Project title:	Asparagus: Sustainable soil management for stand longevity and yield optimization
Project number:	FV 450a
Project leader:	Dr Rob Simmons, Cranfield University
Report:	Final Report, July 2021
Previous reports:	Annual Report, September 2020 Annual Report, July 2019
Key staff:	Lucie Maskova and Dr Lynda Deeks
Location of project:	Gatsford, Ross-on-Wye
Date project commenced:	01/03/2018
Date project completed (or expected completion date):	31/05/2021

DISCLAIMER

The results and conclusions in this report are based on an investigation conducted over a three-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Dr Lynda Deeks

Research Fellow in Soil Science

Cranfield University

Signature .... Date ...01-09-21....

Report authorised by:

Dr Robert Simmons

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GROWER SUMMARY

Headlines

- The results of this study confirm that asparagus yield, profitability, alleviation of soil compaction, increased infiltration and improved soil health can be achieved by moving away from conventional practice and adopting one of several alternative Best Management Practice (BMP) options.
- PAS 100 Compost applied annually to asparagus interrows in combination with shallow soil disturbance (SSD) without annual re-ridging can result in significant (>20%) yield uplift, reduced soil compaction, improved infiltration rates and improved profitability as compared to conventional practice.
- Companion cropping with rye (*Secale cereale*) with annual re-ridging, can result in >20% yield uplift as compared to conventional practice. However, non-ridging carries a risk of a 20% yield penalty compared with conventional practice suggesting that growers need to be confident that they can re-ridge if rye is grown as a companion crop for run-off and erosion control.
- Zero-tillage also referred to as 'ridging for the life of the crop' is associated with improved yield and profitability, reduced soil compaction and improved soil health as compared with conventional practice.
- The FV 450a trial has not yet reached the key phase of crop maturity and economic production which typically occurs between years 4-7. This is the key payback period for growers. Consequently, the impact of BMPs on stand longevity and profitability will continued to be monitored and economic implications assessed.

Background

Conventional operations associated with UK asparagus production, i.e., tillage operations, such as ridging and sub-soiling, spray operations, harvesting (foot-trafficked and/or hand harvested using picking rigs) can result in progressive and severe compaction of all inter-bed wheelings. In addition, 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 productivity and increases the susceptibility to crown and root rots caused by *Phytophthora* and *Fusarium* species.

Further, compaction of wheelings leads to a significant reduction in infiltration resulting in an increased risk of surface water ponding and on sloping land, run-off generation and erosion. In turn, surface water ponding and/or erosion compromises field operations by restricting foot and vehicular traffic, and water ponding in furrows increases the risk of crown and root rots leading to yield decline. The long-term field trials established under this project have evaluated a range of best management practices (BMPs) to prevent and/or mitigate compaction, improve soil structural status in asparagus wheelings and facilitate long-term profitability of asparagus production.

Summary

This report represents the culmination of five years of research activities initiated in 2016 under FV 450 and continued until the end of June 2021 under FV 450a (Figure 1). Continued monitoring of the FV450/450a field trial will continue under FV 450b.

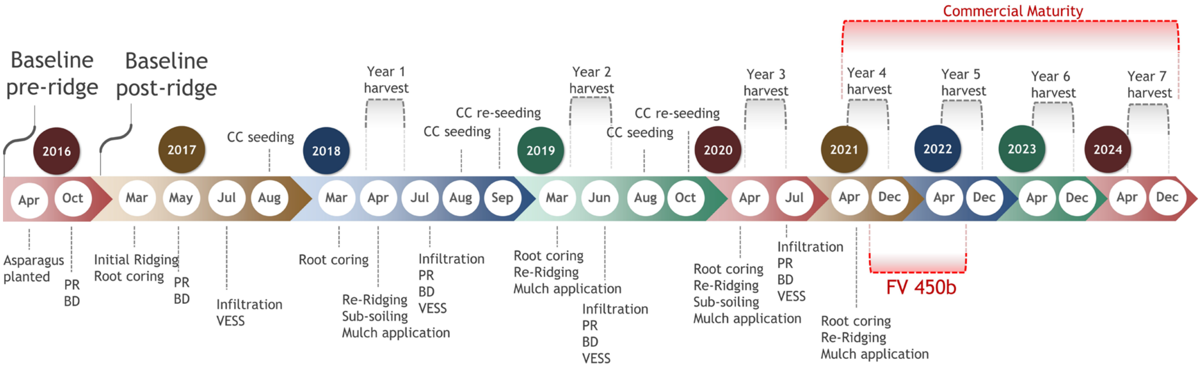


Figure 1. FV 450 / FV 450a project timeline indicating activities undertaken to date and period of commercial maturity.

Performance of Best Management Practices (BMPs) as compared with conventional Practice

Based on the key metrics measured in the 2020 cropping season (5-year-old asparagus stand) a comparative treatment performance evaluation was undertaken to identify BMPs with the most desirable overall impact across multiple performance indicators in comparison with conventional practice (Figure 2). See Appendix A of Science Section for detailed performance score calculation methodology.

Throughout this research, conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without shallow soil disturbance (SSD) applied to the inter-rows (Bare soil No-SSD R). Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

Performance indicators used in this performance assessment included Root Mass Density (RMD), yield, spear size, potential profitability, total storage root soluble carbohydrate (CHO), soil compaction as measured by penetrative resistance (PR) and soil infiltration rates. Final (un-weighted) comparative performance scores range between 2.5 and 9.1. Values close to zero indicate management practices that carry a major risk to the asparagus root growth, yield, productivity and soil erosion risk. In contrast, BMP treatments with values close to 10 infer management practices that promote asparagus root growth, yield, productivity and reduce soil erosion risk.

Relative performance scores indicate that the application of the conventional practice with a performance score of 2.5 carries the highest overall risk to asparagus root growth, yield, productivity, soil erosion risk and consequently asparagus stand longevity. Figure 2 indicates that all BMP treatments evaluated under FV 450a (with the exception of rye non-ridged companion crop) are an improvement on conventional practice, suggesting they could be adopted to drive a major change in the way asparagus is cultivated in the UK. The highest performance scores of 7.0 to 9.1 are primarily linked to the application of straw and PAS 100 mulches to asparagus interrows at 5 and 25 t ha^{-1} per annum respectively in association with interrow shallow soil disturbance and post-mulch application. These BMPs promoted improvements in asparagus root growth, yield, profitability, promoted soil health and reduced soil erosion risk. It is however recommended that growers keep up to date with regulations pertaining to the application of PAS 100 compost to land to ensure that they are compliant.

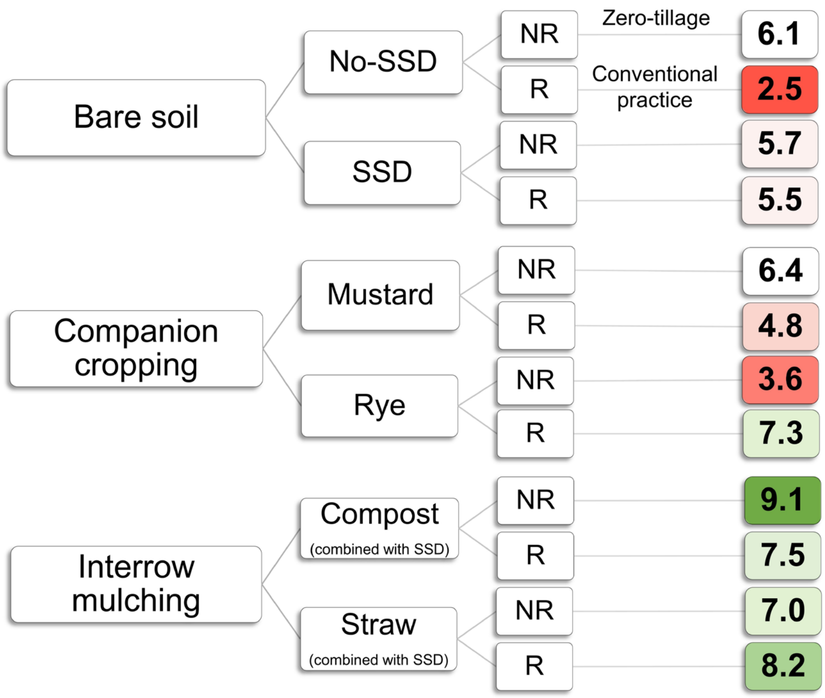


Figure 2. Comparison of asparagus crop performance associated with different management practices applied from 2016-2020. Performance scores range from 0 (worst) to 10 (best).. NR = No annual re-ridging. R = Annual re-ridging, SSD = shallow soil disturbance applied to interrows.

Financial Benefits

This project has provided information on the state of asparagus soils and provides focused, practical and robust guidance on how to identify and alleviate compaction and water-logging in asparagus interrows, thereby reducing the risk of asparagus decline, increasing asparagus yields and farm profitability, while minimising environmental impact. In addition, this project has also provided research outcomes that can feed directly into policy discussions associated with the Environmental Land Management scheme (ELMS) scheme such that asparagus growers can receive 'financial reward in return for delivering environmental benefits'.

An initial cost-benefit analysis for the 2020 harvest demonstrated potential revenue increases of 28-30% and 18% respectively for PAS 100 mulch with shallow soil disturbance (ridged and non-ridged) and zero tillage. Similarly, there was a potential revenue increase for Gijnlim and Guelph Millenium for zero tillage versus conventional practice of 19% and 25% respectively. A more detailed cost-benefit analysis will be done as part of FV 450b.

Action Points

1. In order to prevent storage root damage through re-ridging or subsoiling operations, growers should undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations. Guidance on how to undertake asparagus root coring can be found at: https://www.youtube.com/watch?v=Lms3GfRgiXM.
2. Compost and mulches: Use PAS 100 compost and straw mulch treatments in combination with shallow soil disturbance to significantly reduce soil compaction to 0.5 m depth as compared with conventional practice. This will result in improved infiltration, soil moisture recharge and reduced run-off and erosion risk.

SCIENCE SECTION

Introduction

Field operations associated with UK asparagus production [tillage operations, such as ridging and sub-soiling, spray operations, harvesting (foot-trafficked and/or hand harvested using picking rigs)] can result in progressive and severe compaction of all inter-bed wheelings.

Compaction of wheelings leads to a significant reduction in infiltration resulting in an increased risk of surface water ponding and on sloping land, run-off generation and erosion. In turn, surface water ponding and/or erosion compromises field operations impacting on both foot and vehicular traffic. Niziolomski et al. (2020) demonstrated that shallow soil disturbance (SSD) in association with straw or PAS 100 compost application reduces run-off and erosion by >80%. However, the 3D root profile architecture of the major UK asparagus varieties under different tillage practices is unknown. Consequently, potential root damage associated with the use of SSD to control run-off and erosion has not been assessed.

Pervasive compaction in wheelings where the entire soil volume is compacted, is thought to have a detrimental effect on root growth and hence the volume of soil explored, with consequences for water and nutrient uptake (Tracy et al., 2012). Degradation of soil structure can severely restrict root development (Clark et al., 2003; Grzesiak et al., 2013; Whalley et al., 2006) and compromise the ability of crop plants to access water and nutrients (White and Kirkegaard, 2010), increase susceptibility to disease and pest damage with direct impacts on yield, yield quality and production costs. There remains a paucity of information regarding the extent to which wheeling compaction dictates asparagus root architecture and root profile distribution.

Cover crops (in this project context these will be termed companion crops as they are grown alongside and concurrent to the asparagus) possess traits that can effectively remediate compacted soils (e.g., Kirkegaard et al., 2008). Further, research has demonstrated that the generation of biopores through a bio-drilling effect of break crops in compacted soils can result in increased yield of follow-on crops (Chen and Weil, 2011; Cresswell and Kirkegaard, 1995; Kirkegaard et al., 2008). Plant roots engineer soil structure directly by penetrating and displacing soil, depositing adhesive compounds which encourage aggregation, and indirectly via a range of other root deposits which provide energy and nutrient sources for soil biota (White and Kirkegaard, 2010). These biota improve the architecture of the soil by mechanisms including adhesion, kinetic restructuring and filamentous binding (Miransari, 2014). Residues from the aboveground plant parts, if deposited to the soil, also provide an energy-rich substrate which can be utilised by the biota to drive structural genesis. Further the role of crop canopies, stems and root architecture to reduce soil erosion are well documented (De Baets et al., 2007; Finney, 1984). Optimising the use of cover crops presents an opportunity to provide soil structural rejuvenation and erosion control within asparagus production systems. To date cover/companion crops have not been widely adopted within UK asparagus systems.

Conventional asparagus production in the UK requires annual re-ridging to ensure that adequate soil depth above the emerging crown is maintained to ensure customer yield quality parameters are achieved. 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 productivity (Drost and Wilcox-Lee, 2000; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991) and increases the susceptibility to crown and root rot caused by *Phytophthora megasperma* (Falloon and Grogan, 1991) (now known as *P. asparagi*) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2015, 2001), which leads to yield decline and direct economic losses to the grower.

In contrast, zero tillage options have been shown to significantly increase (>100%) the marketable yield of asparagus spears, as well as crown, fern and bud growth from year two onwards (Wilcox-Lee and Drost, 1991). Root damage associated with annual re-ridging and/or sub-soiling operations has a major impact on stand longevity and productivity (Drost and Wilcox-Lee, 2000; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991) through increasing susceptibility to crown and root rots caused by Fusarium and Phytophthora infections. Several pathogenic *Fusarium* species are associated with asparagus crown and root rots (and other crops), namely *F. oxysporum f. sp. asparagi, F. proliferatum, F. redolens and F. solani* (Elmer, 2015). The adoption of zero tillage by UK growers would be a paradigm shift in asparagus production practices and could have profound implications to the longevity and profitability of UK asparagus stands.

Materials and methods

Establishment of the FV 450/FV 450a long-term experimental field-trial

In April 2016, two replicated field experiments were established at Gatsford Farm, Ross-on-Wye within a 4.5 ha asparagus field. Asparagus 'A' crowns of both Gijnlim and Guelph Millennium varieties were planted on 20-21st of April 2016 on the flat at an intended depth of 0.14 m, at 0.16 m spacing between crowns on 1.83 m wide bed centres. For details of treatments investigated and results to date refer to AHDB FV 450 Final Report (AHDB, 2018). Experiment 1 (48 experimental plots) is restricted to Gijnlim which represents 70% of UK field grown asparagus (Table 1).

Table 1. Experiment 1: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	[1]Conventional practice	R
Gijnlim	[2]Zero-tillage	NR
Gijnlim	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Gijnlim	Companion Crop – rye	R
Gijnlim	Companion Crop – rye	NR
Gijnlim	Companion Crop – mustard	R
Gijnlim	Companion Crop – mustard	NR
Gijnlim	PAS 100 SSD	R
Gijnlim	PAS 100 SSD	NR
Gijnlim	Straw Mulch SSD	R
Gijnlim	Straw Mulch SSD	NR

Annual re-ridging (R) or Non-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included in Experiment 2. [1]Bare soil No-SSD R; [2]Bare soil No-SSD NR. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

Experiment 2 compares varietal differences in root development/architecture and root profile distribution as affected by subsoiling treatments for two widely grown varieties, Gijnlim and Guelph Millennium. Experiment 2 is a full factorial (3-Way Analysis of Variance) design and will elucidate varietal differences in root development/architecture and root profile distribution as affected by SSD treatments and annual re-ridging (R) vs non-ridging (NR) (Table 2).

Table 2. Experiment 2: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	[1]Conventional practice	R
Gijnlim	[2]Zero-tillage	NR
Gijnlim	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Guelph Millennium	[1]Conventional practice	R
Guelph Millennium	[2]Zero-tillage	NR
Guelph Millennium	Bare soil SSD	R
Guelph Millennium	Bare soil SSD	NR

Annual re-ridging (R) or Non-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included from Experiment 1. [1]Bare soil No-SSD R; [2]Bare soil No-SSD NR. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows

Mulch treatments

In 2018, 2019 and 2020 mulch treatments were applied (by Cobrey Farms team) on 20th April, 19th March and 25th March, respectively. PAS 100 compost or straw was applied to three wheelings per treatment (central wheeling and guard rows) at rates of 25 t ha^{-1} and at 6 t ha^{-1} (Niziolomski et al., 2020).

Shallow soil disturbance (SSD) treatments

Shallow soil disturbance (SSD) was applied in April 2018 and in March and June 2020 (due to a missed SSD application post-harvest in 2019) using a winged tine (Niziolomski et al., 2016) operating to 0.25-0.30 m depth to all mulch treatments (PAS 100 compost and Straw mulch) and to applicable bare soil treatments (Tables 1 and 2). In both years, occasional asparagus root damage was observed behind the tine.

Companion Crop treatments

Companion crops were applied to central wheelings only. Rye (*Secale cereale* L. var. Protector) and mustard (*Sinapis alba* L. var. Severka) were broadcast to three wheelings (central wheeling and guard rows) on the 10th August 2017 when asparagus was at full fern stage at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for rye and mustard, respectively. The emergence rate of the companion crops in 2017 achieved sufficient ground cover of 70-75% (Morgan, 2005). In 2018, companion crops were again sown in August at the same rates as 2017 to three wheelings per treatment (central wheeling and guard rows). However, the dry summer of 2018, limited emergence and establishment of both companion crops led to the need for re-application in late September 2018. A field survey undertaken in November 2018 indicated spatially sporadic but good establishment in treated plots. In August 2019, seeding rates of rye and mustard were increased to 200 kg ha^{-1} and 25 kg ha^{-1} to decrease the risk of establishment failure. Nonetheless, poor establishment occurred again, and companion crops were re-applied on the 2nd of October 2019.

The 2018-20 results from the FV 450a trials indicate that the mustard companion crop treatment has no significant impact on soil structural status or asparagus yield as compared with the bare soil conventional or zero-till treatments. As a consequence, in 2020 mustard was replaced with oats (*Avena sativa*) (following agreement from the Project Advisory Group, July 2020). In 2020, both cereal rye and oats were broadcast on the 26th of August at 120 kg ha^{-1} to reflect commercial practice.

Annual re-ridging treatments

Following a visit by the PAG to the field trial in December 2016, it was agreed that due to the shallow depth (circa 0.06 m) of soil above crown and not the anticipated 0.14 m, that all treatments would be re-ridged in the spring of 2017. This was carried out on the 22nd of April 2017. Consequently, it was agreed that the zero-tillage treatment would be implemented from Spring 2018 onwards. In 2018, 2019 and 2020, re-ridging treatments were applied on the 18th April, 15th of March and 24th of March, respectively. In all year's minor root damage was observed during re-ridging. 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 2. 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.

Impact of BMPs on indicators of soil compaction

Soil assessments were conducted within the Experiment 1 plots planted with Gijnlim. Metrics to assess changes in soil structure between treatments included Penetrative Resistance (PR), Infiltration Rate (IR) and Visual Evaluation of Soil Structure (VESS). All measurements were conducted in the compacted central asparagus interrow from two randomly selected plots per treatment. 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 0.90 m distances from the crown) after the first ridging operation. Both legacy and baseline compaction levels were critical to enable soil PR to be linked to the BMP treatments subsequently applied. 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 0.6 m depth (where possible) at a recording interval of 0.01 m. Each plot was sampled at six locations along the length of the plot (5, 10, 15, 20, 25 and 30 m). In addition, in 2020, PR transects were taken tangentially from the asparagus CZL at 0.3 m intervals to the centre of asparagus interrow (0.9 m 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 0.2 mm in 2018, 11.8 mm in 2019 and 1.6 mm in 2020. Soil moisture content (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 h period. As such soil MC was considered to be uniform across treatments when trafficking and tillage events were applied.

Soil moisture normalisation models such as PENETR model (Canarache, 1990) or covariance analysis for correcting cone index to soil moisture content (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 programme. 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, data from each year were evaluated separately.

Infiltration rate was measured in triplicate in each sampled plot (n=12 per treatment per year) concurrently with PR in June 2018, June 2019, and July 2020. Infiltration was measured following a modified USDA single ring infiltrometer method, using a 0.12 m internal diameter PVC ring with falling head (Esparcia, 2014). Infiltration rate classes were adapted from the USDA Soil Quality Test Kit Guide (USDA, 1999).

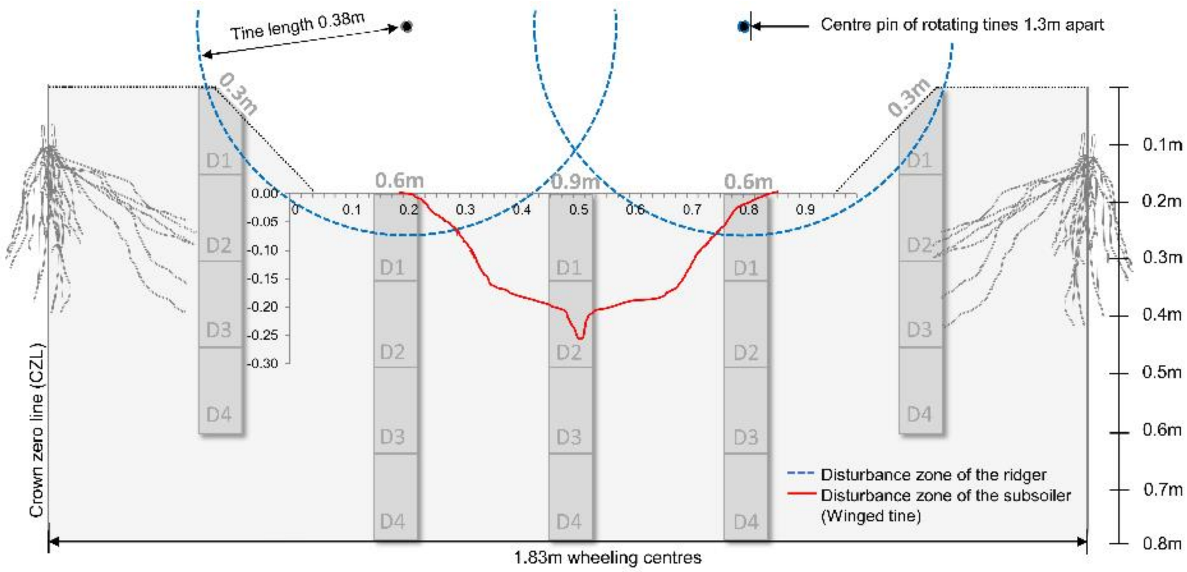


Figure 2. Visualisation of assumed ridger tine disturbance areas and sub-soiler soil disturbance areas with different tine options (Niziolomski et al., 2016) alongside root coring locations.

Impact of BMPs on bio-chemical soil quality indicators

In 2020, 10 sub-samples (0-15 cm 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. 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. 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). Phospholipid fatty acid analysis (PLFA) is a method frequently used to characterise changes in the composition of soil microbial communities (SMC) and to differentiate between fungal and bacterial biomass (Willers et al., 2015). Relative abundance values of each PLFA marker were used to indicate differences in SMC structures.

Assessment of root architecture and root profile distribution

Root architecture was determined following the procedure of Drost and Wilson (2003). The 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, four 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. The total number of root samples collected per treatment each year was 64 (4 locations x 4 distances from the crown x 4 depths).

Root samples taken at different distances from the CZL and depths were assigned a code consisting of two values based on their location coordinates (Figure 3). The first number indicates the distance of the sample from the CZL, e.g., 0.3 m, 0.6 m or 0.9 m. For fields sampled from the wider grower landbank, this spacing varied as a function of wheeling centres (Figures 4 and 5). 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. In order to compare root distribution across multiple treatments, the focus was placed on root distribution in treatment application areas, i.e. 0.30-0.90 m distance from the CZL.

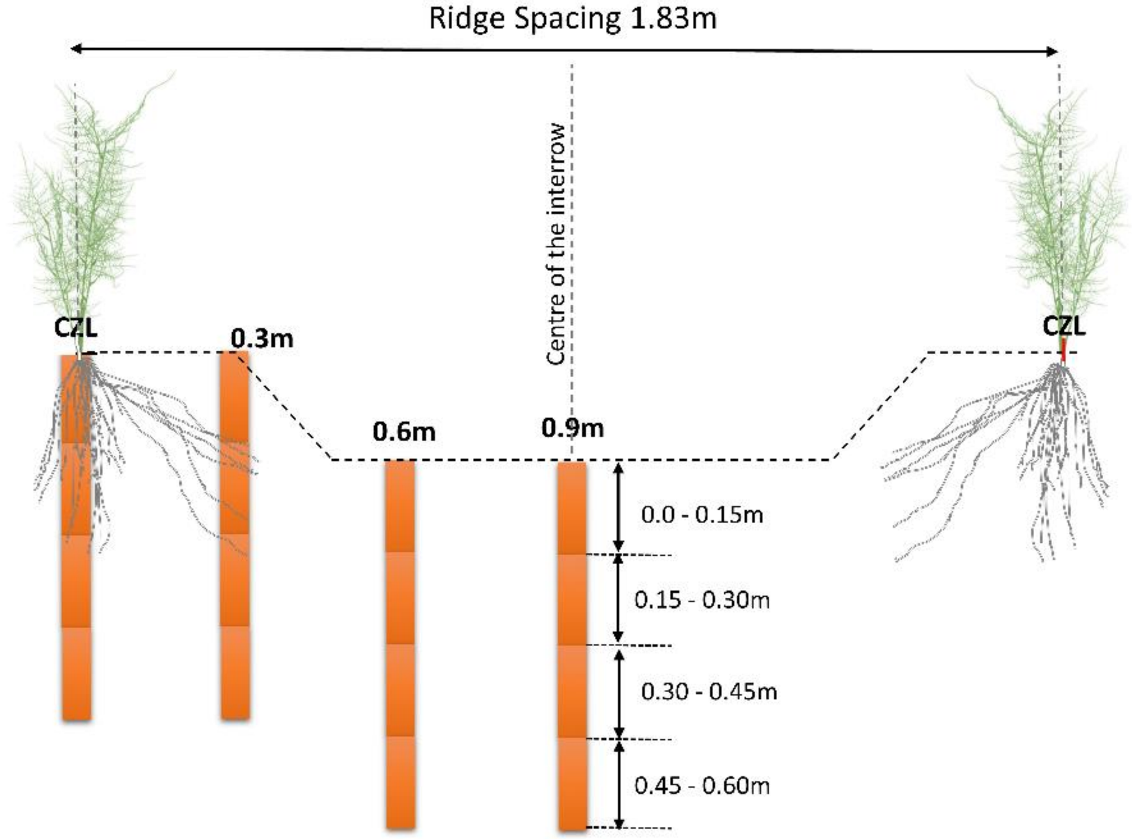
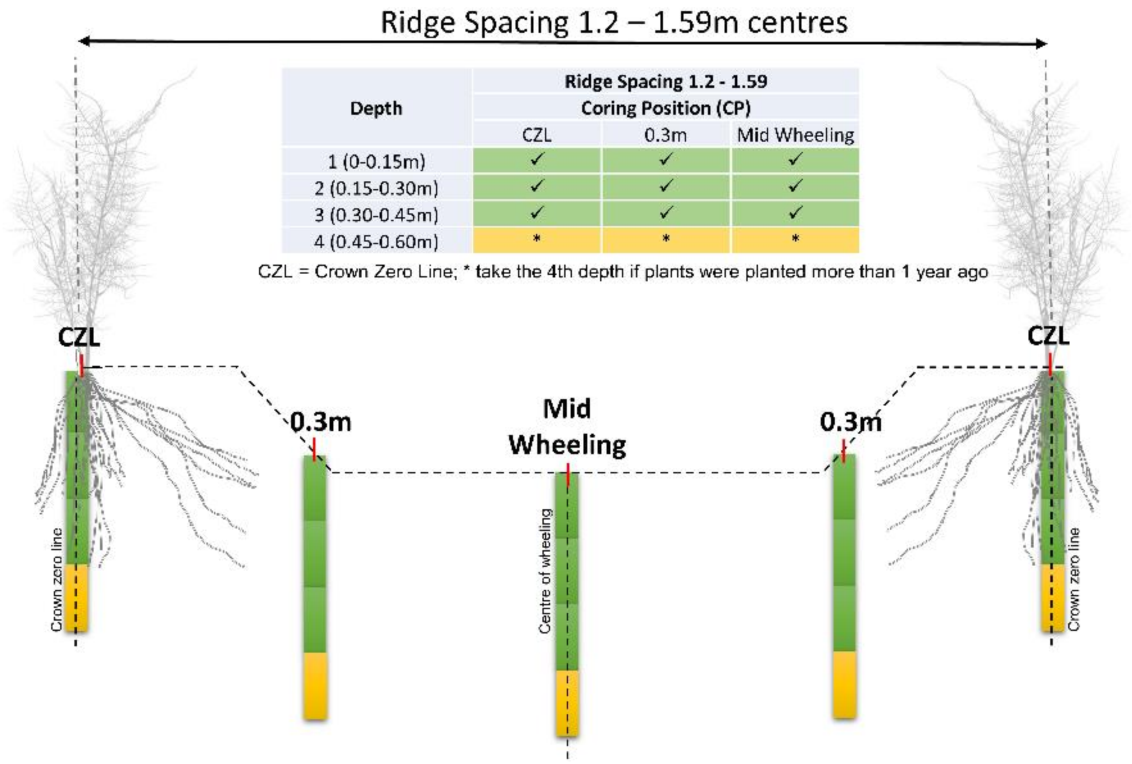
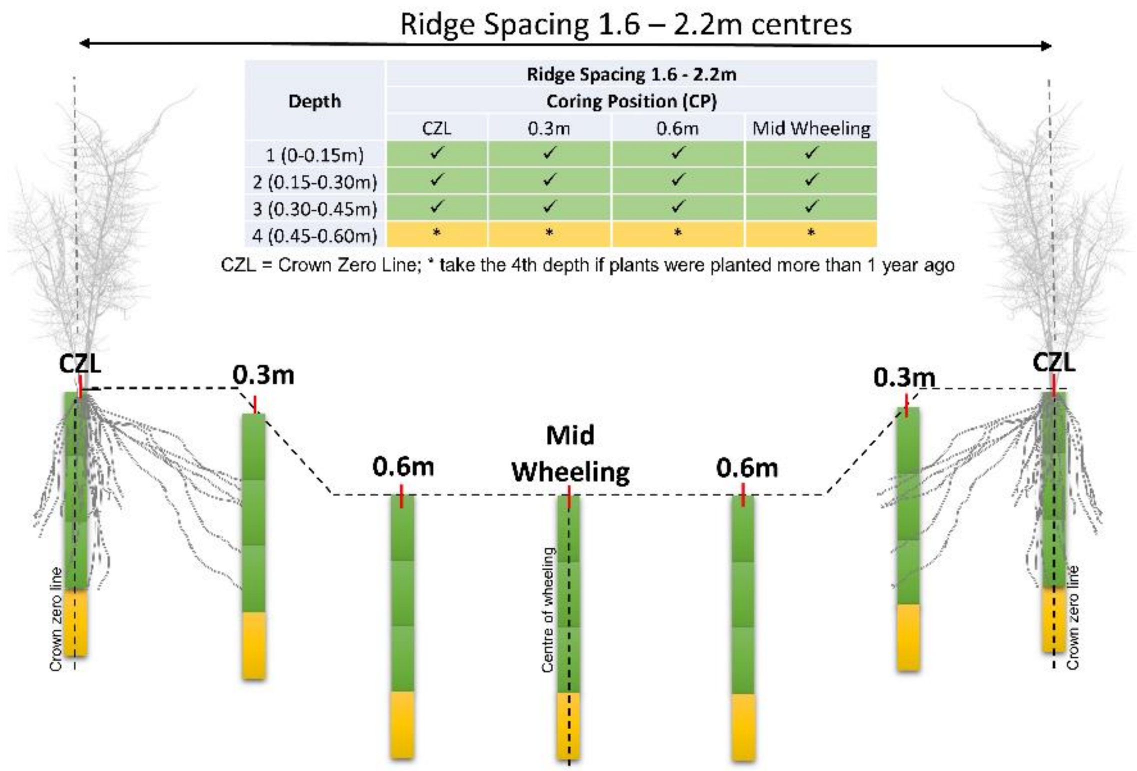


Figure 3. Root coring protocol adopted at the FV 450/FV 450a trial site.



Depth	Ridge Spacing 1.2 - 1.59 Coring Position (CP)		
	CZL	0.3m	Mid Wheeling
1 (0-0.15m)	✓	✓	✓
2 (0.15-0.30m)	✓	✓	✓
3 (0.30-0.45m)	✓	✓	✓
4 (0.45-0.60m)	*	*	*

Figure 4: Root coring positions for asparagus cultivated on ridges with 1.2 – 1.59 m centres.



Depth	Ridge Spacing 1.6 - 2.2m Coring Position (CP)			
	CZL	0.3m	0.6m	Mid Wheeling
1 (0-0.15m)	✓	✓	✓	✓
2 (0.15-0.30m)	✓	✓	✓	✓
3 (0.30-0.45m)	✓	✓	✓	✓
4 (0.45-0.60m)	*	*	*	*

Figure 5: Root coring positions for asparagus cultivated on ridges with 1.6 – 2.2 m centres.

Determination of root mass density

Asparagus storage roots (>2 mm diameter) were separated from soil and stored at <2˚C before further assessment. Roots were carefully washed with tap water to remove soil remnants. Roots already dead (hollow), were grouped away from the fleshy (live) storage roots. From here, roots were weighed, and oven dried at 65˚C for 48 h, and in some cases 72 h until constant mass was achieved. The weight of dry roots was recorded immediately after the drying process. From the root mass data, root mass density (RMD) values were calculated as a ratio between root dry mass (MD) and the root core volume (V), as equation:

$$\mathrm{RMD} = \frac{\mathrm{M_D}}{\mathrm{V}} \ \ (\mathrm{g\,cm^{-3}})$$

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 the 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:

$$TRB = \frac{RMD_{sl}}{RMD_t} \times 100\ (\%)$$

Root Mass Density interpolation maps

To map the spatial distribution of roots, root mass density (RMD) or root biomass as a percentage of total root biomass (TRB%) can be used. All root core samples were given x, y coordinates according to the position from the row (x-value) and soil depth (y-value) they were sampled at and given a corresponding z-value for RMD or TRB. These x, y, z values were then used to construct contour interpolated root mass density maps in in Esri ArcMap™ (GIS software) version using the inverse distance weighing (IDW) geo-statistical interpolation method, predicting values at unmeasured locations (Figure 6).

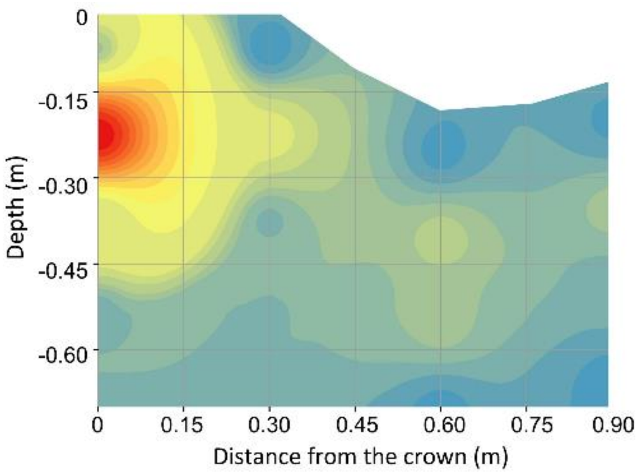


Figure 6. Root mass density (RMD) map generated using the inverse distance weighing (IDW) interpolation method in ARC-GIS.

Crop performance indicators

In 2018, 2019 and 2020, asparagus spears were harvested from all experimental plots. In 2018, spears were harvested between the 24th April to 21st May (28 days) from 19 cuts. In 2019, the harvest season extended to 53 cuts between the 20th April to 17th June (59 days). In 2020, harvest was undergone between the 12th April to 22nd June (72 days) and spears were harvested from a total of 65 cuts. The reduced number of cuts in 2018 reflects conventional practice for a 3-year-old asparagus stand. Spear count for 2018, 2019 and 2020 was determined on seven, nine and eight cuts respectively, which were randomly distributed throughout the harvest period. Total yields were reported as mean total mass of all harvested spears divided by the number of cuts (kg ha^{-1}). Daily average spear mass was then determined by dividing the weight of all spears harvested per plot by the total number of spears harvested on the same day.

Additional spear quality indicators were measured in 2020. Spear diameter, head flowering and head curving were recorded on eight 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 (<10 mm, 10-22 mm and >22mm). Spears with flowering heads and curvature were also weighed and counted.

Determination of root soluble carbohydrate (CHO) values

For both the FV 450 trial plots and the additional fields sampled under the wider root architecture survey the determination of CHO values followed the method outlined in FV 271 Appendix 2 (AHDB, 2007). Asparagus storage roots for the determination of pre-harvest root soluble carbohydrate content (CHO) were obtained in March 2019 and in March 2020 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 treatments were not fully applied at the time of root sample collection. Roots of similar diameters were separated from soil, washed, and frozen at -20ºC 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):

$$\mathrm{CHO}\ (\mathrm{mg\ g^{-1}}) = 21.1 \times \mathrm{Brix\%} + 42.9$$

Estimation of the potential profitability of the BMPs as compared with conventional practice.

Spears harvested in 2020 were divided into three commercial size grades by spear thickness (<10 mm, 10-22 mm and >22 mm) and classed as higher quality 'Class I' spears. Spears with flowering heads and curvature 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 deducting Class II from the total mass of collected spears. 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. Financial implication of BMP application was determined by deducting material costs and treatment application costs from potential revenues. Costs of manual labour, fertiliser and agrochemical costs which were applied equally to all treatments were not accounted for but will be investigated under FV 450b.

Evaluation of disease incidence

It is critical that the effect of the BMPs on disease is monitored since several diseases contribute to yield decline and lower harvestable yield. Disease monitoring was undertaken at the FV 450 trial site by the Cobrey agronomist with assistance from the Cranfield team.

Disease symptoms were monitored and graded on the 9th October 2018, 2nd October 2019 and 25th September 2020 based on observations only.

Cover crop selection and seeding rates

Companion crops included in this trial were rye (*Secale cereale* L. var. Protector) and mustard (*Sinapis alba* L. var. Severka). Rye was adopted as a companion crop due to its weed suppression potential. In the field rye mulch has been found to significantly reduce the germination and growth of several problematic agronomic grass and broadleaf weeds (Schulz et al. 2013). Rye produces a number of allelochemicals including benzoxazinone, phenolic acids, beta-hydroxybutyric acid, hydroxamic acids (Guenzi and McCalla 1966; Chou and Patrick 1976; Carlsen et al. 2008; Schulz et al. 2013; Jabran et al. 2015). The allelopathic potential (influence on the germination, growth and survival of weed species) of rye declines with development (Reberg-Horton et al., 2005), with the period of weed suppression varying from 30-75 days (Weston, 1996).

In addition, rye is a host of arbuscular mycorrhizal fungi (AMF), known to increase mycorrhizal fungus colonisation of the subsequent crop (Kabir and Koide, 2002) and promote yields. AMF form a symbiotic relationship with the roots of most agricultural crops and aid acquisition of soil phosphorus as well as promoting soil aggregation, and carbon sequestration. In addition, AMF have been shown to increase plant resistance to biotic and abiotic stresses (Smith and Read, 2008). Asparagus is strongly mycorrhizal, with root colonization reaching up to 70% (Matsubara et al., 2001). Many species of the AMF glomus are associated with reduced crown and root rot damage from Fusarium infection and improved root health of asparagus (Matsubara et al., 2001). White mustard (*Sinapis alba L.*) was selected for both its tap rooting (Hudek et al., 2021) bio-drilling potential as well as its soil bio-fumigation potential (suppression of Fusarium sp. by isothiocyanates released by Brassica crops (Smolinska et al., 2003). However, it is important to note that Brassica crops do not host arbuscular mycorrhizal fungi (AMF) and indeed can significantly reduce AMF colonisation and yields in the subsequent crop (Njeru et al., 2014).

The aim of utilising contrasting companion crops in the FV 450 asparagus trials was to evaluate the potential for the synergistic enhancement of multiple soil functions such as weed suppression, improving soil structure, promoting AMF and mitigating crown and root rots associated with Fusarium.

Wider asparagus root architecture survey

An online questionnaire (Qualtrics software) with supporting information was distributed to AGA members via British Growers. The objective of this questionnaire was to obtain information pertinent to the selection of fields to be included in the wider grower root architecture survey. The questionnaire was completed by 15 AGA members and included 190 fields (>1100 ha) with a geographical spread that covers Yorkshire, Warwickshire, Hampshire, Lincolnshire, Kent, Worcestershire, Suffolk, Oxfordshire, Shropshire, Norfolk, Gloucestershire and Herefordshire. From summer 2018 to spring 2020 asparagus root coring was undertaken on 28 fields from six growers. The results of this survey, root architecture across the wider grower landbank and implications for damaging roots during sub-soiling and ridging operations were summarised in the FV 450a 2020 Annual Report.

Results

The results presented in this section are from field work and data analyses completed since the last reporting period.

Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without shallow soil disturbance (SSD) applied to the interrows (Bare soil, No-SSD, R). Zero tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD of interrows.

Effect of BMPs on soil physical properties

Penetration resistance (PR)

Mean profile PR values were significantly higher following the 2017 re-ridging undertaken under FV 450 as compared to the 2016 legacy compaction, with mean PR in the interrows (0.90 m distance from the CZL) of 2.56 MPa and 1.80 MPa, respectively. Spatial distribution patterns of pre and post-ridging PR are shown in Figure 7.

Pre-ridging, PR values of 2.3-2.7 MPa were measured at 0.30 m depth and below (Figure 7). Post-ridging, PR of the interrows (90 cm) increased to between 2.7-3.0 MPa. As shown in Table 3, PR values in the interrows were significantly higher post-ridging (2017) as compared to pre-ridging (2016) at the 60 cm distance from the CZL at 0-5, 10-15 and 20-30 cm depths and at the 90 cm distance from the CZL at 5-30 cm depth, corresponding to the assumed zone of influence of the ridger (Figure 2).

Comparison of 2016 legacy compaction and 2020 PR results showed that conventional practice was associated with 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, the combination mulch-SSD treatments exhibited significant decreases in PR beyond the subsoiler working depth. Compared to the 2016 legacy compaction, the PAS 100 SSD compost treatment saw a reduction in PR from 5-40 cm depth while the non-ridged straw mulch SSD treatment achieved significantly lower PR values from 5-20 and 30-50 cm depths as compared with conventional practice.

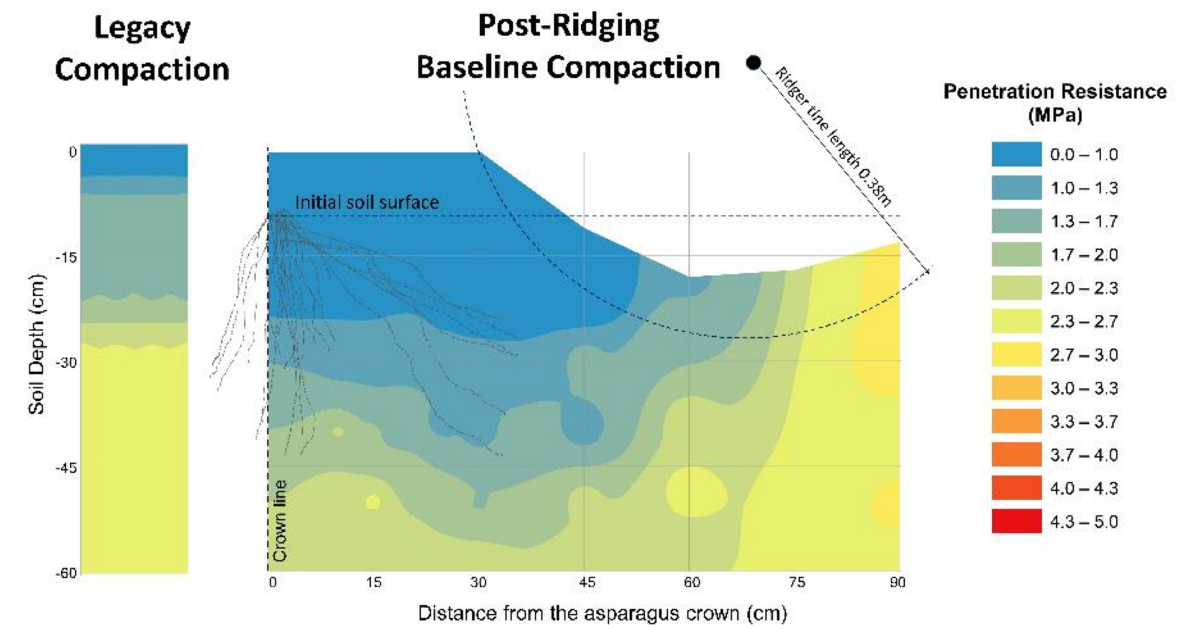


Figure 7. Contour diagrams based on Penetration Resistance (PR) determined at set positions from the crown zero line using the inverse distance weighing (IDW) interpolation. The left image is the 2016 legacy compaction (n=6) and the right, the 2017 post-ridging.

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

PR depth (cm)	2016 legacy compaction	2017 post-ridging				
		Distance from the crown zero 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.

In 2020, PR was measured in the whole soil profile, from the CZL to the centre of the interrow (Figure 8). 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 8b). The zero-tillage treatment (Bare soil No-SSD NR) was associated with reduced PR at depth (45 – 60 cm) compared to all other bare soil treatments (Figure 8). 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 8c and Figure 8d).

All mulch treatments demonstrated a zone of significant PR reduction at the centre of the interrow (at 90 cm from the CZL) which is a direct result of SSD (Figure 9a - Figure 9d). Further, the non-ridged straw mulch SSD treatment PR values in the interrow (90 cm distance from the CZL) did not exceed 2.3 MPa (Figure 9b). 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 9e - Figure 9h). For the non-ridged (NR) mustard treatment, surface PR (**Error! Reference source not found.**f) reached values of up to 5.0 MPa, which are comparable to the deep-seated (45 – 60 cm depth) compaction observed for conventional practice (Figure 8b).

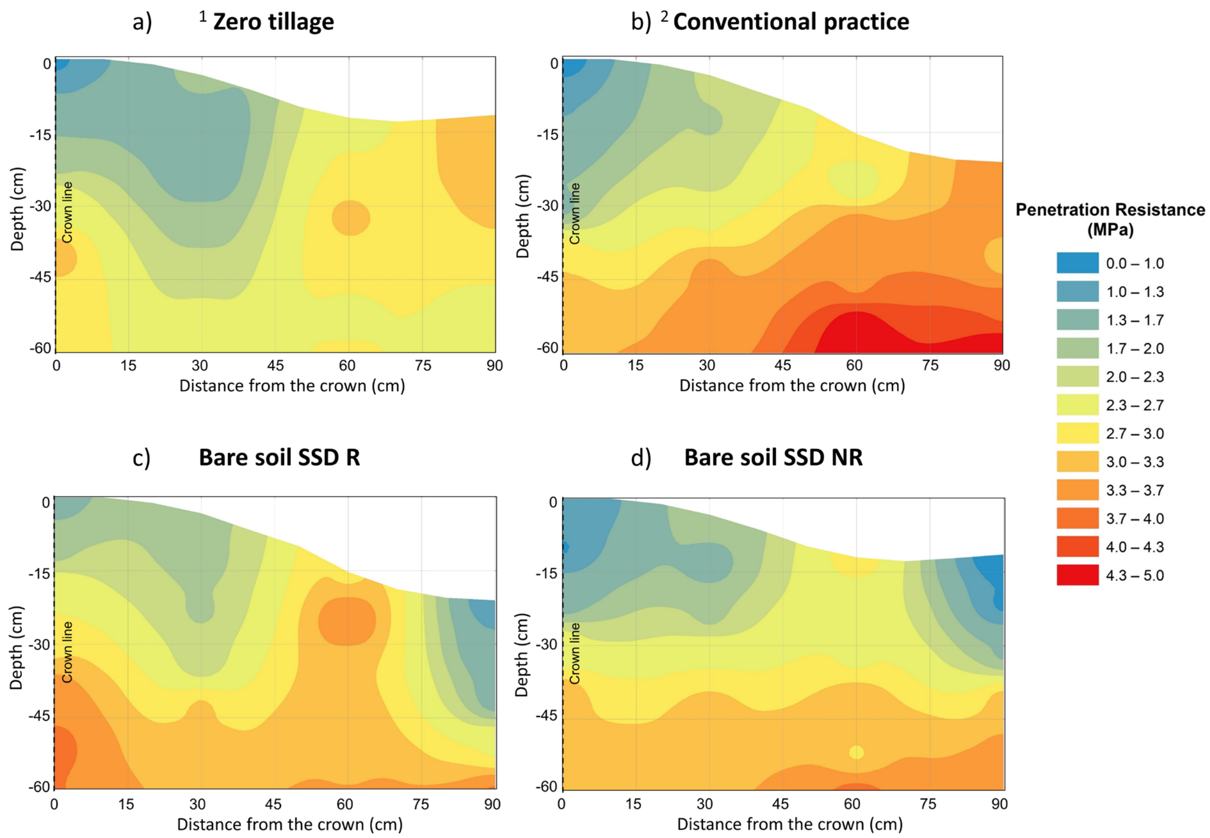


Figure 8. 2020 bare soil treatments contour diagrams based on Penetration Resistance (MPa) transects determined tangential to the crown zero line (n=4) using the inverse distance weighing (IDW) interpolation method. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

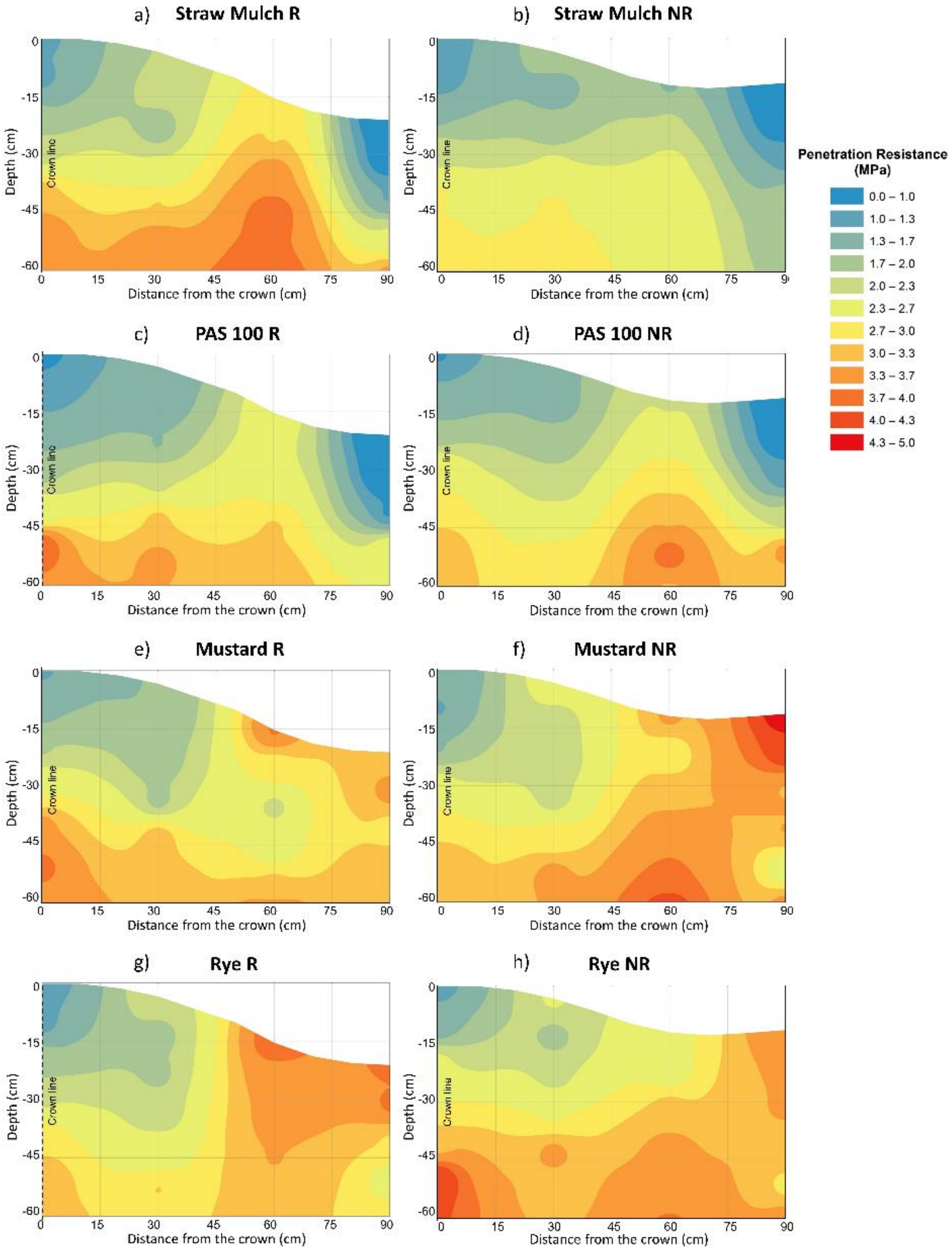


Figure 9. 2020 mulch and companion crop treatments contour diagrams based on Penetration Resistance (MPa) determined at set positions from the crown zero line (n=4) using the inverse distance weighing (IDW) interpolation method.

Root mass density (RMD)

The size of the asparagus root system ('Root Engine') 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). As shown in Table 4 (representing the year-to-year comparison of mean RMD values obtained across all 12 profile sampling locations in all ridged non-SSD treatments in 2020 as compared to the equivalent treatments in 2019), there was an overall and significant reduction in the total RMD (kg m^3) in 2020 compared to 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. All other treatments showed significant RMD reductions of 2-35% in 2020 as compared with 2019 (Table 4). The one exception was the Straw mulch re-ridged (R) treatment, where the mean profile RMD increased from 2019 to 2020 by 7%. Furthermore, in 2020, only Zero-tillage and PAS 100 non-ridged (NR) treatments were associated with a significantly higher whole profile RMD as compared with the Conventional practice (Table 4).

Table 4. Changes in mean root mass density (RMD) (kg m^3) of treatments in 2019 and 2020. Table includes mean RMD of all 12 sampling locations.

Treatment	2019	2020
[1]Zero-tillage	0.67 ^{ef}	**0.49 ^{bcdef}**
[2]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 within the same year. *Significantly different in 2020 as compared to 2019. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

The contrast in the 2019 and 2020 'Root Engine' of the Zero-tillage and the Conventional practice treatments is shown in Table 4 and is also visualised in the root distribution heat map shown in Figure 10. 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 CZL. In contrast, the Zero-tillage treatment was associated with storage roots extending into the interrow. Figure 11 also shows interrow RMD reduction in 2020 as compared to 2019 of Rye R and Mustard R, where treatments also exhibited a decrease in interrow RMDs in 2020 as compared to 2019 (Figure 11). 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 4 and Figures 10 and 12).

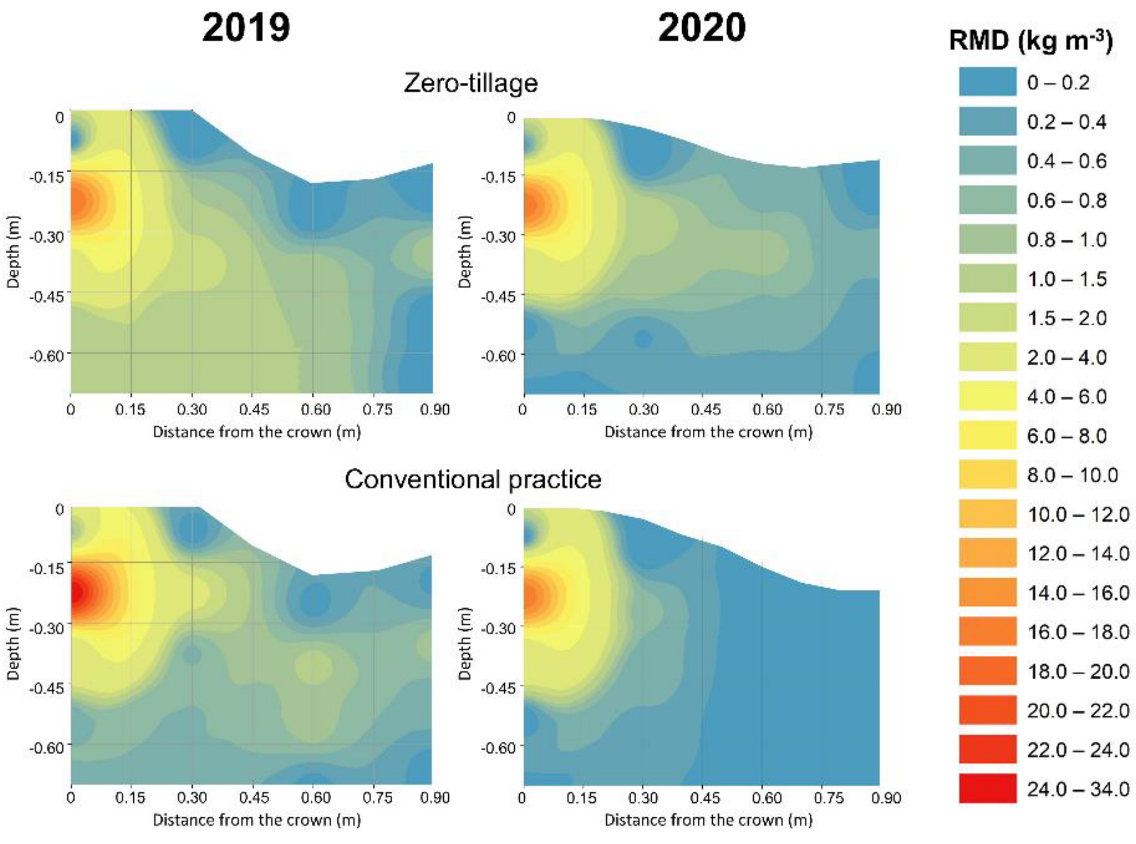


Figure 10. Root distribution heat maps representing root distribution of the Zero-tillage (Bare soil No-SSD NR) and of the Conventional practice (Bare soil No-SSD R) in 2019 and 2020. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

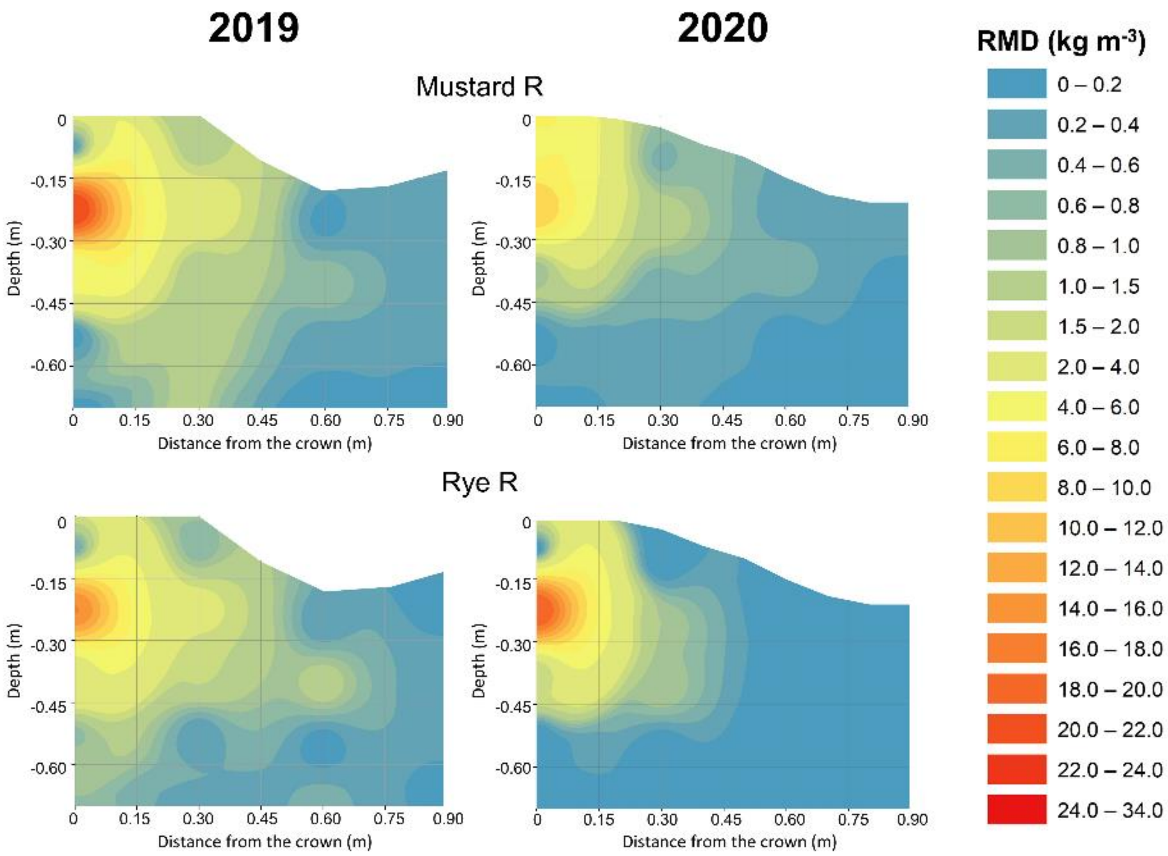


Figure 11. Root distribution heat maps representing root distribution of re-ridged companion crop treatments, Mustard R and Rye R in 2019 and 2020.

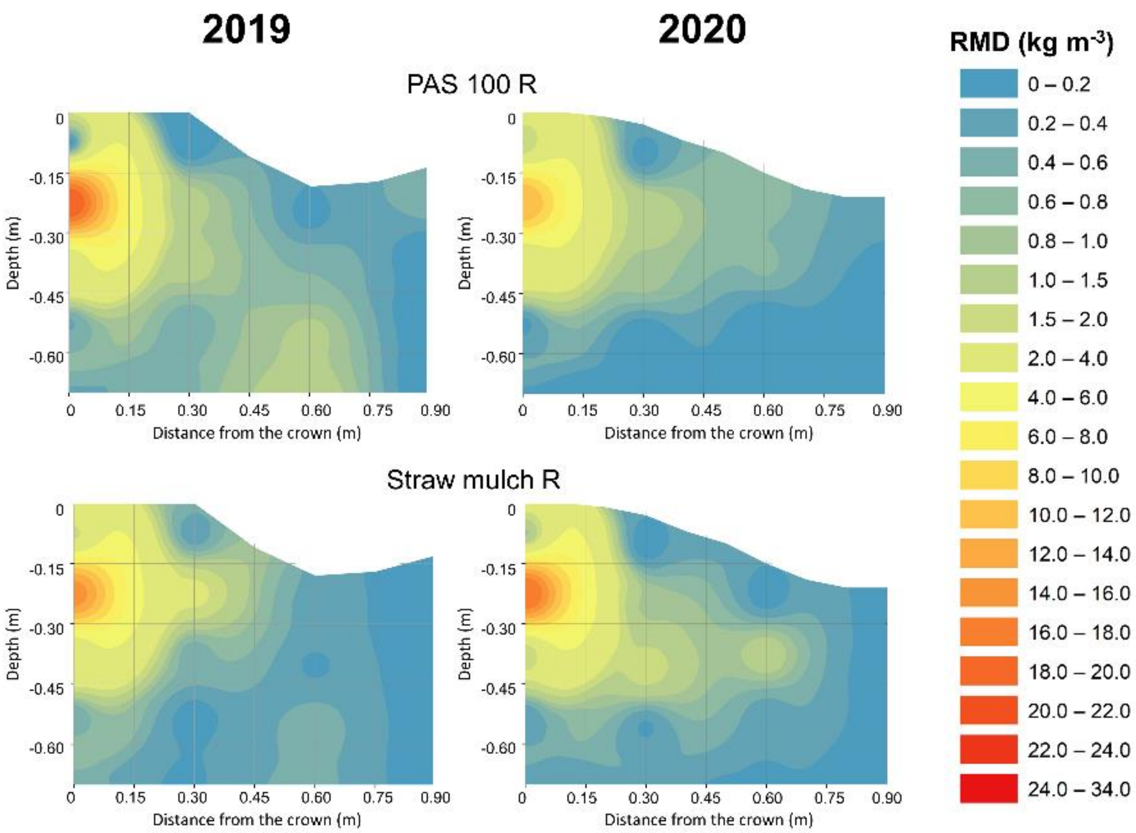


Figure 12. Root distribution heat maps representing root distribution of re-ridged mulch treatments, PAS 100 R and Straw mulch R in 2019 and 2020.

Figure 13 illustrates varietal differences between root mass distribution of Gijnlim and Guelph Millennium. The figure shows that root mass of Guelph Millennium under the Zero-tillage treatment extends into the interrow centres, similar to Gijnlim. However, for Guelph Millennium the root mass is much denser and shallower. Conventional practice in Gijnlim resulted in a ‘Dead zone’ in the interrow areas whereas for Guleph Millennium, although reductions of RMD in the interrows compared to the Zero-tillage are apparent, the visual difference is not as pronounced as in Gijnlim.

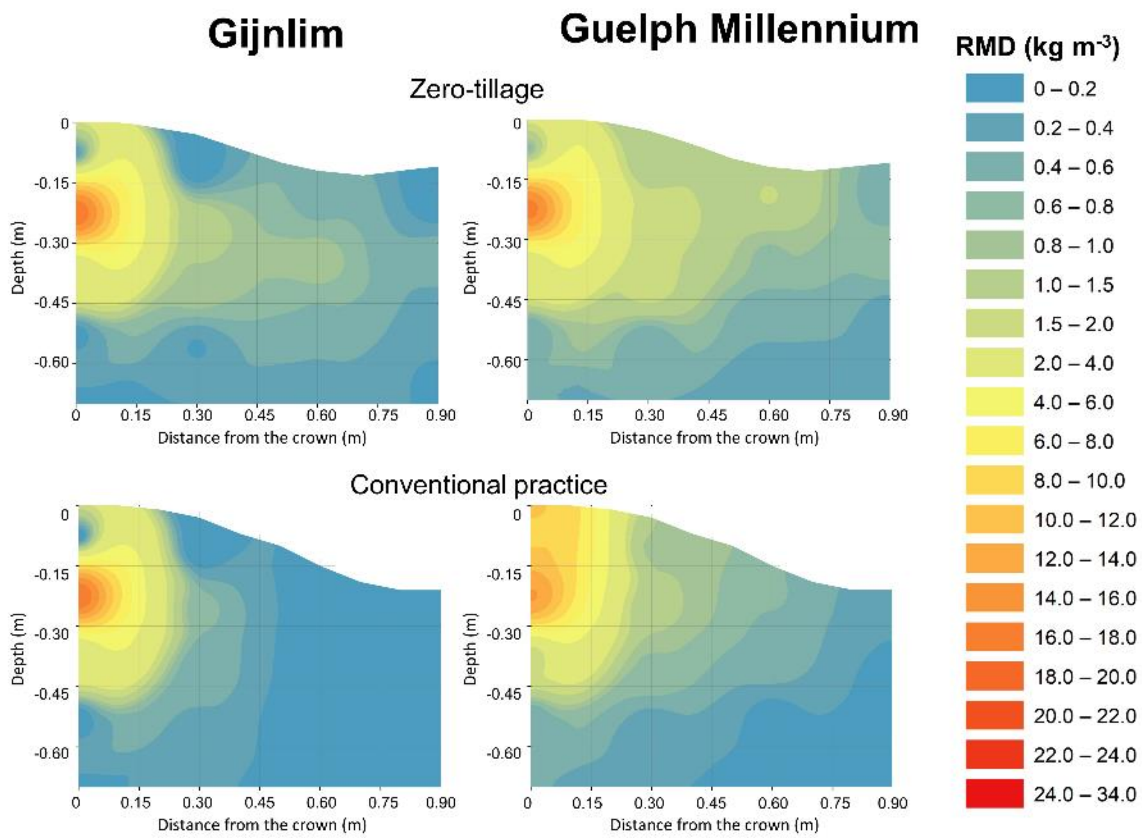


Figure 13. Root distribution heat maps representing 2020 root distribution of the Zero-tillage (Bare soil No-SSD NR) treatment and of the Conventional practice (Bare soil No-SSD R) treatment, Gijnlim and Guelph Millennium. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows

Impact of BMPs on root profile distribution

Root cores extracted in March 2020 were obtained from 6-year old plants which were assumed to be at an age sufficient for reliable interpretation (Wilson et al., 2002) of differences in root distribution between the BMPs following 3 years of treatment applications. 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). 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 5). 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}.

RMD values associated with Conventional practice were 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).

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, BMP treatments which were significantly different from the conventional practice were associated with increases in RMD for those same locations, which indicates that adopting the alternative management practices investigated in this study (Table 1 and Table 2) have the potential to result in an increase in the size of the asparagus 'Root Engine'.

Table 5. Differences in 2020 mean RMD (kg m^{-3}) of all treatments as compared to Conventional practice.

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												
[1]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
[2]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												
[1]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												
[1]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 – 0.15 m, D2 = 0.15 – 0.30 m, D3 = 0.30 – 0.45 m and D4 = 0.45 – 0.6 m. [1]Bare soil No-SSD R; [2]Bare soil No-SSD NR.

Asparagus root profile distribution

Figure 14 illustrates the proportion of total root biomass as TRB (%) and their distribution between all 12 coring locations across all treatments within Experiment 1 (Table 1 Gijnlim variety). 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 0.3 m distance from the CZL contained 57.0 and 62.0% of the TRB and at 0.6 m 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.

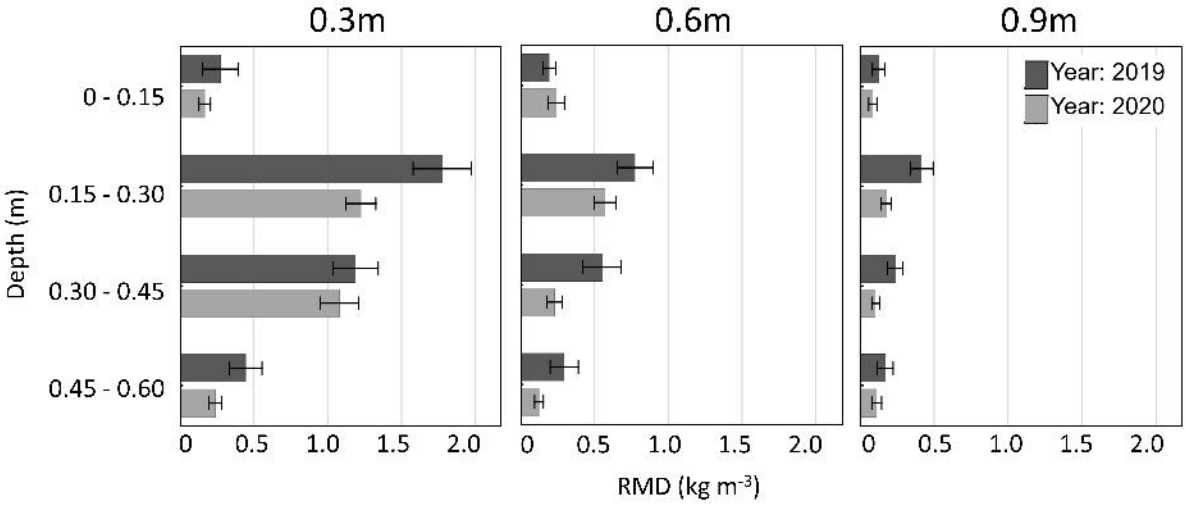


Figure 14. Total Root mass distribution of all treatments for each root coring location from the CZL. Error bars represent ±1 S.E. D1 = 0.0 – 0.15 m, D2 = 0.15 – 0.30 m, D3 = 0.30 – 0.45 m and D4 = 0.45 – 0.6 m depth.

The effect of soil compaction on asparagus storage root distribution

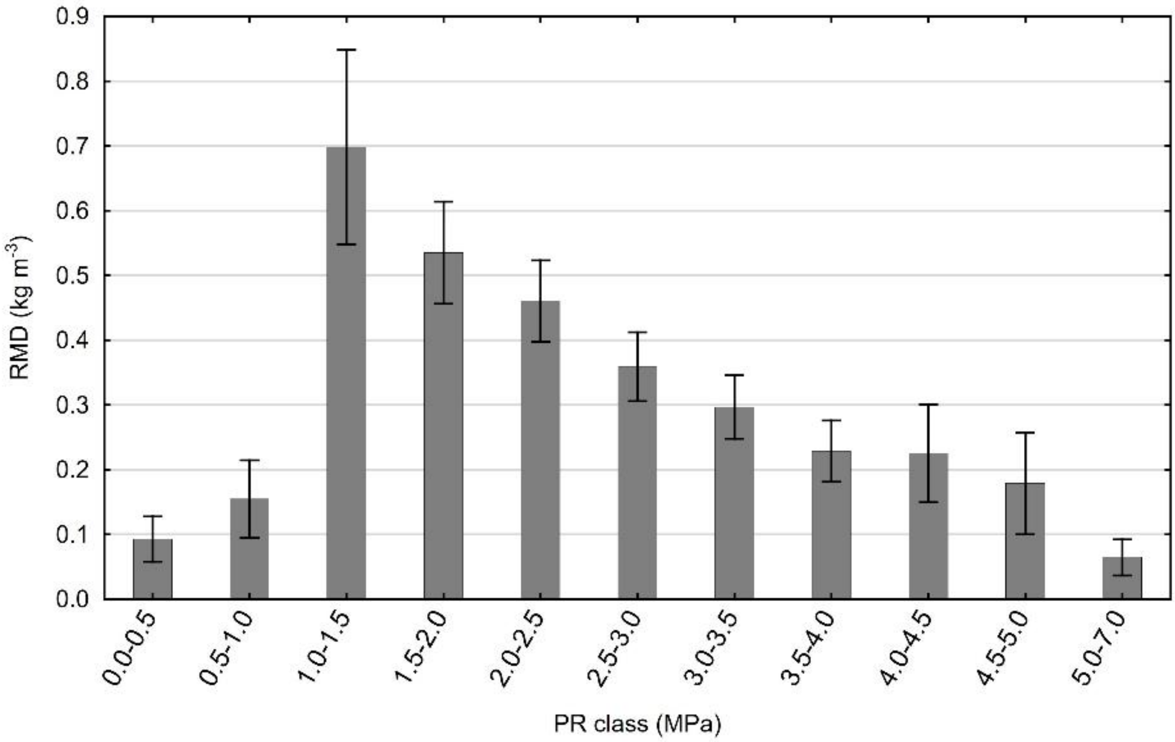


Figure 15. Mean RMD for each Penetration Resistance (PR) class (MPa) (n=564). Data presented represents the mean values for all 12 sampling locations, different depths and distances from the CZL. Error bars represent ±1 S.E. Adapted from Sinnett et al. (2008).

Root samples from all 12 treatments were assigned a mean penetration resistance (PR) value based on PR measurements associated with the coring location and grouped into PR classes (Figure 15). 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 15) with RMD decreasing with increasing PR. Results indicate that 87% of asparagus TRB or 2.35 kg m^{-3} of RMD was found within a PR range of 1.0-3.5 MPa. In contrast, the 3.5-7.0 MPa PR class contained 10% of TRB or 0.70 kg m^{-3} of asparagus RMD (Figure 15). This implies that PR values > 3.5 MPa limit asparagus root development.

Impact of BMPs on asparagus yield and yield quality attributes.

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 also 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 the key factor determining asparagus yield performance which was officially recognised by the *AspireNZ* decision support system of Wilson et al. (2002b). There is significant variation in asparagus storage root CHO levels between plants depending on the size of the root system (Wilson et al., 2008), i.e. target pre-harvest CHO content of small root systems are expected to reach at least 550 mg g^{-1} while in large root systems, the target value is only 450 mg g^{-1} . Furthermore, CHO stored in asparagus roots is subject to seasonal 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 both high spear yields and stand longevity.

Correlation analysis of the yield data indicates that spear size was significantly and positively correlated with yields (Figure 16). The relationship was already observed following the first harvest in 2018. Between 2018 and 2020, the strength of the relationship, as indicated by the correlation coefficient r increased from r=0.30 to r=0.73 and was also followed by an increase in statistical significance. This finding suggests that production of large spears leads to significantly higher total yields. Furthermore, across treatments, from 2018 to 2020, total yields have been decreasing by 21% in 2019 compared to 2018 and by 16% in 2020 compared to 2019. Across all treatments, annual yield reduction has been significant in both 2018 to 2019 and in 2019 to 2020. Nonetheless, there were differences between the yield decrease rate between treatments. As shown in Table 6, the 2018-2019 decrease has been significant for Bare soil SSD NR, PAS 100 R/NR and Straw mulch R/NR treatments. Between 2019 and 2020, yields of all treatment have reduced significantly with the exception of the PAS 100 ridged and non-ridged (R/NR) treatments.

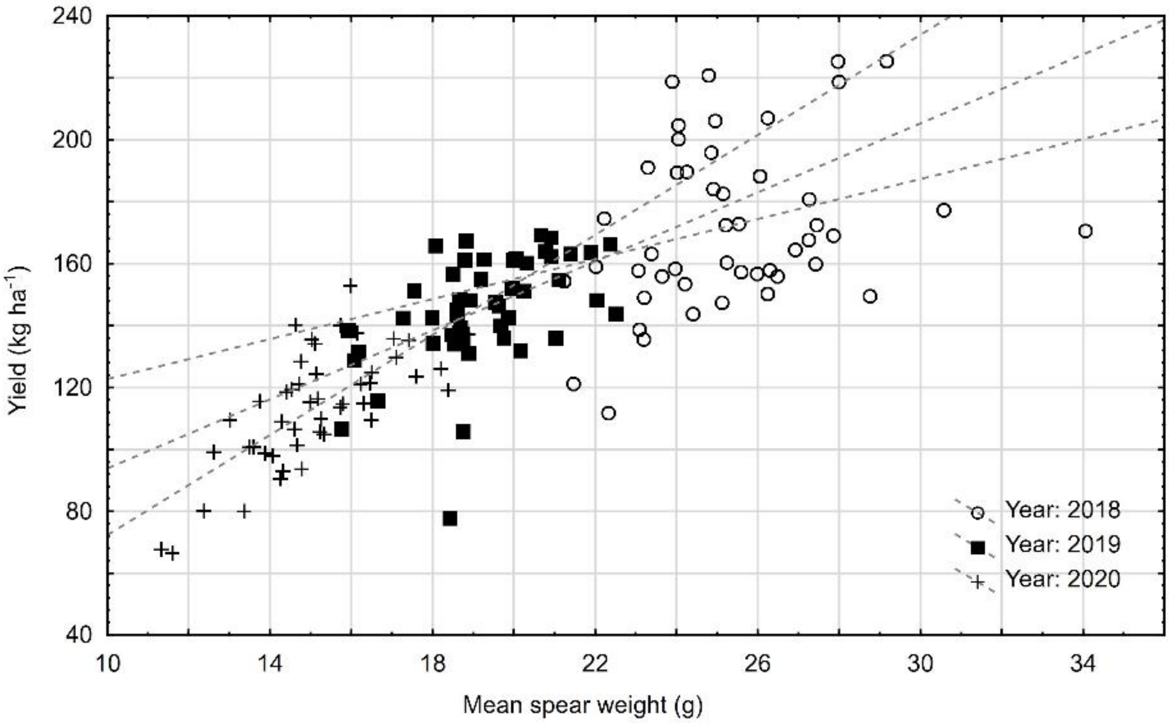


Figure 16. Relationship between asparagus yields (kg ha^{-1}) and average spear weight (g) (n=48). 2018: r^2 = 0.09, r = 0.30, p ≤ 0.05; 2019: r^2 = 0.26, r = 0.51, p ≤ 0.0005; 2020: r^2 = 0.53, r = 0.73, p ≤ 0.0005.

Table 6. Annual year on year percentage (%) yield (kg ha^{-1}) reductions for treatments.

Treatment	2018 to 2019 (%)	2019 to 2020 (%)
Zero-tillage	12 ^{ns}	24 ^{s}
Conventional practice	15 ^{ns}	27 ^{s}
Bare soil SSD NR	21 ^{s}	24 ^{s}
Bare soil SSD R	13 ^{ns}	23 ^{s}
Mustard NR	11 ^{ns}	22 ^{s}
Mustard R	16 ^{ns}	26 ^{s}
PAS 100 NR	22 ^{s}	11 ^{ns}
PAS 100 R	18 ^{s}	14 ^{ns}
Rye NR	6 ^{ns}	25 ^{s}
Rye R	8 ^{ns}	23 ^{s}
Straw Mulch NR	21 ^{s}	19 ^{s}
Straw Mulch R	20 ^{s}	22 ^{s}

S=significant; ns = non-significant. Significance determined following *post-hoc* Fisher analysis.

Links between root CHO, yields and RMD

Extensive research has claimed that asparagus productivity is primarily determined by the root CHO content (Paschold et al., 2008; Shelton and Lacy, 1980; Wilson et al., 2008). Nevertheless, following a simple correlation analysis of yields and root CHO of all treatments, no relationship between these two variables were found. This corroborates the findings reported by Drost (2012). Drost (2012) and Paschold et al. (2008) 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:

$$\text{Total CHO} = \text{Mean CHO content} \times \text{RMD}$$

Using this equation, a weak but significant relationship between total CHO and asparagus yields (Figure 17) was observed. Nonetheless, yields were already found to be positively linked to RMD ($r=0.36$, $r2 = 0.13$, $p \leq 0.05$). Hence, the source of significance in the correlation between the total CHO and yields may simply be the incorporation of the RMD in the equation.

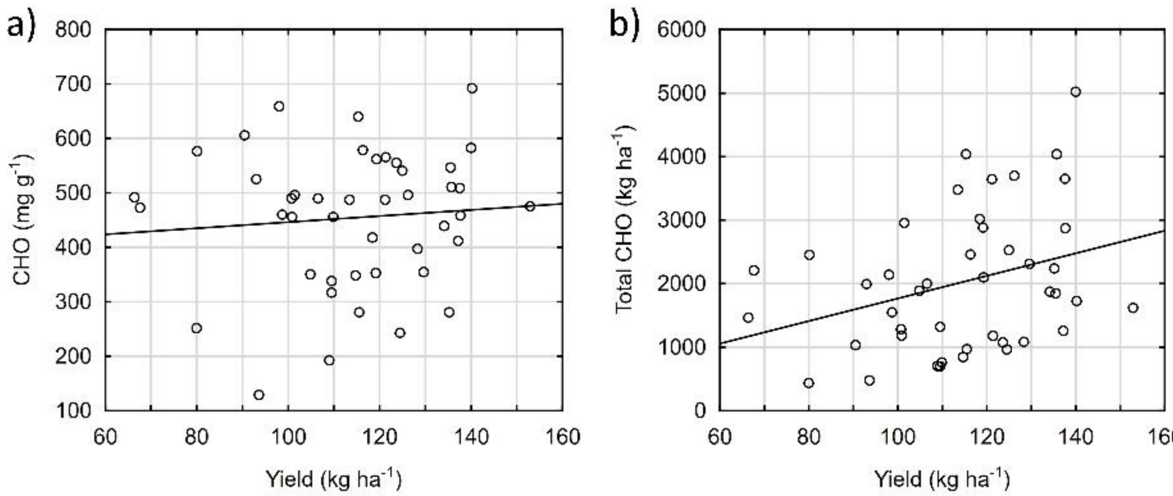


Figure 17. Relationships between; a) yield (kg ha^{-1}) and root CHO content (mg g^{-1}) ($r = 0.089$, $r^2 = 0.00$, p = NS) and between; b) yield (kg ha^{-1}) and total CHO content ($r = 0.32$, $r^2 = 0.10$, $p \leq 0.05$) (N=44).

Impact of BMPs on spear quality and on potential 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 and pest/disease damage. Spear value is determined based on spear grade specifications and on the time of the season. In the UK, there is no legally binding standard for asparagus spear classification.

In 2020, 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 suggesting that head flowering affected a higher proportion of 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 harvested. Rye NR in particular was associated with significantly lower numbers of medium spears (72%) as compared to many other treatments (Table 7). 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.

Due the presence of a positive response of re-ridging of Rye R as compared to Rye NR shown in Table 7, removing rye treatments from the statistical analysis was necessary in order to confirm whether ridging or subsoiling had a significant impact on any other treatments. Following the removal of Rye R and Rye NR from the dataset, re-ridging was found to have a significant negative impact across several yield quality indicators. Re-ridging was associated with significantly higher proportions of thin spears (22%) as compared to non-ridging (17%) across all treatments. Non-ridging was also associated with significantly higher numbers of medium spears (82%) as compared to re-ridging (78%). Re-ridging was however also associated with significantly less spear curving defects (8%) as compared to non-ridging (10%). While ridging had a significant negative impact on spear quality in all treatments with the exception of rye (where the impact of ridging was positive), SSD had no significant impact on any of the spear quality indicators.

Table 7. Impact of BMPs on spear diameter, spear defects and percentage marketable yield summed over the whole 2020 harvest season.

Treatment	Percentage (%) of potential marketable yield				
	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]
Conventional practice	24.5 [cde]	75.5 [abc]	0.00 [a]	26.1 [ab]	9.03 [abc]
Bare soil SSD NR	20.5 [abcd]	79.4 [bcde]	0.23 [ab]	27.8 [ab]	9.61 [bc]
Bare soil SSD R	25.7 [de]	74.0 [ab]	0.57 [b]	26.1 [ab]	6.22 [a]
Mustard NR	18.7 [abc]	81.2 [cde]	0.26 [ab]	23.5 [ab]	10.1 [bc]
Mustard R	22.9 [bcde]	77.1 [abcd]	0.00 [a]	26.3 [ab]	8.07 [ab]
PAS 100 NR	15.1 [a]	84.9 [e]	0.10 [ab]	25.1 [ab]	11.1 [c]
PAS 100 R	19.4 [abcd]	80.4 [bcde]	0.34 [ab]	25.0 [ab]	8.48 [abc]
Rye NR	27.9 [e]	72.0 [a]	0.09 [ab]	30.3 [b]	7.59 [ab]
Rye R	15.6 [a]	84.1 [e]	0.54 [b]	21.3 [a]	9.06 [bc]
Straw Mulch NR	16.0 [a]	84.0 [e]	0.00 [a]	21.4 [a]	9.57 [bc]
Straw Mulch R	17.7 [ab]	82.1 [cde]	0.53 [b]	20.8 [a]	8.46 [abc]

Within each column section, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher analysis

Furthermore, for all treatments, a significant positive relationship (r^2=0.369, $p<0.005$) was found between head flowering (%) and production of thin spears (<10 mm). Crucially, a significant strong negative relationship (r^2=0.541, $p<0.001$) was found between production of thin spears (<10 mm) and potential revenues (Figure 18). 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 in potential revenues (see section below).

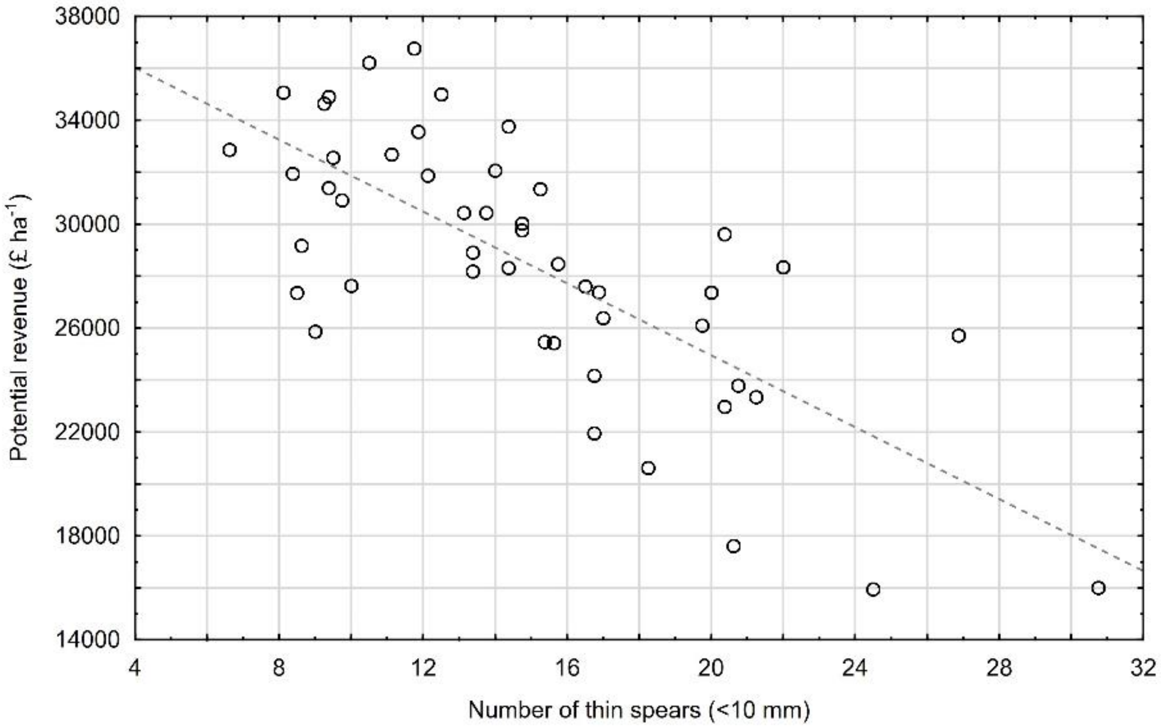


Figure 18. Relationship between numbers of thin spears and sum of potential revenues per plot based on data collected in 2020, including all treatments (N=48); $r^2 = 0.54$, $r = 0.74$, $p \leq 0.001$.

Potential revenues associated with adoption of BMPs

Spear class specifications are set by individual retailers usually following the 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. High quality 'Class I' spears typically sell for *circa* £7.00 per kg early in the season, £4.50 per kg during the main season and for £5.50 per kg in the late season. Lower quality 'Class II' spears sell for approximately £2.00 per kg during the main season. Thin spears of good quality can be sold as fine or extra fine asparagus with a premium of approximately £6.00 per kg.

In 2020, the main season was established between the 25th April – 6th June. Due to the complexity of spear valuation, a simplified value estimation was used disregarding differences in spear diameter and focused on the overall spear quality which significantly affects overall potential revenues. Misshapen and deformed spears (flowering or curved heads) were classified as 'Class II'. All spears without noticeable defects, regardless of diameter, were valued as 'Class I' spears. Both Class I and Class II fell within the marketable yield category and were used to estimate potential revenues.

BMP application costs include material costs and treatment application costs. BMP application costs and potential revenues were estimated on a hectare basis. The cost of straw was adopted from AHDB, 2021 (https://ahdb.org.uk/dairy/hay-and-straw-prices) and based on the average weekly prices of pick up baled wheat straw for 2021, ending with the week of 27th June 2021. PAS 100 compost price was based on prices listed by Sinkfall Recycling, 2021 (https://www.sinkfall-recycling.com/). Companion crops' seed price was estimated using seed prices listed by Cotswold seeds, 2021 (https://www.cotswoldseeds.com/).

Mulch and companion crops final application rates per ha were calculated by multiplying the maximum asparagus interrow area by the initial application rates in t ha^{-1} for mulches and kg ha^{-1} for companion crops. The maximum potential interrow area of 0.56 ha^{-1} per ha was calculated based on approximately 1 m maximum interrows width and on the number of 1.83 spacing asparagus beds per ha. Final application rates were multiplied by the material cost to estimate total treatment application costs in £ ha^{-1}. Costs of material transport were not accounted for.

Cost implications of tillage (Shallow soil disturbance (SSD) and re-ridging (R)) were estimated based on contracting prices survey based on red diesel at 50 ppl (NAAC, 2021) (https://www.naac.co.uk/) of £66.39 ha^{-1} for subsoiling and £259.55 ha^{-1} for bed tillage.

For Experiment 1 (Table 8), the lowest harvest revenue of approximately £25,000 ha^{-1} was linked to the Conventional practice, Bare soil SSD NR and Rye NR treatments. Although

Zero-tillage was associated with approximately 18% increase in potential revenue as compared to the Conventional practice, the potential revenue uplift was not statistically significant at 95% confidence interval. At 90% confidence however, the difference between these two treatments was statistically significant. Significantly higher potential revenues were also associated with the PAS 100 NR, PAS 100 R and Rye R treatments. Critically, potential revenues associated with the PAS 100 treatments equated to a potential gain of 28-30% or approximately £7,000 per ha as compared to the Conventional practice.

Potential revenue values given in Tables 8 and 9 however do not take into account the cost of labour, the cost of material and agrochemical application or the cost of fuel. Potential profits will thus considerably vary from the potential revenue values given and discussed in the current document. Further detailed cost benefit analysis is set to be included as a part of FV 450b project.

Table 8. Experiment 1 estimation of potential revenues per hectare associated with BMPs as compared with Conventional practice.

Treatment	Material cost	SSD application cost	R application cost	Total treatment application cost	Potential revenue
Zero-tillage	-	-	-	£0	*£30,528 [abc]
Conventional practice	-	-	£260	£260	£24,704 [a]
Bare soil SSD NR	-	£66.4	-	£66.4	£25,152 [ab]
Bare soil SSD R	-	£66.4	£260	£326	£25,920 [abc]
Mustard NR	£34.0	-	-	£34.0	£27,928 [abc]
Mustard R	£34.0	-	£260	£294	£26,156 [abc]
PAS 100 NR	£556	£66.4	-	£622	£32,004 [c]
PAS 100 R	£556	£66.4	£260	£882	£31,545 [bc]
Rye NR	£109	-	-	£109	£24,545 [a]
Rye R	£109	-	£260	£368	£32,269 [c]
Straw Mulch NR	£323	£66.4	-	£390	£27,622 [abc]
Straw Mulch R	£323	£66.4	£260	£649	£29,611 [abc]

Values followed by the same letter(s) are not significantly different ($p<0.05$) following One-Way ANOVA and *post-hoc* Fisher analysis. *Note, value is not significantly different at 95% confidence interval but is significantly different from the Conventional practice at 90% confidence interval.

There were no significant differences between mean total potential revenues between varieties (Table 9). Total mean potential revenues from all bare soil Gijnlim treatments were approximately £26,500 and total mean potential revenues from all bare soil Guelph Millennium treatments reached approximately £28,000. There were however significant differences between treatments. Potential revenues of both Gijnlim and Guelph Millennium were lower following application of the Conventional practice as compared to the Zero-tillage. This effect was not significant at 95% confidence interval in Gijnlim (19% reduction in potential revenue) but was significant in Guelph Millennium (25% reduction in potential revenue). Further detailed cost benefit analysis is set to be included as a part of FV 450b project.

Table 9. Experiment 2 estimation of potential varietal differences in potential revenues per hectare.

Variety	Treatment	SSD application cost	Annual ridging (R) application cost	Potential revenue
Gijnlim	Zero-tillage	-	-	£30,528 [bcd]
	Conventional practice	-	£260	£24,704 [ab]
	Bare soil SSD NR	£66.4	-	£25,152 [ab]
	Bare soil SSD R	£66.4	£260	£25,920 [abc]
Guelph Millennium	Zero-tillage	-	-	£32,180 [d]
	Conventional practice	-	£260	£23,997 [a]
	Bare soil SSD NR	£66.4	-	£31,245 [cd]
	Bare soil SSD R	£66.4	£260	£27,644 [abcd]

Values followed by the same letter(s) are not significantly different ($p<0.05$) following One-Way ANOVA and *post-hoc* Fisher analysis.

The impact of soil compaction on asparagus yields

The analysis of relationships between mean profile PR of the interrows and yields revealed a weak but significant negative correlation in 2018 and in 2020 (Figure 19) suggesting that increasing soil compaction of asparagus interrows was linked to asparagus yield reductions.

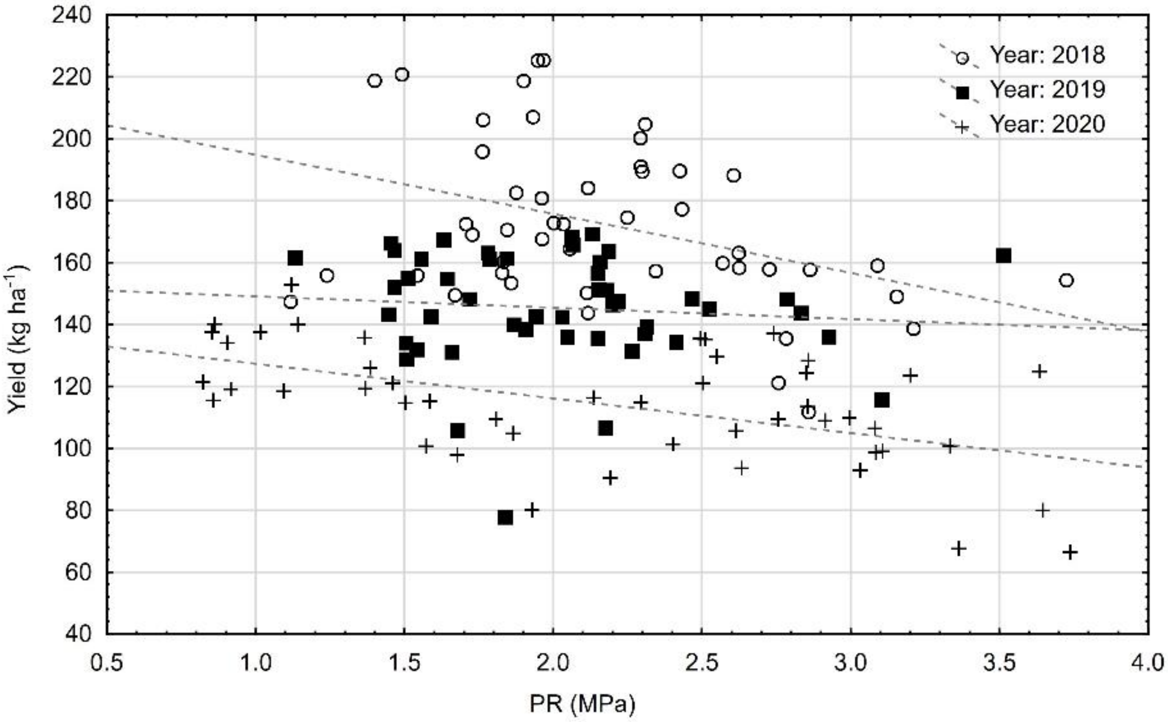


Figure 19. Linear correlation between mean Penetration Resistance (MPa) in the centre of the asparagus interrow and asparagus yields (kg ha^{-1}). Points represent paired values obtained across all treatments. 2018: r^2 = 0.15, r = -0.384, p ≤ 0.05; 2019: r^2 = 0.01, r = -0.097, p = NS; 2020: r^2 = 0.15, r = -0.381, p ≤ 0.05. NS = Not significant at 95% confidence interval.

Changes in soil bio-chemical properties following 3 years of BMP applications

Soil microbial community structure

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).

Phospholipid fatty acid analysis (PLFA) is a method frequently used to characterise changes in the composition of soil microbial communities (SMC) and to differentiate between fungal and bacterial biomass (Willers et al., 2015). In the study, relative abundance values of PLFA markers were used to indicate differences in SMCs. Factor 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 bare soil and companion crop treatments (Figure 20). Shallow soil disturbance (SSD) of interrows, had no impact on SMC community as indicated by scatterplot visualisation (Figure 21Figure). Treatments identified by ridging and non-ridging however formed two distinct PLFA profile groups which split alongside the axes of Factor 1 and Factor 2 (Figure 20 and Figure 22) suggesting that mulches and ridging had a significant impact on SMC structure.

Principle component analysis (PCA) further allowed identification of key PLFA markers within each community revealing that the PLFA marker used to indicate the presence of arbuscular mycorrhizal fungi (AMF) was reduced as a result of re-ridging. Standard analysis of variance (ANOVA) also showed that the relative abundance of PFLA markers used as an indicator of fungal biomass was significantly higher in non-ridged treatments as compared to ridged treatments.

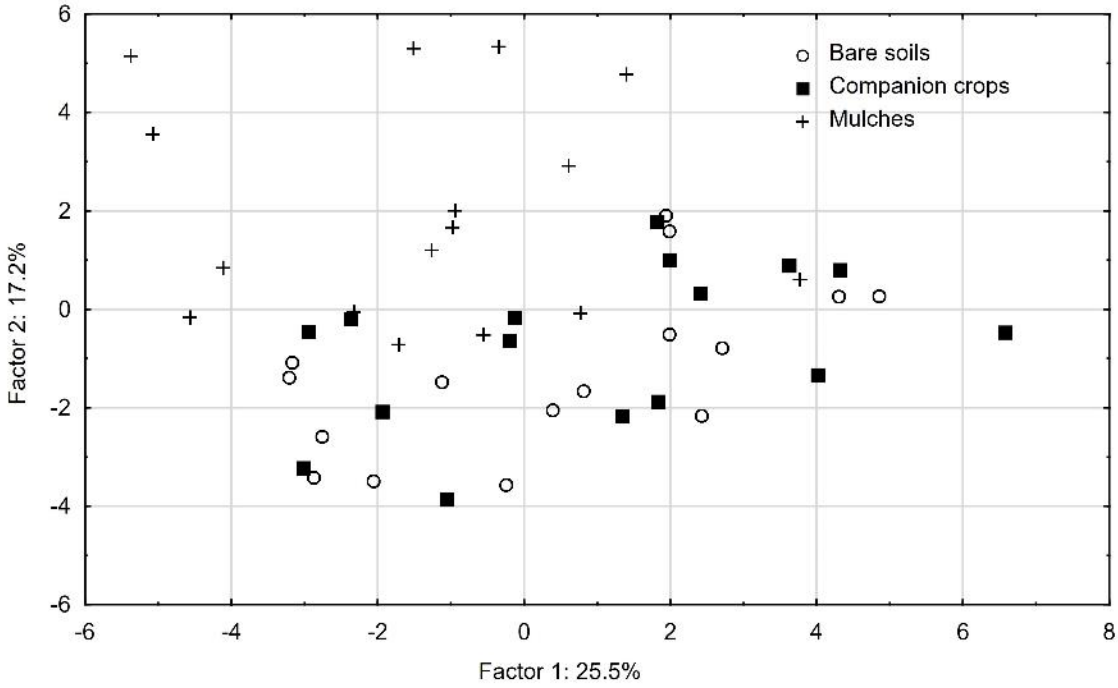


Figure 20. Projection of individual PCA ordination scores showing changes in microbial communities associated with bare soil, mulches and companion crop treatments

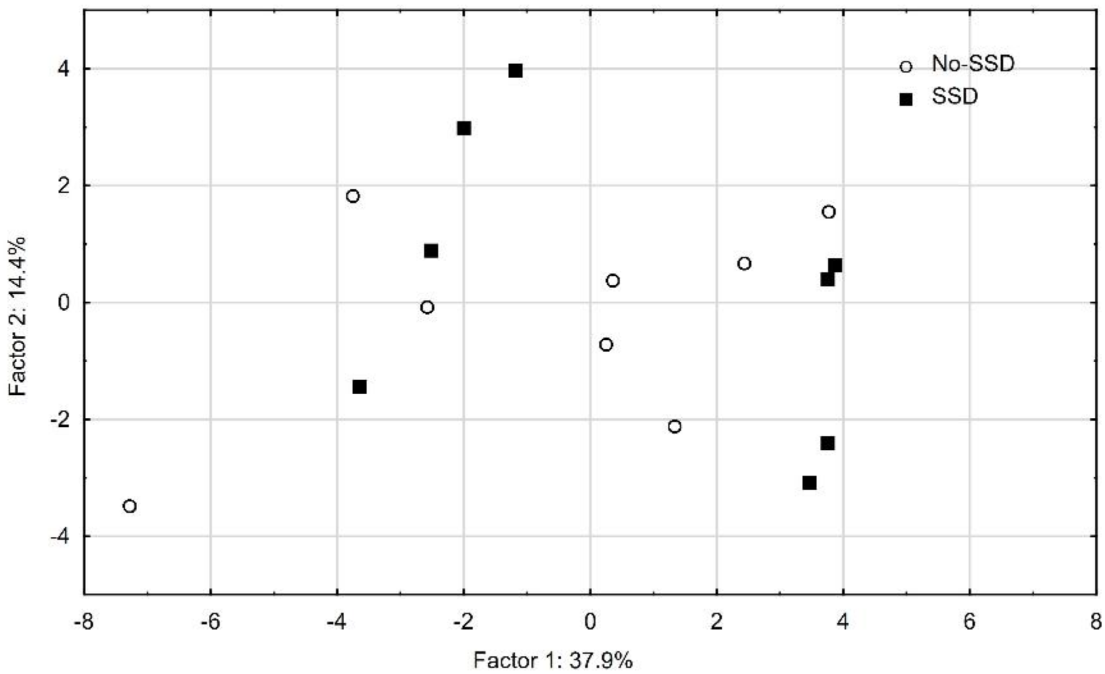


Figure 21. Projection of individual PCA ordination scores showing differences in microbial communities associated within bare soil treatments by subsoiling (SSD) or not subsoiling (No-SSD).

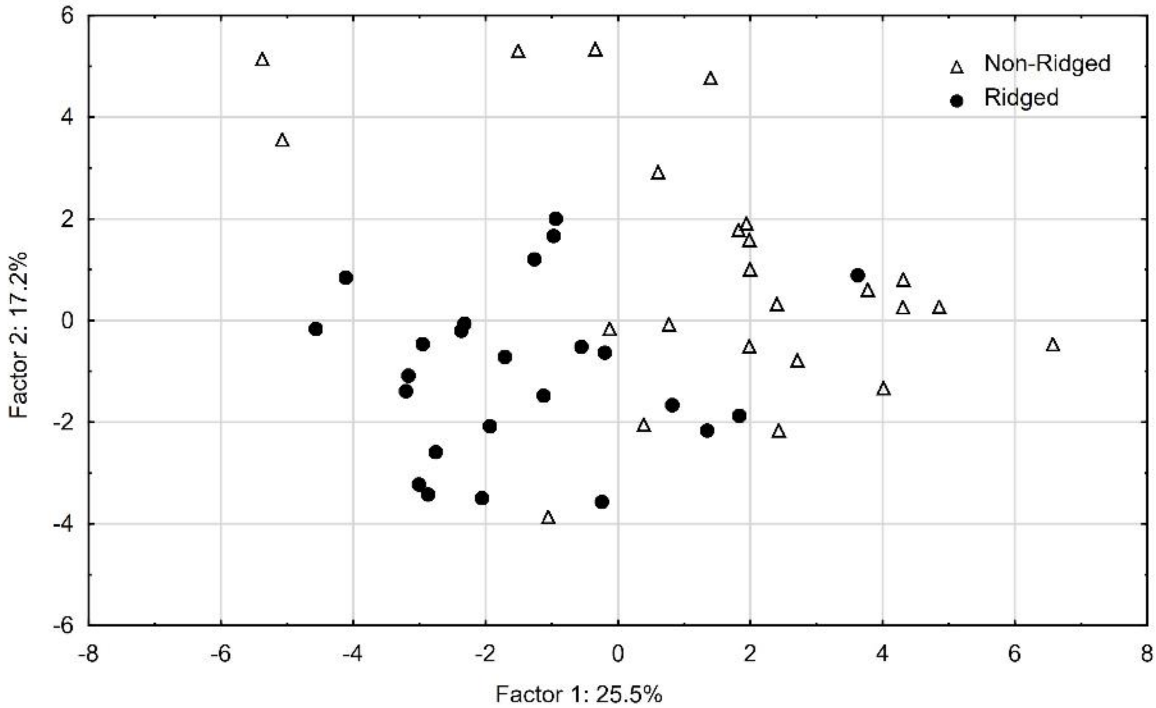


Figure 22. Projection of individual PCA ordination scores showing differences in microbial communities associated by re-ridging (R) or non-ridging (NR).

As shown in Table 10, relative concentrations of bacterial PLFAs were significantly lower in both PAS 100 NR/R as compared to the Conventional practice, Zero-tillage and Mustard NR treatments. Furthermore, mulches had overall significantly less bacteria as compared to all CC and Bare soil treatments. Relative amounts of the AMF marker were significantly higher in mulches as compared to all CC and Bare soil treatments. PAS 100 NR in particular was associated with significantly higher abundance of AMF markers as compared to all other treatments with the exception of PAS 100 R. Highest overall concentrations of fungal biomass were associated with mulch treatments. With the exception of PAS 100 R and Straw mulch NR, PAS 100 NR contained significantly higher relative abundance of fungal biomass as compared to all other treatments. Consequently, mulch treatments contained significantly higher amounts of AMF and fungal biomass as compared to all CC and bare soil treatments. SSD had no impact on the amounts of AMF and fungal biomasses. Re-ridging however significantly decreased relative abundance of fungal biomass across all treatments.

Microbial biomass carbon (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).

Table 10. Soil biological indicators of BMPs.

Treatment	MBC (µg g^{-1})	Fungal PLFA (Mol%)	AMF PLFA (Mol%)	Sum of bacterial PLFAs (Mol%)
Conventional practice	**117 ^{ab}**	**1.11 ^{a}**	**3.55 ^{abcd}**	**32.7 ^{cd}**
Zero-tillage	102 ^{a}	1.70 ^{bcde}	3.07 ^{ab}	33.3 ^{d}
Bare soil SSD NR	127 ^{abc}	1.87 ^{de}	3.18 ^{abc}	32.1 ^{bcd}
Bare soil SSD R	146 ^{abcd}	1.19 ^{ab}	3.82 ^{cde}	32.0 ^{abcd}
Mustard NR	130 ^{abc}	1.50 ^{abcd}	3.01 ^{a}	32.8 ^{cd}
Mustard R	134 ^{abcd}	1.30 ^{abc}	3.62 ^{abcde}	31.9 ^{abcd}
PAS 100 NR	176 ^{cd}	2.41 ^{f}	4.69 ^{f}	30.3 ^{a}
PAS 100 R	182 ^{d}	1.95 ^{def}	4.30 ^{ef}	31.0 ^{ab}
Rye NR	133 ^{abcd}	1.76 ^{cde}	3.25 ^{abc}	32.4 ^{bcd}
Rye R	161 ^{bcd}	1.10 ^{a}	3.69 ^{abcde}	31.5 ^{abc}
Straw Mulch NR	137 ^{abcd}	2.03 ^{ef}	3.75 ^{bcde}	31.5 ^{abc}
Straw Mulch R	157 ^{bcd}	1.81 ^{cde}	3.94 ^{de}	31.2 ^{abc}

MBC = Microbial biomass carbon; AMF = Arbuscular mycorrhizal fungi; PLFA = Phospholipid fatty acid; 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.

Soil chemistry

As shown in Table 11, 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 all CC and bare soil treatments. Tillage (re-ridging or SSD) did not have any significant impact on ammonium-N, nitrate-N or total mineralizable-N concentrations (Table 11).

No significant difference in percentage soil organic matter (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 the Conventional practice, Mustard R and Straw mulch R treatments (Table 11). Furthermore, SOM in asparagus interrows was significantly higher in soils which have been re-ridged compared to soils managed without ridging (Table 11).

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 as 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. Furthermore, Exchangeable-Ca and Mg significantly increased following re-ridging and were linked to elevated soil pH in the interrows (Table 11). 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 significantly 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 11). Furthermore, soil pH was significantly affected by re-ridging, where ridging increased soil pH compared to non-ridging. Available-P was found to be 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. Consequently, re-ridging significantly reduced the amount of available-P in the interrows of compost treated plots although amounts of added P would have been identical, 2749 mg kg^{-1} of P in dry matter compost.

Table 11. A list of parameters for soil chemical indicators of all BMPs.

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.

Evaluation of disease incidence

Results shown in Table 12 include mean disease incidence scores obtained from 2018 to 2020. Monitoring scores ranged from 0 (no disease present, full fern of at least 6') to 5 (disease over whole of fern and rapidly progressing defoliation, unlikely to be economical to harvest). Assessment methods were different between years. 2018 scoring assessed signs of disease on the stem and on fern and ranged from 0 to 2. 2019 disease assessment rated stem condition, fern condition, overall plant condition and signs of Phytophthora with scores ranging from 0 to a maximum of 2. 2020 mean score included *Stemphylium vesicarium*, *Botrytis cinerea* and soil disease which ranged between 1 to a maximum of 4. Disease scores are shown in Tables 12 and 13 but due to differences in assessment methods and lack of quantitative incidence or severity data, no conclusions could be drawn regarding the effect of soil management practices on asparagus disease development.

Table 12. Experiment 1 mean disease incidence scores.

Treatment	2018	2019	2020
Zero-tillage	0.63 ^{a}	0.56 ^{ab}	2.33 ^{bcd}
Conventional practice	0.63 ^{a}	0.69 ^{ab}	2.50 ^{cd}
Bare soil SSD NR	0.50 ^{a}	0.81 ^{b}	2.08 ^{abc}
Bare soil SSD R	0.50 ^{a}	0.50 ^{ab}	2.42 ^{bcd}
Mustard NR	0.75 ^{a}	0.50 ^{ab}	2.00 ^{ab}
Mustard R	0.50 ^{a}	0.75 ^{ab}	2.58 ^{d}
PAS 100 NR	0.63 ^{a}	0.69 ^{ab}	2.08 ^{abc}
PAS 100 R	0.50 ^{a}	0.81 ^{b}	2.08 ^{abc}
Rye NR	0.63 ^{a}	0.81 ^{b}	2.42 ^{bcd}
Rye R	0.50 ^{a}	0.38 ^{a}	2.25 ^{abcd}
Straw Mulch NR	0.50 ^{a}	0.63 ^{ab}	1.83 ^{a}
Straw Mulch R	0.75 ^{a}	0.56 ^{ab}	2.00 ^{ab}

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.

Table 13. Experiment 2 mean disease incidence scores.

Variety	Treatment	2018	2019	2020
Gijnlim	Zero-tillage	0.63 ^{ab}	0.88 ^{b}	2.33 ^{cd}
	Conventional practice	0.63 ^{ab}	0.75 ^{ab}	2.50 ^{d}
	Bare soil SSD NR	0.50 ^{a}	0.88 ^{b}	2.08 ^{bc}
	Bare soil SSD R	0.50 ^{a}	0.50 ^{ab}	2.42 ^{cd}
Guelph Millennium	Zero-tillage	1.00 ^{ab}	0.17 ^{a}	1.56 ^{a}
	Conventional practice	0.50 ^{a}	0.75 ^{ab}	1.58 ^{a}
	Bare soil SSD NR	1.00 ^{ab}	0.50 ^{ab}	1.58 ^{a}
	Bare soil SSD R	0.50 ^{a}	0.25 ^{a}	1.75 ^{ab}

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. It should be noted that disease incidence was based on visual observations only that the methodology used to assess disease incidence varied between years.

Discussion

Impact of BMPs on soil compaction

Previous research has shown that increasing the number of heavy machinery passes increases soil stress, often resulting in high levels of soil compaction. According to Duiker (2004b), the first vehicular pass is responsible for up to 75% increase in soil compaction. Following the first ridging of the FV 450 / 450a trial site in 2017, the mean profile PR of the interrows (90 cm distance from the crown zero line (CZL)) on bare soil treatments increased on average by 47%. By comparison, at 60 cm distance from the CZL, 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 14). Following 10 tractor passes however, all three treatments had significantly lower PR values as compared to the Conventional practice, interrows which were trafficked only 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. This implies that these treatments increase soil resilience to machinery and foot trafficking. Both compost and straw mulch in combination with SSD had similar compaction levels, regardless of the amount of traffic.

Table 14. 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.

In the past 20 years, many authors have argued that zero-tillage or conservation tillage has 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 current project 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. 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.

Impact of BMPs on asparagus root development

Results of this project demonstrate that the second annual re-ridging had a major negative impact on RMD in the Conventional practice, Mustard R and Rye R treatments, as manifest in 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 the 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). The second possible mechanism behind the observed reduction in RMD is related to recovery of root soluble 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 be more likely to 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 the observed significant RMD reductions as measured in March 2020. 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. Furthermore, interrows of those three treatments were essentially devoid of roots. Although the assumed zone of soil disturbance of the ridger (Figure 2), 0.3mD1 and 0,6mD1, did not show any significant year-to-year changes in root masses, re-ridging did have a significant impact on the 0.3mD2 sample location in all three treatments (Table 4). 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 2).

In 2020, the Zero-tillage treatment was associated with significantly higher mean overall RMD as compared to the Conventional practice suggesting that asparagus may 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, indicating that selectively placed tillage could be effectively implemented as part of best management 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 with the Conventional practice. In addition, Bare soil SSD NR, PAS

100 NR and Straw mulch R also had significantly higher mean RMDs 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 to distinguish between different tillage methods. Unlike ridging with no-SSD, SSD has the ability to mitigate negative impacts associated with re-ridging by improving water infiltration and reducing soil compaction of the interrows (Mašková et al., 2021).

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.

The 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 FV 450a trial confirms that in 5 and 6 year old plants, 57% and 62% of Total Root Biomass (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 0.15-0.45 m depth with the 0.15-0.30 m depth alone containing 46% and 45% of TRB. In 2019 and 2020, 27% and 28% of the TRB occurred 0.3 m from the crown at 0.15 – 0.3 m 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) is not carefully managed, productivity will be negatively affected.

Soil compaction is a major factor causing severe root growth restrictions (Bengough, 2012; Clark et al., 2003). The results of the FV 450a project showed that 87% of asparagus TRB was located in areas with PR values ranging from 1.0-3.5 MPa. This is comparable to 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 in which roots would not penetrate demonstrating that soil compaction may not strictly prevent asparagus root growth. FV 450a data however showed that asparagus roots favoured less compacted soils, as TRB values within the 5.0-7.0 MPa PR class of less than 2 % were significantly lower as compared to TRB values associated with the 1.0-3.0 MPa PR class of 74 %.

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. Based on the FV450a results, asparagus roots were more abundant in soil with compaction levels of 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).

Effect of BMPs on Asparagus yield and yield attributes

Spear weight can be an important factor determining profitability. Growers generally prefer larger spears as the grading and packing costs of fewer larger spears are 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 indicated 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 £5,800 ha^{-1} decrease in potential revenues from spears harvested from the Conventional practice. Asparagus yields were strongly correlated with 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 soluble carbohydrate (CHO) content, water stress, air and soil temperature can have a strong impact on spear size 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 in irrigated 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 FV 450a 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. In general, tillage (Re-ridging and SSD) was found to have no significant impact on spear weight across all treatments. Within the Bare soil treatment group however, re-ridging was found to be associated with significantly lower production (6% reduction) of medium spears as compared non-ridged Bare soil treatments and significantly higher production (6% increase) of thin spears as compared to non-ridged Bare soil treatments. Critically, thin spears formed approximal 25% of all harvested spears of the Conventional practice and Bare soil SSD R treatments. Including SSD alongside ridging did not significantly reduce these losses. Furthermore, a 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 project 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 pricing. Finally, as expected, production of thin spears was strongly negatively correlated with potential revenues confirming that abundance of spear defects and thin spears rapidly decrease potential revenues from the harvest. Field monitoring however needs to continue in order to confirm whether the observed reduction in yields and spear quality is temporary or is an indicator of the onset of asparagus decline

Effect of BMPs on soil bio-chemical indicators

Arbuscular Mycorrhizal fungi (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, Gabriel and Ruess, 2012; Wilkes *et al.*, 2020). AMF inoculation has also been showed to be beneficial in asparagus cropping systems (Wacker, Safir and Stephenson, 1990; Pedersen *et al.*, 1991) and to reduce severity of Fusarium (Pedersen *et al.*, 1991; Matsubara, Ohba and Fukui, 2001). The results showed that the relative abundance of the AMF PLFA marker was the highest in mulch treatments as compared to bare soil and companion crop (CC) treatments. On the contrary, Mustard NR had the lowest relative abundance of AMF marker, 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 (White and Weil, 2010; Njeru *et al.*, 2014). Relative abundance of the AMF marker was not different following the use of CCs from the Conventional practice or from the Zero-tillage. Companion crops have been reported to increase AMF populations in soils by providing additional nutrition to AMF during winter periods (Kabir and Koide, 2002). Rye as a CC in particular has been found to increase the abundance of AMF as compared to conventional tillage in maize (White and Weil, 2010; Mathew *et al.*, 2012). In the present project however, no significant impact of rye on AMF abundance was observed. The AMF marker was strongly and positively correlated to 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.

For the FV 450a project, the relative abundance of the AMF PLFA marker was not linked to any of the crop performance indicators. Tillage had been reported to have an impact on fungal commnuities (Frey, Elliott and Paustian, 1999; Lu, Lu and Liao, 2018; Sun *et al.*, 2018) which was confirmed by results presented in the science section where re-ridging was associated with a decrease in the fungal biomass as compared to non-ridging. 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 fungal biomass as compared to Conventional practice. Significant increase in fungal biomass in mulch treatments corresponded to significantly higher moisture content of soils under mulches as compared to bare soil and CC treatments. Consequenlty, both fungal and AMF PLFA markers were positively correlated with soil moisture content.

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, suggesting major difference in the impact of SSD and of ridging on soil microbiology. Although literature does not distinguish between the types of tillage when describing impacts of mechanical soil disturbance, whether it is sub-soiling tillage, discing 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, Elliott and Paustian, 1999). Contrary to findings of Schutter and Dick (2002) who claim that companion cropping (CC) was associated with changes in SMC as compared to bare soil treatments, in the present study, no significant effect of companion crops on SMC was observed. Nontheless, that lack of response of SMC to companion crops may be explained by the relatively short duration of the trial, which was only 3 years combined with a short application time of less than 6 months for CC treatments.

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

The FV 450a trial results found significantly lower N levels in mulch treatments as compared to Bare soil 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 (Cheshire *et al.*, 1999) which would explain in large part the results observed. The nutrient content of PAS 100 compost varies between each individual batch. In 2020 however, composted material analysis of PAS 100 showed Na 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 microbes, converting it back into plant available forms. 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; Pitman, Sanders and Swallow, 1991; Drost and Pedersen, 2018). 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, Artelt and Hermann, 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).

Although SSD had no impact on soil chemical indicators, re-ridging significantly increased soil organic matter (SOM), exchangeable-Ca and Mg and soil pH in interrows. Increase in SOM in re-ridged treatments however contradicts the prevailing paradigm of increased SOM in zero-tillage as compared to Conventional tillage systems (Frey, Elliott and Paustian, 1999; Rahman *et al.*, 2008; Jiang *et al.*, 2011).

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. CEC is closely linked to soil pH as confirmed by the 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 further positively correlated with the AMF bio-marker suggesting that tillage and changes in soil pH can drastically alter soil microbial community structure.

Furthermore, the 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.

Relationships between soil compaction, soil bio-chemical indicators and asparagus performance indicators

It has been shown that the Conventional practice is associated with high levels of soil compaction and 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; White and Kirkegaard, 2010; Novara *et al.*, 2019) and microbial activity (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). Correlation analyses showed that compaction levels were significantly linked to multiple bio-physical and chemical metrics (Table 15). It was found that increased soil compaction of the interrows was linked to lower root mass density (RMD) suggesting that productivity issues may not only be linked to mechanical root damage (Putnam, 1972; Wilcox-Lee and Drost, 1991) but also to compaction levels affecting the size and development of the 'Root Engine' in asparagus. 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 (6-10 yrs) 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 15).

Table 15. 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).

Crop performance indicators	PR
Yield	-0.27
Spear size	-0.10
Revenue	-0.24
RMD	-0.33*
CHO	-0.19
Total CHO	-0.35*
Soil quality indicators	
Dry matter content	0.30*
Microbial biomass carbon	-0.38*
Soil organic matter	-0.11
Ergosterol	-0.20
Nitrate NO3-	0.40*
Ammonium NH4+	0.46*
Total N	0.44*
Ex Ca2+	-0.18
Ex K+	0.27
Ex Mg2+	0.28
Ex Na+	-0.28
CEC	-0.02
Soil pH	-0.17
Available P	-0.01

RMD = root mass density, CHO = root soluble carbohydrate content, CEC = cation exchange capacity. *Significant at $p \leq 0.05$.

High levels of soil compaction were further linked to elevated contents of soil N, likely caused by reduced porosity of the compact soils which would reduce N leaching. Limited root growth caused by higher compaction levels may have also reduced N uptake by roots (Siczek and Lipiec, 2011; Mašková *et al.*, 2019), which may explain higher N content of the compacted interrows.

High PR values were also linked to low relative amounts of arbuscular mycorrhizal fungi (AMF) and low relative amounts of soil fungal biomass. AMF has been shown to have a beneficial impact on asparagus (Wacker, Safir and Stephenson, 1990; Pedersen *et al.*, 1991; Matsubara, Ohba and Fukui, 2001), thus decrease in AMF in asparagus due to high PR values may long-term result in production problems. 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.

General evaluation of the relationships between BMP application and crop performance

Results of this project confirmed the existence of links between the application of BMPs to asparagus interrows and changes in key crop performance indicators. Correlation coefficients establishing the strength and direction of relationships between variables are presented in Table 16 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, yields, potential revenues calculated as a function of total yields and yield quality, CHO, and total CHO obtained by method by Drost (2012), which accounts for the size of the root engine.

The correlation results presented in Table 16 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 (Woolley, et al., 1999; Drost, 2012). Nevertheless, measurements of CHO content of individual roots were not indicative of yields unless RMD was also included.

Soil N content was not linked to crop performance with a single exception that of root CHO, which 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 17 also showed a negative correlation between Mg content, yields and root growth. Magnesium deficiency symptoms have been shown to affect asparagus fern as a partial of full fern chlorosis eventually progressing toward necrosis (AHDB, 2014). Mg deficiency may negatively affect photosynthesis thus be a plausible explanation for the relationship between soil Mg, yields and RMD. 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.

Table 16. 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. *Significant at p≤0.05.

Little is known about the relationships between the soil microbiology and asparagus growth and productivity. Analysing soil microbial community structure (SMC) 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). SMC 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). 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). While bacteria are able to withstand harsher environments (Schmidt et al., 2014), fungi are highly susceptible to disturbance and soil management (Deveau et al., 2018; Schmidt et al., 2019).

As indicated by Table 17, soil microbial community (SMC) structure was linked to asparagus performance indicators. RMD was positively corelated with MBC while total yields were positively correlated with relative amounts of fungal biomass. 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*. PLFA analysis used in the current project does not distinguish between pathological and beneficial fungi. The fungal PLFA biomarker is also a major component of the Fusarium cell membrane (Chen et al., 2001; Xiao et al., 2017). The presence of *Fusarium* in soil samples was however not determined in this project. It is critical that further research addresses whether field management practice affects the occurrence of soil borne diseases in asparagus. Methods allowing detection of *Phytophthora asparagi* and *Fusarium oxysporum* in soil samples include DNA-sequence based identification or species-specific quantitative polymerase chain reaction (qPCR) assay.

Fungal biomass was significantly more abundant in non-ridged treatments as compared to ridged, with higher yields associated with higher concentrations of fungal biomass. PLFA analysis profiles found that a single marker was negatively correlated to all but one crop performance indicator, which was CHO. Although there is limited knowledge of the origin of the marker, available evidence suggests that is may be indicative of the presence of methanotrophic bacteria (Singh and Tate, 2007). Methanotrophs mediate biological oxidation of methane-CH4, 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), the PLFA marker was significantly higher in compact treatments (r=0.42) suggesting prevalence of this marker under anaerobic conditions. Relative concentrations of this marker were associated with decrease in yields and root growth, thus its presence in soils was linked to negative impacts on overall asparagus performance as associated with soil compaction. Finally, it is critical to recognise that PLFA showed multiple markers to be significantly related to asparagus yields, underlining the importance of soil microbial structure in asparagus production systems.

Table 17. 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 revenue	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

*Significant at p≤0.05. RMD = root mass density, CHO = root soluble carbohydrate content, CEC = Cation exchange capacity, MBC = Microbial biomass carbon

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 the science section of the current report and in the Annual Reports 2020 and 2019 showed that SSD and ridging should be considered as two separate practices which impact crop and soil properties very differently. While SSD has the 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, as showed in Figure 2, 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.

Performance of Best Management Practices (BMPs) as compared with Conventional Practice.

A comparative treatment performance evaluation was carried out to identify BMPs with the most desirable overall impact across multiple performance indicators. The evaluation was based solely on the assessment of the most recent 2020 data.

Treatment performance scores were derived using the *post-hoc* Fisher Least Significant Difference (LSD) test, which shows statistically significant differences between pairs of treatments. In the results section, significant differences are indicated in tables by a letter or a group of letters following every value. Performance 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 this performance assessment included Root Mass Density (RMD), yield, spear size, potential profitability, total storage root soluble carbohydrate (CHO), soil compaction as measured by penetrative resistance (PR) and soil 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.

Values close to zero indicate management practices that carry a major risk to the asparagus root growth, yield, productivity and soil erosion risk. In contrast, BMP treatments with values close to 10 infer management practices that promote asparagus root growth, yield, productivity and reduce soil erosion risk.

Calculated relative performance scores indicate that the application of the Conventional practice with the lowest impact score of 2.5 carries the highest overall risk to root growth, yield, productivity and soil erosion risk, consequently risking asparagus stand longevity (Figure 23). Impact scores further indicate that all other treatments were associated with scores higher as compared to Conventional practice.

The performance matrix (Figure 23) indicates that all BMP treatments evaluated under FV 450a (with the exception of rye non-ridged companion crop) are an improvement on Conventional practice. This finding suggests that the BMPs evaluated under FV 450a can be adopted to drive a major change in the way asparagus is cultivated in the UK. The highest performance scores of 7.0 to 9.1 are primarily linked to the application of straw and PAS 100 mulches to asparagus interrows at 5 and 25 t ha^{-1} per annum respectively in association with interrow shallow soil disturbance, post mulch application. These management practices promote improvements in asparagus root growth, yield, profitability, promote soil health and reduce soil erosion risk. It is however recommended that growers keep up to date with regulations pertaining to the application of PAS 100 compost to land to ensure that they are compliant.

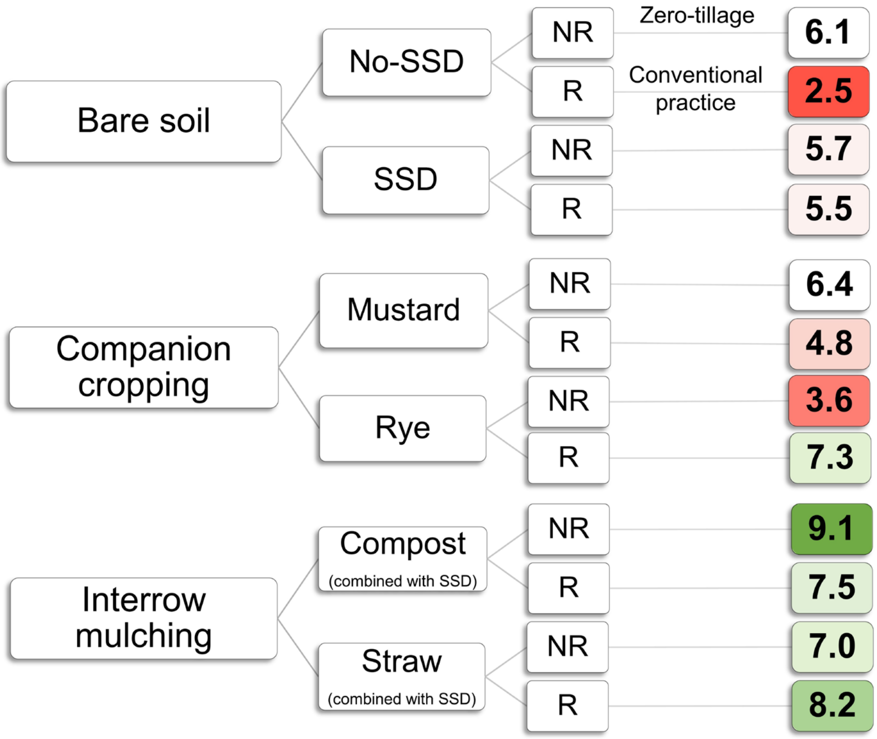


Figure 23. Comparison of asparagus crop performance associated with different management practices applied from 2016-2020. Performance scores range from 0 (worst) to 10 (best). See Appendix A for detailed performance score calculation methodology. NR = No annual re-ridging. R = Annual re-ridging, SSD = shallow soil disturbance applied to interrows. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

Conclusions

- The results of this study confirm that asparagus yield, profitability, alleviation of soil compaction, increased infiltration and improved soil health can be achieved by moving away from Conventional practice and adopting one of several alternative Best Management Practice (BMP) options.
- PAS 100 Compost applied annually to asparagus interrows in combination with shallow soil disturbance (SSD) without annual re-ridging can result in significant (>20%) yield uplift, reduced soil compaction, improved infiltration rates, higher arbuscular mycorrhizal fungal and total fungal abundance and increased potential revenues as compared to Conventional practice.
- Companion cropping with rye (*Secale cereale*) with annual re-ridging, can result in >20% yield uplift as compared to Conventional practice. However, non-ridging carries a risk of a 20% yield penalty compared with Conventional practice suggesting that growers need to be confident that they can re-ridge if rye is grown as a companion crop for run-off and erosion control.
- Zero-tillage also referred to as 'ridging for the life of the crop' is associated with improved yield and potential revenues, reduced soil compaction and improved soil health as compared with Conventional practice.
- The relative abundance of fungal biomass was significantly higher in non-ridged treatments as compared to ridged treatments.
- The combination of shallow soil disturbance and mulch application to interrows significantly improves infiltration and reduces soil compaction to >0.5m depth.
- Shallow soil disturbance has no negative impact on root mass density, asparagus yield arbuscular mycorrhizal fungal and total fungal abundance and is linked to a significant increase in microbial biomass.
- The FV 450a trial has not yet reached the key phase of crop maturity and economic production which typically occurs between years 4-7. This is the key payback period for growers. Consequently, the impact of BMPs on stand longevity and profitability will continued to be monitored and economic implications assessed.

Knowledge and Technology Transfer

The following knowledge and technology transfer activities have been undertaken under this project.

Engagement Activities

- 13th February 2019 Project Advisory Group (PAG) Meeting
- 2nd October 2019 PAG Meeting
- 20th February 2020 Asparagus Growers Association (AGA) meeting
- June 2020 project update in the Asparagus Growers Association (AGA) Newsletter
- 30th July 2020 PAG Meeting

Training Activities

- 2 growers (Suffolk/Norfolk and Warwickshire) were provided with training sessions on the asparagus root coring, including the use of both manual and pneumatic root corers.

Knowledge Exchange

- Results were presented at the Asparagus Innovation Day 2018 on the 20th September 2018. Feedback was extremely positive with x3 groups of participants fully engaged around a pre-prepared soil profile. Visualising asparagus roots and discussing the implications of tillage and ridging on root damage and crown and root rots resulted in several growers agreeing to participate in the FV 450a wider grower-based root coring programme.

- Simmons, R.W. (2018) Getting to the root of the problem. AHDB Grower Issue No. 237 Dec/Jan 2018 pp. 21 https://horticulture.ahdb.org.uk/publication/grower-decjan-2018

- Video tutorial on Asparagus root coring was released on the 12th February 2019 https://www.youtube.com/watch?v=Lms3GfRgiXM

- Simmons, R.W., De Baets, S., Niziolomski, J. C. and Maskova, L. (2018) Companion cropping in asparagus: Impacts on asparagus yield and soil structure. Aspects of Applied Biology 140, Soil Improvement: Impact of management practices on soil function and quality. pp. 55-61.

- Asparagus Root growth patterns Technical Update https://horticulture.ahdb.org.uk/download/12456/file

- 4th June 2019 CHAP Soils Forum 2019 Asparagus field trial demonstration

- 16th July 2019 – The Asparagus Growers Association Biennial Conference in York – Field demonstration given on root coring methodology and discussions around BMP.

- 30th - 31st January 2020 AHDB Crops PhD Conference poster presentation.

- March 2020 Article published in the Asparagus World Magazine N°2

- 6th July 2020 Cranfield and FERA SBSH joint meeting.

- Presentation of major project findings at the AHDB PhD student conference on the 25th – 27th January 2021.

- 8th February – online presentation of the main outcomes of the FV 450a project to the audience of the IAgrE (Institution of Agricultural Engineers) South East Midlands branch

- Follow-up meeting with colleagues from the FERA institute on the 11th March 2021. Both Cranfield and FERA teams have discussed results on soil microbiology and DNA sequencing to date and agreed on a joint publication.

- Article published in the Vegetable Farmer magazine in June 2021 focused on the potential of companion cropping in asparagus systems.


-ASPARAGUS-

EXPLORING THE POTENTIAL OF COMPANION CROPS FOR ASPARAGUS

- Mašková, L., Simmons, R.W., Deeks, L.K., De Baets, S., 2021. Best Management Practices to Alleviate Deep-Seated Compaction in Asparagus (*Asparagus officinalis*) Interrows (UK). Soil Tillage Research 213. https://doi.org/10.1016/j.still.2021.105124

- Successful submission of PhD by Lucie Mašková ‘Alternative cropping practices for sustainable soil management and yield optimisation in asparagus’ submitted on July 12th 2021.

Glossary

BMPs	Best Management Practices
PAG	Principal Asparagus Growers
PR	Penetrative resistance
RMD	Root Mass Density
%TRB	Percentage Total Root Biomass
CZL	Crown zero line
IDW	Inverse distance weighing
VESS	Visual Evaluation of Soil Structure
VSA	Visual Soil Assessment
R	Re-ridging
NR	Non-ridging
SSD	Shallow Soil Disturbance
No-SSD	Without Shallow Soil Disturbance
CC	Companion Crops
CHO	Soluble Root Carbohydrate
ELMS	Environmental Land Management scheme
CRR	Crown and root rot
SMC	Soil microbial community

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Appendix A

Final impact score formula

Impact scores for best management practice treatments were derived from 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 indicated by letters or by a group of letters following each value, which were 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**Error! Reference source not found.**. 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:

$$\text{Final impact score} = \frac{\sum_{n=1}^{7} \text{IP}}{\text{IP}_{\text{MAX}}} \times 10$$

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
[1]Zero-tillage	bcdef	bcde	de	ab	ab	a	ab
[2]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

[1]Bare soil No-SSD NR; [2]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 and equation described in 0.

Treatment	RMD	Yield	Spear weight	Potential revenue	Total CHO	PR	Infiltration rate	IP	Final impact score
[1]Zero-tillage	6	6	8	2	2	1	2	27/44	6.1
[2]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

[1]Bare soil No-SSD NR; [2]Bare soil No-SSD R. RMD = root mass density; CHO = root soluble carbohydrate content, PR = penetration resistance; IP = impact points.

