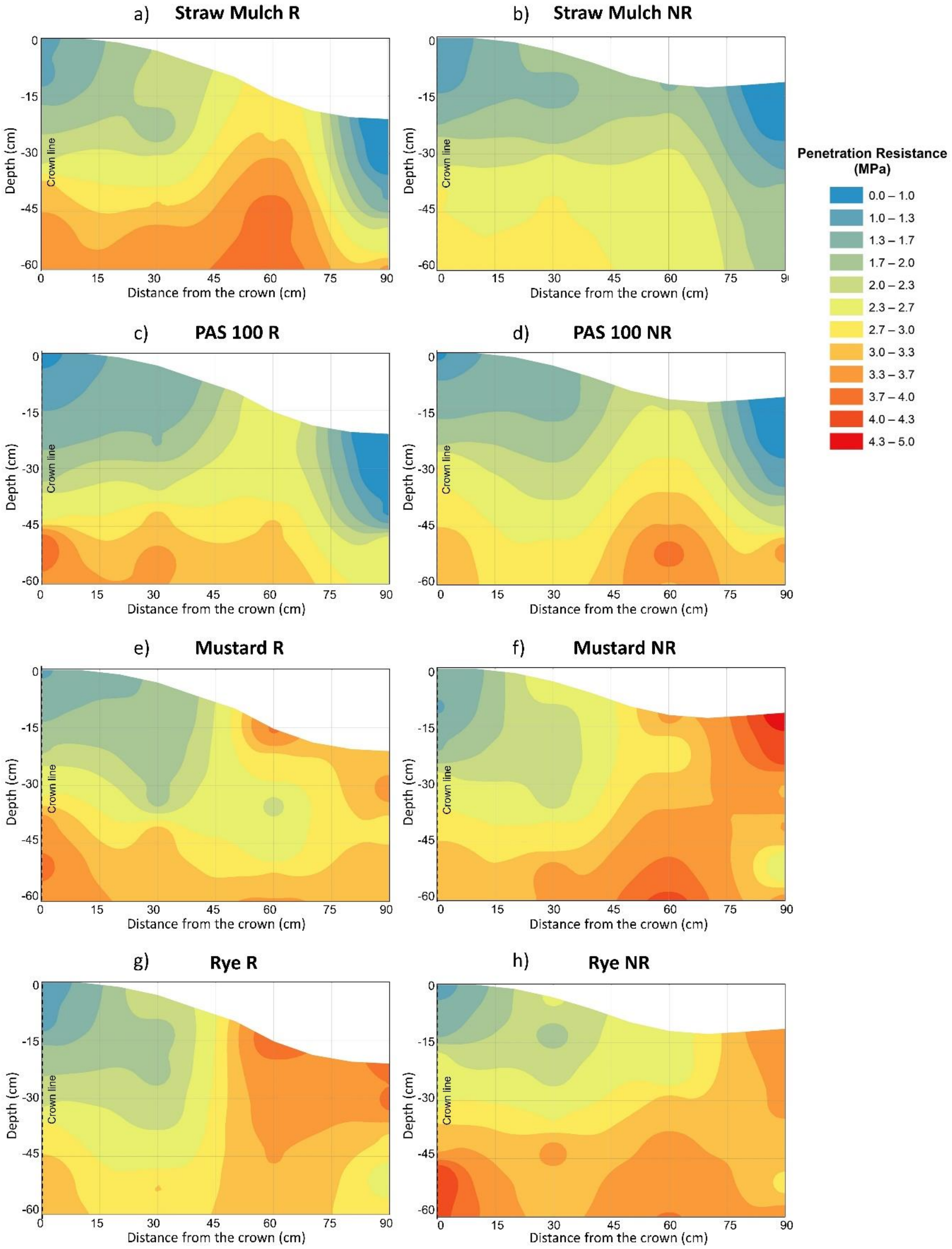

Figure 2-7. 2020 mulch and companion crop treatments contour diagrams based on Penetration Resistance (MPa) determined at set positions from the crown line (n=4) using the inverse distance weighing (IDW) interpolation method.

2.3.3 Soil compaction and asparagus yields

Yield data indicates that re-ridging of Rye R treatment was associated with 28, 26 and 28% higher yields as compared to the Rye NR in 2018, 2019 and in 2020, respectively (Table 2-5). For bare soil interrow treatments, re-ridging in the absence of SSD as seen in the Conventional practice treatment was associated with yield reductions of 12, 15 and 18% as compared to the Zero-tillage treatment in 2018, 2019 and in 2020, respectively (Table 2-5). Although in 2018 and in 2020 the differences between Zero-tillage and the Conventional practice were not significant at 95% confidence interval, decreasing the confidence level to 90% indicates that a significant difference would also be present in 2020. Consequently, re-ridging did have a significant impact on asparagus yields. In contrast, SSD applied to bare soil treatments did not affect yields in any of the three years.

For both the PAS 100 R and NR treatments there was a robust trend for 12-20%, 8-10% and 28-34% yield increases as compared to the Conventional practice in 2018, 2019 and in 2020, respectively (Table 2-5). Although this yield uplift was non-significant in 2018 and 2019 in, 2020 significant yield uplift was observed (Table 2-5). This suggests that long-term application of the PAS 100 R and NR treatments is required in order to promote increased yield as compared with Conventional practice.

Table 2-5. Asparagus yields in 2018, 2019 and 2020 expressed in kg ha^{-1} cut^{-1}. 2018 harvest lasted 28 days (19 cuts); 2019 harvest lasted 59 days (53 cuts); 2020 harvest lasted 72 days (65 cuts).

Treatment	Yield (kg ha^{-1} cut^{-1})		
	2018	2019	2020
Zero-tillage	186^{c}	*163^{b}	124^{bcde}
Conventional practice	**163^{abc}**	**139^{a}**	**101^{ab}**
Bare soil SSD NR	174^{abc}	137^{a}	104^{abc}
Bare soil SSD R	150^{ab}	130^{a}	101^{ab}
Mustard NR	164^{abc}	146^{ab}	113^{abcde}
Mustard R	172^{abc}	145^{ab}	107^{abcd}
PAS 100 SSD NR	196^{c}	152^{ab}	*136^{e}
PAS 100 SSD R	182^{bc}	150^{ab}	*129^{de}
Rye NR	140^{a}	131^{a}	98.6^{a}
Rye R	180^{bc}	*165^{b}	*127^{cde}
Straw Mulch SSD NR	173^{abc}	137^{a}	110^{abcd}
Straw Mulch SSD R	187^{c}	150^{ab}	118^{abcde}

Within each column, values followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. *Treatments associated with significantly higher yield as compared with Conventional practice (highlighted in bold).

Infiltration rates of the asparagus interrows and asparagus yields were not correlated in any of the three years. The analysis of relationships between mean PR of the interrows and yields however revealed a weak but significant negative correlation between these two variables in 2018 and in 2020 (Figure 2-8). Furthermore, correlation coefficients for those two years were nearly identical, with a r = -0.38 in 2018 and r = -0.38 in 2020. These negative correlations suggest that increasing soil compaction of asparagus interrows can have a negative impact on asparagus yields.

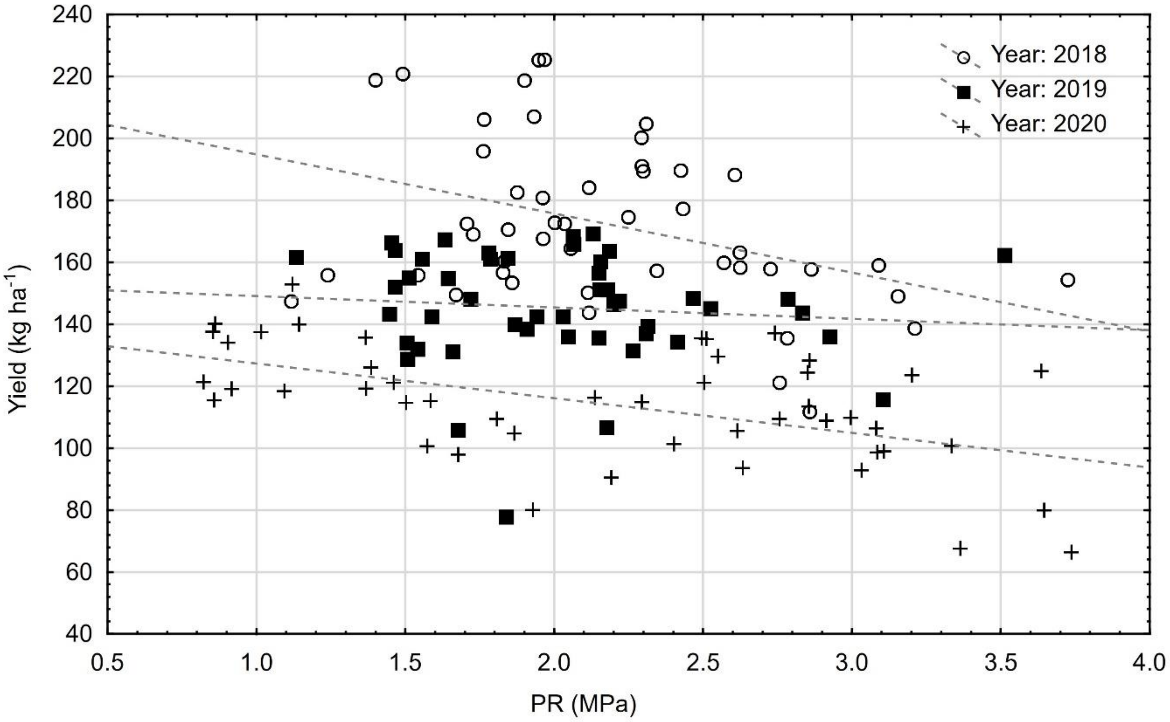

Figure 2-8. Linear correlation between mean Penetration Resistance (MPa) in the centre of the asparagus interrow and asparagus yields (kg ha^{-1}). Points represent paired values obtained across all treatments. 2018: r^2 = 0.15, r = -0.384, $p \le 0.05$; 2019: r^2 = 0.01, r = -0.097, p = NS; 2020: r^2 = 0.15, r = -0.381, $p \le 0.05$. NS = non-significant at 95% confidence interval.

2.4 Discussion

2.4.1 Companion crops

The cultivation of companion cropping in asparagus interrows is a novel strategy which has the potential to redress compaction and increase infiltration through remediation of soil structure and bio-drilling. However, the results of the current study indicate that three cycles of companion cropping with rye or mustard did not increase infiltration rates or decrease compaction compared with the Conventional practice or any other BMP treatment investigated.

These results conflict with the observations of other researchers. Research has shown that companion cropping can be very effective in mitigating soil compaction and increasing water infiltration rates (Alvarez et al., 2017; Clark, 2012; Dabney et al., 2001; Haruna et al., 2018; Howard, 2016; Storr et al., 2019). Available evidence suggests that roots of larger diameters have greater ability to penetrate compacted soils than fibrous roots (Clark et al., 2003; Materechera et al., 1991) and mustard and other tap-rooting species have been reported to have a high bio-drilling potential (Chen and Weil, 2010; Clark et al., 2003; Ren et al., 2019). However, rye has also been associated with reduced soil compaction (Ess et al., 1998) and increased infiltration rates (Kaspar et al., 2001), despite having a fibrous root system. The absence of a measurable improvement in infiltration rates for either of the companion crop treatments in this study may be due to the timing of infiltration tests (done in June/July) and the seasonality of companion crops, which are broadcast in late August/early autumn and subsequently removed in March. Cresswell and Kirkegaard (1995) highlight that the effectiveness of companion crops will depend on the seasonal climate. Even though the effect of bio-drilling is supposedly effective in zero-tillage systems (Chen and Weil, 2010; Williams and Weil, 2004), overall, companion crop non-ridged (NR) treatments did not perform significantly better as compared to companion crop ridged (R) treatments. PR of all companion crops measured in the asparagus interrows (Figure 2-3b, Figure 2-4b and Figure 2-5b) showed generally higher soil compaction in the 0-10 cm depth which are not significantly different from PR levels seen on the Conventional practice. Although bio-drilling effect of companion crops is believed to last even after the crop dies (Cresswell and Kirkegaard, 1995), the results of this study indicate that following an intensive harvest, companion crops were no longer effective in decreasing soil compaction or increasing water infiltration rates.

2.4.2 Mulch and compost

Composts and mulches have been reported to increase soil resilience (Thomas et al., 1996), decrease soil compaction (Arthur et al., 2011), improve water infiltration and water retention (Curtis and Claassen, 2009) and can be reportedly used as an alternative to companion crops (Brennan and Acosta-Martinez, 2017). In the current study, the 2018 and 2020 data showed significant increases in infiltration rates in all mulch and compost treatments as compared to the Conventional practice. The extremely high infiltration rates in 2018 and 2020 were likely caused by the SSD and the subsequent macro-pore formation. In 2019, the annual SSD application was omitted. Even so, a legacy effect was observed with the PAS 100 compost treatments having significantly higher infiltration rates compared to the Conventional practice. Most findings confirm that composts are associated with higher water retention and infiltration rates. Arthur et al. (2011) reported increased macro-porosity following incorporation of composts, Curtis and Claassen (2009) also found that compost-treated plots exhibited improved infiltration rates. Weindorf et al. (2006), however, attributed differences in infiltration rates to soil properties and climate, rather than to the use of compost alone.

Based on the presented PR data, straw mulch and compost were associated with decreased soil compaction of the interrows. Even in 2019, all compost and mulch treatments had significantly lower PR as compared to the Conventional practice to 0-20 cm depth. Furthermore, by 2020, the effect of compost and straw mulch on PR had extended to 0-40 cm depth as compared to the Conventional practice indicating that although SSD helps to loosen the soil surface and incorporate mulches, reduced soil compaction beyond the working depth of the subsoiler (winged tine operating to 0.25-0.30 m depth) can also be attributed to the compost and mulch applications. This corroborates previous research that compost application can significantly reduce soil compaction if incorporated into the soil (Muzzi et al., 1997; Olson et al., 2013; Weindorf et al., 2006). However, the longevity of the effect of compost is debated. Cogger (2005) found that the effect of compost was present even after five years. While, Arthur et al. (2011) suggest the effect of compost is not significant in the long-term. Olson et al. (2013) state that in cases where roots take advantage of the compost application, the effect can last long after decomposition of the compost itself. Several studies also found increased microbial and enzymatic activity under composts (Clark, 2012; Siczek and Frac, 2012; Tu et al., 2006) which can stimulate soil structural improvement. Due to reduced PR values beyond the depth of sub-soiling the results of this study indicate that the long-term use of mulches in combination with SSD in asparagus interrows can significantly reduce deep-seated compaction and alleviate legacy soil compaction.

Although mulches in combination with SSD alleviate soil compaction in the interrows, their use in asparagus still needs to be approached with caution. Although asparagus can temporarily tolerate wet conditions, long term exposure carries the risks of increased pathogen incidence (in particular of *Stemphylium and Phytophthora*) (Saude et al., 2008). Mulches not only retain water in the deeper horizons, but also on the surface. The continuous long-term effect of higher soil moisture status on asparagus root systems and susceptibility to diseases requires further research.

2.4.3 Machinery traffic

Management choices in asparagus impact the number of times each interrow is trafficked and the level of compaction observed (Figure 2-6 and Figure 2-7). Research has shown that increasing the number of heavy machinery passes increases soil stress, often resulting in high levels of soil compaction. Pytka (2005) claims that greatest soil deformations are usually observed during the first two machinery passes. Balbuena et al. (2000) found that 10 passes significantly affected soil physical properties to 50 cm depth compared to a no-trafficked control. While Håkansson (1985) observed that four passes was sufficient to increase soil compaction to 60 cm depth. According to Duiker (2004b), the first vehicular pass is responsible for up to 75% increase in compaction. Following the first ridging in 2017, mean profile PR of the interrows (90 cm distance from the crown line) on bare soil treatments increased on average by 47%. By comparison, at 60 cm distance from the crown line, the increase in PR was approximately 15%.

Since 2017, the Bare soil SSD R, PAS 100 R and straw mulch R interrows have experienced the highest numbers of heavy machinery passes (Table 2-6). However, following 10 tractor passes, all three treatments had significantly lower PR values compared to the Conventional practice, interrows which were trafficked seven times. The positive effect of composts and mulches combined with SSD was able to withstand a high number of tractor passes and critically, significantly reduced PR beyond the working depth of the subsoiler. Although Jourgholami et al. (2020) found that straw mulch was, unlike compost, most effective under minimal traffic intensity, in this study, no significant differences were observed between the effects of compost or straw mulch in combination with SSD and amount of traffic.

Table 2-6. Number of interrow machinery passes per treatment including all passes associated with re-ridging, SSD and fern topping since the first re-ridging operation undertaken in March 2017.

Treatment	Total number of machinery passes since 2017
[1]Zero-tillage	3
[2]Conventional practice	7
Bare soil SSD NR	6
Bare soil SSD R	10
Mustard NR	3
Mustard R	7
PAS 100 NR	6
PAS 100 R	10
Rye NR	3
Rye R	7
Straw mulch NR	6
Straw mulch R	10

[1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

2.4.4 Tillage

Tillage is considered to be a useful approach to improve soil physical properties through promoting water infiltration and facilitating root penetration (Botta et al., 2019; Lipiec and Stępniewski, 1995; Niziolomski et al., 2016; Schneider et al., 2017). In bare soil treatments, SSD as expected, significantly improved infiltration and decreased soil PR of the interrows to the subsoiler operating depth of 25 cm depth. The very rapid infiltration rates observed on all plots subject to SSD in 2018 and 2020 were due to macro-pore formation. Bare soil SSD R did not have extremely high PR values (of up to 5.0 MPa) as observed in the Conventional practice, indicating that on bare soils, SSD was able to remediate compaction of the interrow.

Every field operation requiring use of heavy machinery poses a risk to the soil structure and while sub-soiling may reduce compaction levels, it does not improve soil structure (Duiker, 2004b; Lipiec and Stępniewski, 1995). According to Loper et al. (2010), depending on the local climate and soils, SSD may not affect soil compaction. Cultivations under unsuitable conditions may have detrimental effects on soil structure (Håkansson, 1985). Alakukku et al. (2003) and Chamen et al. (2003) further added that in-furrow ploughing is the most serious source of deep-seated compaction. Håkansson (1985) claims that sub-soiling cannot fully alleviate deep-seated compaction and is also expensive, which was confirmed by our results in which SSD remediated soil compaction to the working depth of the subsoiler however not beyond. In 2019, contractor charges were on average £38.11 ha^{-1} for light cultivations and £59.58 ha^{-1} for sub-soiling (NAAC, 2019). This highlights the importance of carefully considering each sub-soiling operation with regards to possible risks, benefit, and economic cost.

In the past 20 years, many authors argued that zero-tillage or conservation tillage has even greater long-term benefits as compared to regular tillage (Botta et al., 2019; Dang et al., 2018; Duiker, 2004b; Holland, 2004; Raper and Bergtold, 2007; Schneider et al., 2017; Wolz et al., 2018). The present study found that compaction of the zero-tillage treatment at subsoil depth (30-60 cm) in 2020 was similar to the pre-ridging legacy compaction levels measured 4 years earlier. Furthermore, there was no significant difference in the interrow compaction between the 2020 zero-tillage and 2017 post-ridging baseline suggesting that little to no additional compaction occurred between 2017 and 2020 on zero-tillage treatments. Also, as zero-tillage has many advantages over conventional tillage systems, such as reduced labour requirements, decreased surface runoff and erosion and higher biological activity granting soils greater resilience against physical pressure (Duiker, 2004b; Thomas et al., 1996; Wolz et al., 2018), cultivation practices based on decreased soil disruption have a strong potential to prevent deep-seated compaction and increase soil resilience in UK asparagus systems.

2.4.5 Impact of soil compaction on yields in asparagus

Many studies have found that soil compaction results in yield reductions as observed on wheat, peanut and sunflower (Biberdzic et al., 2020; Botta et al., 2018; Hu et al., 2021; Shen et al., 2016; Whalley et al., 2006). Yield decrease has been linked to increased mechanical pressure (Alakukku and Elonen, 1994; Håkansson, 1994), reduced water availability (Whalley et al., 2006) and to reduction in root growth (Lipiec et al., 2003; Soane and van Ouwerkerk, 1995) affecting nutrient uptake (Singh et al., 2015) or a combination of all depending on weather conditions (Lipiec and Hatano, 2003). This study has demonstrated that compaction in asparagus interrows has a negative impact on asparagus yield. Inter annual variability in climate at the study site may in part explain why a relationship between soil PR and yield was found only in 2018 and in 2020.

2.5 Conclusions

The results of this 3-yr field trial indicate that the interrow application of PAS 100 compost and straw mulch in combination with SSD is an effective BMP to alleviate deep-seated compaction in asparagus interrows associated with inter and intra annual tillage, trafficking and harvesting operations as compared with Conventional practice. The PAS 100 compost in combination with SSD treatments are also associated with yield uplift. The high infiltration rates and surface cover associated with the mulch/SSD treatments has also been demonstrated to mitigate runoff and erosion (Niziolomski et al., 2002). In addition, the results indicate that Zero-tillage is a viable option to prevent soil compaction in asparagus interrows without negative impacts on yield. The effect of zero-tillage on soil erosion and run-off control from asparagus fields in the UK requires further research to assess the holistic benefits of this treatment. Contrary to expectations, annual intercropping with either rye or mustard did not remediate interrow soil compaction. This may in large part be due to the seasonality of the companion crops, which are broadcast in late August/early autumn and removed the following March. It is anticipated that the research outcomes from this study will feed directly into policy discussions associated with the future Environmental Land Management scheme (ELMS) in England, which is expected to encourage environmental land management by allowing asparagus growers to receive ‘financial reward in return for delivering environmental benefits’ such as reducing levels of water pollution, flooding, erosion and run-off.

2.6 References

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3 Impact of Best Management Practices on the ‘Root-Engine’ of Asparagus

Abstract

The ‘Root-Engine’ of asparagus (*Asparagus officinalis* L.) is crucial for stand establishment and long-term productivity. The aim of this study was to quantify the long-term impacts of a range of potential Best Management Practices (BMPs) aimed at promoting ‘Root-Engine’ development through profile proliferation of carbohydrate storage roots. The field trial was established in 2016 and treatments were applied annually from 2018-2020. BMPs included (1) companion crops (Rye (*Secale cereale* L.) or Mustard (*Sinapis alba* L.)), (2) interrow surface mulch applications (straw mulch or PAS 100 (Publicly Available Specification) compost in combination with shallow soil disturbance (SSD)) and (3) modifications of the conventional tillage practice (annual re-ridging (R)) by applying or not applying R and by applying or not applying SSD. Mean root mass density (RMD) decreased from 2019 to 2020 in response to weather conditions which most likely affected the ability of the crop to replenish carbohydrate stores. This resulted in significant RMD reductions in re-ridged bare soil and companion crop (CC) SSD treatments. Consequently, re-ridging of asparagus grown with bare soil interrows or with mustard/rye CC without SSD contributed to significant reductions in RMD. All treatments to which SSD was applied did not exhibit significant year-to-year RMD reductions whether ridged or non-ridged indicating that in some years, SSD is associated with increased resilience of the ‘root engine’ to climate variability. The results also indicate that 87% of asparagus total root biomass was associated with soil compaction range of 1.0-3.5 MPa. Straw mulch and compost applications in combination with SSD were associated with no-significant difference in

asparagus RMD between 2019 and 2020, whether ridged or non-ridged. These results suggest that mulch application in combination with SSD help stabilize the mature asparagus ‘Root Engine’.

3.1 Introduction

The size of root system and its distribution affects the ability of plants to access and acquire soil resources which determines crop health and productivity (Bengough, 2012; Lynch, 1995). Restrictions and disruptions to the underground root system can lead to plant stress and early crop decline (Bengough, 2012). Asparagus is a perennial crop with crop maturity and economic production typically occurring between years 4-7 of a 10-year production cycle. With such a long lifespan, it is expected that decisions made in one year determine the next years' crop performance. The root system of *Asparagus Officinalis* consists of 3 main components: (1) crown/rhizome, (2) storage roots and (3) fibrous roots (Drost and Wilson, 2003). Fibrous roots, which are assumed to facilitate water and nutrient uptake, are replaced annually (Reijmerink, 1973) whereas storage roots, which are essential for storage of carbohydrates and productive spear growth, remain functional for up to 6 years (Scott et al., 1939). These carbohydrate storage roots are essentially the 'Root-Engine' which dictates yield and economic profitability. The size and maintenance of this 'Root-Engine' ultimately drives stand longevity.

Re-ridging of asparagus is the dominant practice adopted by UK asparagus growers. This is primarily undertaken to ensure adequate soil depth above the crown, facilitate efficient manual harvesting and to bury fern residue for control of *Stemphylium vesicarium*. Ridging also conveys excess rainfall off the crown area, through the interrows and off the field site to prevent waterlogging (Niziolomski et al., 2020). Although previous research has demonstrated that root damage associated with tillage operations can have a major negative impact on stand longevity and productivity (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Reijmerink, 1973; Wilcox-Lee and Drost, 1991), the impact of annual re-ridging and subsoiling on the ‘Root-Engine’ of asparagus under UK conditions is unknown. Tillage operations carried out in the interrows however pose a risk of damage to storage roots, reduce the size of the carbohydrate storage system (Root-Engine), and create pathways for infections by pathogens such as *Phytophthora asparagi* (Falloon and Grogan, 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2015). Companion cropping with rye is commonly used North American asparagus industry to supress weeds and to provide soil protection through interception of rainfall kinetic energy. Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which are known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991). Furthermore, rye has been reported to have the ability to reduce the severity of *Fusarium* crown and root rot (FCRR) in asparagus (Matsubara et al., 2001). Mustard is known for its extensive tap-rooting system associated with bio-drilling and for its bio-fumigation potential, which has been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998). Hence, companion cropping in asparagus systems may have a beneficial impact on asparagus growth and the overall health.

The expected economic production of asparagus ranges between 10-20 years, due to the ‘asparagus decline’ mainly caused by FCRR, the production period can be limited to only 5-10 years (Elmer et al., 1996). In the UK, it is estimated that losses from asparagus decline can result in up to 60% loss of stand and £16M in lost revenue over a 10 year cropping cycle (AHDB, 2017). Although effects of tillage on asparagus roots over a full growing season were described by Drost and Wilcox-Lee (2000), as re-ridging continues to be adopted as a conventional practice by majority of British growers, the long-term effect of this practice on asparagus root system remains unknown. The aim of this study is to quantify the effects of annual re-ridging and shallow soil disturbance on asparagus root mass distribution, and to investigate the long-term impacts of a range of potential Best Management Practices (BMPs) aimed at optimising the size of the 'Root Engine'.

3.2 Materials and Methods

The trial took place as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The long-term field trial (4.5 ha) is located at Gatsford Farm, Ross-on-Wye, Herefordshire. Two-year-old asparagus 'A' crowns (cultivar 'Gijnlim' which represents 70% of UK field grown asparagus) were planted on 20–21st of April 2016 on the flat at an anticipated depth of 0.14 m, at 0.16 m spacing between crowns. Beds were on 1.83 m wide centres. In spring 2017, all plots were re-ridged as a consequence of the shallowness of the crown (circa 0.06 m) instead of the intended 0.14 m. Conventional agrochemical treatments have been applied to all trial plots from 2016 to 2020.

3.2.1 Experimental Design

The trial investigated the efficacy of a range of potential BMPs (Table 3-1); (1) companion crops (Rye (*Secale cereale* L. var. Protector.) or Mustard (*Sinapis alba* L. var. Severka)), (2) interrow surface mulch (Straw and PAS 100 compost) in combination with shallow soil disturbance (SSD), (3) tillage modifications by ridging (R) or not re-ridging (NR) and by applying SSD no No-SSD including treatments equivalent to the current Conventional practice and Zero-tillage. The experiment comprised 48 randomly distributed, 35 m long treatment plots. Each plot consists of 2 asparagus rows, central interrow and 2 guard interrows separating the treatments. All treatments were replicated in quadruplicate. As appropriate, treatment plots were also separated by tramlines to facilitate sprayer operations.

The tractor used for annual ridging (R) and to apply SSD was a 155 HP with 82.74 kPa on the front tyres and 82.74 kPa on the rear tyres. Assumed tine rotation area of the ridger and soil disturbance pattern of the subsoiler (Niziolomski et al., 2016) are shown in Figure 3-1. SSD was applied in April 2018, March 2020 and in June 2020 (Figure 3-2) using a winged tine operating to 0.25-0.30 m depth to all mulch treatments and to selected bare soil treatments (Table 3-1). Re-ridging was undertaken using a tractor mounted 1.83 m double disk ridger in March 2017 to deepen the soil layer above the crown and then repeated annually, in April 2018, March 2019 and April 2020. As ridging was applied for the first time in April 2018, data from 2019 shows impacts of the first annual ridging event while the 2020 data reflects impacts of two ridging events which took place in two consecutive years.

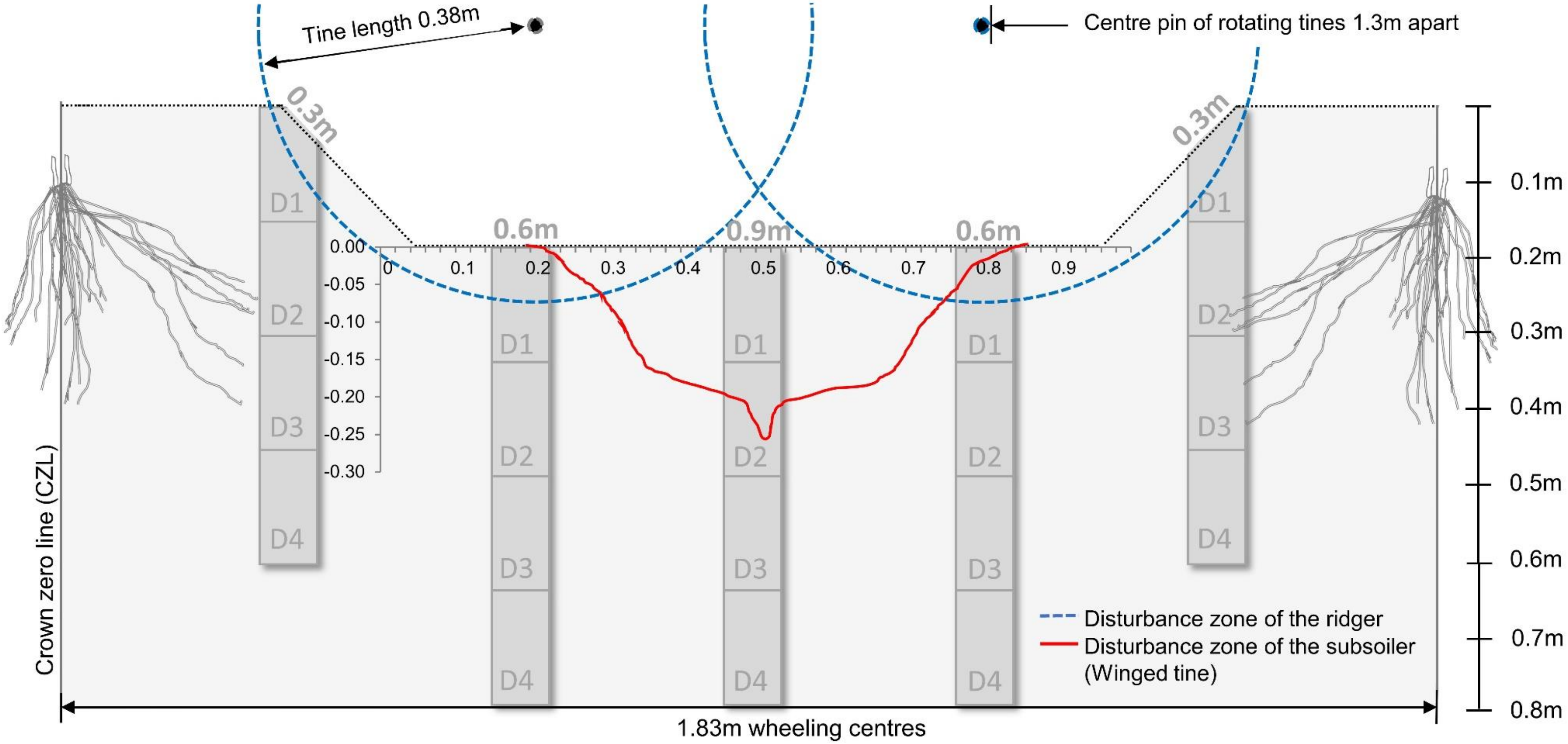

Figure 3-1. Visualisation of assumed ridger tine disturbance areas and subsoiler soil disturbance area (Niziolomski et al., 2016) alongside root coring locations.

Companion crops were broadcast for the first time on the 10th August 2017 when the asparagus was at full fern stage at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard, respectively.

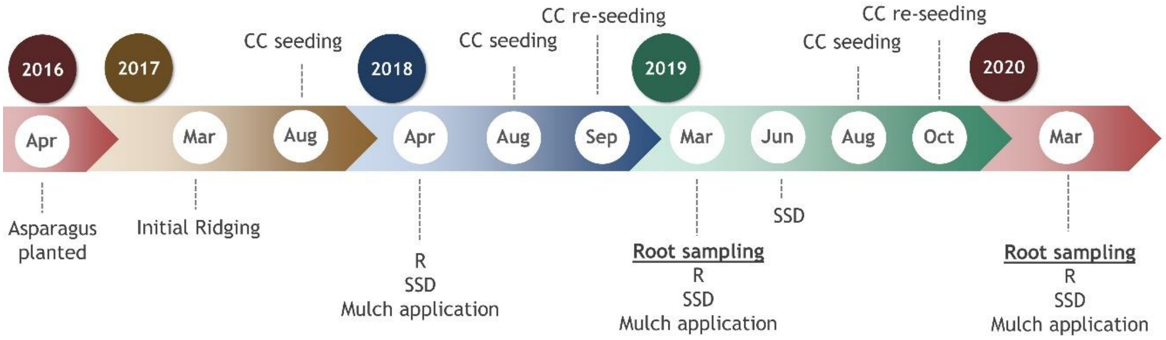

Figure 3-2. Trial activities timeline. R=Ridging; SSD=Shallow Soil Disturbance; CC=Companion Crops.

In the first year, the emergence rate of the companion crops achieve sufficient ground cover of 70-75% (Morgan, 2005). However, in 2018 and 2019, due to predation, seeding rates were increased to 200 kg ha^{-1} and 25 kg ha^{-1} for rye and mustard, respectively and repeated in September 2018 and October 2019. Mulches (PAS 100 and straw mulch) were applied annually in April 2018, March 2019 and March 2020 at rates of 25 t ha^{-1} and 6 t ha^{-1}, respectively. All treatments received a standard annual fertiliser dose of approximately 450 kg ha^{-1} of nitrogen and sulphur (Single Top); 150 kg ha^{-1} of muriate of potash (MOP) and 50 kg ha^{-1} of triple super phosphate (TSP).

Table 3-1. Summary of the experimental treatments.

Treatment	Cover	Annual re-ridging (R)	Sub-soiling (SSD)
Conventional Practice	Bare soil	Ridged	No SSD
Zero Tillage	Bare soil	Non-ridged	No SSD
Bare soil SSD R	Bare soil	Ridged	SSD
Bare soil SSD NR	Bare soil	Non-ridged	SSD
Mustard R	Mustard	Ridged	No SSD
Mustard NR	Mustard	Non-ridged	No SSD
Rye R	Rye	Ridged	No SSD
Rye NR	Rye	Non-ridged	No SSD
Straw mulch SSD R	Straw mulch	Ridged	SSD
Straw mulch SSD NR	Straw mulch	Non-ridged	SSD
PAS 100 SSD R	Compost	Ridged	SSD
PAS 100 SSD NR	Compost	Non-ridged	SSD

NR=no annual re-ridging; R=re-ridging; SSD=shallow soil disturbance.

3.2.2 Sampling methodology

Soil analyses conducted in 2016 indicated that there were no significant differences in the soil parameters tested ($p \leq 0.05$) between plots (Appendix B). Soils at the trial site are Cambisols (IUSS Working Group WRB, 2007) of Eardiston series association (Cranfield University, 2020) with 77% sand, 11% silt and 12% clay composition. Other soil parameters showed soil pH of 6.34 (± 0.03), soil organic matter of 2.78% (±0.03), total soil C of 1.24% (±0.01) and total mineralizable N of 0.13% (±0.001).

2-year-old asparagus ‘A’ crowns were planted in April 2016, hence root samples from March 2019 and 2020 were taken from 5 and 6-year-old plants, respectively.

Root coring procedure adopted from Drost and Wilson (2003) is a relatively simple and easy method allowing mapping of changes in root distribution which accounts for ca. 85% of the total root mass. Annual collection of root samples can be used to effectively map differences between growing practices and their impact on asparagus root growth patterns. For each treatment, 4 randomly selected transects were sampled using a handheld Eijkelkamp bi-partite root auger (internal diameter: 0.08 m, internal core depth: 0.15 m, volume: 754 cm^3). Where soil compaction made hand coring inefficient, root cores were extracted using an Eijkelkamp Soil Column Cylinder Auger (internal diameter: 0.084 m with a volume for each 0.15 m depth of 831 cm^3) which was driven into the soil using a Cobra TT petrol-driven percussion hammer. Root cores were taken at 0.3 m distance intervals starting with the crown zero line (CZL) and subsequently in line with the asparagus crown at distances of 0.3 m, 0.6 m and 0.9 m (centre of asparagus interrow) to a maximum depth of 0.6 m. Total number of root samples collected per treatment each year was 64 (4 locations x 4 distances from the crown x 4 depths). Asparagus storage roots (>2mm diameter) were separated from soil, washed, dried at 65 ˚C for 48-72 h and weighed to estimate the dry root mass density (RMD) which is defined as a ratio between root dry mass (M_D) and the root core volume, as equation 3-1:

$$\mathbf{RMD} = \frac{\mathbf{M_D}}{\mathbf{V}} \quad (\mathbf{g\ cm^{-3}}) \qquad \textbf{(3-1)}$$

Root Biomass as a percentage of the total root biomass (TRB%) was used to express proportionate root distribution for each coring location, where RMD_{Cl} represents sum of RMD for each sample class (i.e. Sample location or PR class) and RMD_t represents the total sum of all RMD in the sample, as equation 3-2:

$$\boldsymbol{TRB} = \frac{\boldsymbol{RMD_{sl}}}{\boldsymbol{RMD_t}} \times \mathbf{100}\ (\%) \qquad \textbf{(3-2)}$$

Root samples taken at different distances from the CZL and depths were assigned a code consisting of two values based on their location coordinates. The first number indicates the distance of the sample from the CZL, e.g., 0.3 m, 0.6 m or 0.9 m. The second number then indicates the depth from which the root core has been extracted. Depth 0-0.15 m as D1, depth 0.15-0.30 m as D2, depth 0.30-0.45 m as D3 and depth 0.45-0.60 m as D4. Subsequently, 12 unique location codes will be used to identify a specific sample location in the soil profile. Those codes are 0.3mD1, 0.3mD2, 0.3mD3, 0.3mD4, 0.6mD1, 0.6mD2, 0.6mD3, 0.6mD4, 0.9mD1, 0.9mD2, 0.9mD3 and 0.9mD4. CZL root data was not included in analyses due to large variability in values obtained from the location. At the time of root sampling, it is impossible to identify the exact crown location. Consequently, some CZL samples contain the whole crown while others do not. Furthermore, in order to compare root distribution across multiple treatments, we opted to focus on analysing root distribution in treatments application areas. Thus, this paper does not discuss differences in crown sizes nor the distribution of roots extending vertically from the crown.

Penetration resistance (PR) transect measurements were taken in June 2020 using a digital Eijkelkamp Penetrologger with a 1.0 cm^2 base area and 60° apex angle cone. PR was measured to 0.6m depth (where possible) at a recording interval of 0.01m, tangentially from the asparagus CZL at 0.3 m, 0.6m and 0.9m. For each treatment, four PR transects were measured.

3.2.3 Statistical Analysis

Statistical analysis was undertaken using the TIBCO Statistica 13.3.0 analytics software. Data was analysed by the standard analysis of variance followed by *post-hoc* Fisher LSD analysis at 95% conf. level. Spatial distribution contour maps were generated using the inverse distance weighing interpolation method (IDW) in Esri ArcMap^{TM} (GIS software) version 10.7.

3.3 Results

3.3.1 Effect of BMPs on the asparagus ‘Root-Engine’

In 2019 (11 months post 1st annual re-ridging), Rye NR mean whole profile RMD values were significantly lower as compared to the Zero-tillage, Conventional practice, Bare soil SSD NR, Mustard R, PAS 100 NR and Rye R treatments (Table 3-2). In contrast, in 2020 (11 months post 2nd annual re-ridging), differences in mean RMD between Rye R and Rye NR were not significant or any other of the BMPs. Conventional practice was however associated with significantly lower mean RMD as compared with the Zero-tillage and PAS 100 NR treatments. As shown in the year-to-year comparison Table 3-3, there was an overall significant reduction in mean whole profile RMD (kg m^3) across all ridged non-SSD treatments in 2020 as compared to the equivalent treatments in 2019. Specifically, 2020 mean profile RMD of the Conventional practice, Mustard R and Rye R had decreased significantly by 75%, 53% and 55% in 2020 as compared to 2019. With the exception of Straw Mulch R mean RMD of which increased by 7%, all other treatments show a decrease in RMD between 2-35%.

Table 3-2. Changes in mean RMD (kg m^3) of treatments in 2019 and 2020. Table includes mean RMD of all 12 sampling locations, 4 different depths and 3 distances from the CZL.

Treatment	2019	2020
Zero-tillage	0.67 ^{ef}	**0.49 ^{bcdef}**
Conventional practice*	0.62 ^{def}	0.16 ^{a}
Bare soil SSD NR	0.58 ^{cdef}	0.42 ^{abcde}
Bare soil SSD R	0.53 ^{bcdef}	0.43 ^{abcde}
Mustard NR	0.42 ^{abcde}	0.41 ^{abcde}
Mustard R*	0.73 ^{f}	0.34 ^{abcd}
PAS 100 NR	0.67 ^{ef}	**0.46 ^{bcdef}**
PAS 100 R	0.53 ^{bcdef}	0.35 ^{abcd}
Rye NR	**0.26 ^{ab}**	0.24 ^{ab}
Rye R*	0.63 ^{def}	0.28 ^{abc}
Straw Mulch NR	0.42 ^{abcde}	0.38 ^{abcde}
Straw Mulch R	0.41 ^{abcde}	0.43 ^{abcde}

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. Highlighted values are significantly different from the Conventional practice. *Significantly different in 2020 as compared to 2019

Table 3-3. Differences between mean 2019 and 2020 RMD values for the Conventional practice, Mustard R and Rye R.

Sample location	Conventional practice		Mustard R		Rye R	
	2019	2020	2019	2020	2019	2020
0.3mD1	0.07	0.04	1.19	0.56	0.65	0.00
0.3mD2	2.32*	0.70*	3.09*	1.29*	2.39*	0.85*
0.3mD3	0.55	0.52	1.13	0.52	1.56*	0.62*
0.3mD4	0.60	0.34	1.18	0.23	0.25	0.33
0.6mD1	0.13	0.11	0.14	0.29	0.21	0.15
0.6mD2	1.10*	0.02*	0.80	0.54	1.22*	0.27*
0.6mD3	0.89*	0.04*	0.23	0.13	0.04	0.49
0.6mD4	0.12	0.04	0.01	0.16	0.50	0.02
0.9mD1	0.16	0.04	0.25	0.24	0.00	0.14
0.9mD2	0.89*	0.03*	0.34	0.09	0.32	0.34
0.9mD3	0.46	0.00	0.28	0.06	0.33	0.14
0.9mD4	0.12	0.00	0.15	0.00	0.12	0.04

*Significant difference between 2019 and 2020 values following One-Way ANOVA and *post-hoc* Fisher LSD.

No significant changes between 2019 and 2020 RMD values occurred at depths of 0-0.15m (0.3mD1, 0.6mD1 and 0.9mD1) and 0.45-0.60m (0.3mD4, 0.6mD4 and 0.9mD4). As shown in Table 3-3, Conventional practice, Mustard R and Rye R, all showed significant 2020 RMD reductions at the 0.3mD2 location compared to the 2019 RMD. In addition, Rye R showed significant reductions in RMD at 0.3mD3 and 0.6mD2 in 2020 as compared with 2019. For the Conventional practice, significant decreases in 2020 RMD were also observed at 0.6mD2 and expanded further to 0.6mD3 and 0.9mD2 as compared with 2019. The contrast in the 2019 and 2020 'Root Engine' of the Zero-tillage and the Conventional practice treatments is shown in Figure 3-3. From 2019 to 2020 the Conventional practice was associated with a decline in RMD in the interrow areas, at 0.6 – 0.9 m distance from the crown. In contrast, the Zero-tillage treatment was associated with storage roots extending into the interrow. Rye R and Mustard R, treatments also exhibited a decrease in interrow RMDs in 2020 as compared to 2019. In contrast, no significant differences in RMD between 2019 and 2020 were observed for the Straw mulch R or NR, PAS 100 R or NR, Bare soil SSD R or NR, or Zero tillage treatments (Table 3-2).

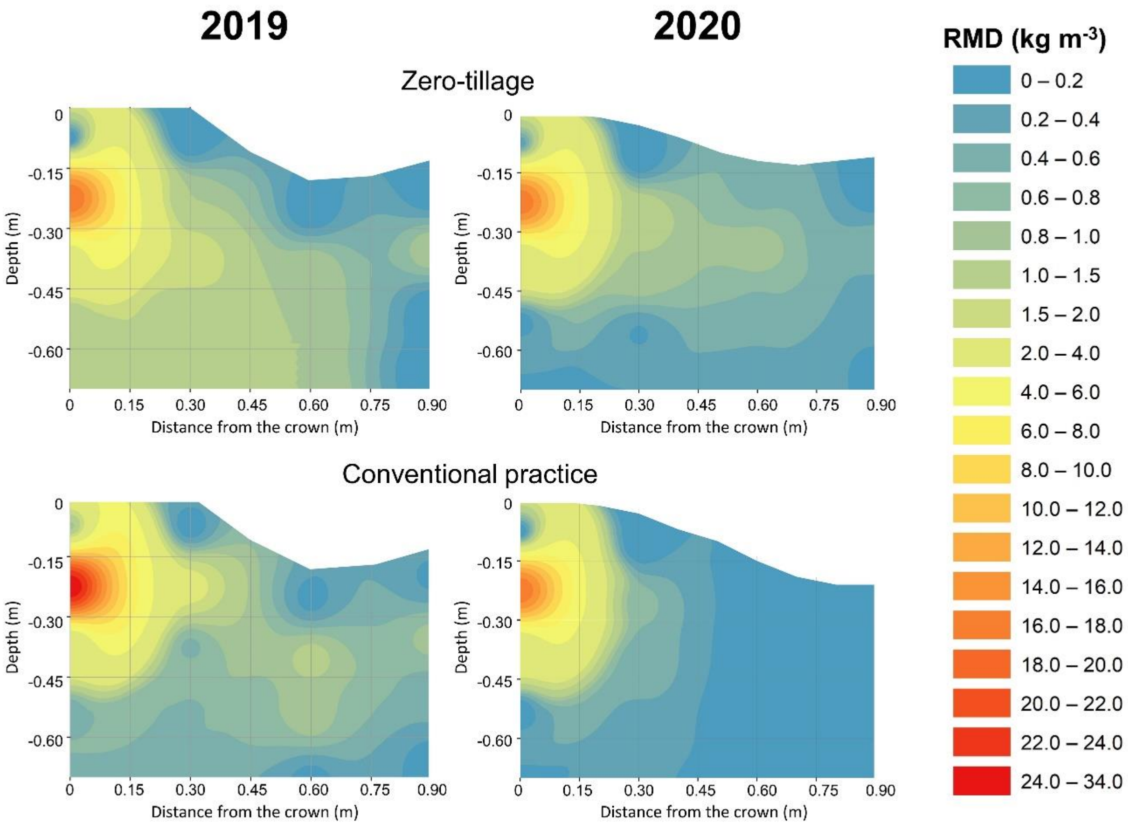

Figure 3-3. Root distribution heat maps representing root distribution of the Zero-tillage and of the Conventional practice in 2019 and 2020.

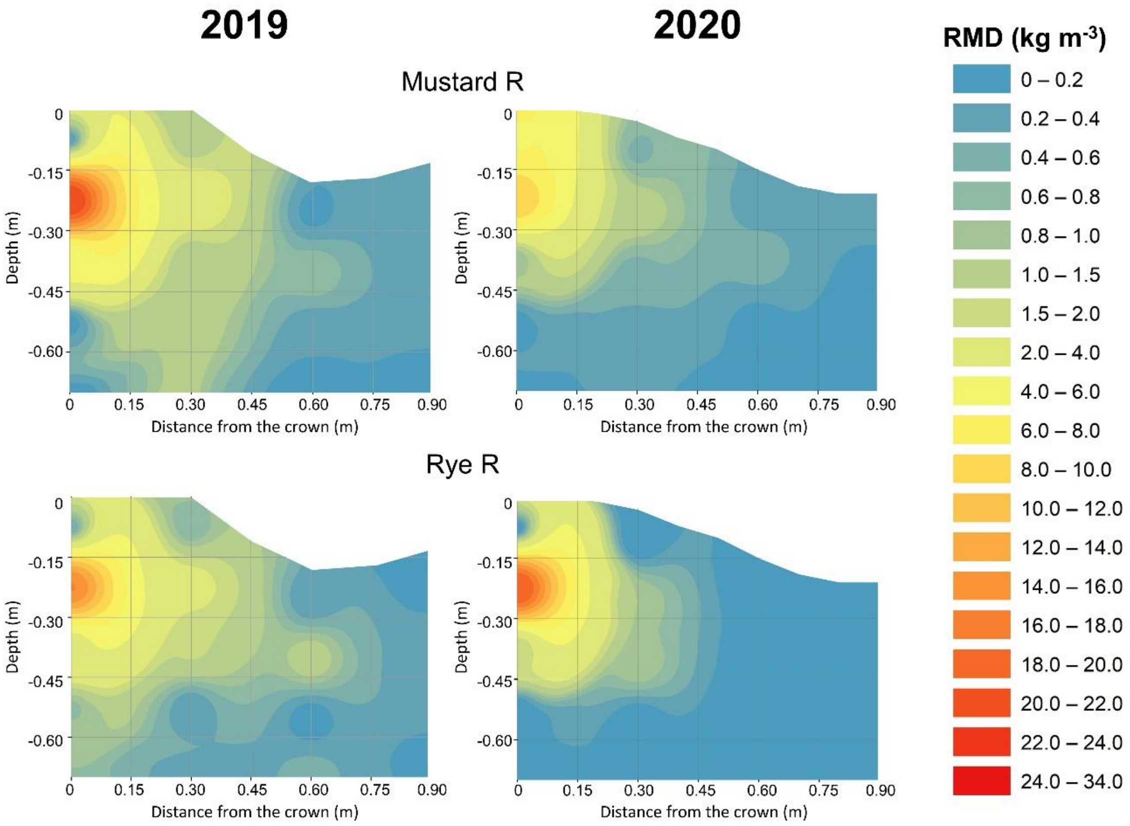

Figure 3-4. Root distribution heat maps representing root distribution of re-ridged companion crop treatments, Mustard R and Rye R in 2019 and 2020.

3.3.2 Impact of BMPs on root profile distribution

Root cores extracted in March 2020 were obtained from 6-year old plants which we assumed to be an age sufficient for reliable interpretation of differences in root distribution between the BMPs following 2 years of treatment applications (Wilson et al., 2002a). All treatments in all sample locations were compared to the Conventional practice. The majority of changes in storage root distribution observed between treatments occurred in the 0.15-0.30 m (D2) depth zone (Table 3-4). Mean RMD values for the Conventional practice at 0.6mD2 and 0.9mD2 were 97.8% and 94.5% lower as compared to the Zero-tillage treatment (Table 3-4). Furthermore, at 0.6mD2, RMD of the Conventional practice was significantly lower as compared to all other bare soil treatments. Mean RMD of the Conventional practice at the centre of the interrow (0.9 m distance from the CZL, 0-0.60 m depth) was only 0.03 kg m^{-3}, which is 94.5% lower than the Zero-tillage treatment with RMD of 0.55 kg m^{-3}. Compared to the Conventional practice, SSD had a positive impact on asparagus RMD. Compared to the Zero-tillage, Conventional practice and re-ridging was however associated with significant root reductions at 0.6mD2 and 0.9mD2.

RMD values associated with Conventional practice were furthermore significantly lower as compared to the Mustard NR (0.6mD2 and 0.9mD4), Mustard R (0.3mD1) and Rye R (0.6mD3, 0.9mD2 and 0.9mD3) treatments (Table 3-4). For the mulch treatments, RMD of PAS 100 NR and Straw Mulch R were significantly higher compared to Conventional practice at 0.3mD1 and 0.3mD2, and at 0.6mD2 and 0.9mD3, respectively. In contrast, no significant differences in RMD were observed between the Conventional practice and the PAS 100 R and Straw Mulch NR treatments.

In general, treatments which were significantly different from the Conventional practice were associated with increases in RMD for those same locations which indicating that adopting any alternative management practice has a potential to result in increased overall root mass density.

Table 3-4. Mean RMD (kg m^{-3}) values of all treatments as compared to the Conventional practice obtained in 2020.

Sample Location	0.3mD1	0.3mD2	0.3mD3	0.3mD4	0.6mD1	0.6mD2	0.6mD3	0.6mD4	0.9mD1	0.9mD2	0.9mD3	0.9mD4
Bare soils												
Conventional practice	0.04^{a}	0.70^{a}	0.52^{a}	0.34^{a}	0.11^{a}	0.02^{a}	0.04^{a}	0.04^{a}	0.04^{a}	0.03^{a}	ND	ND
Zero-tillage	ND	1.33^{ab}	0.98^{a}	0.18^{a}	0.52^{a}	**0.93^{c}**	0.56^{a}	0.32^{a}	0.01^{a}	**0.55^{b}**	0.28^{a}	0.17^{a}
Bare Soil SSD NR	0.13^{a}	1.18^{ab}	1.61^{a}	0.18^{a}	0.12^{a}	**0.37^{b}**	0.31^{a}	0.24^{a}	0.14^{a}	0.21^{ab}	0.24^{a}	0.25^{a}
Bare Soil SSD R	0.19^{a}	**2.20^{b}**	1.51^{a}	0.11^{a}	0.12^{a}	**0.48^{b}**	0.20^{a}	0.11^{a}	0.01^{a}	0.08^{a}	0.17^{a}	0.04^{a}
Companion Crops												
Conventional practice	0.04^{a}	0.70^{a}	0.52^{a}	0.34^{a}	0.11^{a}	0.02^{a}	0.04^{a}	0.04^{a}	0.04^{a}	0.03^{a}	ND	ND
Mustard NR	0.13^{a}	1.32^{a}	1.10^{a}	0.43^{a}	0.37^{a}	**0.77^{b}**	0.04^{a}	0.09^{a}	ND	0.15^{ab}	0.07^{ab}	**0.43^{b}**
Mustard R	**0.56^{b}**	1.29^{a}	0.52^{a}	0.23^{a}	0.29^{a}	0.54^{ab}	0.13^{ab}	0.16^{a}	0.24^{a}	0.09^{a}	0.06^{ab}	ND
Rye NR	0.08^{a}	0.78^{a}	0.76^{a}	0.25^{a}	0.26^{a}	0.45^{ab}	0.02^{a}	0.06^{a}	ND	0.21^{ab}	0.02^{ab}	0.05^{a}
Rye R	0.00^{a}	0.85^{a}	0.62^{a}	0.33^{a}	0.15^{a}	0.27^{ab}	**0.49^{b}**	0.02^{a}	0.14^{a}	**0.34^{b}**	**0.14^{b}**	0.04^{a}
Mulches												
Conventional practice	0.04^{a}	0.70^{a}	0.52^{a}	0.34^{a}	0.11^{a}	0.02^{a}	0.04^{a}	0.04^{a}	0.04^{a}	0.03^{a}	ND	ND
PAS 100 NR	**0.47^{b}**	**1.61^{b}**	1.37^{a}	0.29^{a}	0.06^{a}	0.69^{ab}	0.46^{a}	0.21^{a}	0.06^{a}	0.20^{a}	0.04^{ab}	0.08^{a}
PAS 100 R	0.13^{ab}	1.43^{ab}	0.90^{a}	0.02^{a}	0.63^{a}	0.64^{ab}	0.02^{a}	0.07^{a}	0.21^{a}	0.11^{a}	ND	ND
Straw Mulch NR	0.21^{ab}	1.06^{ab}	1.30^{a}	0.38^{a}	0.24^{a}	0.56^{ab}	0.24^{a}	0.05^{a}	0.06^{a}	0.14^{a}	0.10^{ab}	0.16^{a}
Straw Mulch R	0.11^{ab}	0.97^{ab}	1.78^{a}	0.17^{a}	0.09^{a}	**1.21^{b}**	0.29^{a}	0.17^{a}	0.12^{a}	0.01^{a}	**0.15^{b}**	0.13^{a}

Within each column section, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher analysis. Highlighted values are significantly different from the Conventional practice. ND = No roots detected. D1 = 0.0 – 0.15m, D2 = 0.15 – 0.30m, D3 = 0.30 – 0.45m and D4 = 0.45 – 0.6m.

3.3.3 Asparagus root profile distribution

Figure 3-5 illustrates proportions of total roots as TRB(%) and their distribution between all 12 coring locations. Root coring locations at 0-0.15 m depth, (locations 0.3mD1, 0.6mD1, and 0.9mD1), were associated with 9.3% and 11.5% of storage roots in 2019 and 2020, respectively. In 2019 and 2020, at 0.3m distance from the crown contained 57.0 and 62.0% of the TRB and at 0.6m distance from the crown contained 28.3 and 27.1% of the TRB, respectively. Interrow centres, 0.9 m distance from the crown in 2019 and 2020 were associated with 14.7% and 10.9% of the TRB, respectively.

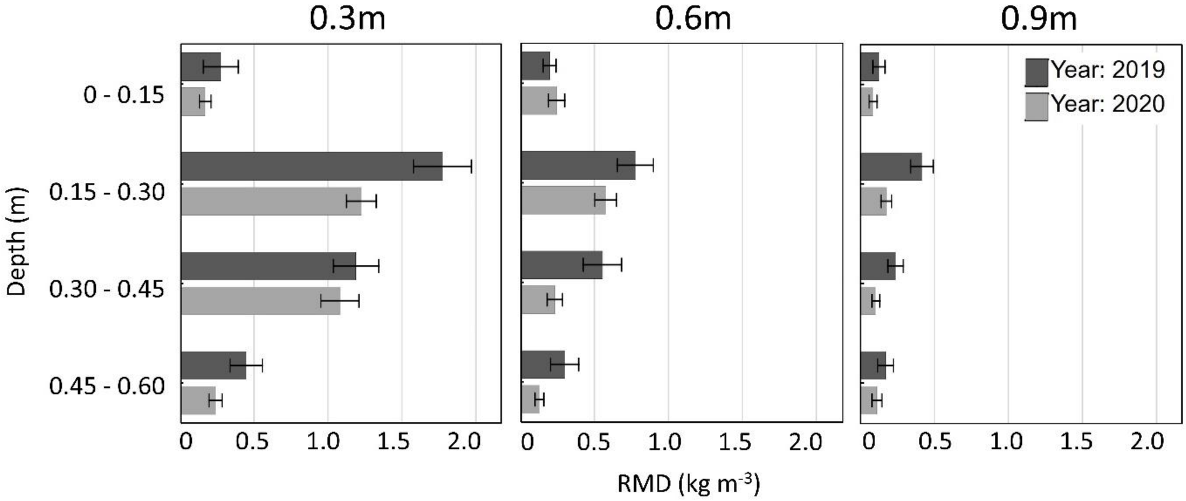

Figure 3-5. Total Root mass distribution of all treatments for each root coring location from the CZL. Error bars represent ±1 S.E. D1 = 0.0 – 0.15 m, D2 = 0.15 – 0.30 m, D3 = 0.30 – 0.45 m and D4 = 0.45 – 0.6 m depth.

3.3.4 Effect of soil compaction on asparagus storage root distribution

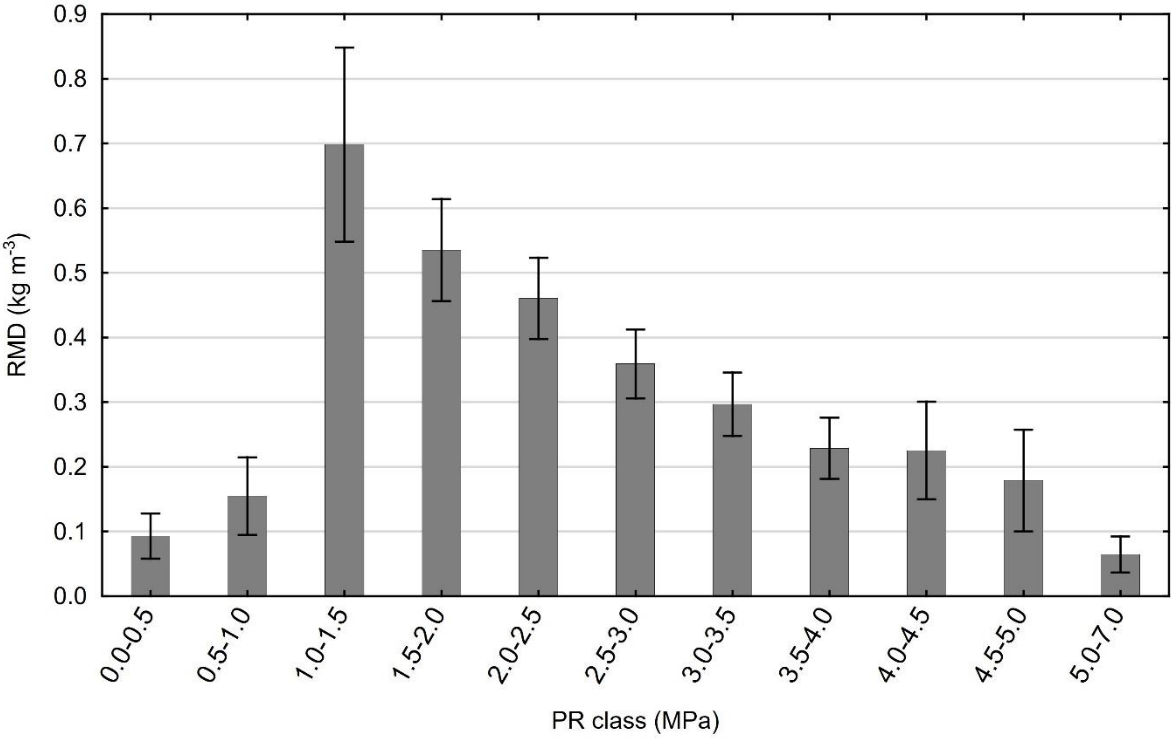

Figure 3-6. Mean RMD per Penetration Resistance (PR) class (MPa) (n=564). Data presented represents the mean values for all 12 sampling locations, different depths and distances from the CZL. Error bars represent ±1 S.E.

Root samples from all 12 treatments were combined and assigned a mean penetration resistance (PR) value based on PR measurements obtained in same the respective area as the root sample and grouped into PR classes (Figure 3-6). RMD classification by PR was then used to assess the extent to which asparagus root growth was affected by soil compaction. The highest mean RMD of 0.70 kg m^{-3} was present in samples found within the 1.0-1.5 MPa class (Figure 3-6) with RMD decreasing with increasing PR. Results indicate that 87% of asparagus TRB was found in the PR range of 1.0-3.5 MPa. In contrast, mean RMD at 4.5-7.0 MPa PR class was only 0.12 kg m^{-3} (Figure 3-6).

3.4 Discussion

As ridging was applied for the first time in April 2018, root data from 2019 showed impacts of the first annual ridging event while the 2020 data reflected impacts of two ridging events which took place in two consecutive years. Re-ridging was applied immediately after root sampling and prior to the start of the harvest.

Results of this study showed that the second annual re-ridging had a negative impact on mean whole profile RMD in the Conventional practice, Mustard R and Rye R treatments, which showed significant reductions in RMD in 2020 as compared to 2019. All three treatments were associated with annual re-ridging without SSD. Due to the 11 month interval between the 2019 re-ridging and 2020 root sampling, weather conditions of 2019 may in part explain the RMD results observed. Mild temperatures (>10°C) trigger the start of asparagus reproductive cycle (Culpepper and Moon, 1939) and in combination with high rainfall can increase disease incidence with *Phytophthora asparagi* (Falloon and Grogan, 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2015). These conditions occurred in February 2020 (approximately 1 month prior to 2020 root sampling), when average daily temperatures surpassed the 10°C mark on several occasions while the total monthly precipitation was 166 mm. Wet summer months are unlikely to be responsible for the overall reduction in RMD as asparagus has been reported to benefit from higher precipitation in the summer (Hartmann, 1981). Although rainfall was also high in October - December 2019, by then the asparagus would have re-entered dormancy. Second possible mechanism behind of the observed reduction in RMD is related to recovery of root carbohydrate levels. The mass of asparagus roots fluctuates through the season as the crop either uses or replenishes its carbohydrate stores (Robb, 1984; Shelton and Lacy, 1980; Wilcox-Lee and Drost, 1991). Failure to accumulate a sufficient amount of carbohydrates in the full fern period of 2019 would significantly impact root masses measured in the spring of 2020. Consequently, re-ridging in March 2019 in combination with climate conditions in 2019 may have contributed to a significant RMD reductions as measured in March 2020. The fact that the differences in RMD in occurred within a space of a single year supports the argument of root carbohydrate reductions, which should be theoretically reversible. Wilson et al. (2008) indicate, that during each annual growth cycle, changes in carbohydrate stores can cause fluctuations of root masses of up to 50%. The reduction in mean whole profile RMD associated with the Conventional practice, Mustard R and Rye R treatments was 75%, 53% and 55%, respectively. These reductions in RMD were recorded when the carbohydrate levels of roots are at their maximum level, i.e. immediately prior to harvest (Wilson et al., 2008). Furthermore, detailed analysis showed that the interrows of those three treatments were essentially devoid of roots. Although the assumed zone of soil disturbance of the ridger (Figure 3-1), 0.3mD1 and 0,6mD1, did not show any significant year-to-year changes in root masses, re-ridging was associated with significant changes in root distribution of the 0.3mD2 sample location in all three treatments (Table 3-3). Conventional practice even saw significant reductions in all root core sampling locations at the 0.15-0.30 m depth. As root reductions could be seen in areas beyond the working depth of the ridger, these results imply that ridging can negatively impact roots beyond the zone of soil disturbance (Figure 3-1).

In 2020, the Zero-tillage treatment was associated with significantly higher mean overall RMD as compared to the Conventional practice. While root masses of the Zero-tillage treatment extended into the interrows, the 2020 Conventional practice interrow was associated with an absence of roots (Figure 3-3). This finding confirms that asparagus could benefit from management practices based on minimal soil disturbance (Drost and Wilcox-Lee, 2000; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). There were however other treatments which were not significantly different from the Zero-tillage, namely Bare soil SSD NR, Bare soil SSD R, Mustard NR, PAS 100 NR and Straw Mulch R, suggesting that selectively placed tillage or a combination of tillage and interrow applications may be an alternative to conventional growing practices. Furthermore, the Bare soil SSD R treatment, which is a modification of Conventional practice to include SSD, was associated with significantly higher RMDs at 0.3mD2 and 0.6mD2 locations as compared to the Conventional practice. Bare soil SSD NR also had significantly higher mean RMD at 0.6mD2 as compared to the Conventional practice. This contradicts the findings of Drost and Wilcox-Lee (2000), who found that tillage of the interrows reduced root growth in all depths and demonstrates the need for better understanding of practical implications of different types of tillage. Unlike ridging, SSD has shown to mitigate negative impacts associated with re-ridging by improving water infiltration and reducing soil compaction of the interrows (Mašková et al., 2021).

The influence of companion crops on the storage root growth dynamics was complex. In 2019, RMD data reflected effects of CCs sown in August 2018 and terminated in February 2019, with the 2020 RMD data reflecting the CCs sown in August 2019 and terminated in February 2020. In 2019, RMDs associated with re-ridged Rye and Mustard treatments were significantly higher compared with Rye and Mustard non-ridged treatments suggesting that re-ridging had a positive impact on asparagus root development. In 2020 however, this effect was not observed. Rye NR companion crop treatment was associated with significantly lower RMDs in both 2019 and 2020 as compared with Zero-tillage treatment. Rye is known to suppress weeds due to its ability to release allelochemicals through root exudation or through the decomposition of plant residues (Macías et al., 2014). Rye was sown in August, sprayed off in February of the following year prior to re-ridging, and rye roots and surface residues are lifted from the interrows and incorporated in the ridge above the asparagus crown. Without ridging, these residues and decomposing roots remain in the interrow, potentially releasing allelochemicals including benzoxazinone, phenolic acids, beta-hydroxybutyric acid and hydroxamic acids (Macías et al., 2014; Schulz et al., 2013). Although the allelopathic potential declines with development (Reberg-Horton et al., 2005), the weed suppressing period varies between 30-75 days (Weston, 1996) and could potentially inhibit asparagus storage root elongation into the interrow. Rye and mustard could also compete with asparagus for water or nutrients (Brainard et al. 2012).

Straw mulch and compost applications in combination with SSD were associated with no-significant difference in asparagus RMD between 2019 and 2020, whether ridged or non-ridged. These results suggest that seasonal reductions in the asparagus ‘Root Engine’ can be mitigated through mulch application in combination with SSD. Although this research is the first to investigate asparagus root development under mulch applications, several studies have observed that straw promoted root growth on a variety of other crop species, such as brinjal, maize, cowpea and rice (Kumar et al., 2018; Maurya and Lal, 1981; Yan et al., 2018).

Root distribution pattern of asparagus was described by Drost and Wilcox-Lee (2000), who found that the majority of storage roots occurred within 0.3 m distance from the crown. The results of the present study confirm that in 5 and 6 year old plants, 57% and 62% of TRB were located at the 0.3 m distance from the crown. Further, 77% and 78% of TRB in 2019 and 2020 were found in the 0.15-0.45m depth with the 0.15-0.30m depth alone containing 46% and 45% of TRB. In 2019 and 2020, 27% and 28% of the TRB occurred 0.3m from the crown at 0.15 – 0.3m depth. This has implications for potential root damage associated with annual re-ridging. Putnam (1972) and others showed yield losses due to tillage and some (Drost and Wilcox-Lee, 2000) related that to crown and root damage. If tillage (re-ridging or SSD) not carefully managed, productivity will be negatively impacted.

Soil compaction is a major factor causing severe root growth restrictions (Bengough, 2012; Clark et al., 2003). In the current study, 87% of asparagus TRB occurred in locations with PR values ranging from 1.0-3.5 MPa. This is comparable to the findings of Sinnett et al. (2008) who found that 91% of tree roots occupied soils of PR below 3 MPa. Highest RMD values were recorded within the 1.0-1.5 MPa PR class and continued to decrease with increasing PR. There was no PR category which roots would not penetrate demonstrating that soil compaction may not strictly prevent asparagus root growth. Data however showed that roots favoured less compacted soils, as RMD values within the 5.0-7.0 MPa PR class were significantly lower as compared to RMD values associated with 1.0-3.0 MPa. Although soil compaction has been reported to reduce root masses of asparagus near the soil surface (Reijmerink, 1973), root-limiting PR for asparagus has never been established and based on our results, asparagus root were more abundant in soil compacted to 1.0-3.0 MPa. Literature places a majority of critical root-limiting PR values within the 2 – 2.5 MPa range (Taylor et al., 1966; Whalley et al., 2007). This limit however varies in soils of different structures and for different crops (Kadžienž et al., 2011; Singh and Sainju, 1998) which is why several authors suggested the root limiting value be increased to at least 3.0 or 3.5 MPa (Boone et al., 1994; de Moraes et al., 2014; Ehlers et al., 1983). It can also be argued that areas of low penetration resistance are identical to areas of natural root growth, which would potentially decrease the probability of penetration resistance affecting root growth in asparagus plants.

3.5 Conclusions

Year-to-year data evaluation is usually difficult as asparagus is sensitive to annual climate variability. It can however help identify BMPs which increase the resilience of the asparagus ‘Root Engine’ to abiotic and biotic stresses. Results from this study indicate that re-ridging of 5-6 year old asparagus (‘Gijnlim’) stands, grown on bare soil interrows or with mustard/rye companion crops without SSD contributed to significant reductions in RMD. Although bare soils treatments to which SSD was applied were also associated with reductions in RMD compared to the Zero-tillage treatment, the reduction in RMD was significantly less compared to the Conventional practice which is re-ridged without SSD on an annual basis. Furthermore, Bare soil SSD, Straw Mulch SSD and PAS 100 SSD compost treatments in combination with SSD did not show any significant year-to-year changes in RMD whether ridged or non-ridged. These results suggest that seasonal reductions in the asparagus ‘Root Engine’ can be mitigated through mulch application in combination with SSD. This has implications for crop productivity and stand longevity in temperate growing conditions.

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4 Impacts of Long-Term Application of Best Management Practices on Yields and Root Carbohydrate Content in Asparagus

Abstract

Yield physiology of asparagus (*Asparagus officinalis* L.) is strongly influenced by biotic factors such as crown and root rot (CRR) caused by *Fusarium spp.* and by abiotic conditions such as climate, length of each harvest, and field management practices. Asparagus yields are linked to the availability of soluble carbohydrates (CHO) in the storage root system which is considered a key factor in asparagus productivity. The aim of this study was to quantify the impacts of the long-term application of a range of potential Best Management Practices (BMPs) on yield and storage root carbohydrate (CHO) content in asparagus through a long-term field trial. The trial was established in 2016 with the asparagus 'Gijnlim' variety. Commercial yields were monitored in 2018, 2019 and 2020. Root CHO content was determined in 2019 and 2020. BMPs included (1) companion crops - Rye (*Secale cereale* L.) or Mustard (*Sinapis alba* L.), (2) interrow surface mulch - straw mulch or PAS 100 (Publicly Available Specification) compost in combination with shallow soil disturbance (SSD), and (3) modifications of the conventional tillage and zero-tillage practices by re-ridging (R) or not ridging (NR) and by applying SSD or not applying SSD. SSD had no significant impact on asparagus yields while re-ridging negatively affected total yields of treatments with bare soil interrows, which were managed without SSD. In 2020, Conventional practice was associated with a 22% yield reduction and *circa* £3,600 ha^{-1} annual loss in potential revenue as compared to the Zero-tillage treatment. Companion cropping with mustard did not have a significant impact on asparagus yields. However, companion cropping with rye without re-ridging was associated with yield reductions of >20% as

compared to the Conventional practice across all three years of the experiment. From a management perspective, if rye was used as a companion crop and soil conditions prohibit re-ridging prior to harvest, growers risk a significant yield penalty. Re-ridging rye however resulted in 10-25% yield increase as compared to the Conventional practice. Compost applied in asparagus interrows (25 t ha^{-1} per year) without re-ridging resulted in improvements to yields of 20%, 10% and 34% in 2018, 2019 and 2020, respectively, as compared to the Conventional practice. Consequently, yield uplift associated with compost in 2020 showed a potential gain of £4,500 – £5,000 ha^{-1} per harvest. No correlation was observed between root CHO content and asparagus yields. The results of this study confirmed that asparagus yield, and thus total income can be significantly improved through implementation of several of the BMPs investigated.

4.1 Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial crop with a complex yield physiology strongly influenced by weather conditions during harvest and by crop management decisions (Shelton and Lacy, 1980; Wilson et al., 2008). Asparagus yield and plant growth is highly dependent on the availability of soluble carbohydrates (CHO) in the storage root system (Wilson et al., 2008). Ultimately, root CHO levels are considered to be a key factor determining asparagus yield performance which was officially recognised by the *AspireNZ* decision support system of Wilson et al. (2002b), which provided growers with an interpretation guide of root CHO content to facilitate better crop management decisions. There is significant variation in asparagus storage root CHO levels between plants depending on the size of the root system (Wilson et al., 2008). Target pre-harvest CHO content of small root systems should reach 550 mg g^{-1} while for large root systems the target content value is only 450 mg g^{-1} . Furthermore, CHO stored in asparagus roots is subject to fluctuations throughout the annual growth cycle (Shelton and Lacy, 1980; Wilson et al., 2008, 2002a). Sufficient CHO levels are necessary for spear production during the harvest season as well as for optimum fern establishment after harvest which is essential for CHO replenishment (Wilson et al., 2002b). Consequently, the ability of asparagus plants to accumulate and translocate adequate CHO is crucial for high spear yields in both the current and subsequent harvests.

Previous research has demonstrated that root damage associated with tillage operations can have a major negative impact on asparagus stand longevity and productivity (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). In contrast, it has been demonstrated that Zero-tillage is associated with significant increases in marketable yield of asparagus spears compared to tilled asparagus (Wilcox-Lee and Drost, 1991). Tillage operations such as sub-soiling of interrow wheelings for runoff and erosion control (Niziolomski et al., 2020) are thought to pose a high risk of damage to asparagus root systems if roots grow into tillage disturbance zones (Niziolomski et al., 2016). While tillage can reduce the size of the root CHO storage, it can also create wound pathways for pathogens such as *Phytophthora asparagi* (Falloon and Grogan, 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2015). In intensive commercial systems the expected economic production of asparagus should range between 10-20 years. However, chronic disease incidence and ‘asparagus decline’ can limit the commercial production period to only 5-10 years (Elmer et al., 1996) and result in significant economic losses to the grower. Between 2010 and 2019, the asparagus cultivation area in the UK increased by 40% and the value of home marketed production increased by 27% (Defra, 2020) marking a significant expansion in UK asparagus production. Losses due to ‘asparagus decline’ were estimated to be >£16 million revenue over a 10 year cultivation cycle (AHDB, 2017).

Re-ridging of asparagus is the conventional practice adopted by British asparagus growers which is applied in order to promote the growth of spears meeting customer specifications, to raise asparagus beds for efficient manual harvest, and as a means of conveying excess rainfall away off field. Subsoiling is also commonly used to alleviate interrow compaction as a result of intensive machinery and foot trafficking (Niziolomski et al., 2020, 2016). Consequently, conventional operations associated with tillage, harvest and agronomy of asparagus in the UK pose a risk to crop productivity and stand longevity. Companion cropping with rye is commonly practiced by North American asparagus growers for weed suppression and to provide soil protection from rainfall erosion (Brainard, 2012). Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which is known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991). Rye has also been reported to have the ability to reduce the severity of *Fusarium* crown and root rot in asparagus (Matsubara et al., 2001). Mustard is known for its bio-drilling (Cresswell and Kirkegaard, 1995; Hudek et al., 2021) effect due to its tap-root system and for its bio-fumigation potential, which has been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998).

While best management practices (BMPs) are widely used to reduce negative environmental impacts of agriculture in several crops such as winter cereals, potatoes and vines (Deasy et al., 2009; Gordon et al., 2011; Judit et al., 2011), impacts of BMPs on asparagus cropping systems have not been assessed by research. Furthermore, the impacts of BMPs on spear weight, spear quality and potential yield profitability have not been quantified. Long-term implications of annual re-ridging and subsoiling on asparagus yields and root CHO levels in UK asparagus also remain unknown. As management decisions in asparagus can have a significant impact on plant growth, root CHO content and yields (Wilson et al., 2002b), alternative management practices need to be subject to thorough assessment prior to wider commercial application. The aim of this study was to critically evaluate the impacts of a range of potential Best Management Practices (BMPs) on marketable asparagus yields, yield quality, root CHO content and potential revenues, as compared with UK conventional practice

4.2 Materials and Methods

The field trial was undertaken as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The long-term field trial (4.5 ha) is located at Gatsford Farm, Ross-on-Wye, Herefordshire. Asparagus ‘A’ crowns of Gijnlim variety (represents 70% of UK field grown asparagus) were planted on 20–21st of April 2016 on a flat surface at an anticipated depth of 0.14 m and 0.16 m spacing between crowns. Beds were on 1.83 m wide centres. In spring 2017, all plots were re-ridged as a consequence of the shallowness of the crown (*circa* 0.06 m) instead of the intended 0.14 m. Conventional agrochemical treatments have been applied to all trial plots from 2016 to 2020.

4.2.1 Experimental Design

The trial investigated a range of potential BMPs (Table 4-1); (1) companion crops (Rye (*Secale cereale* L. var. Protector.) or Mustard (*Sinapis alba* L. var. Severka)), (2) interrow surface straw mulch or PAS 100 (Publicly available specification) compost combined with shallow soil disturbance (SSD) and (3) a variation of tillage practices (re-ridging (R) or not ridging (NR), SSD or No-SSD) and the Conventional practice equivalent and Zero-tillage. All products (compost, mulch and companion crops) used in the experiment were applied only in the asparagus interrows and subject to SSD so as to replicate the bio-drilling and canopy effects associated with companion crops. The experiment comprised 48 randomly distributed, 35 m long treatment plots. Each plot consists of 2 asparagus rows, central interrow and 2 guard interrows to separate treatments. As appropriate, treatment plots were also separated by tramlines to facilitate sprayer operations. All treatments were replicated in quadruplicate.

SSD was applied in April 2018, March 2020 and in June 2020 using a winged tine operating to 0.25-0.3m depth to all mulch treatments (straw mulch and PAS 100 compost) and to selected bare soil treatments (Table 4-1). Re-ridging was undertaken using a tractor mounted 1.83 m double disk ridger in March 2017, April 2018, March 2019 and April 2020. Companion crops were broadcast for the first time on the 10th August 2017 at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard, respectively.

In the first year, the emergence rate of the companion crops achieved sufficient ground cover of 70-75% (Morgan, 2005). However, for companion crops initially sown in August 2018 and 2019, but due to predation, seeding rates were increased to 200 kg ha^{-1} and 25 kg ha^{-1} for rye and mustard, respectively and sown again in September 2018 and October 2019. Mulch and compost were applied annually in April 2016, April 2018, March 2019 and March 2020 at rates of 25 t ha^{-1} and 6 t ha^{-1} for PAS 100 and straw mulch, respectively. All treatments received a standard annual fertiliser dose of approximately 450 kg ha^{-1} of nitrogen and sulphur (Single Top); 150 kg ha^{-1} of muriate of potash (MOP) and 50 kg ha^{-1} of triple super phosphate (TSP).

Table 4-1. Summary of the experimental treatments.

Treatment	Cover	Annual re-ridging (R)	Sub-soiling (SSD)
Conventional Practice	Bare soil	Ridged	No SSD
Zero Tillage	Bare soil	Non-ridged	No SSD
Bare soil SSD R	Bare soil	Ridged	SSD
Bare soil SSD NR	Bare soil	Non-ridged	SSD
Mustard R	Mustard	Ridged	No SSD
Mustard NR	Mustard	Non-ridged	No SSD
Rye R	Rye	Ridged	No SSD
Rye NR	Rye	Non-ridged	No SSD
Straw mulch SSD R	Straw mulch	Ridged	SSD
Straw mulch SSD NR	Straw mulch	Non-ridged	SSD
PAS 100 SSD R	Compost	Ridged	SSD
PAS 100 SSD NR	Compost	Non-ridged	SSD

NR=no annual re-ridging; R=re-ridging; SSD=shallow soil disturbance.

4.2.2 Sampling methodology

In 2018, 2019 and 2020, asparagus spears were harvested from all experimental plots. In 2018, spears were harvested from the 24th April to 21st May (28 days; 19 cuts). In 2019, the harvest season extended from the 20th April to 17th June (59 days; 53 cuts). In 2020, harvest was undergone from the 12th April to 22nd June (72 days; 65 cuts). The reduced number of cuts in 2018 reflects conventional practice for a 3yr old asparagus stand. Spear count for 2018, 2019 and 2020 was determined on 7, 9 and 8 cuts, which were randomly distributed throughout the harvest period. Daily average individual spear weight per plot was determined by dividing the weight of harvested spears on the same day for each treatment (n=4 per treatment), as (4-1):

$$\textbf{Average spear weight (g)} = \frac{\textbf{Total spear weight (g)}}{\textbf{Total spear count}} \qquad \textbf{(4-1)}$$

Additional spear quality indicators were measured in 2020. Spear diameter, head flowering and head curving were recorded on 8 cuts throughout the harvest period, in order to determine the impact of the BMPs on spear quality and potential revenue. Based on Bussell et al. (2000), such simplified (non-daily) recording methods can be used to obtain marketable yield values with 90% accuracy. Harvested spears were divided into three commercial size grades by spear thickness (<10mm, 10-22mm and >22mm). Spears with flowering heads and curvature were also weighed and counted and were graded as a lower quality 'Class II' spears. Marketable yields were calculated as a sum of both Class I and Class II spears. Proportions (%) of high quality 'Class I' spears were obtained by subtracting Class II spears from the total mass of collected spears. In 2020, potential revenues were calculated by extrapolating spear quality data over the full harvest period to estimate the impacts of spear quality on field management profitability, as equation (4-2):

$$\mathbf{Revenue}\ (£) = \Big[\big((\mathbf{total\ spear\ weight} - (\mathbf{Class\ II\ spears}\ (\%) \times \mathbf{total\ spear\ weight})\big) \times \mathbf{Class\ I\ value}\ (£)\Big] + [(\mathbf{Class\ II\ spears}\ (\%) \times \mathbf{total\ spear\ weight}) \times \mathbf{Class\ II\ value}\ (£)] \qquad \textbf{(4-2)}$$

Asparagus storage roots for the determination of pre-harvest root soluble carbohydrate content (CHO) were obtained in March 2019 and in March 2020 when CHO content should be the peak, at 0.15-0.30 m depth from the crown zero line (CZL) following the root coring procedure of Drost and Wilson (2003). CHO values for 2018 were not collected as not all treatments had been fully applied at the time of root sample collection. Root samples were collected using a handheld Eijkelkamp bi-partite root auger (internal diameter: 0.08 m, internal core depth: 0.15 m, volume: 754 cm^3). Roots of similar diameters were separated from soil, washed, and frozen at -20^{o}C prior to CHO analysis. Determination of CHO followed the method outlined by Wilson et al.

(2002). Roots were cut into smaller pieces and crushed in a garlic press. Obtained root sap was then used to determine Brix% values using a refractometer (Atago PR-32α) with a range of 0 to 32% Sugar (Brix%). Brix values were converted to equivalent root CHO content using the linear regression equation of Wilson et al. (2008) (4-3):

$$\mathbf{CHO}\ (\mathbf{mg\ g^{-1}}) = \mathbf{21.1} \times \mathbf{Brix\%} + \mathbf{42.9} \qquad \textbf{(4-3)}$$

4.2.3 Statistical Analysis

Statistical analysis was undertaken using the TIBCO Statistica 13.3.0 analytics software. Significant differences in asparagus yield and spear weight were determined by analysis of variance (ANOVA) repeated measures and by *post-hoc* Fisher LSD analysis at 95% conf. level. Root CHO levels were analysed by one-way ANOVA and by *post-hoc* Fisher LSD analysis at 95% conf. level. Pairwise comparison test was used to elucidate differences between specific treatments. Pearson correlation coefficients were calculated to determine the relationships between yield variables and root CHO.

4.3 Results

Soil analyses conducted in 2016 indicated that there were no significant differences in the soil parameters tested ($p \leq 0.05$) between plots (Appendix B). Soils at the trial site are Cambisols (IUSS Working Group WRB, 2007) of Eardiston series association (Cranfield University, 2020) with 77% sand, 11% silt and 12% clay composition. Other soil parameters showed soil pH of 6.34 (± 0.03), soil organic matter of 2.78% (±0.03), total soil C of 1.24% (±0.01) and total mineralizable N of 0.13% (±0.001).

4.3.1 Impact of BMPs on asparagus yield and spear weight

Due to the year-on-year variability in yields caused by changes in annual weather patterns, data from each year was analysed separately. Yield data for 2018-2020 was also reported by Maskova et al. (2021) as kg ha^{-1} per cut. In 2018, there were only a few significant differences in total asparagus yields between treatments (Figure 4-1). None of the BMP treatments were associated with total yields significantly different from the Conventional practice. The Bare soil SSD R treatment yield was significantly (19%) lower compared to Zero-tillage treatment. Rye NR treatment yields were 25%, 28%, 23%, 22% and 25% lower as compared to the Zero-tillage, PAS 100 NR, PAS 100 R, Rye R and Straw mulch R treatments, respectively. Within Bare soil treatments, isolated effects of re-ridging and of SSD were associated with any significant changes to yields.

The 2019 total yield data showed that the yields for the Zero-tillage and Rye R treatments were significantly higher as compared to the Conventional practice, Bare soil SSD NR, Bare soil SSD R, Rye NR and Straw Mulch NR (Figure 4-1). Furthermore, re-ridging in the absence of SSD was found to have a negative impact on yield with Conventional practice associated with a 15% lower yield as compared to

Zero-tillage. Similar to 2018 the Rye NR treatment was associated with a 21% reduction in yield as compared to the Rye R treatment. Similar to the previous year, in Bare soil treatments, neither re-ridging nor SSD were associated with any significant changes to yields.

Contrary to 2019, the 2020 yield results showed that Zero-tillage was not significantly different from the Conventional practice (Figure 4-1). Furthermore, re-ridging was associated with significantly lower yields across all bare soil treatments. In contrast, both the PAS 100 R and NR treatments were in 2020 associated with 28-34%, 24-30%, 29-35% and 31-38% higher yields as compared to the Conventional practice, Bare soil SSD NR, Bare soil SSD R and Rye NR treatments, respectively. Except for Rye R and NR treatments, ridging had no significant effect on asparagus yields. It is of note that the Rye R treatment was associated with 28, 26 and 28% higher yields as compared to the Rye NR in 2018, 2019 and in 2020, respectively. Following pairwise comparison test, the difference between Rye R and Rye NR was significant in 2018 and 2019. Yields from the Conventional practice were significantly 12, 15 and 18% lower as compared to the Zero-tillage treatment in 2018, 2019 and in 2020, respectively.

In addition to yield variation between various BMPs, significant differences were also observed in mean spear weight. As shown in Table 4-2, the mean weight of spears harvested from the Rye NR treatment was significantly lower compared to multiple other treatments. Rye NR spears were consistently significantly lighter as compared to spears from the PAS 100 NR, Rye R and Straw Mulch R/NR treatments by 14-17%, 13-19% and by 14-23% in 2018, 2019 and in 2020, respectively. Spears harvested from the Rye R treatment were on the other hand consistently (16-23%) and significantly heavier compared to spears harvested from the Rye NR treatment. Although mean spear weight was similar between the Zero-tillage and the Conventional practice in 2018 and in 2019, in 2020, Zero-tillage spears were 14% heavier compared to spears from the Conventional practice.

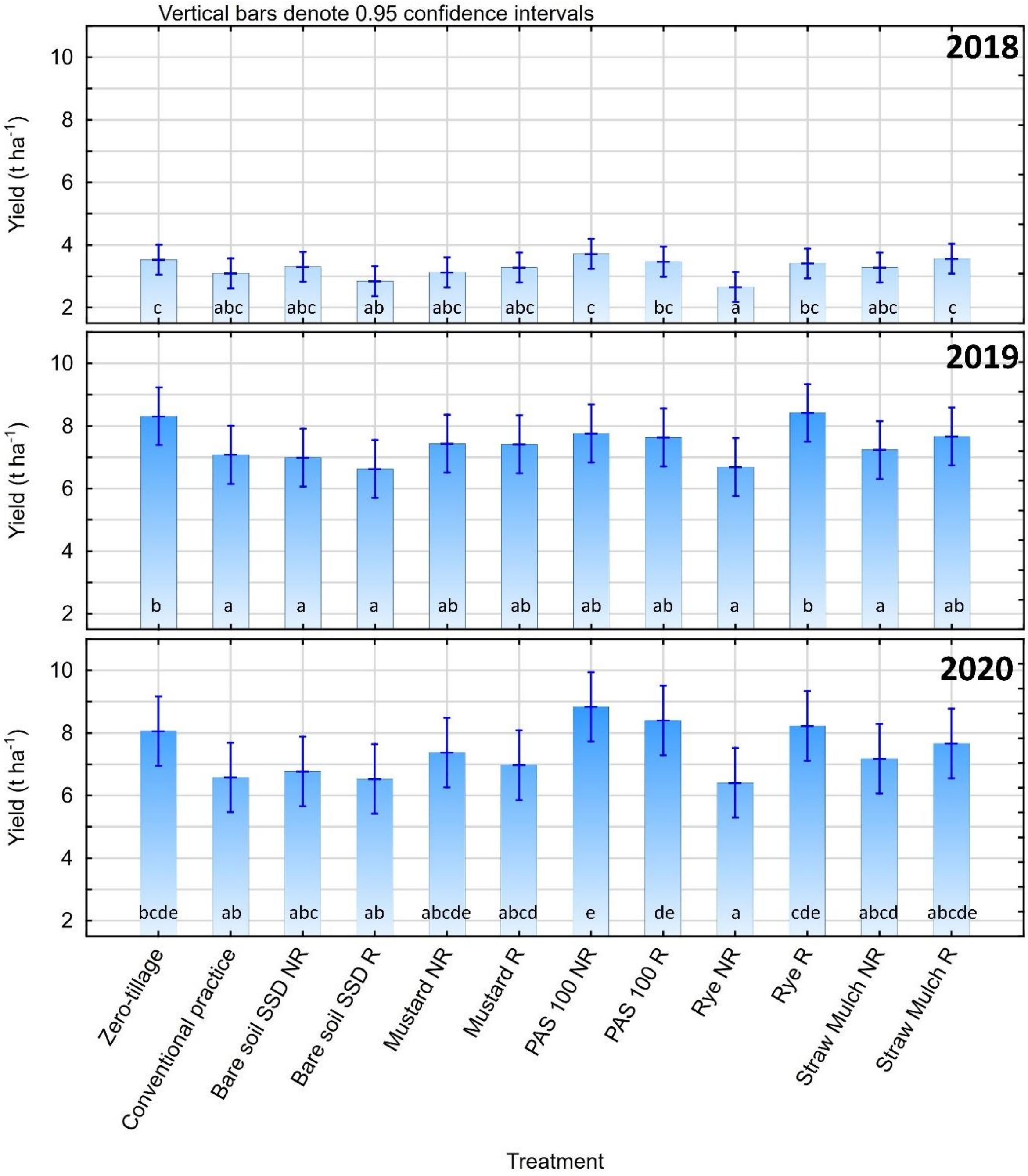

Figure 4-1. Total asparagus yields (t ha $^{-1}$) over three (2018-2020) full harvest seasons. 2018 harvest lasted 28 days (19 cuts); 2019 harvest lasted 59 days (53 cuts); 2020 harvest lasted 72 days (65 cuts). Bars followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

Correlation analysis indicated that spear size was significantly positively correlated with yields (Figure 4-2). Between 2018 and 2020, the strength of the relationship, as indicated by the correlation coefficient r increased from r=0.58 to r=0.67. This finding suggests that production of large spears is the main reason for higher recorded yields. Furthermore, since 2018, mean spear size has decreased every year by a consistent 22%.

Table 4-2. Differences in mean spear weight (g) between treatments for the 2018, 2019 and 2020 harvests.

Treatment	Average spear weight (g)		
	2018	2019	2020
Zero-tillage	24.3 ab	20.7 b	16.5 de
Conventional practice	24.5 ab	19.4 b	14.2 abc
Bare soil SSD NR	26.5 b	18.6 ab	14.6 abcd
Bare soil SSD R	25.3 ab	18.8 ab	13.6 ab
Mustard NR	24.4 ab	19.9 b	15.3 bcde
Mustard R	26.2 b	19.0 b	14.6 abcd
PAS 100 NR	25.9 b	19.4 b	17.0 e
PAS 100 R	25.3 ab	18.8 ab	15.1 abcde
Rye NR	22.3 a	16.9 a	13.1 a
Rye R	26.6 b	20.7 b	17.0 e
Straw Mulch NR	26.7 b	19.4 b	15.2 bcde
Straw Mulch R	26.2 b	19.4 b	16.0 cde

Within each column, values followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

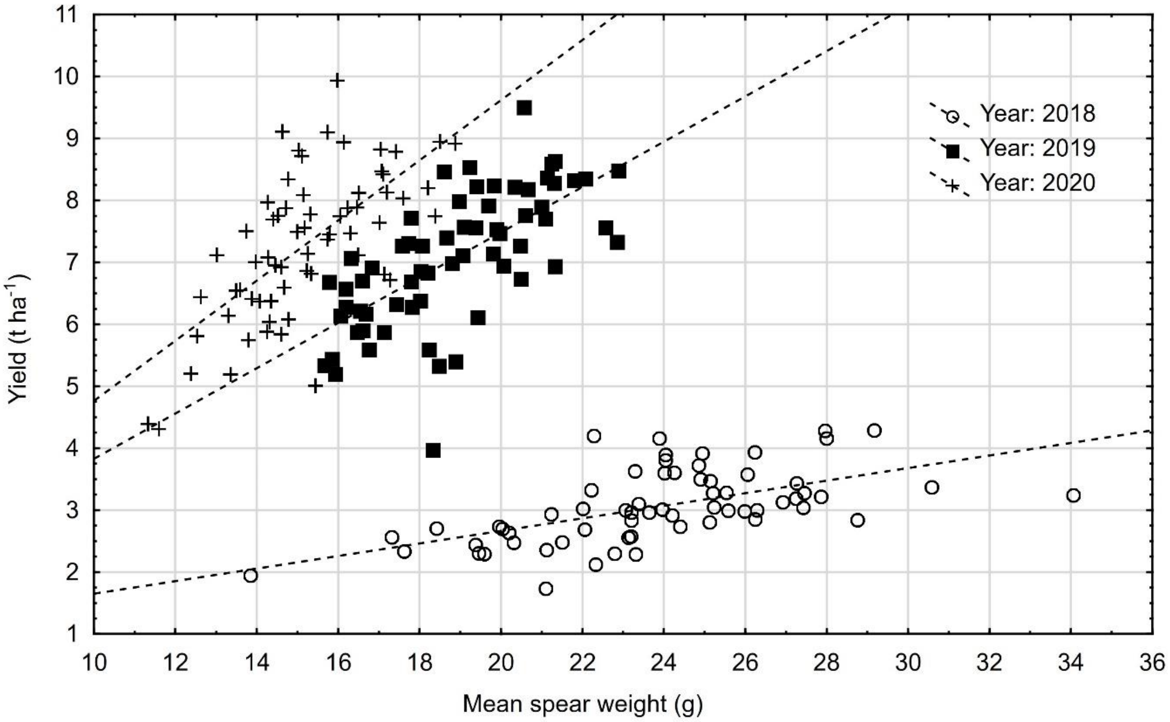

Figure 4-2. Relationship between total asparagus yields (t ha^{-1}) and average spear weight (g) of all treatments and replicated (n=48). 2018: $r^2 = 0.34$, r = 0.58, ***$p < 0.001$; 2019: $r^2 = 0.44$, r = 0.67, ***$p < 0.001$; 2020: $r^2 = 0.45$, r = 0.67, ***$p < 0.001$.

4.3.2 Impact of BMPs on asparagus storage root CHO content

Across all treatments, 2019 and 2020 mean pre-harvest storage root CHO values ranged from 508 – 632 mg g^{-1} and 377 – 525 mg g^{-1}, respectively (Table 4-3). The difference between the mean 2019 and 2020 CHO values was significant. The 2019 mean CHO values were within the target range for pre-harvest root CHO content of 450-550 mg g^{-1} outlined by Wilson et al. (2008). In contrast, the 2020 mean CHO values of the Zero-tillage, Bare soil SSD NR, Mustard NR, PAS 100 R and Rye R treatments were associated with CHO values below this target range (Wilson et al. 2008) indicating inadequate CHO levels for optimum harvest. Nonetheless, the same treatments were not linked to lower yields. Remarkably, PAS 100 R and Rye R had yields significantly higher as compared to the Conventional practice which had adequate CHO levels of 506 mg g^{-1} (Table 4-3). No significant differences in root CHO values were observed between treatments in 2019. In 2020 however, the Zero-tillage treatment had significantly lower root CHO content compared to the Conventional practice and Straw Mulch R (Table 4-3). Finally, mean root CHO across all treatments significantly decreased in 2020 as compared to 2019 by 18%.

Table 4-3. 2020 and 2019 storage root CHO values (mg g^{-1}). Roots were obtained from the 0.15-0.30 m depth at the crown zero line.

Treatment	CHO (mg g^{-1})	
	2019	2020
Zero-tillage	632^{a}	*377^{a}
Conventional practice	508^{a}	506^{b}
Bare soil SSD NR	517^{a}	*418^{ab}
Bare soil SSD R	555^{a}	481^{ab}
Mustard NR	525^{a}	*426^{ab}
Mustard R	592^{a}	491^{ab}
PAS 100 NR	596^{a}	502^{ab}
PAS 100 R	540^{a}	*435^{ab}
Rye NR	513^{a}	484^{ab}
Rye R	547^{a}	*419^{ab}
Straw Mulch NR	565^{a}	477^{ab}
Straw Mulch R	566^{a}	525^{b}
Total Annual Mean (all treatments)	556	454

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. *Mean CHO values below the target range (450-550 mg g^{-1}) outlined by Wilson et al. (2008).

4.3.3 Impact of BMPs on spear quality and potential yield revenues in 2020

In general, spear quality is determined by spear diameter, spear weight, and by spear defects as affected by physiological disorders such as head flowering, curvature, wilting or tip rot. Spear value is determined by spear grade specifications and on the time of the season. In the UK, there is no legally binding standard for asparagus spear classification. Spear class specifications are however set by individual retailers usually following the British Asparagus Growers Association (AGA) standards for spear quality specification. Each season is generally divided into 3 price bands: (1) Early season, (2) main season and (3) late season. Spear quality is divided in two classes, high quality ‘Class I’ and lower quality ‘Class II’. Thin spears of good quality can be sold as fine or extra fine asparagus at a premium as fine or extra fine asparagus. This premium is however barely sufficient to cover the extra costs of harvesting, grading and packing. Thus, in general, growers prefer medium (10-22mm diameter) or thick (>22mm diameter) spears which are easier and less costly to harvest and pack.

In this study, a simplified yield value estimation was adopted which disregarded differences in spear diameter and focused on overall spear quality which significantly affects overall profits. Misshapen and deformed spears (flowering or curved heads) were classified as ‘Class II’ and priced at £1.50 per kg [Personal communication John Chinn, Cobrey Farms]. All spears without noticeable defects, regardless of diameter, were valued as ‘Class I’ spears and priced at £3.00 per kg [Personal communication John Chinn, Cobrey Farms]. Both Class I and Class II fell within the marketable yield category and were used to estimate potential revenues, as shown in Table 4-4.

Across all treatments, the abundance of spear defects (head flowering and curving) fluctuated through the season. In the first week, approximately 21% of harvested spears were affected by head curving while in the last week, the affected spear proportion decreased to only 5%. The percentage of spears with flowering heads however increased towards the end of the season, from 11% at the beginning of the harvest to approximately 30% in the last week of harvest. While curving affected on average only 9% of harvested spears, flowering affected approximately 25% of all harvested spears. Most head flowering was observed on the Rye NR (30%) as compared to Rye R (21%), Straw Mulch NR (21%) and Straw Mulch R (21%) treatments.

Spear thickness also gradually reduced towards the end of the harvest season. Thick spears (>22 mm diameter) were overall quite rare and accounted for only about 0.2% of spears and were produced solely during the early season and in the first half of the main season. There were most often produced by Bare soil SSD R, Rye R and Straw Mulch R while three treatments, the Conventional practice, Mustard R and Straw Mulch R produced no thick spears. Medium spears (10-22 mm diameter) were most abundant and accounted for approximately 80% of all spears. Rye NR in particular was associated with significantly lower numbers of medium spears (72%) as compared to many other treatments (Table 4-4). The same treatment also had the highest numbers (28%) of thin spears (<10mm). High overall production of thin spears was associated with Bare soil SSD R (26%), Conventional practice (25%) and Mustard R (23%). In contrast, PAS 100 NR, Rye R and Straw Mulch NR treatments produced only between 15-16% of thin spears. Noticeable is also the difference between Zero-tillage and Conventional practice where in Zero-tillage, thin spears accounted for 17%

of spears as compared to the Conventional practice which was associated with 25% of total spear production classified as thin spears. For Bare soil treatments only, re-ridging was associated with significantly lower proportions of medium spears (10-22mm) and with significantly higher proportions of thin spears (<10mm). Re-ridged Bare soil treatments produced approximately 75% of medium spears compared to 81% from non-ridged treatments and approximately 25% of thin spears compared to 19% from non-ridged treatments.

Furthermore, a significant positive relationship ($r^2=0.369$, $p<0.005$) was found between and head flowering (%) and production of thin spears (<10mm) for all treatments. Crucially, a significant strong negative relationship ($r^2=0.541$, $p<0.001$) was found between production of thin spears (<10mm) and potential revenues (Figure 4-3). This finding indicates that production of thin spears was not only associated with increased production of open-headed spears (flowering), but also with a decrease of potential revenues from the harvest.

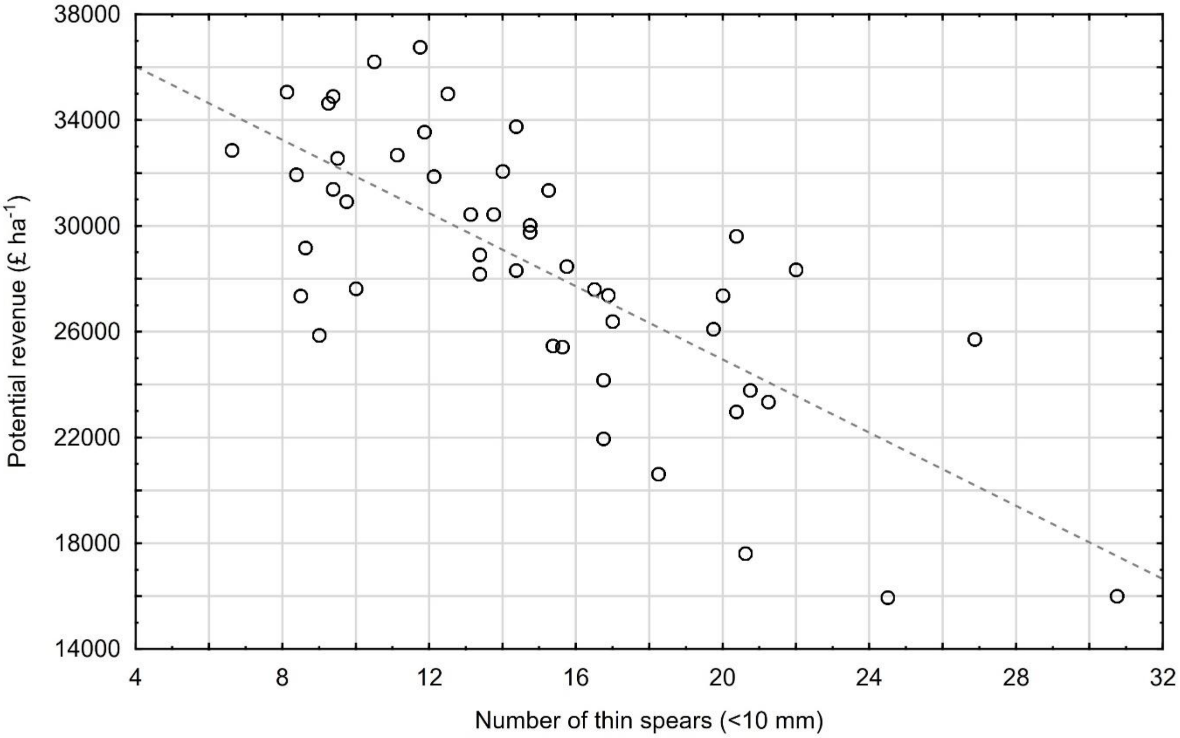

Figure 4-3. Relationship between numbers of thin spears and sum of potential revenues per plot based on data collected in 2020, including all treatments (N=48); $r^2 = 0.54$, r = 0.74, $p \leq 0.001$.

Finally, total potential revenue was found to vary amongst treatments. Lowest harvest revenue of approximately £16-£17,000 ha^{-1} were associated with the Conventional practice, Bare soil SSD NR and Rye NR treatments (Table 4-4). Although the 21% increase in potential revenue associated with the Zero-tillage (£30,528 ha^{-1}) as compared to the Conventional practice (£20,400 ha^{-1}) was not statistically significant at 95% confidence interval, at 90% confidence, the difference between these two treatments was statistically significant. Significantly higher potential revenues of £21,800, £21,300 and £21,600 ha^{-1} were associated with the PAS 100 NR, PAS 100 R and Rye R treatments (Table 4-4). Critically, revenue associated with the PAS 100 treatments was associated with a potential gain in asparagus spear values of 21-23% gain in potential value of the harvest as compared to the Conventional practice.

Table 4-4. Impact of BMPs on spear diameter, spear defects and on potential revenues summed over the whole 2020 harvest season.

Treatment	Percentage (%) of marketable yield					Potential Revenue (thousand £ ha^{-1})
	Class I			Class II		
	<10mm (Thin)	10-22mm (Medium)	>22mm (Thick)	Flowering	Curving	
Zero-tillage	17.1 ^{ab}	82.8 ^{de}	0.16 ^{ab}	23.2 ^{ab}	11.1 ^{c}	£20.4 ^{bcd}
Conventional practice	24.5 ^{cde}	75.5 ^{abc}	0.00 ^{a}	26.1 ^{ab}	9.03 ^{abc}	£16.8 ^{ab}
Bare soil SSD NR	20.5 ^{abcd}	79.4 ^{bcde}	0.23 ^{ab}	27.8 ^{ab}	9.61 ^{bc}	£16.9 ^{ab}
Bare soil SSD R	25.7 ^{de}	74.0 ^{ab}	0.57 ^{b}	26.1 ^{ab}	6.22 ^{a}	£17.1 ^{ab}
Mustard NR	18.7 ^{abc}	81.2 ^{cde}	0.26 ^{ab}	23.5 ^{ab}	10.1 ^{bc}	£18.9 ^{abcd}
Mustard R	22.9 ^{bcde}	77.1 ^{abcd}	0.00 ^{a}	26.3 ^{ab}	8.07 ^{ab}	£17.7 ^{abc}
PAS 100 NR	15.1 ^{a}	84.9 ^{e}	0.10 ^{ab}	25.1 ^{ab}	11.1 ^{c}	£21.8 ^{d}
PAS 100 R	19.4 ^{abcd}	80.4 ^{bcde}	0.34 ^{ab}	25.0 ^{ab}	8.48 ^{abc}	£21.3 ^{cd}
Rye NR	27.9 ^{e}	72.0 ^{a}	0.09 ^{ab}	30.3 ^{b}	7.59 ^{ab}	£16.4 ^{a}
Rye R	15.6 ^{a}	84.1 ^{e}	0.54 ^{b}	21.3 ^{a}	9.06 ^{bc}	£21.6 ^{cd}
Straw Mulch NR	16.0 ^{a}	84.0 ^{e}	0.00 ^{a}	21.4 ^{a}	9.57 ^{bc}	£18.4 ^{abcd}
Straw Mulch R	17.7 ^{ab}	82.1 ^{cde}	0.53 ^{b}	20.8 ^{a}	8.46 ^{abc}	£19.8 ^{abcd}

Within each column, values followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

4.4 Discussion

Research conducted over the past 50 years has shown that tillage operations can have a major negative impact on asparagus root growth and yields through damage to the root system which reduces the size of the root engine (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). Presented results indicate that in asparagus grown on 1.83m centres, SSD could be applied using a winged tine operating to 0.25-0.3m depth without significantly impacting asparagus yields or root CHO content across mulch and bare soil treatments. In contrast, annual re-ridging negatively affected yields of non-SSD Bare soil treatments.

Yields of the Conventional practice were consistently lower compared to the Zero-tillage treatment. Between 2018 and 2020, yield reductions of 12-18% associated with re-ridging of Conventional practice were comparable to findings of Wilcox-Lee and Drost (1991) who observed tilled asparagus (cultivar '*Centennial*') marketable yields decreased over a 4 year period from 12% to 51% as compared to a no-till treatment. Furthermore, while mean spear weight in 2018 and 2019 did not differ significantly between the Zero tillage and Conventional practice in 2020, the mean spear weight from the Conventional practice treatment was significantly 14% lower as compared to Zero-tillage. Spear weight can be an important factor determining yield profits. Growers generally prefer larger spears as the grading and packing cost of fewer larger spears is lower as compared to a larger number of small spears. Larger diameter spears can also be linked to plant vigour (Dufault and Ward, 2005). Hence spear size has a strong potential to impact profit margins as heavier spears from the Zero-tillage would not only cost less to process and pack, but the cost of production would also be lower due to the absence of costs associated with tillage. Spear quality metrics revealed that in 2020, Conventional practice produced an abundance of thin spears which formed approximately 25% of the total spear production. Compared to the Zero-tillage where thin spears accounted for 17%. This difference led to an approximately £3,600 ha^{-1} decrease in potential revenues from spears harvested from the Conventional practice.

Results from the companion crop treatments were mixed. Yield and mean spear weight from both Mustard R and Mustard NR were not significantly different from the Conventional practice during the study period (2018-2020). These results correspond with the findings of Ngouajio et al. (2014) who found that a mixture of Brassicas (radish (*Raphanus sativus* L.) and brown mustard (*Brassica juncea* L.)) applied as a companion crop had no impact on asparagus yields. While re-ridging had no significant impact on asparagus yield of treatments seeded with mustard, it significantly impacted yields of rye companion crop treatments. In 2018 and in 2019, annual re-ridging in the rye companion crop treatments resulted in significant increases in asparagus yields as compared to the non-ridged (NR) Rye treatment. This was in large part due to the significantly 19% lower spear weight associated with the Rye NR (17.1 g) as compared to Rye R (21.1 g) treatment. As a result, Rye NR was linked to a significantly higher production of thin and Class II spears which led to an approximately £5,200 ha^{-1} decrease in potential revenues as compared to Rye R. Rye was sown for the first time in August 2017 and sprayed off in February 2018. In the Rye R treatment, following re-ridging in April 2018, roots and rye residues were lifted from the interrows and incorporated in the soil above asparagus crown. In Rye NR treatment however, these residues remained in the interrows undisturbed, potentially increasing the duration during which the rye root biomass release a number of allelochemicals including benzoxazinone, phenolic acids, beta-hydroxybutyric acid and hydroxamic acids (Macías et al., 2014; Schulz et al., 2013). Allelochemicals has a potential to reduce plant vigour and although there are no reports of plant competition between asparagus and other crops, significant yield reductions of Rye NR treatments may suggest the presence of allelopathy. These results contradict observations of North American growers who successfully grow asparagus on flat beds without tillage and with rye as a companion crop. Companion crops are sown when fern is fully developed thus rye had no impact on fern development. Rye could compete with mature asparagus fern for water or nutrients thus affect yields and CHO assimilation (Brainard, 2012; Brainard et al., 2012). The impact would however be similar for both Rye R and Rye NR treatments. Root CHO values of Rye treatments were also not affected as compared to the Conventional practice. Nevertheless, in 2019 and in 2020, Rye R treatments were associated with significantly higher mean yields, mean spear weights and potential revenues as compared to the Conventional practice. The period between ridging and crop response was also extremely short as significant yield reduction from Rye NR was already observed in 2018 which was only nine month post the 2017 companion crop treatment application. Length of the period between ridging always ranged between 7 to 50 days. Brainard et al. (2012) however observed that cereal rye broadcast at 188 kg ha^{-1} and rotavated immediately after harvest in late June had no effect on asparagus yields. It is important to note that from a management perspective, if rye is grown as a companion crop and soil conditions prohibit re-ridging prior to harvest, the growers risk a significant yield penalty of circa 20% as compared with the conventional practice. Annual re-ridging had no impact on asparagus yields under interrow applications of PAS 100 compost and Straw Mulch. As such any potential yields loss associated with annual re-ridging and SSD is offset by the benefits of Straw Mulch and PAS 100 compost application. Although yields from Straw Mulch treatment were not significantly higher as compared to the Conventional practice, the PAS 100 compost was in 2020 associated with a significant yield uplift as compared to the Conventional practice. A similar finding was observed by Ngouajio et al. (2014) who found that dairy compost significantly improved asparagus yield and numbers of spears as compared to the control with no soil amendment. PAS 100 yield uplift may be in part due to the additional macro/micronutrient load and/or a stimulation of soil microbiology associated with compost addition. Straw mulch and compost were each year applied within a month prior to the beginning of the harvest. Composts have been repeatedly linked to increased soil temperatures (Deguchi et al., 2009; Naeini and Cook, 2000) while straw mulch is often associated with lower, and less fluctuating soil temperatures as compared to bare soils (Gaur and Mukherjee, 1980; Yordanova, 2017). The increase of soil temperature under composts could therefore play a role in enhanced yields as spear production in asparagus is known to be strongly depend on soil temperature (Bouwkamp and McCully, 1975; Culpepper and Moon, 1939; Gąsecka et al., 2013). Ultimately, further research needs to be undertaken in order to gain a better understanding of mechanisms behind yield uplift associated with composts application accompanied by SSD.

The results of this study also demonstrate that mean asparagus yields are strongly related to spear weight as treatments associated with higher yields also grew spears which were heavier while poorly yielding treatments often produced lighter spears. In asparagus, both yield volume and quality decline after several years of consecutive production. Based on Elmer et al. (1996), plants usually however do not show any changes before their third production year suggesting that from 2020 onwards, measurable differences between treatments should be even more pronounced. Decline symptoms include growth of thinner spears of lower quality and eventually lead to death of the crown (Elmer et al., 1996; Schofield, 1991). Noperi-Mosqueda et al. (2020) for example found that spears from fields with asparagus decline weighed 22% less than spears from fields without decline. Spear weight and quality is however one of the key factors determining price. Consequently, asparagus decline leads to decreased marketable spear quality, plant productivity and plant density, ultimately causing economic losses (Elmer, 2018; Noperi-Mosqueda et al., 2020).

Apart from the asparagus decline, other factors such as root CHO content, water stress, air and soil temperature can have a strong impact on the sizes of spears, and hence on commercial spear value (Bouwkamp and McCully, 1975; Haynes, 1987; Paschold et al., 2002). Multiple studies have found that summer irrigation or precipitation significantly increase asparagus yields and spear sizes in the following year (Hartmann, 1981; Sterrett et al., 2019). Drost (1999) for example found that in a four year experiment, marketable yields of irrigated asparagus were on average 21 to 26% higher as compared to non-irrigated treatments.

As thicker spears are priced higher due to lower costs associated with harvesting and packing (Dufault and Ward, 2005; Paschold et al., 2002; Watanabe et al., 2018), growers generally aim for higher production of larger spears. Results from the current field trial showed that spear weight and quality can be modified by the application of selected BMPs. Production of thick spears (>22.0 mm diameter) was overall low and accounted on average for only 0.2% of all spears. Within the Bare soil treatment group, re-ridging was found to be associated with significantly lower production (6%) of medium spears and significantly higher production (6%) of thin spears as compared to non-ridged Bare soil treatments. Critically, thin spears accounted for approximately 25% of all harvested spears of the Conventional practice and Bare soil SSD R treatments. Consequently, re-ridging of asparagus grown with bare interrows resulted in estimated losses of circa £3,600 ha^{-1} as compared to bare interrow asparagus grown without re-ridging. Including SSD alongside ridging did not significantly reduce these losses. Other studies (Wilcox-Lee and Drost, 1991) reported a decrease in marketable yields following tillage. In 2020, re-ridging of asparagus with bare interrows also significantly lowered mean asparagus yields. The impact of tillage on total marketable value of the harvest was however significant and revealed losses ranging from circa £4,300 to £5,500 ha^{-1} as compared to Zero-tillage. Furthermore, positive relationship between head flowering and production of thin spears indicates that thin spears were associated with increased occurrence of open-headed spears, potentially further decreasing overall yield quality and total revenues. Production of spears with flowering heads increases in hot periods, usually late in the season (AHDB, 2014). This corresponds with the findings of this study where head flowering increased towards the end of the harvest and accounted for 30% of all harvested spears compared to 9% at the beginning of the harvest. Spear curving defect however prevailed at the start of the harvest and decreased towards the end from 21% to 5% in the last harvest week. Literature suggests that curving of spears occurs during periods of rapid growth when water losses from tips of spears surpass speed of moisture supply and can even occur in adequate soil moisture conditions (AHDB, 2014). Critically, spears with defects are classified as Class II which has a major impact on spear vlaue. While Class I spears can be valued at approximately £3.00 per kg, Class II only sell for for around £1.50 per kg. Finally, production of thin spears was strongly negatively correlated with potential revenues confirming that abundance of spear defects and thin spears rapidly decrease potential profits from the harvest. Field monitoring however needs to continue in order to confirm whether yields and spear quality was linked to the onset of asparagus decline.

4.5 Conclusions

Results of this 3-yr asparagus harvest trial confirm that asparagus yields can be modified through the careful selection of BMPs. Although tillage has been reported to have a negative impact on asparagus, SSD was found to have no significant impact on asparagus yields. Re-ridging was however associated with significantly lower yields in treatments with bare soil interrows managed without SSD. Although re-ridging of asparagus with rye companion crop was associated with significantly higher yields as compared to the Conventional practice, non-ridging carries a risk of a *circa* 20% yield penalty suggesting that growers need to be confident that they can re-ridge if rye is grown as a companion crop for runoff and erosion control. The use of composts in asparagus interrows resulted in yield improvements and was not significantly affected by re-ridging. Due to lower yields associated with Conventional practice, a gradual shift from this practice should be encouraged. Finally, spear quality was found to be significantly affected by BMP application and was further found to have a significant impact on potential revenues. These findings underline the importance of future research directed towards BMPs in asparagus. Although some meaningful differences could be observed in the current trial after 3 years of harvests, long-term observations need to continue in order to assess the long-term impact of BMPs on preventing or delaying the onset and rate of asparagus decline and treatment profitability.

4.6 References

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5 Changes in Soil Microbial Communities and Soil Chemical Parameters Following Long-Term Application of Best Management Practices in Asparagus

Abstract

Soil chemistry and soil microbiology are affected by field management practice. Little is however known about the impacts of management practice on soil bio-chemistry in asparagus cropping systems. The aim of this study was to quantify changes and links between soil bio-chemical indicators by applying a set of potential Best Management Practices (BMPs) in asparagus (Asparagus *officinalis* L.*)*. A replicated field trial was established in 2016 with the asparagus cultivar 'Gijnlim'. BMPs included (1) companion crops Rye (*Secale Cereale* L.), Mustard (*Sinapis alba* L.), (2) interrow surface mulch applications (straw mulch, PAS 100 compost) and (3) variations of the tillage practice (re-ridging (R) or not ridging (NR) and applying SSD or not applying SSD) including Conventional practice and Zero-tillage. Soil samples were collected after 3 years of continuous treatment application. Soil analyses included Soil organic matter (SOM%), microbial biomass carbon (MBC), Phospholipid fatty acids (PLFA), ergosterol, NH_4-N Ammonium-N, NO_3-N nitrate-N, Total N, soil pH, cation exchange capacity (CEC), exchangeable Ca, Mg, Na, K and available P. Results indicated that neither rye or mustard companion crop treatments were associated with significant changes in any soil chemical or biological properties as compared to the Conventional practice. Application of mulches in combination with SSD was associated with significant changes to the soil microbial community, with significantly higher relative concentration of the arbuscular mycorrhizal fungi marker 16:1ω5 and fungal 18:2ω6,9, as compared to both companion crop and bare soil treatments. Mulch treatments

however also had significantly lower N levels. Annual re-ridging was associated with a significant decrease in fungal communities accompanied by increase in soil pH. SSD was however not associated with the same effect indicating that impacts of ridging and subsoiling on soil microbiology vary. This study demonstrates that interrow mulch application and changes in tillage practice cause changes in soil microbial community structure over relatively short time frames (3 years) and also change other chemical indicators such as soil pH which may have an impact on nutrient availability and crop performance. It was further shown that type of tillage, such as SSD or rigding, largely determine the scale of impacts on soil bio-chemistry.

5.1 Introduction

Although US asparagus industry commonly applies reduced tillage and rye cover crops in conventional asparagus production, in the UK, the majority of British asparagus growers adopts a conventional practice consisting of asparagus grown on raised ridges. Rye is commonly grown by North American asparagus growers as a weed suppressor providing additional protection to soil from splash erosion and from the frost. Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which are known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991) and was reported to have the ability to reduce the severity of *Fusarium* crown and root rot (Matsubara et al., 2001) which is responsible for declining yields in asparagus systems (Elmer et al., 1996; Yergeau et al., 2006). Mustard is known for its bio-drilling (Cresswell and Kirkegaard, 1995) effect due to the tap-root system and for its bio-fumigation potential, which has also been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998). Re-ridging in asparagus cropping systems is applied for various reasons, to promote growth of larger spears, to raise asparagus beds for efficient manual harvest and as a means of conveying excess rainfall away from the asparagus crown to avoid waterlogging. Subsoiling can also be used to alleviate interrow compaction which is a result of intensive machinery and foot traffic (Niziolomski et al., 2020, 2016). Although the impact of tillage depends on soil type, cropping system, climate and management practice (Rahman et al., 2008), short-term benefits of tillage tend to be negated by long-term negative consequences of repeated soil disturbance (Soane and van Ouwerkerk, 1995). Conventional tillage involving high mechanical pressures and frequent soil turnover gradually decrease soil organic matter (SOM) which has further negative implications on water holding capacity, aggregate stability, nutrient concentrations and overall soil quality (Bronick and Lal, 2005; Lal, 1993). Past research provided evidence that tillage operations in asparagus systems can have a major negative impact on asparagus stand longevity and productivity (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). Thus, conventional operations associated with tillage, harvest and agronomy of asparagus in the UK may play an important role in asparagus pose a major risk to crop productivity and stand longevity.

Field management practices such as soil disturbance and crop rotations have been reported to influence soil physical properties, soil microbial communities and soil nutrient content (Balota et al., 2004; Mathew et al., 2012; Rahman et al., 2008). Consequently, shifts in soil bio-chemistry influence a number of soil functions including nutrient cycling and soil resilience to environmental and mechanical pressures (Bronick and Lal, 2005). The impact of the management practice on soil bio-chemistry however depends on a variety of factors including soil texture, crop species and environmental conditions (Rahman et al., 2008).

BMPs, such as reduced tillage, companion cropping or mulching have been used to reduce the negative environmental impacts of agriculture in several crops such as winter cereals or potatoes (Deasy et al., 2009; Gordon et al., 2011). The impacts of BMPs in asparagus systems have not been addressed by previous research. Furthermore, long-term implications of the UK conventional practice on soil bio-chemical indicators in asparagus are unknown. Although management practices can have a profound effect on microbial communities which can potentially be used as an early indicator of changes in soil quality and functionality (Bending et al., 2000), changes in soil chemistry may only be detectable after several years of treatment applications (Mathew et al., 2012). The aim of this study was to quantify the impact of potential BMPs on a selection of soil quality indicators (SQIs) and on changes in soil microbial community structure in asparagus as compared to the conventional growing practice.

5.2 Materials and Methods

The field trial was undertaken as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The trial taking up a total area of 4.5 ha is located at Gatsford Farm, Ross-on-Wye, Herefordshire (51°55′55″N , 002°33′35″W). Asparagus ‘A’ crowns of Gijnlim variety representing 70% of UK field grown asparagus (AHDB, 2017), were planted on 20–21st of April 2016 on a flat surface at an anticipated depth of 0.14 m and 0.16 m spacing between crowns. Distance between each asparagus bed formed above the natural terrain was 1.83 m. In spring 2017, all plots were re-ridged as the intended crown depth (0.14 m) had not been reached (only ca. 0.06 m). Conventional agrochemical treatments have been applied to all trial plots from 2016 to 2020. Between 2018 and 2020, the trial site was characterised by mean annual precipitation of 665 mm, average annual temperature of 10.8°C and average wind speed of 4.5 km h^{-1}.

5.2.1 Experimental Design

The field trial included a range potential BMPs (Table 5-1); (1) companion crops - Rye (*Secale cereale* L. var. Protector.) or Mustard (*Sinapis alba* L. var. Severka), (2) interrow surface mulch (straw mulch or PAS 100 compost) applied in combination with shallow soil disturbance (SSD), (3) tillage modifications by ridging (R) or not re-ridging (NR) and by applying SSD no No-SSD. Treatments included a Conventional practice equivalent as Bare soil No-SSD R and a Zero-tillage as Bare soil No-SSD NR. Mulching products, Straw mulch or PAS 100 certified quality compost (WRAP, 2011) were applied only in the interrows and further subsoiled to replicate bio-drilling and canopy effects associated with companion crops. All treatments were replicated in quadruplicate. The experiment comprised a total of 48 randomly distributed, 35 m long, 1.83 m wide treatment plots. Each plot consisted of 2 raised beds planted with asparagus, central interrow between these two beds, and 2 guard interrows situated to the left and to the right from the plot to separate each treatment. All treatments received a standard annual fertiliser dose of approximately 450 kg ha^{-1} of nitrogen and sulphur (Single Top); 150 kg ha^{-1} of muriate of potash (MOP) and 50 kg ha^{-1} of triple super phosphate (TSP).

SSD was applied in April 2018 and in March and June 2020 using a winged tine operating to 0.25-0.30 m depth to all mulch treatments (PAS 100 Compost and Straw) and to selected bare soil treatments (Table 5-1). Re-ridging was undertaken using a tractor mounted 1.83 m double disk ridger in March 2017, April 2018, March 2019 and April 2020. CCs were broadcast for the first time on the 10th of August 2017 at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard (Clark, 2012), respectively.

In the first year, the emergence rate of the companion crops achieved ground cover of 70-75% which is sufficient cover based on Morgan (2005). However, for CCs sown in August 2018 and 2019, due to predation, seeding rates were increased to 200 kg ha^{-1} and 25 kg ha^{-1} for rye and mustard, respectively and repeated in September 2018 and October 2019. Mulches were applied annually in April 2016, April 2018, March 2019 and March 2020 at rates of 25 t ha^{-1} and 6 t ha^{-1} for PAS 100 compost and Straw mulch, respectively (Niziolomski et al., 2020). PAS 100 compost nutrient content varies by batch. 2020 composted material analysis results showed N content of 3 402 mg l^{-1}, 828 mg l^{-1} of phosphorus-P, 2 477 mg l^{-1} of potassium-K, 13 070 mg l^{-1} of calcium-Ca, 1 933 mg l^{-1} of magnesium-Mg and 777 mg l^{-1} of sodium-Na in fresh mass.

Table 5-1. Summary of the experimental treatments.

Treatment	Cover	Annual re-ridging (R)	Sub-soiling (SSD)
Conventional Practice	Bare soil	Ridged	No SSD
Zero Tillage	Bare soil	Non-ridged	No SSD
Bare soil SSD R	Bare soil	Ridged	SSD
Bare soil SSD NR	Bare soil	Non-ridged	SSD
Mustard R	Mustard	Ridged	No SSD
Mustard NR	Mustard	Non-ridged	No SSD
Rye R	Rye	Ridged	No SSD
Rye NR	Rye	Non-ridged	No SSD
Straw mulch SSD R	Straw mulch	Ridged	SSD
Straw mulch SSD NR	Straw mulch	Non-ridged	SSD
PAS 100 SSD R	Compost	Ridged	SSD
PAS 100 SSD NR	Compost	Non-ridged	SSD

NR=non-ridged; R=re-ridged; SSD=shallow soil disturbance.

5.2.2 Sampling methodology

Baseline soil analyses conducted in 2016 during the trial establishment period indicated that there were no significant differences in tested soil parameters ($p \leq 0.05$) between plots. Soils at the trial site are Cambisols (IUSS Working Group WRB, 2007) of Eardiston series association (Cranfield University, 2020) with 77% sand, 11% silt and 12% clay composition. Other soil parameters were soil pH of 6.34 (± 0.03), soil organic matter of 2.78% (±0.03), total soil C of 1.24% (±0.01) and total N of 0.13% (±0.001). Mean bulk density of the upper 15 cm of soil was 1.71 (± 0.01) determined following standard laboratory methods (DEFRA, 1986).

In 2020, 10 sub-samples (0-15cm depth) were obtained from the central interrows of each plot and combined into a composite soil sample following the procedure outlined in BS 3882:2015. All soil samples were obtained with a Dutch auger (7 cm drilling diameter and 10 cm sample length). Soil organic matter (SOM%) was determined following the loss-on-ignition method based on the BS EN 13039:2011. Microbial biomass carbon (MBC) determination was based on a fumigation-extraction procedure identical to ISO 14240-2:2011. Ergosterol was determined following the ultrasonic extraction method adopted from Ruzicka et al. (1995) using duplicated samples, one of which received 100 µg of ergosterol in 1 ml n-hexane-propan-2-ol (98:2 v/v). 10 ml of methanol:ethanol (4: 1 v/v) was then added to all samples, followed by the additional 20 ml (19 ml for samples with ergosterol) of n-hexane-propan-2-ol (98:2 v/v) before sonicating. Approximately 2ml of the upper layer is centrifuged and subject to chromatography to estimate ergosterol concentrations. Mineral nitrogen (NH_4-N Ammonium-N, NO_3-N nitrate-N, Total N), soil pH, cation exchange capacity (CEC), exchangeable Ca, Mg, Na, K and available P were determined following standard laboratory methods (DEFRA, 1986). Phospholipid fatty acid (PLFA) profiles were determined using a Pawlett et al. (2013) method modified from Frostegard et al. (1993). Lipids were extracted using a chloroform:methanol:citrate buffer solution (1:2:0.8 v/v/v) (Bligh and Dyer, 1959), fractioned and subjected to mild alkaline methanolysis. Fatty acid methyl esters (FAMEs) were analysed by gas chromatography and calculated as relative concentration (mol%). PLFA results were expressed as a percentage of the chromatogram peak area relative to the summed area of all PLFA peaks. Relative abundance values were used to indicate differences in microbial community structures and in selected markers. Phospholipid fatty acid analysis (PLFA) is a method frequently used to characterise changes in the composition of soil microbial communities and to differentiate between fungal and bacterial biomass (Willers et al., 2015). A total of 31 PLFA markers (Table 5-2) were used to assess the soil microbial community composition and dominance in all treatments. The 18:2ω6,9 marker has been used as an indicator of fungal biomass (Bååth, 2003; Frostegård and Bååth, 1996; Olsson et al., 1995) and 16:1ω5 as an indicator of the presence of AMF (Olsson, 1999). These fatty acids can be used as an estimate of relative changes in soil microbial community composition. Fungal-bacterial ratio (F:B ratio) was obtained by dividing the fungal biomarker 18:2ω6,9 by sums of bacterial fatty acid markers, including; i15:0, ai15:0, 15:0, i16:0, i17:0, ai17:0, 17:0c, 17:0, and 19:0c (Frostegård and Bååth, 1996). The 16:1ω5 marker was used as an indicator of the relative abundance of arbuscular mycorrhizal fungi (AMF) (Olsson, 1999).

Table 5-2. PLFA classification adopted from Olsson et al. (1995); Frostegard et al. (1993); Hanajík et al. (2016); Mitchell et al. (2010); Wilkinson et al. (2002) and Zelles (1997).

PLFA	Used as a marker for
14:0	General bacterial marker
15:0i	Gram (+) bacteria
15:0ai	Gram (+) bacteria
15:0	General bacterial marker
16:0i	Gram (+) bacteria
16:1ω11t	
16:1ω7c	Gram (-) bacteria
16:1ω5	Arbuscular mycorrhizal fungi
16:0	General bacterial marker
Me17:0 isomer	Gram (+) bacteria
Me17:0 isomer2	
17:0i	Gram (+) bacteria
cyc17:0 isomer	
17:0 ai	Gram (+) bacteria
17:0br	Methanotrophic bacteria
17:1ω8c	
17:0c	Gram (-) bacteria
17:1ω8t	
17:1ω7	
17:0 (12Me)	
18:2ω6,9	Saprotrophic fungi
18:1ω9c	Cyanobacteria
18:1ω7t	Gram (-) bacteria
18:1ω13	
18:0	Gram (+) bacteria
18:0 (10Me)	Gram (+) bacteria
19:1ω6	
19:0c	Gram (-) bacteria
20:4 (5,8,4,11,14)	Cyanobacteria, Arbuscular mycorrhizal fungi
20:5ω3	Cyanobacteria
20:0	

5.2.3 Statistical Analysis

Statistical analysis was performed using the TIBCO Statistica 13.3.0 analytics software. PLFA profiles were analysed by Principal Component Analysis (PCA). Relative amounts of PLFA markers and all other variables were analysed by one-way ANOVA with *post-hoc* Fisher LSD analysis at 95% confidence interval. Pearson correlation was used to determine relationship coefficients between variables.

5.3 Results

5.3.1 Changes in soil biological indicators

PCA analysis of PLFA profiles comparing all 12 treatments revealed that Factor 1 and Factor 2 together explained 43% of variance (Figure 5-1). PLFAs with high negative loading (<-0.8) on Factor 1 axis included 16:1ω11t, bacterial 16:1ω7c and 18:1ω7t, and AMF 16:1ω5 (Table 5-3. PLFAs with a significant (<-0.8 or >0.8) loading on Factor 1 and Factor 2.Table 5-3). A single fatty acid of positive loading (>0.8) in Factor 1 was 17:0(12Me). Two fatty acids, fungal 18:2ω6,9 and 20:4(5,8,4,11,14) which may represent cyanobacteria or AMF (Nordby et al., 1981; Olsson et al., 1995; Veum et al., 2019) had a positive loading on Factor 2 (Table 5-3. PLFAs with a significant (<-0.8 or >0.8) loading on Factor 1 and Factor 2.Table 5-3).

Table 5-3. PLFAs with a significant (<-0.8 or >0.8) loading on Factor 1 and Factor 2.

PLFA	Factor 1	Factor 2
16:1ω11t	**-0.84**	0.11
16:1ω7c	**-0.89**	0.00
16:1ω5	**-0.84**	0.37
17:0 (12Me)	**0.80**	-0.43
18:2ω6,9	0.09	**0.85**
18:1ω7t	**-0.90**	0.06
20:4 (5,8,4,11,14)	0.23	**0.84**

Factor 1 and Factor 2 case coordinates were plotted into a scatterplot to visualise distribution of PLFA community patterns as affected by re-ridging, subsoiling and by interrow cover treatment group. PLFA profiles of mulch treatments were separated from all other treatments, which are bare soils and companion crops. Figure 5-1 shows PCA ordination of all treatments including bare soil, mulches and companion crops. As shown in Figure 5-2, subsoiling had no impact on soil microbial community composition of bare soil treatments. All 12 treatments were further identified by re-ridging and non-ridging and formed two PLFA profile groups which split alongside the axes of Factor 1 and Factor 2 (Figure 5-3).

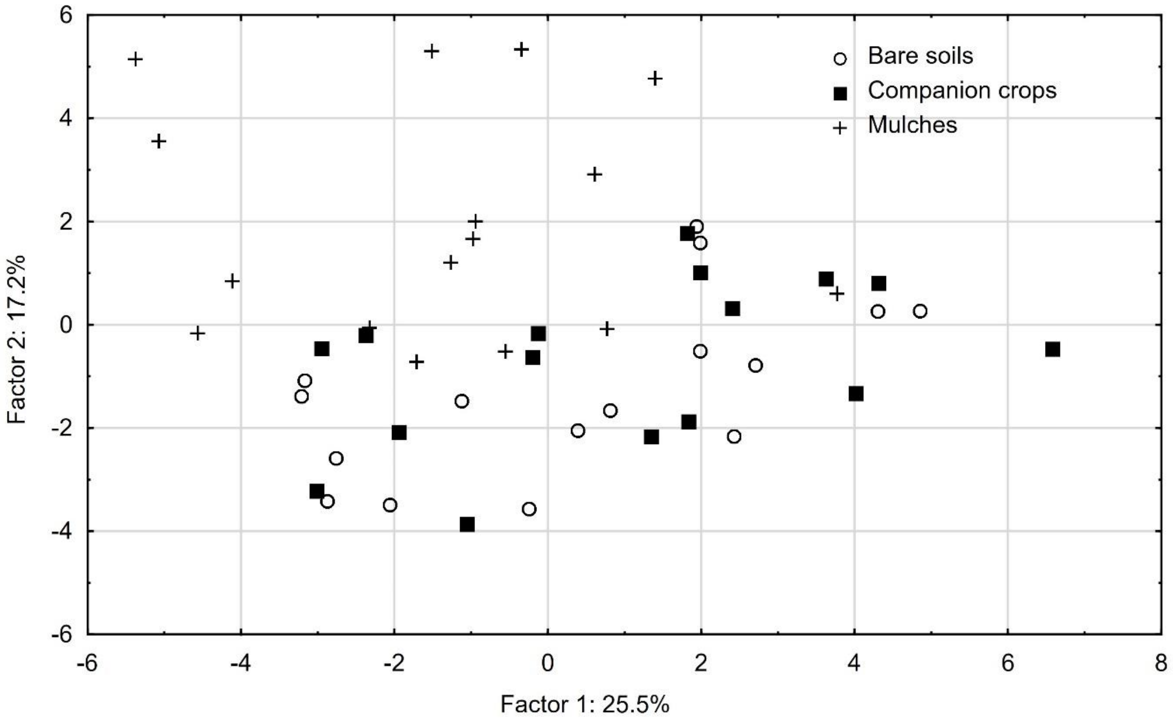

Figure 5-1. Projection of individual PCA ordination scores showing changes in microbial communities associated with all 12 treatments including bare soils, mulches and companion crops.

Separation of R and NR communities in PCA allowed us to identify a subset of key PLFA markers within each community (Figure 5-4). In ridged treatments, Factor 1 and Factor 2 together explained 39% of variance. Factor 1 negative loading PLFAs included bacterial 16:1ω7c, 18:1ω7t and 16:1ω5 AMF marker. Factor 1 PLFA marker with a positive loading was bacterial 16:0i. PLFA 15:0 and was the only PLFA influencing Factor 2 ordination. In non-ridged treatments however, Factor 1 and Factor 2 explained 48% of variance. Factor 1 negative ordination PLFAS were 16:1ω11t, bacterial 16:1ω7c and AMF 16:1ω5 while 17:0 (12Me) had a positive loading. Factor 2 included two bacterial PLFAs of negative loading, which were 15:0 and 16:0i. Standard analysis of variance also confirmed that relative abundance of multiple fatty acids was significantly affected by ridging. Ridging for example increased relative amounts of bacterial PLFAs 15:0i, 16:1ω7c, Me17:0 isomer, Me17:0 isomer2, 18:1ω7t and 18:1ω13 compared to non-ridging. In contrast, non-ridging increased the relative amounts of bacterial 16:0i, fungal 18:2ω6,9 and of two PLFAs, 20:4 (5,8,4,11,14) and 20:5ω3 compared to ridging. SSD significantly decreased relative amount of 19:0c.

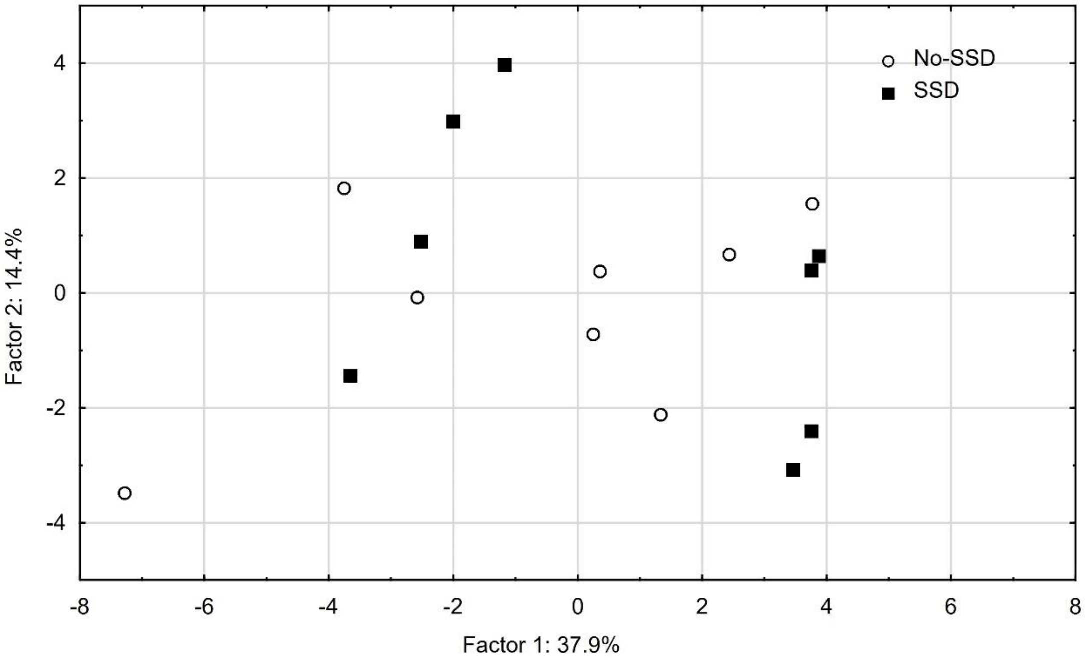

Figure 5-2. Projection of individual PCA ordination scores showing differences in microbial communities within bare soil treatments by subsoiling (SSD) or not subsoiling (No-SSD).

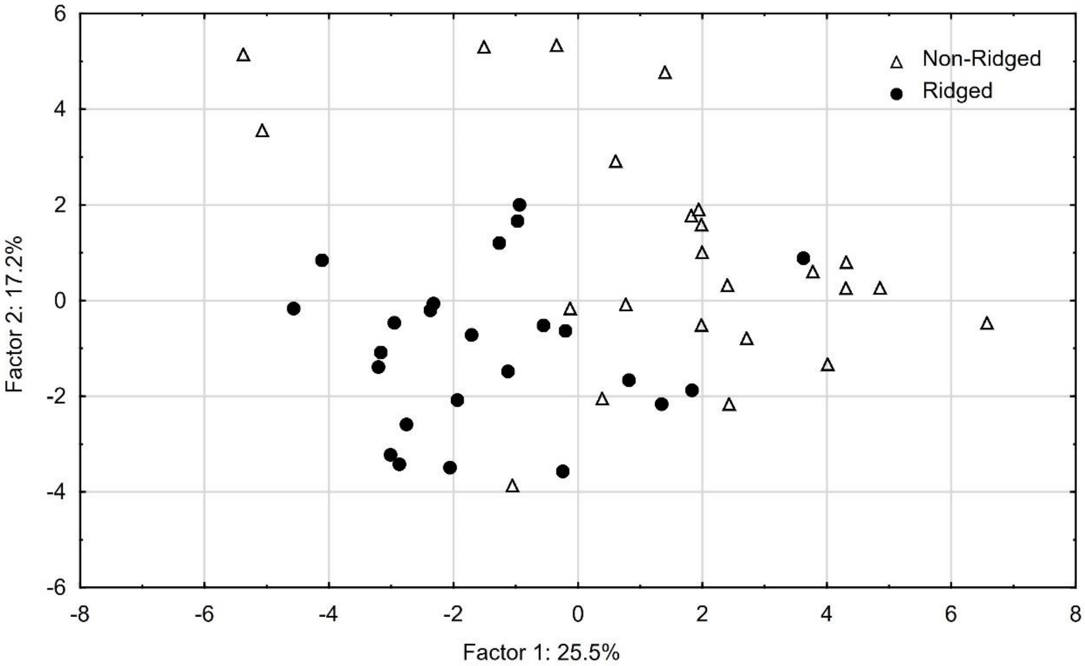

Figure 5-3. Projection of individual PCA ordination scores showing differences in microbial communities associated by re-ridging (R) or non-ridging (NR) of all 12 treatments.

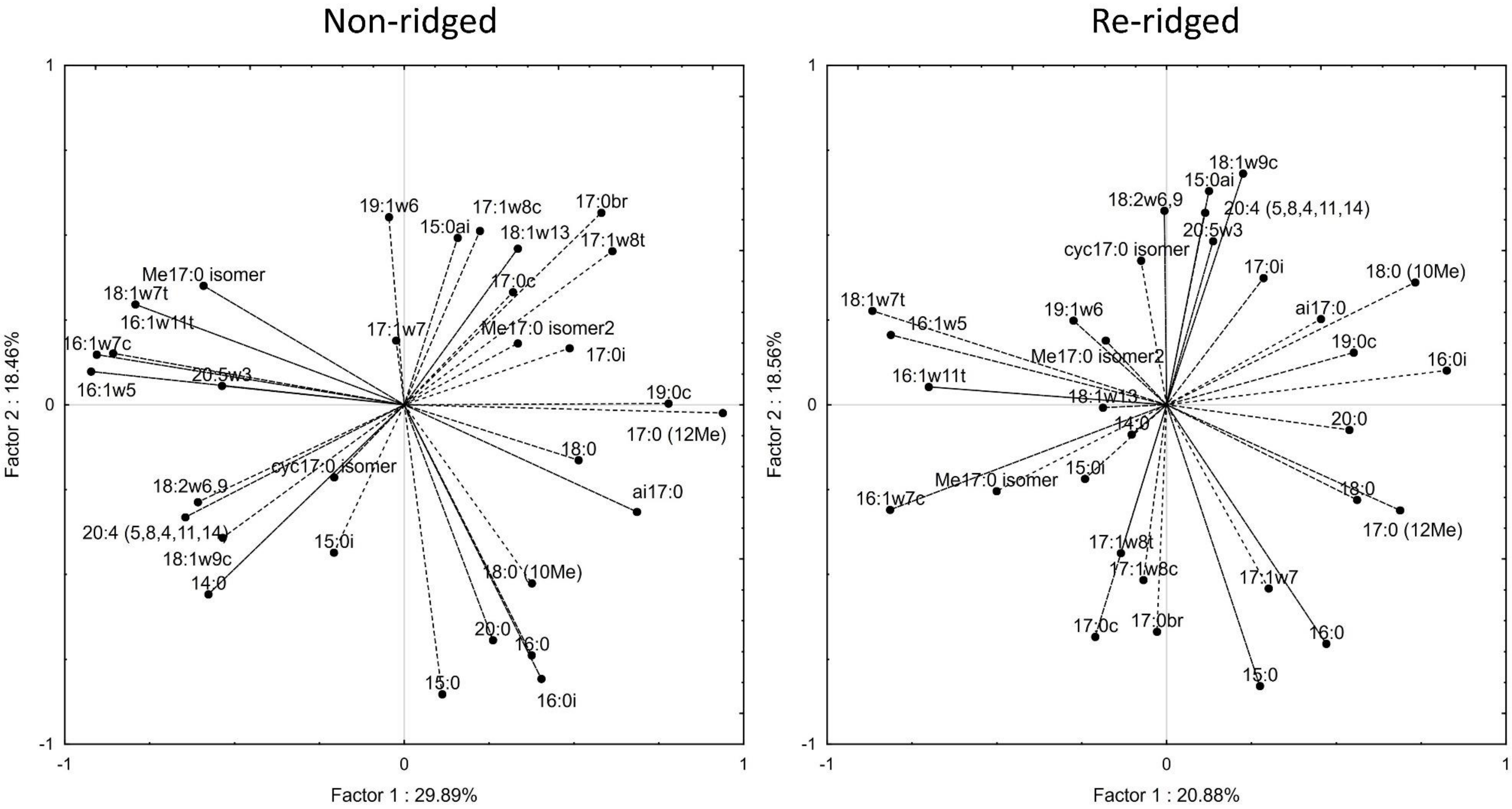

Figure 5-4. Factor-plane variable projection of fatty acids in non-ridged (left) and re-ridged treatments (right).

Sum of relative concentrations of bacterial PLFAs was significantly lower for both PAS 100 NR/R as compared to CT, ZL and Mustard NR (Table 5-4). Although the amount of bacterial PLFA was not affected by annual re-ridging, the impact of SSD on the bare soil treatment group was significant and contributed to higher amounts of bacteria. Furthermore, mulches had overall significantly less bacteria as compared to both the CC and Bare soil treatments.

As shown in Table 5-5, relative abundance of mycorrhizal 16:1ω5 was significantly higher in the mulch treatment group as compared to both the CC and Bare soil treatments. PAS 100 NR was associated with a significantly higher abundance of AMF 16:1ω5 as compared to all other treatments with the exception of PAS 100 R. Highest concentration of fungal marker 18:2ω6,9 was also found within the mulch treatment group. With the exception of PAS 100 R and Straw mulch NR, PAS 100 NR contained significantly higher relative abundance of fungal marker 18:2ω6,9 as compared to all other treatments. Consequently, mulch treatments had significantly more 16:1ω5 and 18:2ω6,9 as compared to the CC and all Bare soil treatments. Subsoiling had no effect on neither 16:1ω5 nor 18:2ω6,9. Ridging however significantly decreased relative abundance of 18:2ω6,9 across all treatments (Table 5-4). Impact of ridging on 16:1ω5 was not significant. Fungal biomass as indicated by ergosterol however did not differ between treatments and was not affected by tillage or by interrow cover. Microbial biomass C (MBC) was significantly higher in PAS 100 NR/R treatments as compared to the Conventional practice and Zero-tillage treatments. The mulch treatment group in general was associated with significantly higher MBC (163 µg/g) as compared with bare soil treatment group (123 µg/g).

In addition, the Fungal:Bacterial ratio was significantly lower for the Conventional practice compared to PAS 100 NR/R, Straw mulch NR/R, Zero-tillage, Bare soil SSD NR and Rye NR treatments (Table 5-5). Further, the Fungal:Bacterial ratio was significantly higher for the mulch treatment group as compared to Bare soil and CCs grouping. Shallow soil disturbance (SSD) of interrows had no impact on Fungal:Bacterial ratios however the impact of re-ridging was significant and Fungal:Bacterial ratio was significantly lower in treatments which were re-ridged on an annual basis as compared to non-ridged treatments (Table 5-4).

Table 5-4. List of soil parameters significantly affected by ridging within all treatments.

	F:B	18:2ω6,9 (mol%)	Ex. Ca (mg kg^{-1})	Ex. Mg (mg kg^{-1})	Soil pH
R	0.04 ^{a}	1.41 ^{a}	814 ^{b}	117 ^{b}	5.83 ^{b}
NR	0.06 ^{b}	1.88 ^{b}	387 ^{a}	100 ^{a}	5.31 ^{a}

R/NR = ridging/non-ridging. F:B = Fungal:Bacterial ratio. Within each column, values followed by the same letter(s) are not significantly different following one-way ANOVA and *post-hoc* Fisher LSD at 0.95.

Table 5-5. Soil biological indicators of BMPs.

Treatment	Ergosterol (g kg^{-1})	MBC (µg g^{-1})	18:2ω6,9 Mol%	16:1ω5 Mol%	Sum of bacterial PLFAs Mol%	F:B
Conventional practice	**0.16^{a}**	**117^{ab}**	**1.11^{a}**	**3.55^{abcd}**	**32.7^{cd}**	**0.03^{a}**
Zero-tillage	0.42^{a}	102^{a}	1.70^{bcde}	3.07^{ab}	33.3^{d}	0.05^{bcde}
Bare soil SSD NR	0.36^{a}	127^{abc}	1.87^{de}	3.18^{abc}	32.1^{bcd}	0.06^{de}
Bare soil SSD R	0.13^{a}	146^{abcd}	1.19^{ab}	3.82^{cde}	32.0^{abcd}	0.04^{ab}
Mustard NR	0.36^{a}	130^{abc}	1.50^{abcd}	3.01^{a}	32.8^{cd}	0.05^{abcd}
Mustard R	0.13^{a}	134^{abcd}	1.30^{abc}	3.62^{abcde}	31.9^{abcd}	0.04^{abc}
PAS 100 NR	0.40^{a}	176^{cd}	2.41^{f}	4.69^{f}	30.3^{a}	0.08^{f}
PAS 100 R	0.47^{a}	182^{d}	1.95^{def}	4.30^{ef}	31.0^{ab}	0.06^{ef}
Rye NR	0.44^{a}	133^{abcd}	1.76^{cde}	3.25^{abc}	32.4^{bcd}	0.05^{cde}
Rye R	0.26^{a}	161^{bcd}	1.10^{a}	3.69^{abcde}	31.5^{abc}	0.03^{ab}
Straw Mulch NR	0.35^{a}	137^{abcd}	2.03^{ef}	3.75^{bcde}	31.5^{abc}	0.07^{ef}
Straw Mulch R	0.46^{a}	157^{bcd}	1.81^{cde}	3.94^{de}	31.2^{abc}	0.06^{de}

F:B = Fungal:Bacterial PLFA ratio; MBC = Microbial biomass carbon; R/NR = ridging/non-ridging; SSD = subsoiling; Conventional practice = Bare soil No-SSD R; Zero-tillage = Bare soil No-SSD NR. Within each column, values followed by the same letter(s) are not significantly different following one-way ANOVA and *post-hoc* Fisher LSD at 0.95.

5.3.2 Changes in soil chemistry

As shown in Table 5-6, nitrate-N levels were significantly lower in PAS 100 R/NR, Straw mulch R/NR and in Bare soil SSD R as compared to the Rye R treatments. Soil ammonium-N levels in PAS 100 R/NR were significantly lower as compared to Bare soil SSD NR, Mustard R/NR and Rye R treatments. Ammonium-N levels in the Conventional practice treatment were not significantly different from all other treatments except for PAS 100 R. Total mineralizable-N was significantly lower in the PAS 100 R treatment as compared to the Conventional practice, Zero-tillage, Bare soil SSD NR, Mustard NR and Rye R treatments however was no different from other mulch treatments. In general, mulch treatment group was characterised by significantly lower ammonium-N, nitrate-N and total mineralizable-N levels as compared to both the CC and Bare Soil treatments groups. Tillage (re-ridging or SSD) did not have any significant impact on ammonium-N, nitrate-N or total mineralizable-N concentrations (Table 5-6).

No significant difference in SOM% was observed between Bare Soil treatments. Although no treatments had SOM levels significantly different from the Conventional practice, SOM was significantly higher in the PAS 100 R treatment compared to all other treatments except for Conventional practice, Mustard R and Straw mulch R treatments (Table 5-6). SOM content in interrow wheelings was significantly higher in soils which have been re-ridged compared to soils managed without ridging (Table 5-6).

Exchangeable-Ca was significantly higher in the Conventional practice as compared to the Zero-tillage, Bare soil SSD NR, Mustard NR and Straw mulch NR treatments.

The highest Exchangeable- Ca levels were present in the Bare soil SSD R treatment which was significantly higher compared to all other treatments except the Conventional practice and PAS 100 R/NR treatments. Exchangeable-Mg concentrations were significantly lower in the Zero-tillage, Bare soil SSD NR, and Straw mulch NR treatments as compared to Mustard R and Rye R. Exchangeable-K (was significantly lower in Bare soil SSD NR and compared to the Conventional practice, Bare soil SSD R, Mustard R/NR, PAS 100 NR and Rye R treatments. Further, Exchangeable-Na was significantly higher in the PAS 100 R/NR treatments as compared to all other treatments. Consequently, mulch treatments were associated with significantly higher Exchangeable-Na as compared to the Bare soil treatment group. Further, the CCs treatments were associated with significantly higher Exchangeable-K as compared to the Bare soil treatment group. Furthermore, Exchangeable-Ca and Mg significantly increased following re-ridging and were linked to elevated soil pH in the interrows (Table 5-4 and Table 5-6).

Cation exchange capacity (CEC) was found to be significantly lower in the Zero-tillage, and Bare soil SSD NR treatments compared to Conventional practice and PAS 100 R/NR. Soil pH was also lower in the Zero-tillage and Bare soil SSD NR treatments compared to Conventional practice, Bare soil SSD R, Mustard R, PAS 100 R/NR, Rye R and Straw mulch R treatments (Table 5-6). Furthermore, soil pH was significantly affected by re-ridging, where ridging increased soil pH compared to non-ridging. Available-P was then significantly lower in Bare soil SSD R compared to all other bare soil treatments, Mustard R and PAS 100 NR. Highest amounts of available-P were associated with PAS 100 NR treatment, which was significantly higher as compared to PAS 100 R. Thus, ridging significantly reduced the amount of available-P in the interrows, although P added in soils to both treatments via compost was identical, 828 mg l^{-1} in fresh or 2749 mg kg^{-1} in dry matter.

Following correlation analysis of signature PLFAs with SQIs, a weak though significant correlation was found between the fungal marker 18:2ω6,9 and ergosterol ($r^2=0.13$, $r=0.36$, $p<0.05$). Mycorrhizal marker 16:1ω5 was significantly and positively correlated with MBC ($r^2=0.22$, $r=0.48$, $p<0.001$), soil pH ($r^2=0.53$, $r=0.73$, $p<0.0001$), CEC ($r^2=0.30$, $r=0.55$, $p<0.0001$), Exchangeable-Na ($r^2=0.28$, $r=0.53$, $p<0.001$), and with Exchangeable-Ca ($r^2=0.51$, $r=0.71$, $p<0.001$). The AMF 16:1ω5 marker was further negatively correlated with dry matter content ($r^2=0.36$, $r=-0.60$, $p<0.001$), whereas the fungal 18:2ω6,9 was not (Table 5-7). Sum of bacterial PLFAs was strongly and negatively correlated to the AMF 16:1ω5 PLFA. Significant negative relationships were also found between the sum of bacterial PLFAs and MBC, Exchangeable-Ca, Mg and Na, CEC and soil pH. Positive correlations were also found between the sum of bacterial PLFAs and dry matter content and ammonium-N. MBC was positively correlated with the AMF marker 16:1ω5, Exchangeable-Ca, Na and with soil pH. SOM% was not correlated with none of the SQIs.

Table 5-6. Mean parameters for soil chemical indicators of all BMP treatments.

Treatment	DMC (%w/w)	Nitrate NO_3^- (mg kg^{-1})	Ammonium NH_4^+ (mg kg^{-1})	Total N (kg ha^{-1})	SOM%	Ex Ca^{2+} (mg kg^{-1})	Ex Mg^{2+} (mg kg^{-1})	Ex K^+ (mg kg^{-1})	Ex Na^+ (mg kg^{-1})	Available P (mg l^{-1})	CEC (meq 100g^{-1})	Soil pH
Conventional practice	**87.5 ^{bc}**	**94.0 ^{bc}**	**33.0 ^{bcde}**	**238 ^{cd}**	**2.91 ^{abcd}**	**753 ^{cdef}**	**120 ^{abc}**	**293 ^{b}**	**11.3 ^{a}**	**56.3 ^{bc}**	**9.18 ^{bcd}**	**5.70 ^{cdef}**
Zero-tillage	87.5 ^{bc}	80.3 ^{abc}	34.0 ^{bcde}	214 ^{bcd}	2.60 ^{ab}	173 ^{a}	94.8 ^{a}	278 ^{ab}	10.3 ^{a}	56.3 ^{bc}	8.25 ^{a}	5.03 ^{a}
Bare soil SSD NR	87.5 ^{bc}	81.2 ^{abc}	40.7 ^{de}	229 ^{bcd}	2.48 ^{ab}	185 ^{a}	98.3 ^{ab}	311 ^{b}	11.8 ^{a}	57.5 ^{bc}	8.23 ^{a}	5.13 ^{a}
Bare soil SSD R	87.0 ^{abc}	50.6 ^{a}	7.37 ^{ab}	109 ^{ab}	2.71 ^{abc}	1104 ^{f}	113 ^{abc}	173 ^{a}	9.00 ^{a}	40.8 ^{a}	9.10 ^{abcd}	6.10 ^{f}
Mustard NR	87.8 ^{c}	84.5 ^{abc}	40.9 ^{de}	235 ^{cd}	2.43 ^{a}	338 ^{ab}	103 ^{abc}	340 ^{b}	11.3 ^{a}	52.2 ^{abc}	8.55 ^{abcd}	5.28 ^{abc}
Mustard R	87.6 ^{c}	73.5 ^{abc}	37.8 ^{cde}	209 ^{abcd}	3.17 ^{cd}	721 ^{cde}	123 ^{bc}	318 ^{b}	11.3 ^{a}	58.3 ^{bc}	8.73 ^{abcd}	5.80 ^{ef}
PAS 100 NR	85.8 ^{ab}	67.2 ^{ab}	6.92 ^{ab}	139 ^{abc}	2.70 ^{abc}	869 ^{def}	99.3 ^{ab}	333 ^{b}	20.0 ^{b}	63.2 ^{c}	9.43 ^{d}	5.85 ^{ef}
PAS 100 R	87.1 ^{bc}	45.3 ^{a}	2.27 ^{a}	89.1 ^{a}	3.34 ^{d}	986 ^{ef}	113 ^{abc}	280 ^{ab}	20.0 ^{b}	48.5 ^{ab}	9.33 ^{cd}	6.05 ^{ef}
Rye NR	88.0 ^{c}	74.9 ^{abc}	25.7 ^{abcde}	189 ^{abcd}	2.54 ^{ab}	412 ^{abc}	109 ^{abc}	287 ^{ab}	12.5 ^{a}	50.4 ^{abc}	9.00 ^{abcd}	5.33 ^{abcd}
Rye R	87.2 ^{bc}	108 ^{c}	44.9 ^{e}	287 ^{d}	2.68 ^{abc}	707 ^{bcde}	128 ^{c}	357 ^{b}	14.0 ^{a}	46.4 ^{ab}	9.08 ^{abcd}	5.73 ^{def}
Straw Mulch NR	85.2 ^{a}	52.6 ^{a}	9.90 ^{abc}	117 ^{abc}	2.62 ^{ab}	346 ^{ab}	95.5 ^{a}	261 ^{ab}	9.50 ^{a}	49.9 ^{abc}	8.30 ^{ab}	5.25 ^{ab}
Straw Mulch R	86.4 ^{abc}	53.2 ^{a}	12.5 ^{abcd}	123 ^{abc}	3.05 ^{bcd}	613 ^{bcd}	105 ^{abc}	250 ^{ab}	10.3 ^{a}	51.8 ^{abc}	8.48 ^{abc}	5.63 ^{bcde}

DMC = Dry matter content; SOM= Soil organic matter; CEC = Cation exchange capacity; Ex = Exchangeable; R/NR = ridged/non-ridged; SSD = subsoiling. Within each column, values followed by the same letter(s) are not significantly different following post-hoc Fisher LSD at 0.95.

Table 5-7. Correlation matrix showing Pearson correlation coefficients (r) between each variable pair (N=48).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
B	0.18																
C	0.36*	0.22															
D	-0.22	0.47*	0.22														
E	0.17	-0.37*	-0.23	**-0.79***													
F	0.32*	0.27	**0.99***	0.33*	-0.37*												
G	0.12	-0.13	-0.27	**-0.60***	**0.62***	-0.36*											
H	-0.19	-0.13	-0.17	-0.27	0.19	-0.19	0.13										
I	-0.24	-0.25	-0.23	-0.42*	0.32*	-0.27	0.21	**0.86***									
J	-0.22	-0.19	-0.21	-0.34*	0.26	-0.24	0.17	**0.97***	**0.95***								
K	0.19	0.01	0.09	0.15	-0.16	0.11	0.05	-0.18	-0.23	-0.21							
L	-0.33*	0.37*	-0.25	**0.71***	**-0.54***	-0.16	-0.25	-0.37*	-0.48*	-0.43*	0.19						
M	-0.15	0.14	-0.37*	0.25	-0.36*	-0.30*	-0.09	0.08	0.00	0.04	0.20	**0.51***					
N	-0.01	0.06	0.12	-0.05	0.01	0.12	-0.04	**0.58***	**0.64***	**0.63***	0.03	-0.32*	-0.01				
O	0.14	0.48*	0.33*	**0.53***	-0.39*	0.38*	-0.29*	0.10	-0.07	0.03	0.08	0.35*	0.27	0.30*			
P	0.30*	0.06	0.33*	-0.05	0.05	0.30*	-0.02	0.23	0.17	0.21	0.10	-0.32*	-0.38*	0.37*	0.10		
Q	-0.18	0.23	-0.14	**0.55***	**-0.51***	-0.06	-0.38*	-0.11	-0.32	-0.21	0.07	**0.72***	**0.54***	-0.12	**0.53***	-0.05	
R	-0.37*	0.40*	-0.22	**0.73***	**-0.57***	-0.13	-0.24	-0.34*	-0.41*	-0.39*	0.21	**0.98***	**0.55***	-0.24	0.39*	-0.34*	**0.66***

(A) Ergosterol (g kg^{-1}), (B) MBC (µg g^{-1}), (C) 18:2ω6,9 (mol%), (D) 16:1ω5 (mol%), (E) Bacterial PLFAs (mol%), (F) F:B ratio, (G) Dry Matter Content (%w/w), (H) Nitrate NO_{3-} (mg kg^{-1}), (I) Ammonium NH_4+ (mg kg^{-1}), (J) Total N (kgN ha^{-1}), (K) Soil Organic Matter (SOM%), (L) Ex Ca^{2+} (mg kg^{-1}), (M) Ex Mg^{2+} (mg kg^{-1}), (N) Ex K^{+}(mg kg^{-1}), (O) Ex Na^{+} (mg kg^{-1}), (P) Available P (mg l^{-1}), (Q) CEC (meq 100g^{-1}), (R) Soil pH.

* significant at 0.05 confidence level. Highlighted in bold are coefficients greater than 0.5 or smaller than -0.5.

5.4 Discussion

5.4.1 Soil biology

The results showed that the relative abundance of the 16:1ω5 marker was highest in PAS 100 compost treatments, significantly so as compared to the Conventional practice, Zero-tillage and Rye NR and Mustard NR treatments. Consequently, the relative abundance of the 16:1ω5 marker was significantly higher in the sum of all mulch treatments as compared to bare soil and CC treatment groups. Compost application has often been linked to positive or no effects on AMF communities (Cavagnaro, 2015). Duong et al. (2012) found that in a pot experiment with wheat (*Triticum aestivum* L.), compost application significantly increased AMF colonisation by up to 50%. Lee et al. (2019) also found that in a pepper (*Capsicum annuum* L.) pot experiment, food waste compost applied at 20 t ha^{-1} increased AMF by over 50% compared to zero compost application. Ngo and Cavagnaro (2018) however found that AMF colonisation was lower when municipal green-waste compost was added to soils planted with tomato or wheat at 6 t ha^{-1}. The authors further argued that AMF formation was mainly reduced due to concomittant increases in P and N resulting from compost addition. Püschel et al. (2016) also noted that AMF benefits are maximised under low P and high N fertilization regimes. Baltruschat et al. (2019) then confirmed decreased AMF diversity in soils with high N and P feritiliser inputs. Although evidence suggests that high P content may inhibit AMF colonisation as would be seen in compost amended treatments, in the current study, significantly higher abundance of 16:1ω5 indicating the presence of AMF was observed in mulches as compared to all other treatment groups. The 16:1ω5 marker was not linked to P content however was negatively correlated to the amounts of ammonium-N and total mineralizable-N.

On the contrary, Mustard NR had the lowest relative abundance of AMF marker 16:1ω5, significantly less as compared to Bare soil SSD R and to all mulch treatments. This finding confirms that Brassicas may be linked to reduced AMF colonisation (Njeru et al., 2014; White and Weil, 2010). Relative concentrations of 16:1ω5 were not significantly different in any of the CC treatments from the Conventional practice or Zero-tillage. CCs have been reported to increase AMF populations in soils by providing additional nutrition to AMF during winter periods (Kabir and Koide, 2002). The presented results contradict the finding of Schutter and Dick (2002), who found that in companion cropping systems (including oats, vetch and winter wheat), the abundance of the AMF 16:1ω5 marker was significantly higher compared to fallow. Rye CC in particular has been found to increase the abundance of AMF as compared to conventional tillage in maize (Mathew et al., 2012; White and Weil, 2010). In the present study, no significant impact of rye on AMF abundance was observed.

AMF 16:1ω5 marker was strongly and positively correlated to Exchangeable-Ca and soil pH. This finding coincides with results reported by Liu et al. (2020) who found that acidic soils with pH 4.5 significantly decreased AMF colonisation by up to 90% compared to soils of pH 6.5 suggesting a strong relationship between the growth of AMF and soil pH. Rohyadi et al. (2004) however noted that although pH had a significant impact on AMF colonisation, the impact varied significantly between different AMF species. AMF have the ability to establish mutualistic symbiosis with roots of the majority of plant species (Smith and Read, 2008). AMF root colonisation enhances plant nutrient uptake by increasing root surface area of the host and increases plant resistance to both biotic and abiotic stresses (Gianinazzi et al., 2010; Ngosong et al., 2012; Wilkes et al., 2020). AMF inoculation has also been showed to be beneficial in asparagus cropping systems (Pedersen et al., 1991; Wacker et al., 1990) and to reduce severity of Fusarium (Matsubara et al., 2001; Pedersen et al., 1991). The 16:1ω5 fatty acid is used to estimate relative abundance of AMF (Olsson et al., 1995). However, this has been previously criticised due to evidence of its presence in some bacteria (Frostegård et al., 2011). Ngosong et al. (2012) even suggest that the use of the 16:1ω5 marker should be limited to laboratory experiments only. Based on Olsson (1999), the use of the 16:1ω5 marker however should be sufficient to indicate the relative abundance of AMF as its general occurrence in other fungi is rare. Although Olsson et al. (2003) states that AMF do not contain ergosterol making it an unsuitable marker for AMF estimation, Frey et al. (1992) found changes in ergosterol content in roots infected with AMF *Glomus Intraradices*. In the current study, the presence of AMF was estimated using 16:1ω5 PLFA marker.

In the current study, both ergosterol and the 18:2ω6,9 marker were used to asses changes in fungal communities (Olsson, 1999). Frostegård and Bååth (1996) suggested that 18:2ω6 marker could be used as a fungal indicator while other studies found no relationship between ergosterol levels and 18:2ω6 (Amir et al., 2008; Malosso et al., 2004; McKinley et al., 2005). Malosso et al. (2004) however found that the fungal 18:2ω6,9 failed to detect changes in communities which were apparent from ergosterol. Several other studies also suggested that 18:2ω6,9 marker should not be used as a standalone fungi indicator due to its presence in plant membranes (Olsson, 1999; Zelles, 1997). Ergosterol on the other hand is specific for higher fungi and does not occur in plants (Amir et al., 2008; Frostegård and Bååth, 1996; Olsson, 1999). Resuts presented in his study showed a significant weak (r^2=0.13, R=0.36, $p<0.05$) relationship between ergosterol and the fungal 18:2ω6,9 marker suggesting that both methods were potentially sucessful in detecting fungal communities in the field experiment.

Tillage had been reported to have an impact on fungal commnuities (Frey et al., 1999; Lu et al., 2018; Sun et al., 2018) which was reflected in presented study where re-ridging was associated with a decrease in the fungal 18:2ω6,9 marker as compared to non-ridging. This corroborates the findings of other studies which found significantly higher abundance of fungal biomass in Zero-tillage as compared with Conventional tillage (Frey et al., 1999; Mathew et al., 2012; Rahman et al., 2008). The negative impact of tillage on soil fungi was likely due to the inability of fungi to form hyphae in unstable environments with frequent soil disturbance (Wardle, 1995). Across all CC treatments, only Rye NR was found to have been linked to a significant increase in the 18:2ω6,9 fungal marker as compared to Conventional practice. Similar findings were reported by Mathew et al. (2012) who found that a non-ridged Rye treatment had an increased abundance of fungi compared to conventional tillage. Significant increase in 18:2ω6,9 fungal marker in mulch treatments corresponded to significantly lower dry matter content of soils under mulches as compared to bare soil and CC treatments. Consequenlty, both fungal 18:2ω6,9 and AMF 16:1ω5 markers were negatively correlated with dry matter content. Same results were reported by Frey et al. (1999), who also found positive relationship between fungal biomass and soil moisture content suggesting that fungal biomass is higher in soils with higher moisture content, such as in mulch treated soils.

The sum of bacterial PLFAs was significantly lower in mulch treatments, which were also linked to high concentrations of fungal and AMF biomass. This suggests that soil environments which benefitted fungal development were less favourable for colonisation by bacteria. Fungal 18:2ω6,9 PLFA was however not correlated to the sum of bacterial PLFAs. Nonetheless, bacterial PLFAs were significantly correlated the AMF 16:1ω5. Both AMF and bacterial PLFA indicators were also correlated with soil pH as relative abundance of bacteria decreased while AMF 16:1ω5 marker abundance increased with increasing pH. Although relative amounts of bacterial PLFAs were not affected by re-ridging, SSD in bare soils contributed to significantly higher bacterial abundance. Opinion on this subject varies; while some observed significant increase abundance of bacteria in zero-tillage managed soils (Rahman et al., 2008), others reported no impact (Frey et al., 1999; Mathew et al., 2012). Interestingly, while SSD did have a significant impact on soil bacteria, it had no impact on fungal concentrations while ridging did have a significant impact on soil fungi but not on soil bacteria, which would suggest that the impact of SSD and of ridging on soil microbiology varies. Although literature does not distinguish between the types of tillage when describing impacts of mechanical soil disturbance, whether it is type deep tillage, disking or ridging, results presented above suggest that the impact of tillage on soil microbiology depends on the type of disturbance.

Microbial community structures are an important factor governing nutrient turnover and availability (Frey et al., 1999). Contrary to findings of Schutter and Dick (2002) who claim that companion cropping was associated with changes in soil microbial community as compared to bare soil treatments, we found no significant effect of companion crops on soil microbial community in asparagus. Nontheless, that lack of response of soil microbial community to companion crops may explaied by the relatively short duration of the trial, which was only 3 years combined with a short application time of less than 6 months.

Limited amount of research has investigated the impact of soil microbial community structure on asparagus. Hamel et al. (2005) however found that shifts in the soil microbial community in asparagus (*Jersey Giant* cultivar) were associated with the onset of *Fusarium* crown and root rot (FCRR) suggesting that soil microbial community may play a key role in maintaining asparagus health. Though, it remains unclear whether changes in soil microbial communities could be a result of higher FCRR incidence or whether higher FCRR incidence is a result of shifts in microbial community structures as caused by abiotic factors such as tillage, intercropping or mulching (Hamel et al., 2005). Although this paper does not investigate differences in FCRR incidence between treatments, changes in soil microbial community following ridging an application of mulches suggest that investigation into pathological diseases should be included into the next stage of the trial assessment.

5.4.2 Soil Chemistry

5.4.2.1 Companion crops

Rye has been reported to increase SOM, especially in Zero-tillage systems (DeLaune et al., 2019; Mathew et al., 2012). Although CCs in general are often used to increase SOM and are linked to increased MBC and CEC (Bronick and Lal, 2005; Schutter and Dick, 2002), in this study, no increase in SOM, MBC or CEC was observed in the CC treatments compared to Conventional practice. In fact, CCs had very little impact on soil chemistry as compared to Conventional practice and Bare soil treatments. This is likely due to the relatively short time (circa 6 months since seed broadcast until termination) of CCs remaining undisturbed in the soil. The only exception was an elevation in exchangeable-K, levels of which were significantly higher in CCs as compared to Bare soil treatments. A similar finding was observed by DeLaune et al.

(2019) who reported significantly higher soil Exchangeable- K levels in rye as compared with non-rye treatments.

5.4.2.2 Mulches

Contrary to findings of Lee et al. (2019) who found that food waste compost application increased soil N content, the current study found significantly lower N levels in mulch treatments as compared to Bare soil treatments. This might be of concern as low N can lead to N immobilisation and impede plant N-uptake (Cogger, 2005; Pawlett et al., 2015). Furthermore, the mulches group of treatments had significantly higher levels of Exchangeable-Na as compared to all other treatments. Based on Stamatiadis et al. (1999), composts with high salts e.g. sodium-Na, may elevate soil electrical conductivity which may consequently decrease mineralizable-N content, thus lead to reduced nutrient cycling and plant growth. Straw decomposition can also lead to N immobilization and N consumption due to high C:N ratio of straw (Cheshire et al., 1999; Yan et al., 2018) which would explain results described above. Nutrient content of PAS 100 compost varies by each individual batch. In 2020 however, composted material analysis of PAS 100 showed N content of 777 mg l^{-1} (or 2580 mg ka^{-1} in dry matter). Thus, repeated annual application would have contributed to increased soil Na content. Nonetheless, N immobilisation promoted by composts with high Na content or by straw decomposition processes does not remove N from the soil, rather it is converted to forms which are not available to plants (Siedt et al., 2021). Furthermore, organic N can be easily re-mineralised by the soil microbial community, converting it back into plant available forms. Finally, immobile N will affect different crops differently. Although high N fertiliser input in asparagus systems have been reported to increase yields and plant growth (Drost and Pedersen, 2018), research has yet to provide a clear answer to nutrient requirements and nutrient uptake of asparagus. Multiple studies focused on answering questions about asparagus nutrient requirements, research conducted to date was however not able to draw definitive conclusions on relationships between nutrient application and asparagus growth (Brown and Carolus, 1965; Drost and Pedersen, 2018; Pitman et al., 1991). Furthermore, asparagus N uptake occurs only for a limited time, in the UK typically from June to October during the fern-stage, which has a potential to decrease asparagus N requirements compared to other crops (Paschold et al., 1996). Consequently, limited availability of N in asparagus systems may not be a limiting factor, especially due to increased amounts of microbial biomass associated with interrow mulching which have the ability to mineralise organic N into plant available forms (Siedt et al., 2021).

Type of mulch used in the experiment did have a significant impact on several variables. Use of PAS 100 compost was associated with significantly higher levels of Exchangeable Ca and Na, CEC and pH as compared to the Straw mulch. Lee et al. (2019) also found higher pH after food waste compost application in a pepper (*Capsicum annuum* L.) pot experiment. Contrary to studies reporting an increase in soil C, P and K concentrations in straw and composts amended soils (Pinamonti, 1998; Siedt et al., 2021), in the current study, none of these variables were significantly affected.

5.4.2.3 Tillage

Tillage affects soil nutrient concentrations and has been linked to decreased SOM and overall soil quality (Bronick and Lal, 2005; Lal, 1993; Rahman et al., 2008). The impact of tillage however depends on soil type, crop species, climate and management practice (Rahman et al., 2008). Research conducted over the past 50 years has been able to show that tillage in asparagus systems can have a major negative impact on both root growth and yields of asparagus (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). Although re-ridging significantly increased SOM, exchangeable-Ca and Mg and soil pH in interrows across all treatments, re-ridging was not associated with changes in SOM in bare soil treatments. This contradicts the prevailing paradigm of increased SOM in zero-tillage as compared to Conventional tillage systems (Frey et al., 1999; Jiang et al., 2011; Rahman et al., 2008). Re-ridging however significantly affected exchangeable-Ca, exchangeable-Mg, soil pH and CEC in bare soil treatments.

N content was not significantly affected by neither SSD or ridging, despite multiple studies previously linked higher N content to zero-tillage systems (Frey et al., 1999; Jiang et al., 2011; Mathew et al., 2012). Higher exchangeable-Ca and Mg levels in re-ridged as compared to non-ridged treatments may be linked to higher soil compaction levels in ridged treatments (Mašková et al., 2021). CEC dictates cation retention ability thus soils with low CEC can develop cation deficiencies (Brady and Weil, 1996). Although CEC was not significantly affected by ridging (p=0.07), CEC was significantly positively correlated with both exchangeable-Ca and Mg. It can be hypothesised that higher soil compaction levels may have led to reduced Ca and Mg leaching, thus contributed to higher Ca and Mg contents of re-ridged treatments. Similar was found by Thomas et al. (2007) who claims that although tillage had no impact on exchangeable-Ca content, exchangeable-Mg was greater in conventional tillage as compared to reduced and to zero-tillage. Same study also reported on significantly lower CEC in zero-tillage as compared to reduced or conventional tillage. Szatanik-Kloc et al. (2018) further found that CEC decreased in compacted soil by 28-45 %.

Rahman et al. (2008) however found higher Exchangeable K, Mg and Ca in zero-tillage as compared to conventional tillage systems while Ishaq et al. (2002) found that tillage had no impact on soil N or K content.

CEC is closely linked to soil pH as confirmed by positive correlation between these two variables in the current study. Re-ridging has been linked to a significant increase in soil pH from 5.3 in non-ridged treatments to 5.8 in ridged treatments. Soil pH was also positively correlated with the AMF 16:1ω5 marker. Overall, the influence of the AMF PLFA marker in the current asparagus trial was very strong. The 16:1ω5 marker correlation with bacterial PLFAs and soil pH was stronger compared to 18:2ω6,9 which is commonly used to indicate non-AMF fungal biomass, further contradicting findings of Bååth and Anderson (2003) who reported and strong relationships between soil pH and fungal 18:2ω6,9. Soil pH influences multiple soil processes, such as ion solubility, microbial activity and clay dispersion (Haynes and Naidu, 1998). The results of this study confirm that even minor changes in soil pH can drastically change soil microbial community. For example, the relative abundance of monosaturated 16:1ω5, 16:1ω7c and 18:1ω7 increased with increasing pH and i16:0 and cy19:0 decreased with increasing pH. Identical results were reported by multiple other studies (Bååth and Anderson, 2003; Fernández-Calviño et al., 2010; Rousk et al., 2010). In addition to pH, the soil microbial community was also influenced by tillage and annual ridging in particular. Initial pH measured in the field trial in 2016 was 6.3 (± 0.03) and by 2020, it decreased to a mean value of 5.6 (± 0.10) across all treatments indicating a significant decrease. Optimal pH range for asparagus had been established to be between 6.0-7.0 (Hazelton and Murphy, 2007) indicating that asparagus may have little tolerance towards acidic soils. Consequently, ridging, which was associated with higher pH compared to non-ridging, increased soil pH closer to the asparagus optimum. Nonetheless, literature reporting on the impact of tillage on soil pH varies. Many authors found that tillage had no impact on soil pH (Domínguez and Bedano, 2016; Edwards et al., 1992; Mathew et al., 2012; Neugschwandtner et al., 2014) while others observed higher soil pH in tilled soils as compared to zero-tillage (Hulugalle et al., 2007; Lal, 1999; Montesdeoca et al., 2020; Rahman et al., 2008). Rahman et al. (2008) suggests that lower soil pH in zero-tillage may be caused by debris decomposition enhancing microbial activity and concentration of electrolytes which resulting in reductions of pH levels. AMF communities themselves have been reported to be highly susceptible to soil disturbance (Jiang et al., 2011; Wilkes et al., 2020). Brito et al. (2012) found that conventional tillage decreased AMF diversity by 40% as compared to zero-tillage. Mathew et al. (2012) and Lu et al. (2018) also found that zero-tillage had a positive impact on AMF communities as compared to conventional tillage.

5.5 Conclusions

Although changes in soil chemistry and microbiology usually occur only after > 10 years of continuous treatment application, the results of this study indicate that only 3 years into the experiment, multiple significant differences in soil chemical and biological indicators have occurred as a result of annual BMP application in asparagus. Companion cropping was not associated with changes in biological or chemical parameters as compared with Conventional practice, likely a results of the relatively short trial duration in which 3 years of companion cropping may have not been long enough for significant changes to occur. Nonetheless, mulches and tillage practice did have a significant impact on both soil chemical indicators and soil microbial community. Low N levels in mulch treated interrows however may be of concern in cropping systems relying on N inputs. Furthermore, a strong relationship between soil pH and the relative abundance of AMF revealed that tillage practice, soil pH and soil microbial communities were closely linked. Scientific literature does usually not differentiate between different types of mechanical disturbance. Results presented by this research however showed that impacts of SSD and re-ridging on soil microbial community varied, suggesting that the type of tillage largely determines the changes in soil bio-chemistry. Decrease in microbial diversity and decrease in AMF have been associated with the onset of *Fusarium* CRR in asparagus (Hamel et al., 2005). Chronologycal order of these changes is however remains unclear. Results presented in the current study suggest that mulches and re-ridging had a profound impact on soil microbial community structure. Further research may provide evidence to confirm whether mulches or changes to the tillage practice may delay or prevent onset of FCRR in asparagus

5.6 References

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6 Synthesis

6.1 Introduction

This research programme aimed to critically evaluate a range of potential Best Management Practices (BMPs) to reduce the long-term negative impacts of conventional UK asparagus cultivation practices on soil compaction, the asparagus 'Root Engine' and yield. The research first analysed the impacts of BMPs and of tillage intensity associated with trafficking on soil compaction and on infiltration rates in the interrows (Chapter 5, objectives 1 and 3). Next focus was placed on assessing the impacts of BMP and of annual tillage intensity on key crop performance indicators such as root distribution, yield, yield quality and on potential profits (Chapters 3 and 4, objectives 2 and 3). The final part of the research critically evaluated relative differences in soil quality indicators (SQIs) between Conventional practice and BMPs and how tillage and interrow interventions such as mulches or companion crops affected the soil microbial community and physico-chemical SQIs (Chapter 5, objectives 2 and 3). Literature reviews presented in Chapter 2 – Chapter 5 identified gaps in knowledge in terms of lack of knowledge on alterative management practices to support sustainable asparagus production and environmental protection. Yet in order to conclude findings of this research and to understand the relationships occurring between metrics investigated in previous chapters, results need to be co-analysed and considered as a whole.

The aim of this final chapter of this thesis is therefore to further investigate and discuss relationships between crop performance indicators presented in Chapters 3 and 4 and SQIs presented in Chapters 2 and 5. This chapter will evaluate the latest data from 2020. Section 6.2 of this chapter will focus on investigating the links between soil compaction and crop performance indicators and SQIs. Section 6.3 will further address questions regarding asparagus physiology and investigate relationships between root development, root CHO content and yields. Cross-study analysis of relationships between all tested crop performance indicators and SQIs will be presented and discussed in Section 6.4. The impacts of the current conventional tillage practice on asparagus root system will be summarised in Section 6.5. Final evaluation of BMPs will be presented in Section 6.6. Finally, Section 6.7 of this chapter will discuss requirements for the wider adoption of tested BMPs and suggest directions for future research as well as make recommendations for their respective adoption by the UK and global industry.

6.2 Links between soil compaction, soil bio-chemical indicators and asparagus performance

Conventional asparagus production has been associated with gradual decline in crop productivity. Conventional practice applies excessive mechanical pressures resulting in high levels of soil compaction and in drastic shifts in soil microbial community structure consequently jeopardising soil systems future functionality. Soil compaction may be the most immediate impact of intensive agriculture which disrupts key soil functions such as water regulation (ability of soil to receive, retain and release water), nutrient cycling (Bronick and Lal, 2005; Novara et al., 2019; White and Kirkegaard, 2010) and microbial activity due to losses in soil biodiversity (Bronick and Lal, 2005). According to the FAO (2017), soil compaction and soil erosion are major threats to sustainable soil management. In England and Wales only, costs associated with the negative impacts of soil compaction were estimated to reach approximately £472 million per annum (Graves et al., 2015).

Chapter 2 focused on assessing differences in interrow compaction and water infiltration between treatments following 3 years of annual treatment application. Relationships between soil compaction and crop performance, soil nutrient content and soil microbiology were however not be analysed. Correlation analyses showed that compaction levels were significantly linked to multiple bio-physical and chemical metrics (Table 6-1). It was found that increased compaction in the interrows was linked to lower root mass density suggesting that decrease in productivity is not only linked to mechanical root damage (Putnam, 1972; Wilcox-Lee and Drost, 1991) but the impact of soil compaction on the size and development of the ‘Root Engine’ in asparagus should also be considered. Soil compaction is known to reduce root elongation in the majority of crop species (Clark et al., 2003; Whalley et al., 2007). Prior to this research, compaction had not established as a strictly limiting factor for root growth in asparagus. Although 3 years of continuous BMP treatment application was not enough for significant links between soil compaction and yields to emerge, it should be noted that further observations are needed due to the long (6-10yrs) commercial life expectancy of asparagus. It could by hypothesised that high penetrative resistance (PR) values may affect crop productivity long-term, especially due to already evident negative relationship between PR and root development (Table 6-1).High levels of soil compaction were further linked to elevated contents of soil N (Table 6-1), likely caused by reduced porosity of compact soils which would reduce vertical N leaching. An immediate effect of soil compaction is reduced porosity which restricts water movement (Lipiec and Stępniewski, 1995). Soil compaction reducing root growth may have also reduced N uptake by roots (Mašková et al., 2019; Siczek and Lipiec, 2011), which may explain higher N content of the compacted interrows. A number of PLFA markers were found to be positively or negatively correlated with compaction as represented by PR (Table 6-2). High PR values were, for example, linked to low relative amounts of arbuscular mycorrhizal fungi (AMF) indicated by the 16:1ω5 PFLA marker, low relative amounts of the fungal 18:2ω6,9 marker and to low relative amounts of the indicator of cyanobacteria or AMF, 20:4(5,8,4,11,14) (Nordby et al., 1981; Olsson et al., 1995). Thus, high compaction levels were associated with an overall decrease in soil fungi and cyanobacteria. As AMF has been shown to have a beneficial impact on asparagus (Matsubara et al., 2001; Pedersen et al., 1991; Wacker et al., 1990), it can be concluded that the decrease in AMF in asparagus due to high PR values is undesirable. Consequently, soil compaction in asparagus systems should be avoided due to its connections to reduced root development and reduced abundance of beneficial microbial taxa such as AMF.

Table 6-1. Correlation matrix showing Pearson correlation coefficients (r) between mean Penetration Resistance (PR) of the interrows for the whole measured profile (0-0.60m) as an indicator of soil compaction levels and all other experimental metrics (N = 43-48).

Crop performance indicators	PR	Infiltration rate
Yield	-0.27	0.19
Spear size	-0.10	-0.01
Revenue	-0.24	0.19
RMD	**-0.33***	0.28
CHO	-0.19	0.17
Total CHO	**-0.35***	**0.34***
Soil quality indicators		
Dry matter content	**0.30***	0.03
Microbial biomass carbon	**-0.38***	0.28
Soil organic matter	-0.11	0.04
Ergosterol	-0.20	0.14
Nitrate NO_{3-}	**0.40***	-0.16
Ammonium NH_4+	**0.46***	-0.19
Total N	**0.44***	-0.18
Ex Ca^{2+}	-0.18	-0.05
Ex K^+	0.27	0.00
Ex Mg^{2+}	0.28	**-0.33***
Ex Na^+	-0.28	-0.04
CEC	-0.02	-0.22
Soil pH	-0.17	-0.02
Available P	-0.01	0.10

RMD = root mass density, CHO = root soluble carbohydrate content, CEC = cation exchange capacity, PLFA = phospholipid fatty acid.

*Significant at p≤0.05.

Table 6-2. Correlation matrix showing Pearson correlation coefficients (r) between Penetration Resistance (PR) an indicator of soil compaction levels and all other experimental metrics (N = 43-48).

PLFA classification	PLFA Marker	2020 PR	2020 inf
Bacteria	14:0	-0.25	0.14
	15:0i	0.01	0.14
	15:0ai	-0.15	-0.06
	15:0	0.18	-0.08
	16:0i	0.12	0.05
	16:1w7c	-0.09	-0.01
	16:0	0.24	-0.12
	Me17:0 isomer	-0.01	-0.05
	17:0i	0.13	-0.13
	17:0ai	0.15	-0.12
	17:0c	**0.34***	-0.05
	18:1ω7t	**-0.30***	0.13
	18:0	0.22	-0.19
	18:0 (10Me)	0.11	0.13
	19:0c	**0.32***	-0.19
Methanotrophs	17:0br	0.27	-0.27
Fungi	16:1ω5	**-0.44***	0.17
	18:2ω6,9	**-0.52***	**0.42***
Cyanobacteria	18:1ω9c	**-0.29***	**0.43***
	20:4 (5,8,4,11,14)	**-0.43***	0.26
	20:5ω3	**-0.31***	-0.02
Unclassified	16:1ω11t	**-0.34***	0.12
	Me17:0 isomer2	0.13	-0.18
	cyc17:0 isomer	-0.27	0.12
	17:1ω8c	0.12	-0.07
	17:1ω8t	**0.40***	-0.23
	17:1ω7	-0.03	-0.11
	17:0 (12Me)	**0.45***	-0.26
	18:1ω13	**0.42***	**-0.37***
	19:1ω6	-0.08	-0.01
	20:0	0.01	-0.05

*Significant at p≤0.05. PLFA classification adopted from Olsson et al. (1995); Frostegard et al. (1993); Hanajík et al. (2016); Mitchell et al. (2010); Wilkinson et al. (2002) and Zelles (1997).

6.3 Links between root CHO, yields and RMD

Although Chapter 3 investigated asparagus yields and root CHO content as affected by the application of various BMPs, links between yields and CHO were not addressed. Extensive research claims that asparagus productivity is primarily determined by the root CHO content (Paschold et al., 2008; Shelton and Lacy, 1980; Wilson et al., 2008). Following a simple correlation analysis of yields and root CHO of all treatments, this study however found no relationship between these two variables. This corroborates the findings reported by Drost (2012). Drost (2012) and Paschold et al. (2008) however investigated the CHO-yield dependence further and found that the size of the root system needs to be accounted for when estimating CHO stores within the asparagus 'Root Engine' which can then finally be linked to asparagus productivity. Thus, total CHO was calculated using the method proposed by Drost (2012), which accounts for the dry root mass density (RMD) to obtain an estimate of the total field CHO stores (6-1):

$$\mathbf{Total\ CHO = Mean\ CHO\ content\ \times\ RMD} \tag{6-1}$$

Using this equation, a weak but significant relationship between total CHO and asparagus yields (Figure 6-1) was observed. Nonetheless, yields were already found to be positively linked to RMD ($r=0.36$, $r^2 = 0.13$, $p \leq 0.05$) (Table 6-3, Section 6.4). Hence, the source of significance in the correlation between the total CHO and yields may be the incorporation of the RMD in the equation.

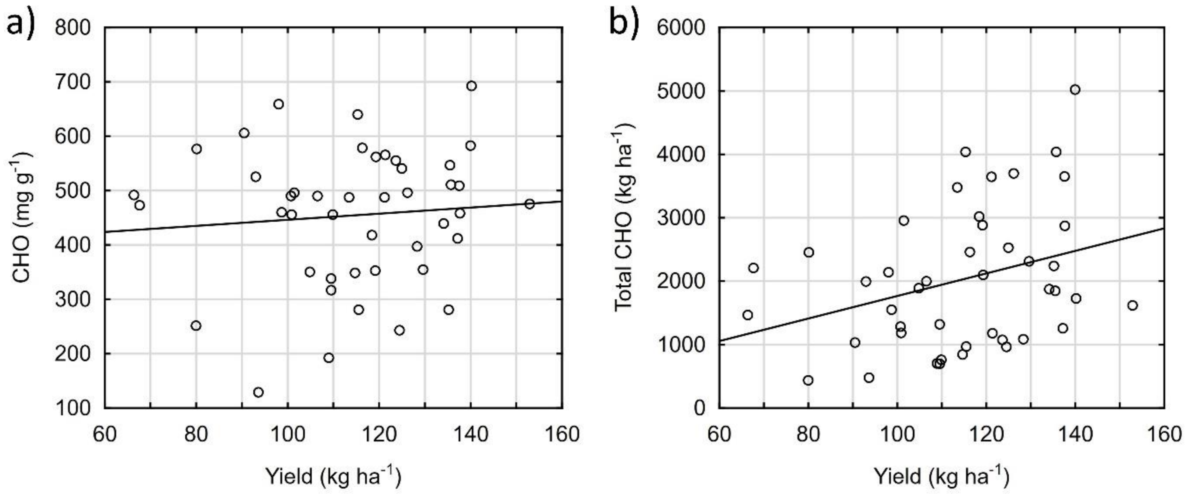

Figure 6-1. Relationships between; a) yield (kg ha^{-1}) and root CHO content (mg g^{-1}) ($r = 0.089$, $r^2 = 0.00$, p = NS) and between; b) yield (kg ha^{-1}) and total CHO content ($r = 0.32$, $r^2 = 0.10$, $p \leq 0.05$) (N=44).

6.4 Cross-study evaluation of the impacts of BMP application

Results of this research confirmed the existence of links between the application of BMPs to asparagus interrows and changes in key crop performance indicators. The results presented in Chapter 2 – Chapter 5 however address only some of these interconnections between variables and correlations within the whole dataset were not determined. Correlation coefficients establishing the strength and direction of relationships between variables are presented here using the Pearson correlation method with pairwise data deletion, which considers every numeric value pair separately thus variables with missing data do not result in case removal. Each coefficient was computed using between 43 to 48 variable pairs. Crop performance indicators were RMD (Chapter 3), yields (Chapter 4), potential profits calculated as a function of total yields and yield quality (Chapter 4), CHO (Chapter 4) and total CHO obtained by Equation 6-1 (Chapter 4).

The correlation results presented in Table 6-3 indicate that size of the asparagus 'Root Engine' and asparagus yields were significantly and positively correlated. Other research, however, suggests that asparagus productivity is dependent on the amount of CHO stored within the root system (Paschold et al., 2008; Shelton and Lacy, 1980; Wilson et al., 2008) rather than on the size of the 'Root Engine' itself. As RMD was found to be positively correlated to both yields and spear size, available evidence suggests that the total yield mass is dictated by the size of the 'Root Engine' rather than by the amount of energy (CHO) contained within it e.g., the fuel tank. It goes without saying that root CHO stores play a key part in asparagus physiological processes and drive spear production (Drost, 2012; Woolley et al., 1999). Nevertheless, measurements of CHO content of individual roots were not indicative of yields unless RMD was also included.

Table 6-3. Correlation matrix showing Pearson correlation coefficients (r) between each pair of crop performance indicators (N = 43-48).

	RMD	Yield	Spear size	CHO	Total CHO
RMD	1.00				
Yield	**0.36***	1.00			
Spear size	**0.41***	**0.72***	1.00		
CHO	0.01	0.09	-0.05	1.00	
Total CHO	**0.87***	**0.32***	0.28	**0.46***	1.00

RMD = root mass density, CHO = root soluble carbohydrate content.

Soil N content was not linked to crop performance with a single exception that of root CHO. As shown in Table 6-4, root CHO content was negatively correlated with ammonium-N. The literature suggests that there may be a competition between ammonium-N and carbohydrate assimilation in maize (Schortemeyer et al., 1997). High compaction levels were also linked to elevated N concentrations, suggesting that elevated compaction levels may negatively affect CHO assimilation. Results shown in Table 6-4 also showed a negative correlation between Mg content, yields and root growth. Magnesium deficiency symptoms were however linked to having a negative effect on asparagus fern as a partial of full fern chlorosis eventually progressing toward necrosis (AHDB Asparagus nutrient management, Crop Walkers Guide) which contradicts presented findings. Available P in the interrows was also positively correlated with yields and spear size which confirms the findings of Drost (2018) who found P additions to have a beneficial impact on asparagus yields.

Little is known about the relationships between the soil microbiology and asparagus growth and productivity. Analysing PLFAs has been proved useful for between site comparisons as management induced changes in the soil microbial community structure appear over the short-term, sometime within the space of a single year (Carter et al., 1999; McKinley et al., 2005). PLFA analysis however does not provide information about species diversity and richness which are the main characteristic of the soil microbiome known to have a positive impact on soil functions (Wagg et al., 2019). Consequences of a particular microbial structure on soil functioning and on soil-plant interactions have also been subject to very little research. Both soil fungi and bacteria form dynamic communities facilitating soil functions by modifying their environment (Deveau et al., 2018). Fungi have the ability to form new microhabitats and to increase soil pH towards neutral values above 5.0 which in turn stimulates bacterial growth (Deveau et al., 2018). Bacteria are able to withstand harsher environments (Schmidt et al., 2014) while fungi are highly susceptible to disturbance and soil management (Deveau et al., 2018; Schmidt et al., 2019).

As indicated by Table 6-4, soil microbial community structure was significantly linked to asparagus performance indicators. RMD was positively corelated with MBC while total yields were positively correlated with relative amounts of fungal PLFA. Nonetheless, a high abundance of soil fungal biomass in asparagus production systems can be of concern due to the risk of infections by soil-borne pathogens such as *fusarium oxysporum*. Dominant PLFA markers present in *Fusarium* isolates were identified to be 16:0, 18:0, 18:1ω9 and 18:2ω6,9 (Chen et al., 2001; Xiao et al., 2017). Consequently, 18:2ω6,9 which is commonly used as a fungal biomarker is also a major component of the Fusarium cell membrane. The presence of *Fusarium* in soil samples was however not determined by this research. It is critical that further research addresses the knowledge gap that currently exists in relationships between field management and the degree of disease occurrence in asparagus. Methods allowing detection of *Stemphylium vesicarium*, *Phytophthora asparagi* and *Fusarium oxysporum* in soil samples include DNA-sequence based identification or species-specific quantitative polymerase chain reaction (qPCR) assay. Based on PLFA data presented in Chapter 5, tillage (ridging and SSD) had no impact on neither 16:0, 18:0 and on 18:1ω9 makers which may be indicative of *Fusarium* in PLFA profiling. The fungal PFLA marker 18:2ω6,9 however was significantly more abundant in non-ridged treatments as compared to ridged. Should the relative abundance of 18:2ω6,9 also indicate the presence of *Fusarium*, these results would suggest that non-ridging is associated with significantly higher abundance of this pathogenic fungi. Results however also suggest that higher yields were associated with higher concentrations of the 18:2ω6,9 PLFA marker which may be considered an indicator of the presence of beneficial fungi rather than pathogenic organisms. Interestingly, Gu et al. (2020)

found that Fusarium was associated with elevated soil P levels. Although as mentioned above, the presence of Fusarium at the trial site has not been confirmed, the correlation analysis (Table 6-4) indicates that available-P was significantly and positively related to the relative abundance of several PLFA markers associated with Fusarium, namely 16:0, 18:1ω9 and 18:2ω6,9 (r=0.39, 0.37 and 0.33, respectively) (Chen et al., 2001; Xiao et al., 2017).

Multiple PLFA markers were significantly correlated to at least one of the crop performance indicators (Table 6-4). One PLFA marker in particular however, 18:1ω13, was negatively correlated to all but one crop performance indicator, which was CHO. Evidence suggests that the 18:1ω13 PFLA marker may be indicative of the presence of methanotrophic bacteria (Singh and Tate, 2007). Methanotrophs mediate biological oxidation of methane-CH_4, and are able to degrade environmental contaminants (Singh and Tate, 2007). Although methane oxidation can occur in both aerobic and anaerobic conditions (Holmes et al., 1999), 18:1ω13 was also significantly higher in compact soils (r=0.42) suggesting prevalence of this marker under anaerobic conditions. As relative concentrations of 18:1ω13 were associated with decrease in yields and root growth, 18:1ω13 presence in soils within asparagus systems was linked to negative impacts on overall crop performance as associated with soil compaction. Finally, it is critical to recognise that several PLFA markers were found to be significantly related to asparagus yields, underlining the importance of soil microbial structure in asparagus production systems.

Table 6-4. Correlation matrix showing Pearson correlation coefficients (r) between each variable pair (N = 43-48). PLFAs include **markers significantly correlated with at least one of the crop performance indicators.**

	Yield	Spear size	Potential profits	RMD	CHO	Total CHO
Dry matter content	0.17	-0.16	0.12	0.01	0.01	0.07
Soil organic matter	0.23	0.10	0.15	-0.04	0.28	0.15
Ergosterol	0.21	0.23	0.01	0.10	0.00	0.04
Nitrate NO_{3-}	0.03	0.09	0.02	0.01	-0.18	-0.02
Ammonium NH_4+	-0.10	-0.01	-0.10	0.05	**-0.33***	-0.06
Total N	-0.03	0.05	-0.03	0.03	-0.26	-0.04
Ex Ca^{2+}	-0.10	-0.15	0.00	-0.15	0.03	-0.12
Ex K^+	0.15	0.25	0.07	0.10	-0.23	-0.02
Ex Mg^{2+}	**-0.38***	-0.19	**-0.36***	**-0.36***	-0.01	**-0.31***
Ex Na^+	0.15	0.18	0.07	0.00	-0.09	-0.07
CEC	-0.13	-0.06	-0.08	-0.27	-0.12	**-0.31***
Soil pH	-0.11	-0.16	-0.01	-0.15	0.03	-0.11
Available P	**0.30***	**0.34***	0.14	0.15	-0.21	0.05
MBC	0.21	0.16	0.20	**0.30***	0.01	0.27
Fungal PLFA	**0.30***	0.11	0.19	0.20	0.19	0.23
Bacterial PLFAs	0.04	-0.08	-0.03	-0.03	-0.22	-0.12
PLFA						
17:0i	-0.09	-0.18	-0.16	**-0.29***	0.00	-0.27
17:0ai	0.06	-0.03	-0.07	0.02	**-0.34***	-0.18
17:0c	**-0.39***	-0.22	**-0.36***	-0.08	0.02	-0.06
17:1ω8t	**-0.41***	-0.21	**-0.37***	-0.11	-0.08	-0.13
18:2ω6,9	**0.31***	-0.03	0.20	0.21	0.19	0.24
18:1ω9c	**0.39***	-0.05	**0.35***	0.11	0.26	0.22
18:1ω13	**-0.53***	**-0.45***	**-0.44***	**-0.46***	-0.11	**-0.44***
18:0 (10Me)	**0.38***	0.14	**0.32***	0.15	0.02	0.15
20:4 (5,8,4,11,14)	**0.33***	0.23	0.22	**0.30***	0.09	0.26
20:5ω3	0.26	**0.39***	0.19	0.12	-0.06	0.03

*Significant at $p \leq 0.05$. RMD = root mass density, CHO = root soluble carbohydrate content, PLFA = phospholipid fatty acid, CEC = Cation exchange capacity, MBC = Microbial biomass carbon

6.5 The magnitude of the effect of annual re-ridging on asparagus root system

Tillage has been reported to promote asparagus decline (Myers, 2011; Snowdon, 1991), however the magnitude of this impact has not been quantified before. Furthermore, research seldom distinguishes between subsoiling and ridging when referring to tillage. Ridging is a main part of what is considered to be the UK conventional growing practice. Results presented in Chapters 2 to 5 showed that SSD and ridging should be considered as two separate practices which impact crop and soil properties very differently. While SSD has an ability to reduce interrow compaction and increase infiltration rates without any major negative impacts on the asparagus ’Root Engine’ or productivity, annual re-ridging was associated with reductions in RMD, yield productivity and severely aggravated compaction in interrows.

While SSD is linked to soil sub-surface disturbance to circa 0-0.25m depth with minimal concurrent disruption to the soil surface, ridging effectively strip soil from the interrow and transfers it on top and to the sides of the asparagus ridges. Consequently, although SSD loosens compacted interrows and while doing so potential root breakage can occur, it also generates cracks and macropores in the soil enabling root growth and enhancing water movement. Ridging on the other hand causes major compaction issues (Mašková et al., 2021) while disturbing and re-organising the whole microbial community present on and close to the soil surface in the interrow. Annual re-ridging disturbs soil stabilisation processes, removes plant residues and exposes bare soils to soil erosion and at the same time inflicts further compaction due to vehicular traffic when the soil is close to field capacity. Ridging can also inflict mechanical damage to roots which can extend to the shoulder of the ridge and further into the interrows. Although the working depth of the ridger is only approximately 2.5 cm in the interrow centres, it is enough to effectively damage all roots located close to the soil surface. Furthermore, unlike SSD, ridging can damage roots as close as 0.3 m to the asparagus crown in the shoulder of the ridge which has a potential to promote crown infections by pathogenic organisms (Elmer, 2015; Falloon and Grogan, 1991). Nonetheless, damaging storage roots may not be the only cause of negative impacts on asparagus health. Drost and Wilcox-Lee (2000) argued that tillage occurring immediately prior to the harvest season also damages fibrous roots at their most active thus restricting nutrient and water uptake. Consequently, ridging can negatively affect asparagus not only by reducing the size of the ’Root Engine’, increasing soil compaction and through introduction of diseases but also by disrupting the ability of plants to intake soil resources.

6.6 Comparative treatment performance evaluation

A comparative treatment performance evaluation was carried out to identify BMPs with the most desirable overall impact across multiple performance indicators, which were described in Chapters 2, 3 and 4. The evaluation was based solely on the assessment of the most recent 2020 dataset.

Treatment relative impact scores were derived using the *post-hoc* Fisher Least Significant Difference (LSD) test, which shows statistically significant differences between pairs of treatments. In tables, significant differences are indicated by a letter or a group of letters following every value. Impact score values were assigned based on these between-treatment differences. Supplementary information describing the full calculation process is included as an appendix (Appendix A). Soil physical indicators and crop performance indicators used in the evaluation matrix included only values in which positive or negative impact can be determined. For example, soil microbial community values could not be included due to varying interpretation options. Performance indicators used in the assessment were RMD, yield, spear size, potential revenue reflecting impacts of total yields and spear quality on revenue, total CHO representing the total potential field CHO content per area unit, PR and infiltration rates. Individual scores were awarded based on higher values being more desirable as compared to low values with the exception of soil compaction where lower compaction values are preferred. Final impact scores range between 0 to 1 with 0 being the worst and 10 being the best, as:

- Close to or at 0 = Management practice carries a major risk to the crop growth, productivity and soil functionality
- Close to or at 10 = Management practice benefits crop growth, productivity and soil functionality

Calculated relative scores indicate that the application of the Conventional practice with the lowest impact score of 2.5 carries the highest overall risk to asparagus health, productivity, profitability and soil functionality, consequently risking asparagus stand longevity (Figure 6-2). Impact scores further indicate that all other treatments were associated with scores higher as compared to Conventional practice. This finding suggests that the BMPs can be adopted to drive a major change in the way asparagus is cultivated in the UK. Highest scores between 7.0 to 9.1 were linked to the use of mulches implying that mulch applied to asparagus interrows in association with SSD has not only beneficial impacts on crop health and productivity but also reduces negative impacts associated with re-ridging

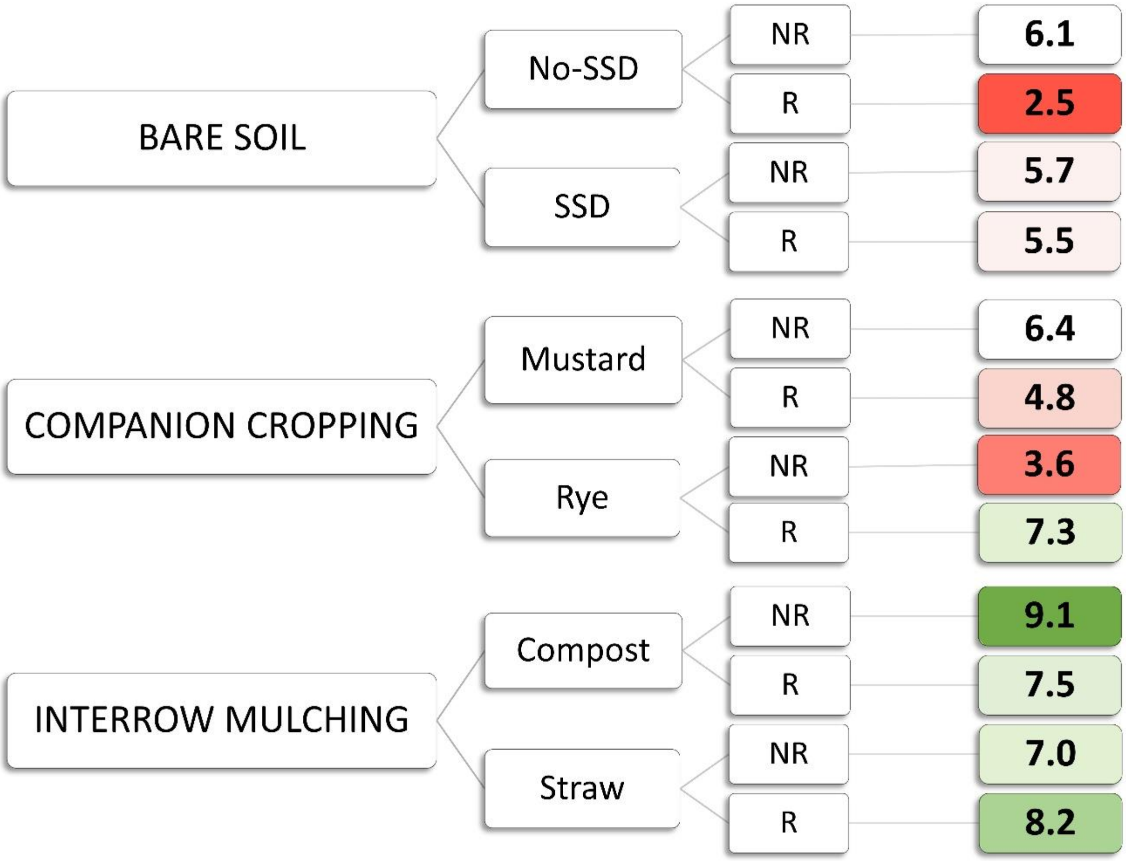

Figure 6-2. Final impact scores related to the use of different BMPs, ranging from 0 (worst) to 10 (best). Bare soil No-SSD R treatments is the Conventional practice equivalent. Detailed impact score calculation method is included as an Appendix A.

6.7 Wider impacts and recommendations for future research

This research has demonstrated the effectiveness of the BMPs, evaluated to have beneficial impacts on soil health, crop health and productivity in UK asparagus. The next section discusses wider impacts of the research conducted in this thesis and suggests areas for future research.

6.7.1 Global impacts

Domestic asparagus production is struggling to match the pace of increasing demand and popularity as reflected by growing import rates which rose between 2014 and 2019 by nearly 25%. Import rates currently account for approximately 70% of the domestic consumption (Defra, 2020). Due to these high import rates from countries experiencing severe water scarcity such as Spain, Mexico or Peru, UK consumed asparagus has been rated as the highest energy demand vegetable out of a list consisting of a total 56 vegetable products (Frankowska et al., 2019). These facts underline the importance of research into alternative growing practices to support the increase of sustainable domestic asparagus production. Undertaking such steps could potentially decrease the dependence of the UK retail sector on air freight and decease primary energy demand and greenhouse gas emissions associated with the import of the fresh produce (Frankowska et al., 2019).

6.7.2 BMP evaluation

It is important to acknowledge that the evaluation matrix presented in Section 6.6 was based on data obtained in the 3rd year of treatment application within a single field trial, thus should be used as a relative comparison between BMPs applied and monitored. In wider application, impacts of BMPs presented and rated in this research may vary from site to site. Thus, confirming applicability of presented results on a wider scale within the wider grower community is crucial. Testing a selection of BMPs described by this research in other parts of the UK could feed into a database for the development of weight factors to optimise impact scores by local conditions such as soil type, local climate or asparagus cultivar. It is envisaged that correcting the evaluation matrix with data obtained from a more diverse grower base would allow for wider application of BMPs within the UK asparagus industry.

Zero-tillage treatment has been shown to have no negative impacts on compaction levels suggesting that Zero-tillage may be a better and cost-effective alternative to the Conventional practice due to reduced machinery requirements. Yields from Zero-tillage treatments were also significantly higher as compared to the Conventional practice suggesting increased profitability associated with the Zero-tillage treatment. Impact of the treatment on runoff and soil erosion has not been tested however infiltration rates were not significantly different from the Conventional practice. Offsite environmental impacts of the BMPs thus remain unknown. Data provided by this research however suggests that systems based on reduced tillage should be addressed in future research.

Results presented by this research showed that mulches in combination with SSD were associated with increased levels of productivity. PAS 100 Compost in particular was associated with significantly higher (18-20%) yields as compared with the Conventional practice. Further research is required to determine the specific reasons for this yield uplift. Thus, the use of mulches in combination with SSD in asparagus systems should be investigated further with regards to changes in soil nutrient content and in soil microbial community structure. The mulch-SSD treatments were also effective in alleviating compaction beyond the working depth of the subsoiler. Soil compaction in modern agriculture is extremely costly and difficult to remediate and mulch-SSD treatments could provide an effective way to prevent and reduce subsoil compaction not only in asparagus but also in other row crops. It has been previously shown that mulches (without SSD) in asparagus interrows are effective in reducing soil loss generated by surface runoff (Niziolomski et al., 2020). Consequently, mulch-SSD treatments applied to asparagus interrows can potentially enhance spear production rates and also ensure that measures to reduce environmental impacts of asparagus production have been taken. It has also been suggested that outcomes of this research can provide evidence that land management planning provides benefits for farmers while delivering valuable environmental outcomes such as reducing levels of soil erosion and run-off to support policy discussions associated with the future Environmental Land Management scheme (ELMS) in England.

The research showed that mustard was not associated with significant benefits to either soil quality or asparagus productivity. The benefits/impacts of Rye as a companion crop however, although commonly used within the North American asparagus industry, was found to be strongly depend on whether annual ridging was applied or not. Companion cropping is considered to be a common practice applied to a variety of field crops. Based on this research however, companion crops in asparagus should be investigated further investigating alternative species such as oats (*Avena sativa*) prior to wider industrial application.

Finally, this research provided evidence that the application of the current Conventional practice carries a major risk to the crop growth, productivity, stand longevity and soil functionality. Thus, this practice should be revised and replaced by one of the BMPs investigated in this study to ensure sustainable asparagus production and soil protection.

6.7.3 Asparagus yields and root CHO content

Within the asparagus science community, root CHO values are often used in yield prediction models. Nonetheless, none of the 3 years of yield data has been found to be related to root CHO content. Yields were however found to be linked to root mass density. The research thus suggests that yield prediction models by CHO may not be practical and need to be subject to further extensive research.

Scientific literature has never linked asparagus yields to the soil microbial community structure. Results presented in Chapters 5 and 6 however showed multiple soil microbial community markers were correlated with yields. This would suggest that in order to gain full understanding on asparagus yield physiology, it is critical that further research addresses the lack of knowledge about relationships between spear production and specific soil quality indicators. Soil microbial community structure in particular may be a crucial component in asparagus production. High abundance of fungi in soils cropped with asparagus can be indicative of both beneficial and pathogenic species. In order to determine the full scale of impacts of potential BMPs on asparagus, further research needs to be undertaken to include species-specific soil analyses to quantify contents of pathogenic species such as *Fusarium.*

6.7.4 Future research

This research provided evidence underlining the importance of future research directed towards BMPs in asparagus. While this research observed and evaluated the impacts of BMPs on 3 year old plants, the commercial life-span of asparagus normally ranges between 10-15 years. Although some meaningful differences could be observed in the current trial after 3 years of data collection, longer-term observations need to continue in order to assess the long-term impact of BMPs on preventing or delaying the onset and rate of asparagus decline and to confirm treatment profitability. Continued observations are critical in order to assess relative abundance of diseases such as crown and root rot. Future research should focus on carrying out a cost-benefit analysis of treatments application. Although potential revenues based on treatment productivity and yield quality were calculated in Chapter 4, the full financial implications of adopting these practices need to be evaluated.

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7 Conclusions

This research aimed to address the lack of alternatives to the UK Conventional asparagus management practice which has been linked to high rates of soil erosion and early decline in asparagus productivity. The research further sought to identify a set a BMPs to reduce negative impacts of the Conventional practice on soil quality and on crop performance indicators. This study is the first study to use BMPs in asparagus cropping systems to investigate the impacts of annual tillage (as differentiated between annual ridging and shallow soil disturbance in interrows) on yields, yield quality, potential revenues, soil compaction, soil bio-chemical indicators and on shifts in microbial community structure caused by the treatment applications.

Key findings:

- BMPs were effective in alleviating soil compaction of the interrows and confirm that annual re-ridging in the absence of SSD was associated with increased compaction levels (Chapter 2, objectives 1 and 3).
- BMPs were associated with changes to the size of ’Root Engine’ and root distribution. Application of SSD or the application of mulches in combination with SSD increased resilience of the root system to adverse conditions. It was suggested that re-ridging without SSD may increase susceptibility of the asparagus root system to negative abiotic factors resulting in overall reductions in its size (Chapter 3, objectives 2 and 3).
- BMPs had a significant impact on asparagus yields and on overall profitability as compared with Conventional practice. There was however

a lack of response of root CHO content to BMP application (Chapter 4, objectives 2 and 3).

- Use of BMPs was associated with changes in soil bio-chemical indicators. Ridging in particular had a strong impact on soil microbial community structure (Chapter 5, objectives 2 and 3).
- Annual re-ridging associated with the current Conventional practice was found to carry major risks to crop growth, productivity and soil quality (Chapters 2, 3, 4 and 5).
- Use of mulches in combination with shallow soil disturbance in asparagus interrows was associated with multiple benefits to the crop performance and soil quality. Interrow mulching further significantly reduced the severity of negative impacts associated with re-ridging on crop growth, crop productivity and soil compaction. Consequently, interrow mulching is recommended for wider practical application (Chapter 6) .

Results presented in Chapter 2 identified that annual re-ridging is the main cause of extreme compaction levels of the interrows. Zero-tillage treatment which is effectively a modification of the Conventional practice without annual re-ridging was associated with significantly lower compaction levels as compared to the Conventional practice, further confirming the scale of negative impacts ridging had on soil compaction. It was also found that compaction levels of the Zero-tillage treatment after a complete 3 year absence of tillage did not exceed legacy compaction levels which were obtained during the trial establishment period. This is an indicator of increased soil resilience to the effects of vehicular and foot-traffic associated with asparagus field management and harvest. Although companion cropping was not effective in remediating compaction levels compared to the Conventional practice, interrow mulching with compost and straw mulch (in combination with SSD) significantly decreased compaction levels beyond the working depth of the subsoiler. Finally, soil compaction negatively affected root mass density (RMD). Although links between soil compaction and yields were not statistically significant, it may be expected that through reductions to the 'Root Engine', high compaction levels will have a negative impact on yields in the longer-term (section 0).

Year-to-year weather conditions were found to significantly affect RMD. RMD values of all treatments decreased from 2019 to 2020 however the reduction was significant only for the Conventional practice and both companion crop treatments which were re-ridged. Re-ridging with the absence of SSD thus likely increased crop susceptibility to adverse weather conditions linked to the inability to recharge soil moisture further impeding the ability of plants to replenish root carbohydrate stores. Findings presented in Chapter 3 further suggest that the use of mulches in combination with SSD helped stabilise the size of the mature 'Root Engine'. It was further found that high compaction levels are likely a limiting factor for asparagus root growth.

BMPs were found to have the ability to significantly improve yield quantity, quality and potential revenues. As stated in Chapter 4, SSD did not affect crop productivity or profitability. Re-ridging with the absence of SSD was however linked to overall yield reduction. Revenue calculation further revealed that

Conventional practice could potentially result in revenue losses of up to £5,500 ha^{-1} per annum as compared to the Zero-tillage practice. Yield values obtained from treatments under companion crops showed that companion cropping in UK asparagus systems needs to be approached with special caution in regard to asparagus productivity. This was due to unprecedented significant yield reductions associated with the rye treatment managed without ridging as compared to re-ridged rye suggesting that growers would potentially risk a *circa* 20% yield penalty if field conditions prohibit application of ridging. These effects were reported from the beginning of the experiment and imply underlying competition between asparagus and rye. As mustard did not exhibit these effects, it was suggested that although rye cannot be recommended at this time, other companion cropping options should remain available for future investigation. Compost application in combination with SSD in particular was associated with significant yield uplifts as compared to the conventionally managed plots. Productivity of treatments managed under PAS 100 compost in combination with SSD was also not affected by re-ridging. BMPs had an overall impact on total yields but also on yield quality which effectively determined potential revenues. Consequently, adoption of BMPs other than the Conventional practice has the potential to generate additional incomes of up to £7,600 ha^{-1} per annum.

Root soluble carbohydrate content (CHO) was investigated in response to great coverage of the topic in the scientific literature. Results presented in Chapter 4 however showed that contrary to the prevailing paradigm, CHO content between treatments did not differ, alongside the overall absence of relationships between root CHO and crop productivity (Section 6.3).

BMPs were also associated with shifts in soil microbial community structure (Chapter 5). Re-ridging significantly reduced the relative abundance of soil fungi compared to non-ridging. It was further found that the relative concentrations of arbuscular mycorrhizal fungi and relative concentrations of soil bacteria were linked to soil pH which was significantly higher in re-ridged treatments. This observation of the relationship between re-ridging, soil pH and soil microbial community indicated that ridging has the ability to drastically modify soil conditions. This research also showed that although scientific literature does not usually differentiate between types of tillage (SSD or ridging), the type did play a significant role in transforming the soil microbial community structure. The use of mulches was also associated with changes to the soil microbiome. Mulches contributed to higher relative concentrations of arbuscular mycorrhizal fungi and fungal biomass. Mulches however also had a strong effect on soil N levels which were significantly reduced in mulch as compared to all other treatments. This finding may have implications for nutrient cycling, plant nutrient uptake and potentially affect plant growth. In asparagus systems, high concentrations of soil fungi may also be an indication of the presence of soil-borne fungal pathogens such as *fusarium oxysporum* (Section 6.4). Although this research does not confirm the presence of Fusarium, high relative concentrations of fungal biomass in asparagus may be associated with long-term negative impacts on asparagus productivity and will need to be addressed by subsequent research.

In conclusion, the presented research showed that the field management practice currently adopted by the majority of British asparagus growers is unsustainable and poses high risks to both the soil environment and asparagus productivity. Through evalutation of this unique experimental field trial, this research further adressed critical knowledge gaps on the links beween asparagus performance, field managament and soil quality, and generated new knowledge by identifying and evaluating a set of management practices to be considered for practical application.

APPENDICES

Appendix A Final impact score formula

Impact scores were derived the *post-hoc* Fisher Least Significant Difference (LSD) test, which compares mean values of every treatment pair to indicate significant differences between treatments. Based on these differences, each treatment was assigned a relative performance score. Significant differences between treatments were in Chapters 2, 3 and 4 indicated by letters or by a group of letters following each value, which brought forward and used to form a classification system. For each variable, letters or groups of letters were sorted alphabetically and assigned a score value, ranging from the worst to the best. As an example, impact points for the total CHO variable were deducted from letters indicating significant between-treatment differences shown in Table A-1. Within the Total CHO column, there is a set of 3 letter combinations of ‘a’, ‘ab’ and ‘b’. These were assigned values of ‘a’ = 1; ‘ab’ = 2; ‘b’ = 3. These final points are shown in Table A-2. The amount of impacts points per treatment ranged between a minimum of 7 points to a maximum of 44 points. The final impact score was obtained by dividing the impact point (IP) value by the sum of maximum obtainable points (IP_{MAX}), as follows (A-1):

$$\mathbf{Final\ impact\ score} = \frac{\sum_{\mathbf{n=1}}^{\mathbf{7}} \mathbf{IP}}{\mathbf{IP_{MAX}}} \times \mathbf{10} \qquad \mathbf{(A\text{-}1)}$$

Table A-1. Letters obtained from the *post-hoc* Fisher Least Significant Difference (LSD) test, indicating significant differences between treatments for each indicator measured in 2020, including root growth, total yields, potential revenues, total CHO, soil compaction and water infiltration rates.

Treatment	RMD	Yield	Spear weight	Potential revenue	Total CHO	PR	Infiltration rate
*Zero-tillage	bcdef	bcde	de	ab	ab	a	ab
**Conventional practice	a	ab	abc	a	a	ab	a
Bare soil SSD NR	abcde	abc	abcd	a	b	ab	de
Bare soil SSD R	abcde	ab	ab	ab	b	b	de
Mustard NR	abcde	abcde	bcde	ab	ab	b	c
Mustard R	abcd	abcd	abcd	ab	ab	b	ab
PAS 100 NR	bcdef	e	e	b	b	c	d
PAS 100 R	abcd	de	abcde	b	ab	c	de
Rye NR	ab	a	a	a	ab	cd	bc
Rye R	abc	cde	e	b	ab	cd	abc
Straw Mulch NR	abcde	abcd	bcde	ab	ab	cd	de
Straw Mulch R	abcde	abcde	cde	ab	b	d	e

*Bare soil No-SSD NR; **Bare soil No-SSD R. RMD = root mass density; CHO = root soluble carbohydrate content, PR = penetration resistance.

Table A-2. Relative treatment performance score matrix. Impact points deducted from between-treatment significance indicators shown in Table A-1 following the process described in Appendix A. Final impact score was obtained following the equation (A-1).

Treatment	RMD	Yield	Spear weight	Potential revenue	Total CHO	PR	Infiltration rate	IP	Final impact score
*Zero-tillage	6	6	8	2	2	1	2	27/44	6.1
**Conventional practice	1	2	3	1	1	2	1	11/44	2.5
Bare soil SSD NR	5	3	4	1	3	2	7	25/44	5.7
Bare soil SSD R	5	2	2	2	3	3	7	24/44	5.5
Mustard NR	5	5	6	2	2	3	5	28/44	6.4
Mustard R	4	4	4	2	2	3	2	21/44	4.8
PAS 100 NR	6	9	9	3	3	4	6	40/44	9.1
PAS 100 R	4	8	5	3	2	4	7	33/44	7.5
Rye NR	2	1	1	1	2	5	4	16/44	3.6
Rye R	3	7	9	3	2	5	3	32/44	7.3
Straw Mulch NR	5	4	6	2	2	5	7	31/44	7.0
Straw Mulch R	5	5	7	2	3	6	8	36/44	8.2

*Bare soil No-SSD NR; **Bare soil No-SSD R. RMD = root mass density; CHO = root soluble carbohydrate content, PR = penetration resistance; IP = impact points.

Appendix B Baseline soil parameters

Table B-1. Soil parameters based on measurements taken in 2016-2017, during the field trial establishment period.

ID	Soil organic matter (%)	Available P (mg kg^{-1})	Available Mg (mg kg^{-1})	Available K (mg kg^{-1})	Soil pH	Total N (%)	Total C (%)	C/N Ratio
1	2.58	11.3	172	57.8	6.38	0.12	1.19	9.90
2	2.53	9.00	171	41.6	6.34	0.11	1.05	9.28
3	2.59	8.70	167	44.8	6.47	0.12	1.06	9.09
4	2.76	8.30	191	48.0	6.12	0.12	1.10	9.20
5	2.64	10.1	178	54.2	6.21	0.12	1.17	9.42
6	2.74	9.20	174	70.7	5.80	0.11	1.02	9.15
7	2.74	9.70	179	58.7	6.43	0.13	1.14	9.00
8	2.91	10.0	180	82.7	6.40	0.14	1.36	9.72
9	2.68	9.00	174	67.2	6.30	0.13	1.18	9.15
10	2.80	5.70	167	67.8	6.21	0.12	1.16	9.79
11	2.95	6.40	193	45.8	6.05	0.13	1.22	9.19
12	3.07	7.50	185	56.6	6.83	0.13	1.27	9.49
13	2.84	7.90	200	55.2	6.54	0.13	1.30	9.64
14	3.29	7.40	195	53.3	6.64	0.14	1.32	9.33
15	2.84	6.90	190	47.4	6.43	0.14	1.34	9.68
16	3.17	7.10	189	55.7	6.41	0.13	1.32	10.2
17	3.36	9.30	173	62.0	6.63	0.14	1.52	10.7
18	2.68	7.20	170	60.8	6.20	0.13	1.30	10.1
19	3.01	6.90	178	53.5	6.50	0.13	1.42	11.1
20	3.18	8.80	156	78.4	6.21	0.14	1.39	9.82

ID	Soil organic matter (%)	Available P (mg kg^{-1})	Available Mg (mg kg^{-1})	Available K (mg kg^{-1})	Soil pH	Total N (%)	Total C (%)	C/N Ratio
21	2.90	5.30	148	80.4	6.32	0.13	1.24	9.51
22	2.77	7.20	148	51.4	6.13	0.12	1.18	9.62
23	3.06	8.70	159	67.3	6.54	0.13	1.29	9.67
24	3.08	8.10	143	113	6.70	0.12	1.14	9.58
25	3.15	6.10	164	60.2	6.07	0.13	1.29	10.3
26	2.88	5.20	157	60.1	6.20	0.12	1.14	9.70
27	3.03	7.60	152	78.6	6.06	0.12	1.22	9.81
28	2.84	7.60	141	49.8	6.40	0.11	1.18	10.6
29	2.86	9.40	136	57.0	6.70	0.11	1.06	9.50
30	2.93	8.40	149	54.8	6.22	0.12	1.15	9.66
31	3.19	11.3	149	68.6	6.77	0.13	1.25	9.54
32	3.35	11.6	161	72.9	6.24	0.14	1.37	9.80
33	2.67	9.30	156	65.8	6.32	0.13	1.25	9.63
34	2.92	10.1	152	66.5	6.22	0.12	1.13	9.62
35	2.90	10.5	174	52.9	6.57	0.13	1.24	9.71
36	3.11	14.0	175	62.9	6.16	0.13	1.39	10.5
37	2.89	11.8	163	57.1	6.46	0.15	1.55	10.6
38	2.59	12.2	162	71.7	6.34	0.14	1.38	9.91
39	2.70	12.0	163	75.2	6.23	0.13	1.37	10.2
40	2.73	12.3	156	88.7	6.37	0.13	1.33	10.1
41	2.48	11.0	152	62.0	6.01	0.12	1.15	9.62
42	2.47	10.3	144	89.9	6.12	0.13	1.25	9.62
43	2.57	9.30	160	62.0	6.10	0.12	1.20	9.69

ID	Soil organic matter (%)	Available P (mg kg^{-1})	Available Mg (mg kg^{-1})	Available K (mg kg^{-1})	Soil pH	Total N (%)	Total C (%)	C/N Ratio
44	2.76	10.3	196	84.7	6.36	0.14	1.36	9.82
45	2.66	9.30	178	51.7	6.70	0.12	1.24	9.96
46	2.47	9.50	184	49.9	6.21	0.11	1.14	10.1
47	2.71	8.10	176	48.0	6.16	0.12	1.12	9.31
48	2.39	9.40	156	42.9	6.20	0.11	1.05	9.57
49	2.59	11.5	156	47.5	6.37	0.14	1.36	9.94
50	2.73	12.5	153	50.3	6.27	0.13	1.28	10.1
51	2.47	10.1	159	51.6	6.25	0.13	1.18	9.44
52	2.31	10.8	143	51.0	6.23	0.12	1.17	9.89
53	2.61	11.6	129	49.6	6.44	0.13	1.32	9.99
54	2.63	9.50	142	62.5	6.37	0.12	1.26	10.1
55	2.47	10.5	133	65.9	6.32	0.10	1.09	10.4
56	2.62	9.10	148	71.1	6.09	0.12	1.16	9.56
57	2.63	8.70	151	50.5	6.23	0.13	1.23	9.57
58	2.63	10.8	170	55.2	6.66	0.13	1.31	9.98
59	2.77	9.30	178	47.2	6.29	0.13	1.27	10.0
60	2.60	9.30	184	44.2	6.41	0.12	1.18	10.0
61	2.64	7.90	184	46.6	6.50	0.13	1.30	9.71
62	2.67	8.10	170	40.5	6.50	0.12	1.19	9.95
63	2.51	7.60	159	39.9	6.46	0.12	1.17	9.85
64	2.66	7.90	170	83.6	6.39	0.13	1.37	10.5