Project title:	**Asparagus: Sustainable soil management for stand longevity and yield optimization**
Project number:	FV 450a
Project leader:	Dr Rob Simmons, Cranfield University
Report:	Year 2 Annual Report, September 2020
Previous report:	FV 450a Year 1 Annual Report FV 450 Final Report
Key staff:	Lucie Maskova and Dr Lynda Deeks
Location of project:	Gatsford, Ross-on-Wye
Industry Representative:	Phil Langley Sandfield Farms
Date project commenced:	01/03/2018
Date project completed (or expected completion date):	31/05/2021

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The results and conclusions in this report are based on an investigation conducted over a one-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.

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CONTENTS

GROWER SUMMARY

Headlines

- The impact of soil management practices on asparagus production (two varieties, Gijnlim and Guelph Millenium) has been monitored annually since 2016.
- Significant effects of zero tillage, ridging, shallow-soil disturbance, compost, mulch and companion crops on asparagus yield, root architecture and interrow wheeling soil compaction have been observed and will continue to be monitored as the crop moves into the phase of peak commercial production.
- Soil profile maps of root biomass derived from asparagus fields across the UK have enabled growers to see the potential risk of cultivations such as sub-soiling and annual ridging causing root damage in their crops.

Background

Conventional operations associated with UK asparagus production, i.e. tillage, spraying and harvesting, can result in progressive and severe compaction of all inter-bed wheelings. In addition, research 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. Both root damage and crown and root rots contribute significantly to yield decline.

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 are evaluating a range of best management practices to prevent and/or mitigate compaction, improve soil structural status in asparagus wheelings and facilitate long-term profitability of asparagus production. The experimental trials are comparing shallow soil disturbance (SSD) and mulch attenuation options, cover/companion cropping, and zero-tillage options against conventional practice. A further objective is to increase the relevance of potential best management practices by critically evaluating the asparagus root system architecture associated with the wider UK asparagus grower land bank and relevant cropping practices.

Summary

In April 2016 two replicated field experiments were established at Gatsford Farm, Ross-on-Wye. For full detail of the treatments investigated and results to date refer to the following reports: FV 450 Final Report (2018) and FV 450a Year 1 report (2019).

Experiment 1 (48 experimental plots) is restricted to Gijnlim which represents 70% of UK field grown asparagus.

Experiment 1: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	Companion Crop – rye	R
Gijnlim	Companion Crop – rye	NR
Gijnlim	Companion Crop – mustard	R
Gijnlim	Companion Crop – mustard	NR
Gijnlim	PAS 100 compost SSD	R
Gijnlim	PAS 100 compost SSD	NR
Gijnlim	Straw Mulch SSD	R
Gijnlim	Straw Mulch SSD	NR
Gijnlim	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Gijnlim	Conventional Practice	R
Gijnlim	Zero-tillage	NR

Annual re-ridging (R) or Zero-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included in Experiment 2.

Experiment 2 compares varietal differences in root development/architecture and root profile distribution as affected by sub-soiling treatments for two widely grown varieties, Gijnlim and Guelph Millennium.

Experiment 2: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Gijnlim	Conventional Practice	R
Gijnlim	Zero-tillage	NR
Guelph Millennium	Bare soil SSD	R
Guelph Millennium	Bare soil SSD	NR
Guelph Millennium	Conventional Practice	R
Guelph Millennium	Zero-tillage	NR

Annual re-ridging (R) or Zero-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included from Experiment 1.

The timing of treatment applications, root coring, yield monitoring and soil structural assessments are indicated in Figure A.

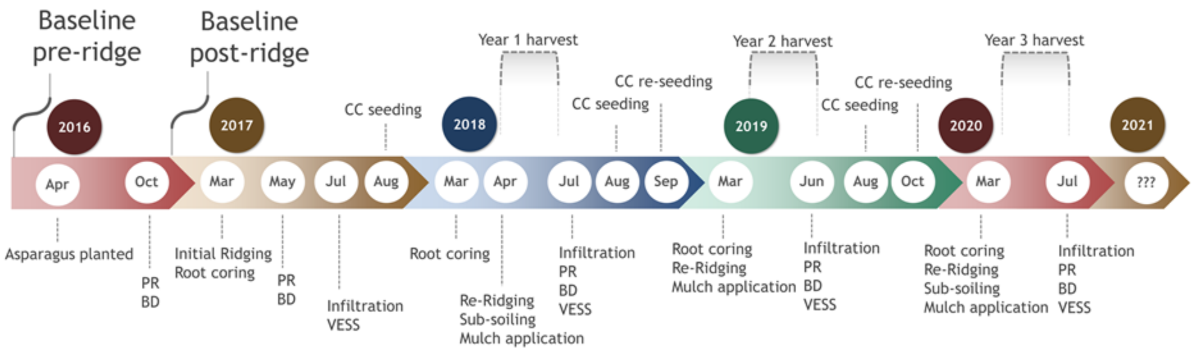


Figure A. FV 450 and FV 450a project timeline

Impact of treatments on asparagus yield

Experiment 1

- The PAS 100 compost treatments (ridged and non-ridged in combination with shallow soil disturbance) were associated with a 20% uplift in asparagus yield as compared to conventional practice and rye non-ridged treatments. Conventional practice is defined as annual re-ridging with no shallow soil disturbance applied to interrow wheelings (Figure B)

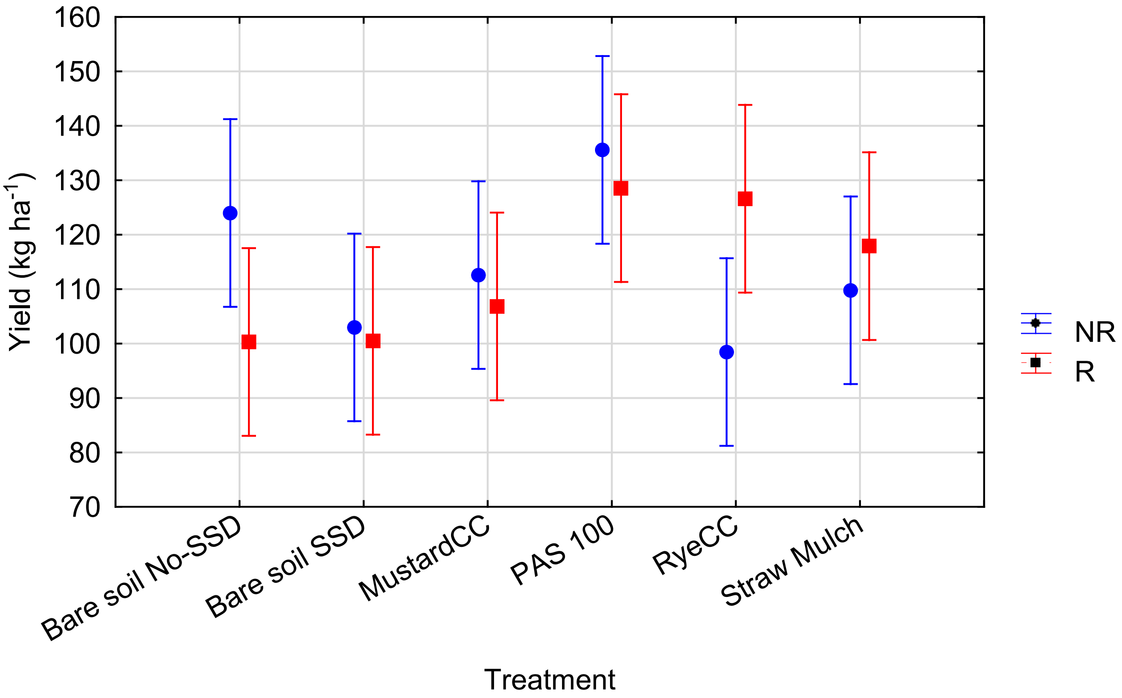


Figure B. Differences in 2020 Gijnlim yield (kg ha^{-1}) between Experiment 1 treatments. Vertical bars denote 0.95 confidence intervals.

- The rye non-ridged treatment continues to be associated with a 23% reduction in yield as compared to the rye ridged treatment.
- In 2020, (in contrast to 2018 and 2019) no significant difference in yield was observed between the comparable Gijnlim and Guelph Millennium treatments.

Experiment 2

- As observed in 2019, for both Gijnlim and Guelph Millennium, annual re-ridging associated with conventional practice was associated with a 20-24% reduction in yield as compared with the equivalent zero-tillage treatments. This may in part corroborate previous research showing that that annual re-ridging causes root damage and yield reductions.

Impact of treatments on storage root soluble carbohydrate (CHO) levels

Experiment 1

- Despite some clear yield differences, there was no effect of treatments on root CHO values in either 2019 or 2020.

Experiment 2

- The 2020 results follow the 2018 and 2019 findings that asparagus storage root CHO values for Guelph Millennium are significantly higher than the equivalent for Gijnlim, irrespective of treatment.

Impact of treatments on mitigating interrow wheeling compaction

In this project, penetrative resistance (PR) is used as a measure of soil compaction, with higher PR values indicative of higher levels of soil compaction.

- Conventional practice (defined as annual re-ridging with no shallow soil disturbance applied to interrow wheelings) was associated with significantly higher PR from 0.0-0.2 m depth as compared to all other bare soil treatments. In contrast, significantly lower PR values across the soil profile from the zero-tillage treatment indicated less soil compaction as compared to all other bare soil treatments.
- In both 2019 and 2020, companion cropping did not significantly affect PR as compared with conventional practice. This was unexpected as the companion crops were based on previous studies, expected to bioremediate soil structure.

- In 2020, PR was significantly reduced in the interrow wheelings to 0.25 m depth for all shallow soil disturbance treatments. Furthermore, the straw mulch and PAS 100 compost treatments (applied in conjunction with shallow soil disturbance) resulted in significantly less compaction than conventional practice to greater than 0.5 m depth.
- In 2020, infiltration rates in all treatments subject to shallow soil disturbance were classified as “Very Rapid” (>500 mm h^{1}) and were significantly higher than for conventional practice (“Moderate”, 23.2 mm h^{-1}).
- The results suggest that the combination of mulch application (either PAS 100 Compost or straw) to interrow wheeling and shallow soil disturbance significantly reduces deep seated compaction and increases infiltration. This has implications for runoff and erosion control as well as soil moisture re-charge.

Impact of treatments on root architecture

Experiment 1

- Significant differences in whole profile root mass density (RMD) were observed between the zero tillage and conventional practice treatments. This was due to significant differences in RMD at 0.15 – 0.30 m depth, 0.3, 0.6 and 0.9 m from the crown zero line. These differences amount to between a 48-98% increase in RMD associated with the zero-tillage treatment. This indicates that annual re-ridging damages storage roots. However, to date, no significant reduction in yield or increase in disease incidence has been observed in relation to this treatment.

Experiment 2

- Guelph Millennium is associated with a shallower rooting tendency as compared with Gijnlim. For the zero-tillage treatment, which essentially allows the asparagus roost to grow undisturbed, Guelph Millennium is associated with 66-100% higher RMD at 0.0 – 0.15 m depth at 0.3 and 0.6 m from the crown zero line, as compared with Gijnlim.

Potential root damage associated with sub-soiling and ridging operations

Experiment 1 and 2

- Across all treatments, sub-soiling (shallow soil disturbance) in interrow wheelings could potentially damage up to 5% of the total root biomass under a range of tine configurations used at an operating depth of 300 mm. Annual ridging operations also have the potential to damage up to 5% of total root biomass.

Wider grower landbank:

Root samples collected from asparagus fields in 2019-2020 were used to create field-specific ‘root heat maps’ showing root biomass at different depths and distances from the crown. These maps can be used by growers to determine the risk of root damage following different cultivation practices in individual fields. As an example of this, maps for 3- and 11-year old crops of Gijnlim, respectively for two fields from Grower E, indicate the following:

- Gijnlim planted as A crowns grown on 1.80 m centres, aged 2-6 years old would be associated with damage to <2% of total root biomass under all tine configurations investigated by Niziolomski, et al. (2016) to an operating depth of 300 mm (Figure C). The root heat map also suggests that re-ridging has the potential to damage on average 5-8% of total root biomass.
- In contrast, for 11-year old Guelph Millennium planted on 1.5 m centres, there is potential for 8-11% of storage root total biomass to be damaged when using the winged with shallow leading tine, winged tine and modified para-plough investigated by Niziolomski, et al. (2016) to a 300 mm operating depth (Figure D). Approximately, 2-5 % of total root biomass could potentially be damaged using the narrow tine and narrow with shallow leading tine configurations investigated. With re-ridging, there is the potential to damage 11-14% of total root biomass. This is due to both the age of stand and shallower rooting habit of Guelph Millennium.

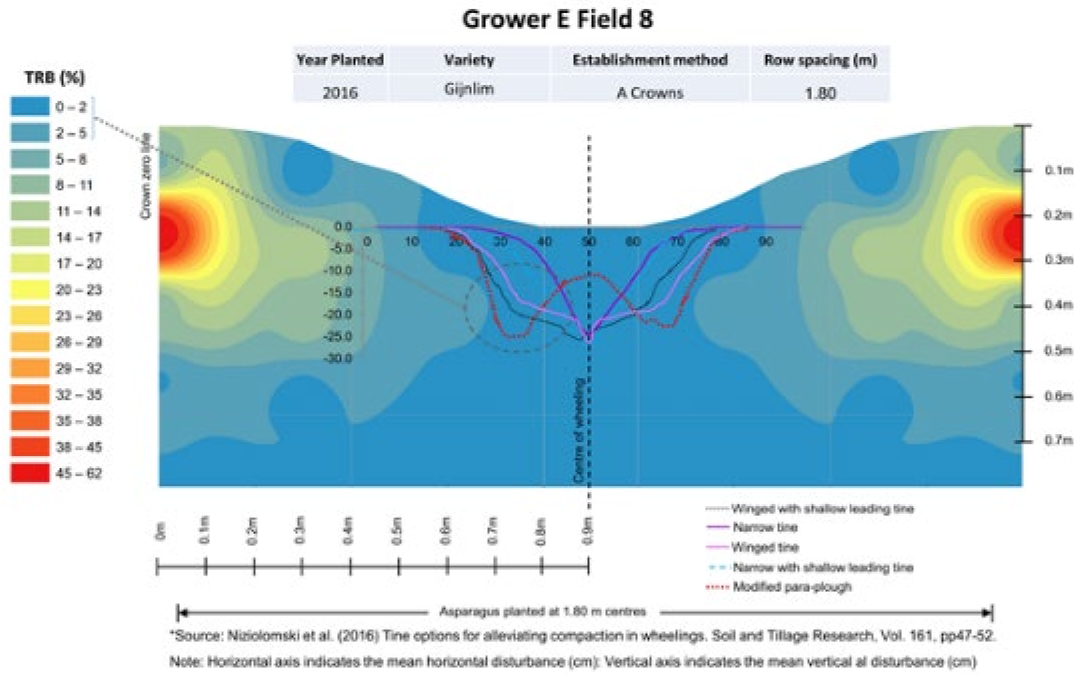


Figure C. Grower E total root biomass: root map for 3-year old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations to 300 mm depth.

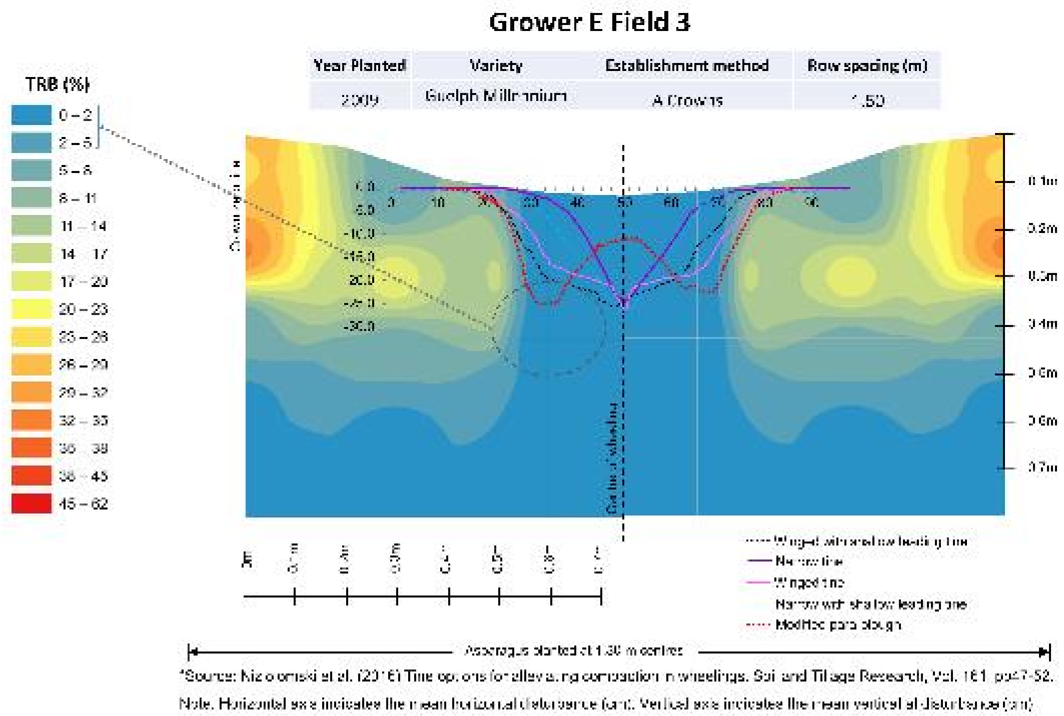


Figure D. Grower E total root biomass: root map for 11-year old Guelph Millennium A-Crowns. Potential root damage associated with sub-soiling operations to 300 mm depth.

Financial Benefits

It is envisaged that this project will provide information on the state of asparagus soils and provide focused, practical and robust guidance on how to identify and alleviate compaction and water-logging in asparagus wheelings, thereby reducing the risk of asparagus decline, increasing asparagus yields and farm profitability, while minimising environmental impact. In addition, this project will also provide 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'.

Over a 10-year cropping cycle, asparagus decline largely attributed to *Fusarium* and *Phythophtora* species can result in up to 60% loss of stand amounting to up to £16M in lost revenue. A 10% reduction in yield losses due to asparagus decline would amount to a saving in the region of £160,000 to UK asparagus growers per year.

Action Points

This is the 4th year of this long-term replicated field trial now continued under FV 450a. However, key action points are beginning to emerge.

Cereal rye (*Cereale secale*) is grown as a companion crop to mitigate run-off and erosion over the autumn and winter periods. This is in line with the Farming Rules for Water and the expected requirements of the Environmental Land Management scheme (ELMS) scheme. There is now robust evidence that when rye (*Cereale secale*) is grown as a companion crop and ridging cannot be undertaken the following spring that a significant (*circa* 20%) yield reduction can be expected. However, if ridging can be undertaken no yield penalty is observed as compared with conventional practice or zero-tillage.

The results continue to support the recommendation that 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.

Reference

Niziolomski, J.C., Simmons, R.W., Rickson, R.J. and Hann, M.J. (2016). Tine options for alleviating compaction in wheelings. Soil and Tillage Research, 161, 47-52.

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 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; Whalley et al. 2006; Grzesiak et al. 2013) and compromise the ability of crop plants to access water (White & Kirkegaard, 2010) and nutrients (Seymour et al. 2012), 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; Seymour et al. 2012). 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 (Kirkegaard et al. 2008; Cresswell & Kirkegaard, 1995; Chen and Weil, 2011; Seymour et al. 2012). 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 & Kirkegaard, 2010). These biota improve the architecture of the soil by mechanisms including adhesion, kinetic restructuring and filamentous binding (Miransari, 2014). Residues from the above-ground plant parts, if deposited to the soil, also provide an energy-rich substrate which can be utilised by the biota to drive structural genesis. Furthermore, the role of crop canopies, stems and root architecture to reduce soil erosion are well documented (Finney, 1984, De Baets et al., 2007). 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 & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) and increases the susceptibility to crown and root rot caused by *Phytophthora megasperma* (Falloon & Grogan 1991) (now known as *P. asparagi*) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2001; 2015) 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 & Drost 1991). Root damage associated with annual re-ridging and/or sub-soiling operations has a major impact on stand longevity and productivity (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & 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 for 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	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
Gijnlim	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Gijnlim	Bare soil No-SSD	R
Gijnlim	Bare soil No-SSD	NR

Annual re-ridging (R) or Zero-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included in Experiment 2.

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	Bare soil SSD	R
Gijnlim	Bare soil SSD	NR
Gijnlim	Bare soil No-SSD	R
Gijnlim	Bare soil No-SSD	NR
Guelph Millennium	Bare soil SSD	R
Guelph Millennium	Bare soil SSD	NR
Guelph Millennium	Bare soil No-SSD	R
Guelph Millennium	Bare soil No-SSD	NR

Annual re-ridging (R) or Zero-ridging (NR). Shallow soil disturbance (SSD). Treatments highlighted in green are included from Experiment 1.

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

In 2018 and 2020, shallow soil disturbance (SSD) was applied on 20th April, 24th March (due to a missed SSD application post-harvest in 2019) and the 22nd of June using a winged tine (Niziolomski et al., 2016) at 0.25 - 0.3 m depth. In both years, occasional asparagus root damage was observed behind the tine.

Companion Crop treatments

In 2017, rye and white mustard were seeded on 10th August at rates of 150 kg ha^{-1} and 19 kg ha^{-1}, respectively. Companion crops were applied to the central wheeling only. 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. Consequently, they were re-applied in late September 2018. A field survey undertaken in November 2018 indicated spatially sporadic but good establishment in treated plots. In August 2019, companion crops rye (*Cereale secale* L var. Protector) and mustard (*Sinapis alba* L. var. Severka) were sown at rates of 200 kg ha^{-1} and 25 kg ha^{-1}, respectively to three wheelings (central wheeling and guard rows). Due to poor establishment, the 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

In 2018, 2019 and 2020, re-ridging treatments were applied on the 18th April 15th of March and 24th of March, respectively. In all years root damage was observed during re-ridging.

Soil structural assessments:

Metrics to assess changes in soil structure between treatments included Penetrative resistance (PR), Visual Evaluation of Soil Structure (VESS) and Infiltration Rate (IR). Baseline sampling took place in April 2016. The 2020 assessment was carried out on the 7th of July 2020 within the central wheeling of two randomly selected plots per treatment. The 2020 assessment PR was determined using a digital Eijkelkamp Penetrologger with a 1.2 cm^2 30° internal angle cone. Every plot was sampled at 3, 6, 9, 12, 15, and 18 m along the plots central wheeling, to a depth of 0.5 m at 0.1 m intervals. Within each treatment BD, VESS and Infiltration rate were sampled at x3 randomised locations. BD was taken at 0.05 m depth with a core of 0.03 m depth x 0.05 m internal diameter and further processed to obtain Loss on Ignition (Schulte, et al., 1991; Arshad MA et al., 1996). Infiltration rate 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). VESS was performed at 0-0.3 m depth, following Ball et al., (2007) and Guimarães et al., (2011).

Assessment of root architecture and root profile distribution

Root architecture is determined following the procedure of Drost and Wilson (2003). At the FV 450/FV 450a trial site, root cores are taken on the crown zero line (CZL) from between two plants and subsequently in line with the crown at distances of 0.3 m, 0.6 m and 0.9 m (Figure 8). For fields sampled from the wider grower landbank, this spacing will vary as a function of wheeling centres (Figures 9 and 10). Root cores are typically extracted with an Eijkelkamp bi-partite hand held root auger (internal diameter: 0.06 m, volume: 754 cm^3) at the following soil depths: 0.00 - 0.15 m, 0.15 - 0.30 m, 0.30 - 0.45 m and 0.45 – 0.6 m. Where soil compaction and/or soil moisture status makes hand coring inefficient, root cores were extracted using an Eijkelkamp Soil Column Cylinder Auger (internal diameter: 0.1 m with a volume for each 0.15 m depth of 1,178 cm^3). This was driven into the soil using a Cobra TT petrol-driven percussion hammer.

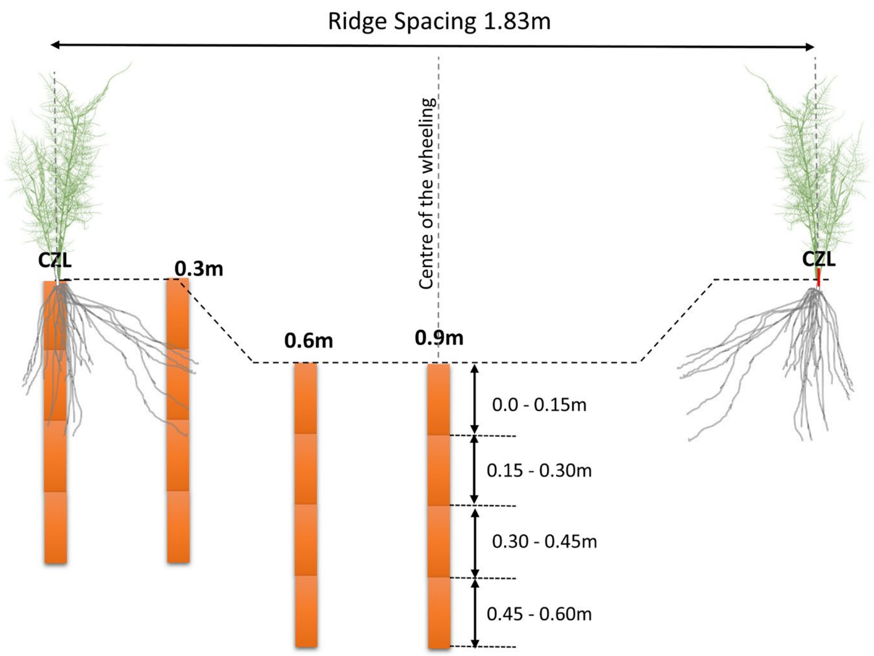
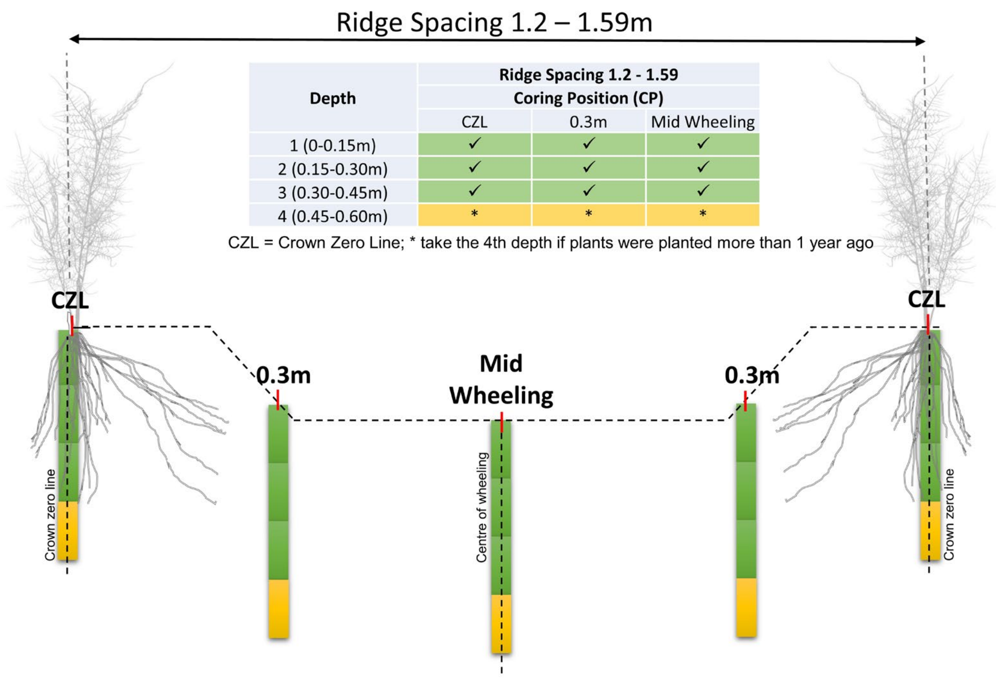


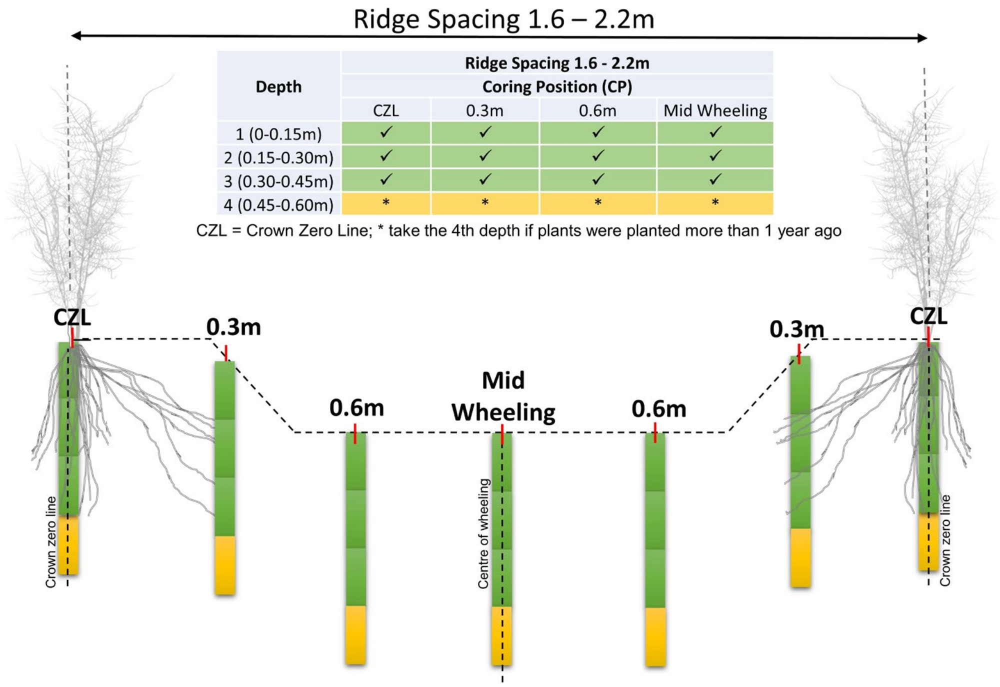
Figure 8. Root coring protocol adopted at the FV 450/FV 450a trial site.



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)	*	*	*

CZL = Crown Zero Line; * take the 4th depth if plants were planted more than 1 year ago

Figure 9: 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)	*	*	*	*

CZL = Crown Zero Line; * take the 4th depth if plants were planted more than 1 year ago

Figure 10: Root coring positions for asparagus cultivated on ridges with 1.6 – 2.2 m centres.

Determination of root mass density

Field asparagus storage root samples are stored at <2˚C before further assessment. Roots are carefully washed with tap water to remove soil remnants. Roots already dead (hollow), are grouped away from the fleshy (live) storage roots. From here, roots are weighed and oven dried at 60-65 ˚C for 48 h, and in some cases 72 h until constant mass is achieved. The weight of dry roots is recorded immediately after the drying process. The dry weight of dead roots is recorded separately. From the root mass data, root mass density (RMD) values are calculated as follows: RMD = RM /V, where RM is root mass (kg) and V is volume of the root core (m^3).

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 are 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 are then used to construct contour interpolated root mass density maps in ARC-GIS using the inverse distance weighing (IDW) geo-statistical interpolation method predicting values at unmeasured locations (Figure 11).

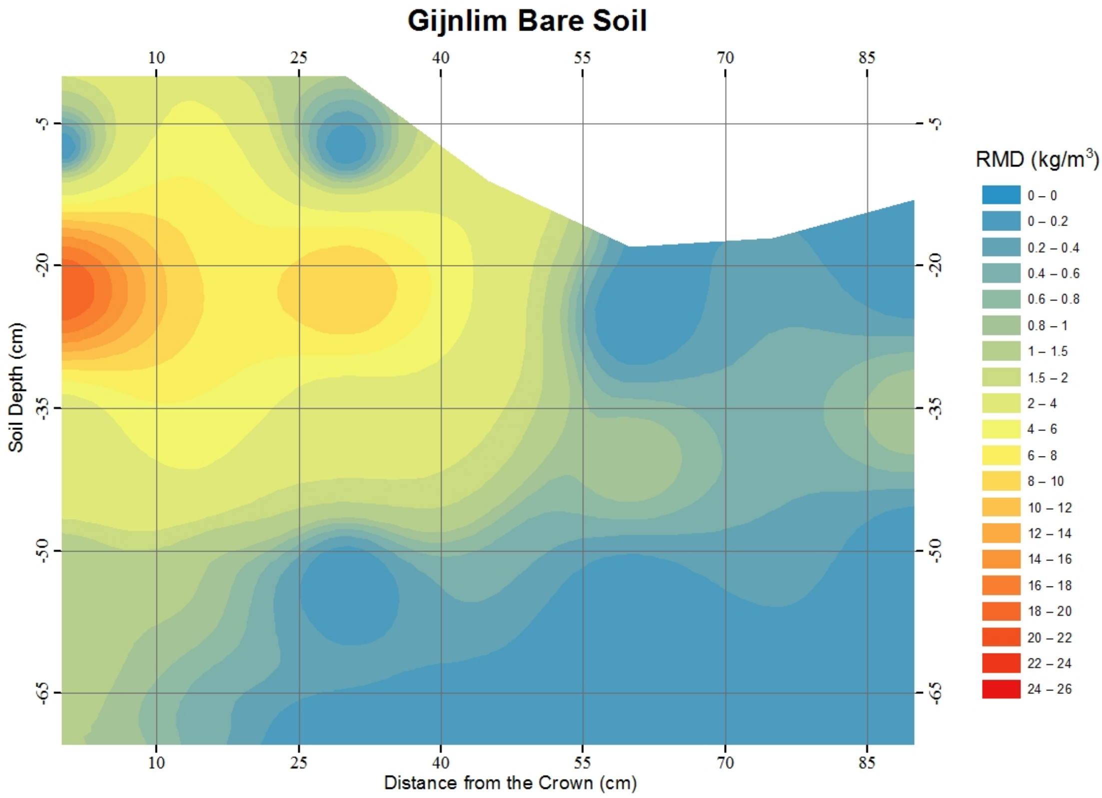


Figure 11. Root mass density (RMD) map generated using the inverse distance weighing (IDW) interpolation method in ARC-GIS.

At the AGA Technical Meeting in September 2018 feedback from growers was that Percentage Total Root Biomass (%TRB) following the traffic light system adopted in FV 450 (AHDB, 2018) provides a more effective visualization of potential root damage associated with SSD and/or ridging operations. Essentially, for each trial, plot and participating grower field, average RMDs for each sampling position (depth/distance from the CZL) are expressed as proportions of the average total plant root biomass (TRB%). Consequently, %TRB visualizations have been adopted (Figure 12).

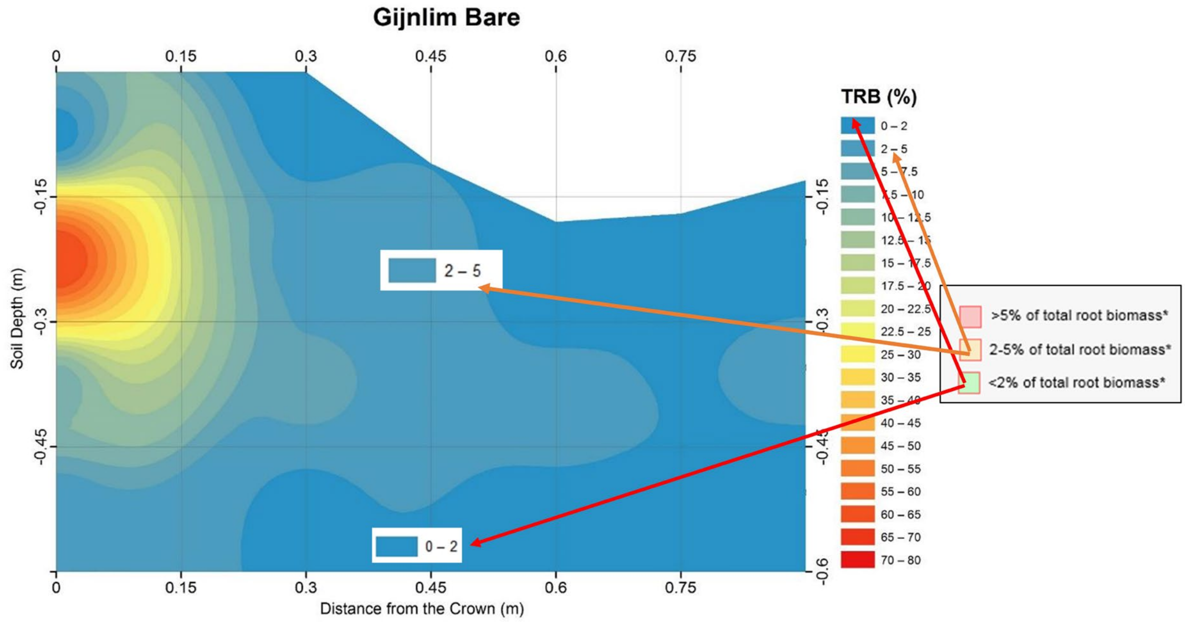


Figure 12. Interpolated total plant root biomass (TRB%) map generated using the inverse distance weighing (IDW) interpolation method in ARC-GIS.

Crop performance indicators

Crop performance indicators include on a per-cut basis, the number and weight of spears within the grade ranges <10 mm, 10-22 mm and >22 mm. In addition, the harvest length (days) and total yield per day (kg ha^{-1}), will be determined. The spear defect traits 'Head Flowering' and 'Head Curving' are also recorded.

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 will follow the method outlined in FV 271 Appendix 2. Brix values will be determined using an Atago PR-32a (alpha) Brix refractometer. Brix values will then be converted to equivalent root CHO contents on a dry weight basis using the linear regression equation of Wilson et al. (2002).

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 will be undertaken at the FV 450 trial site by the Cobrey agronomist with assistance from the Cranfield team. The impact of diseases is monitored during the spear stage through an assessment of harvested yield. During the fern stage, the incidence of ferns exhibiting symptoms of Stemphylium purple spot, Fusarium and Phytophthora crown and root rot, are recorded.

Cover crop selection and seeding rates:

Companion crops included in this trial were rye (*Cereale secale* 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, phenolicacids, 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 fungal 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., 2014). Many species of the AMF genus *Glomus* are associated with reduced crown and root rot damage from *Fusarium* infection and improved root health of asparagus (Matsubara et al., 2001, 2014).

White mustard (*Sinapis alba L*.) was selected for both its tap rooting bio-drilling potential as well as its soil bio-fumigation potential (suppression of *Fusarium* spp. by isothiocynates 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* spp.

Selection of fields for wider asparagus root architecture survey

As agreed by the Project Advisory Group (15th December 2017) in February 2018, 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. This was not dissimilar to the Grower Questionnaire that was circulated under FV 271 (FV 271 Final Report Appendix 1) used to identify potential asparagus crops for the AspireUK project. However, additional questions were included. The following information was gathered. Year planted, Variety planted, Area planted (ha), planting density (plants per ha) Establishment method (crowns or modules), row spacing (m), planting depth (m), field ridging (Y/N) if Y then frequency and year in which first ridged, year of first harvest, sub-soiling of wheeling (Y/N) if Y then frequency of sub-soiling and planting depth. In addition, the questionnaire sought to obtain specific Field location (Map Sheet and NG Code) so that soil type can be derived from LandIS (www.landis.org.uk).

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.

In terms of varieties grown, 56%, 15%, 8% and 20% of the fields were under Gijnlim, Guelph Millennium, Mondeo and Other, respectively (Figure 13a). Row spacings (Figure 13a) were dominated by 1.8-1.83 m centres representing 50% of fields with 34% of fields on 1.5-1.54 m centres and 15% outside of this range (including 1.2, 1.6, 1.75 and 2.0 m centres). With regards planting method (Figure 13c), 66%, 31% and 3% of fields were planted as A Crowns, B Crowns and Modules, respectively. Further, 31% of fields were re-ridged on an annual basis, 55% are re-ridged depending on situation and were 14% non-ridged (Figure 13e). In addition, only 16% of fields were regularly sub-soiled. Age of stand (Figure 13d) was dominated by <3 year old stands (51.4%) followed by 3-6 year old stands (36.4%) and > 6 year old stands (12.2%). This may be indicative of the severity of asparagus die-back across the UK grower landbank. The responses to the questionnaire were used to identify fields to incorporate in the wider asparagus root architecture survey conducted during 2018-2020 (Table 3). Key selection criteria included variety (Gijnlim, Guelph Millennium and Mondeo), planting method (A-Crowns, B-Crowns or Modules), years planted (2012-2017), annual ridging (Y/N) and sub-soiling (Y/N).

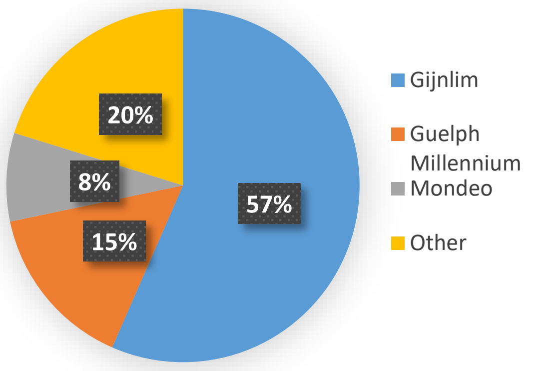


Figure 13a. Dominant asparagus varieties cultivated

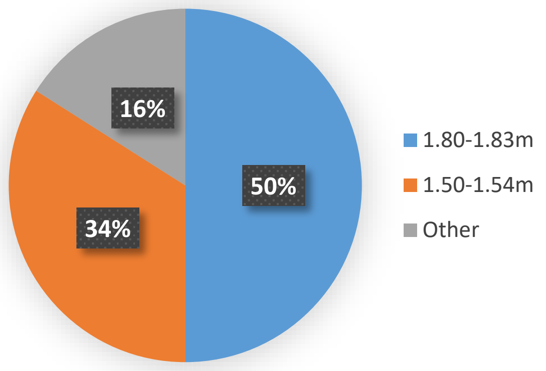


Figure 13b. Dominant row spacing’s

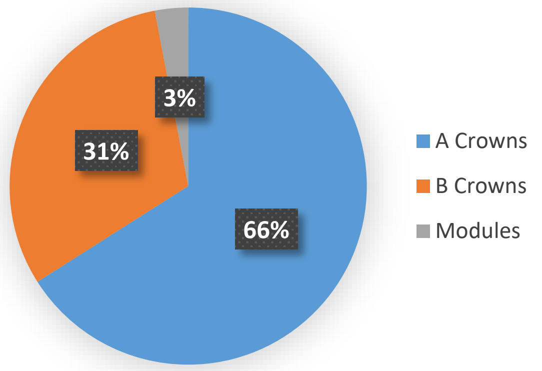


Figure 13c. Dominant planting method

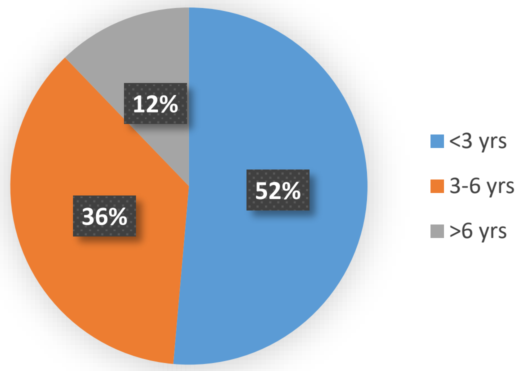


Figure 13d. Dominant age of stand

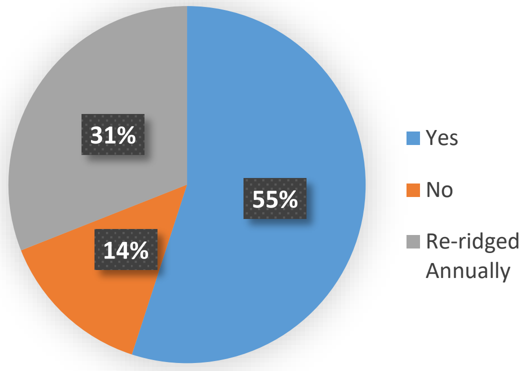


Figure 13e. Adoption of re-ridging

Table 3. Fields identified to incorporate in the wider asparagus root architecture survey conducted during 2018-2020

Farm	Field	Year Planted	Variety	Establishment method	Planting density	Row spacing (m)	In-row spacing (m)	Re-ridged	Subsoiled
A	5	2013	Millennium	A Crowns	35000	1.50	0.19	Yes	Yes
	6	2014	Millennium	A Crowns	31000	1.50	0.22	Yes	Yes
	7	2015	Mondeo	A Crowns	30000	1.50	0.22	Yes	Yes
	8	2016	Millennium	A Crowns	40000	1.50	0.17	Yes	Yes
	9	2017	Mondeo	Modules	40000	1.50	0.17	No	Yes
B	1	2016	Gijnlim	A Crowns	30000	1.52	0.20	Yes	No
	2	2014	Gijnlim	A Crowns	30000	1.52	0.20	Yes	No
C	5	2015	Gijnlim	A Crowns	21500	1.60	0.25	No	No
D	2	2016	Millennium	Modules	33000	2.00	0.30	No	No
	4	2016	Gijnlim	A Crowns	28500	2.00	0.35	No	No
	5	2016	Gijnlim	Modules	28500	2.00	0.35	No	No
	6	2017	Mondeo	A Crowns	28500	2.00	0.35	No	No
E[2018]	1	2014	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	2	2016	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
F	1	2014	Millennium	B Crowns	21500	1.83	0.25	Yes	No
	2	2014	Gijnlim	B Crowns	21500	1.83	0.25	Yes	No
	3	2015	Gijnlim	A Crowns	21500	1.83	0.25	Yes	No
	4	2015	Gijnlim	B Crowns	21500	1.83	0.25	Yes	No
	5	2015	Millennium	B Crowns	21500	1.83	0.25	Yes	No
	6	2017	Gijnlim	A Crowns	21500	1.83	0.25	Yes	No
	7	2017	Gijnlim	B Crowns	21500	1.83	0.25	Yes	No
	8	2017	Millennium	A Crowns	21500	1.83	0.25	Yes	No
E[2020]	3	2009	Millennium	A crowns	34000	1.50	0.02	Yes	No
	5	2014	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	4	2014	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	6	2015	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	7	2016	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	8	2016	Gijnlim	A crowns	24000	1.80	0.03	Yes	No
	9	2017	Gijnlim	A crowns	24000	1.80	0.02	Yes	No
	10	2018	Gijnlim	A crowns	24000	1.80	0.02	Yes	No

(orange)	Sampled in Autumn 2018
(blue)	Sampled in Summer 2018
(light green)	Root data received in May 2018 (Fresh root mass)
(green)	Grower self-cored in Sep 2019
(yellow)	Grower self-cored in Feb 2020

Results

Impact of FV 450 best management practices (BMPs) on 2019 and 2020 asparagus yield and spear size.

In 2019 asparagus yield monitoring data was collected from 20th April to 17th June from 53 cuts. Spears size were counted on 9 occasions. In 2020, yield monitoring data was collected between the 12th April to 22nd June from 65 cuts. Spears size was counted on 8 occasions.

2019: Impact of Experiment 1 (Gijnlim) BMPs on asparagus yield and spear size

In general few significant differences in yield and spear size were observed between treatments. With the exception of the rye ridged (R) and non-ridged (NR) treatments, ridging had no significant impact on yield or spear size (Table 4, Figure 14 and 15). The Rye NR treatment was associated with a 20% reduction in yield compared to the Rye R treatment. This is in large part due to the significantly 19% lower spear weight associated with the Rye NR (17.1 g) as compared to Rye R (21.1 g) treatment.

Table 4. Differences in 2019 Gijnlim yield and spear size between Experiment 1 BMPs.

Treatment	Total yield (kg ha^{-1})	Average (n=9) spear weight (g)
[1]Bare Soil No-SSD NR	157 ^{bc}	21.2 ^{a}
[2]Bare Soil No-SSD R	134 ^{ab}	19.7 ^{a}
Bare Soil SSD NR	132 ^{a}	19.0 ^{ab}
Bare Soil SSD R	125 ^{a}	19.3 ^{ab}
MustardCC NR	140 ^{abc}	20.2 ^{a}
MustardCC R	140 ^{abc}	19.4 ^{ab}
PAS 100 NR	146 ^{abc}	19.7 ^{a}
PAS 100 R	144 ^{abc}	19.1 ^{ab}
RyeCC NR	126 ^{a}	17.1 ^{b}
RyeCC R	159 ^{c}	21.1 ^{a}
Straw Mulch NR	137 ^{abc}	19.5 ^{a}
Straw Mulch R	145 ^{abc}	19.6 ^{a}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.

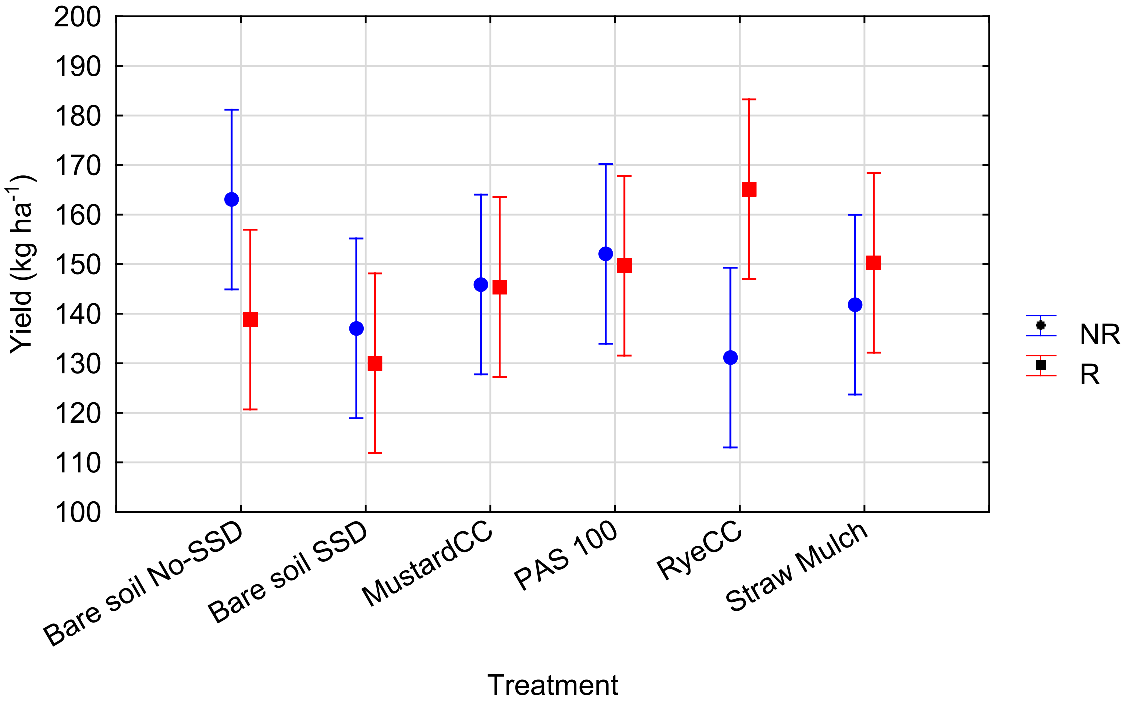


Figure 14. Differences in 2019 Gijnlim yield (kg ha^{-1}) between Experiment 1 BMP treatments. Vertical bars denote 0.95 confidence interval.

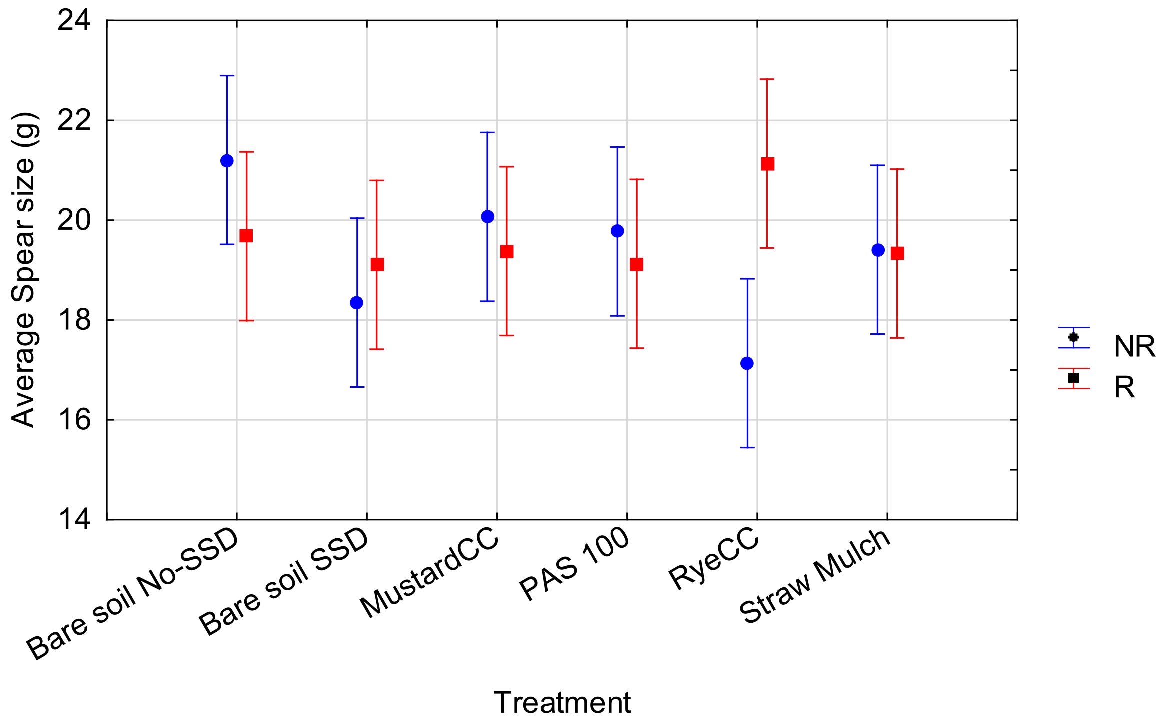


Figure 15. Differences in 2019 Gijnlim mean (n=9) spear size (g) between Experiment 1 BMP treatments .Vertical bars denote 0.95 confidence interval.

2019: Impact of Experiment 2 BMPs on varietal differences (Gijnlim vs Guelph Millennium) in asparagus yield and spear size.

The 2019 a significant >20% difference in yield was observed between the Gijnlim and Guelph Millennium zero-till treatments (Bare Soil No-SSD NR) and the Gijnlim and Guelph Millennium conventional treatments (Bare Soil No-SSD R) with values of 163 and 118 kg ha^{-1} and 138 and 111 kg ha^{-1}, respectively (Figure 16 and 17). For the Gijnlim and Guelph Millennium zero-till treatments (Bare Soil No-SSD NR) this is in large part due to the significant (22%) difference in spear size.

In contrast no significant differences in yield were observed between the Gijnlim and Guelph Millennium treatments which received SSD (Table 5).

Table 5. Differences in 2019 yields and spear size between Gijnlim and Guelph Millennium BMPs.

Variety	Treatment	Total yield (kg ha^{-1})	Average (n=9) spear weight (g)
G^A	[1]Bare Soil No-SSD NR	163 ^{c}	21.2 ^{d}
GM^A		118 ^{ab}	16.7 ^{a}
G^A	[2]Bare Soil No-SSD R	139 ^{b}	19.7 ^{cd}
GM^A		111 ^{a}	18.2 ^{abc}
G^A	Bare Soil SSD NR	137 ^{b}	18.3 ^{abc}
GM^A		121 ^{ab}	16.3 ^{a}
G^A	Bare Soil SSD R	130.0 ^{ab}	19.1 ^{bcd}
GM^A		118 ^{ab}	16.9 ^{ab}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.

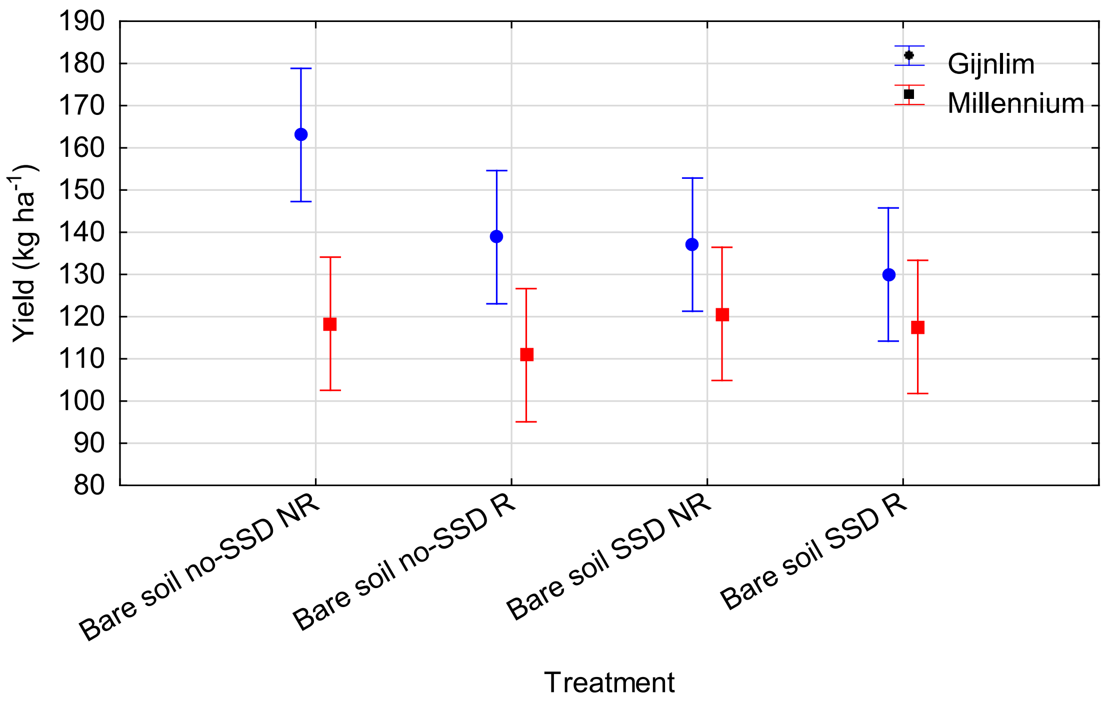


Figure 16. Varietal differences in 2019 Gijnlim and Guelph Millennium yield (kg ha^{-1}) between Experiment 2 BMP treatments. Vertical bars denote 0.95 confidence interval.

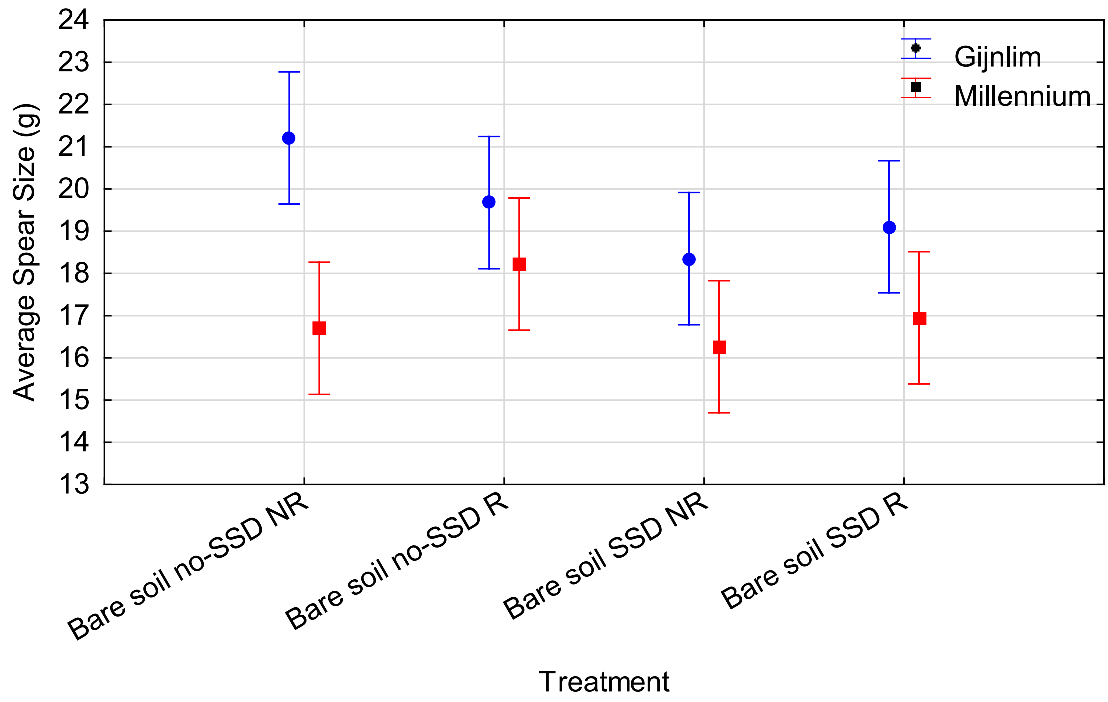


Figure 17. Varietal differences in 2019 Gijnlim and Guelph Millennium spear size (g) between Experiment 2 BMP treatments. Vertical bars denote 0.95 confidence interval.

2020: Impact of Experiment 1 (Gijnlim) BMPs on asparagus yield and spear size

In 2020, PAS 100 ridged (R) and PAS 100 non-ridged (NR) yielded treatments were associated with significantly higher asparagus yields as compared to Bare soil No-SSD R, Bare soil SSD NR, Bare soil SSD R and RyeCC NR treatments (Table 6, Figure 18 and 19). This may be due to the additional macro/micro nutrient load associated with the PAS 100 compost, reduction in penetrative resistance (PR) and/or a stimulation of soil microbiology associated with the PAS 100 treatments. Further research needs to be undertaken to clarify the yield uplift associated with PAS 100 compost. With the exception of the RyeCC NR and RyeCC R treatments, ridging had no effect on asparagus yield. The Rye NR treatment was associated with a 23% reduction in yield as compared to Rye R. This trend was also observed in 2018 and 2019.

Significant differences in spear size were observed between BMP treatments. The zero-till (Bare soil No-SSD NR) , PAS 100 NR and Rye R treatments were associated with significantly larger spears as compared to Bare soil No-SSD R (conventional practice), Bare soil SSD R and Rye NR treatments (Table 6, Figure 18 and 19).

Table 6. Differences in 2020 Gijnlim yield and spear size between Experiment 1 BMPs.

Treatment	Total yield (kg ha^{-1})	Average (n=8) spear weight (g)
[1]Bare Soil No-SSD NR	124 ^{bcde}	16.5 ^{cd}
[2]Bare Soil No-SSD R	100 ^{ab}	14.2 ^{ab}
Bare Soil SSD NR	103 ^{abc}	14.6 ^{abc}
Bare Soil SSD R	101 ^{ab}	13.1 ^{a}
MustardCC NR	113 ^{abcde}	15.3 ^{bcd}
MustardCC R	107 ^{abcd}	14.6 ^{abc}
PAS 100 NR	136 ^{e}	17.0 ^{d}
PAS 100 R	129 ^{de}	15.1 ^{bcd}
RyeCC NR	98.4^{a}	13.1 ^{a}
RyeCC R	127 ^{cde}	17.0 ^{d}
Straw Mulch NR	110 ^{abcd}	15.2 ^{bcd}
Straw Mulch R	117 ^{abcde}	16.0 ^{bcd}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice

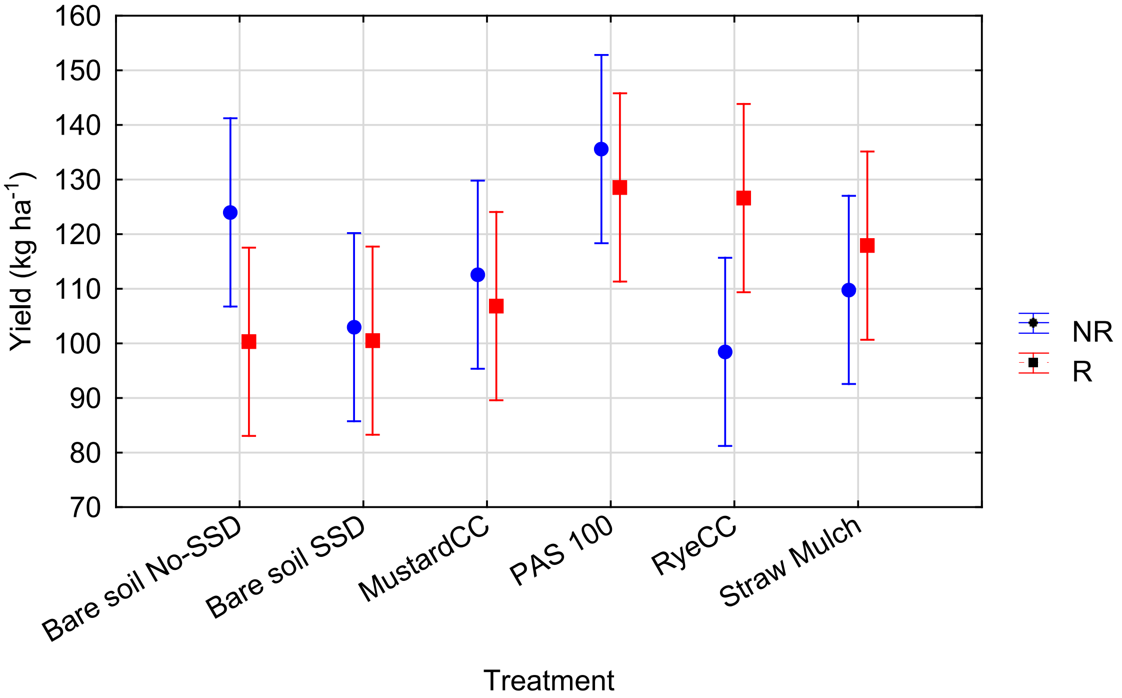


Figure 18. Differences in 2020 Gijnlim yield (kg ha^{-1}) between Experiment 1 BMP treatments. Vertical bars denote 0.95 confidence interval.

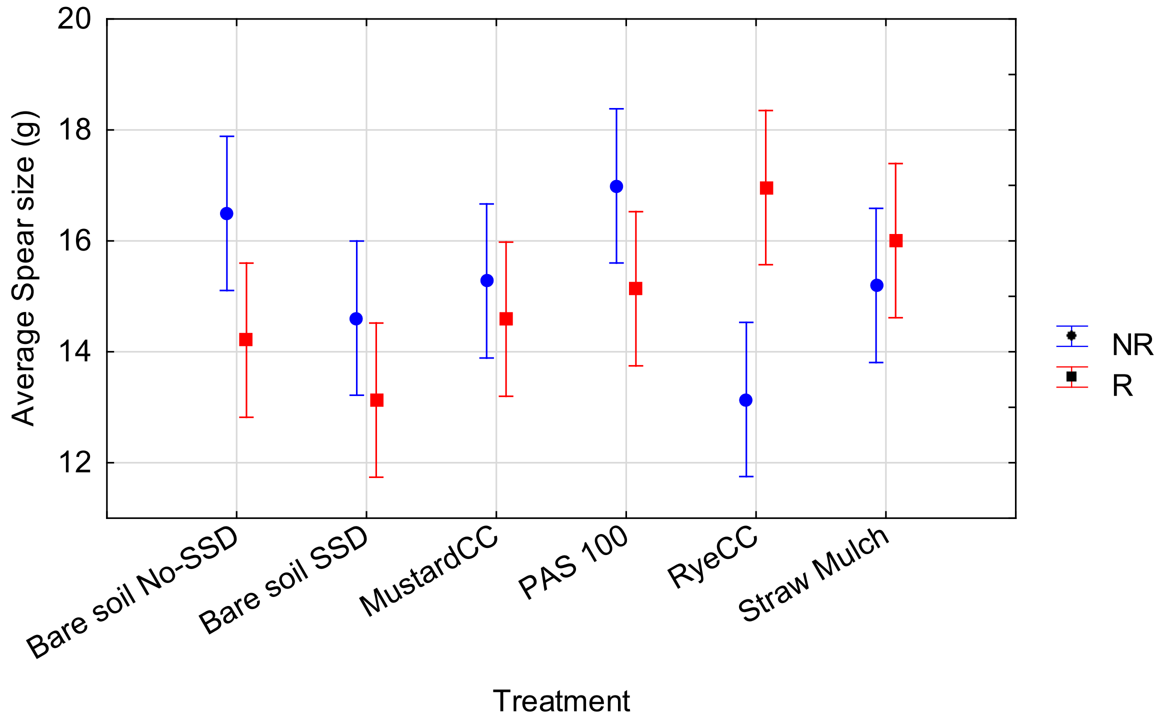


Figure 19. Differences in 2020 Gijnlim mean (n=8) spear size (g) between Experiment 1 BMP treatments. Vertical bars denote 0.95 confidence interval.

2020: Impact of Experiment 2 BMPs on varietal differences (Gijnlim vs Guelph Millennium) in asparagus yield and spear size.

In contrast to the 2018 and 2019 yield data, in 2020 no significant difference in yield was observed between the comparable Gijnlim and Guelph Millennium treatments (Table 7, Figure 20 and 21). It is important to note that for both Gijnlim, and Guelph Millennium ridging associated with the conventional practice (Bare soil No-SSD R) was associated with a 20% and 24% reduction in yield as compared with the zero-tillage (Bare soil No-SSD NR) treatment. This may in part corroborate the findings of (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) that annual re-ridging causes root damage and yield reductions.

Significant reductions in spear size were also observed for Gijnlim between the conventional practice (Bare soil No-SSD R) and Bare soil SSD R treatments and the zero-tillage (Bare soil No-SSD NR) treatment with values of 14.2, 13.1 and 16.5 (g) respectively. In contrast, no differences in spear size was observed between the Guelph Millennium treatments (Table 7, Figure 20 and 21).

Table 7. Differences in 2020 yields and spear size between Gijnlim and Guelph Millennium BMPs.

Variety	Treatment	Total yield (kg ha^{-1})	Average (n=8) spear weight (g)
G^{A}	[1]Bare Soil No-SSD NR	124 ^{c}	16.5 ^{c}
GM^{A}		117 ^{bc}	15.9 ^{bc}
G^{A}	[2]Bare Soil No-SSD R	100 ^{ab}	14.2 ^{ab}
GM^{A}		89.0 ^{a}	15.3 ^{bc}
G^{A}	Bare Soil SSD NR	103 ^{ab}	14.6 ^{abc}
GM^{A}		112 ^{bc}	14.8 ^{abc}
G^{A}	Bare Soil SSD R	101 ^{ab}	13.1 ^{a}
GM^{A}		103 ^{ab}	15.0 ^{abc}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.

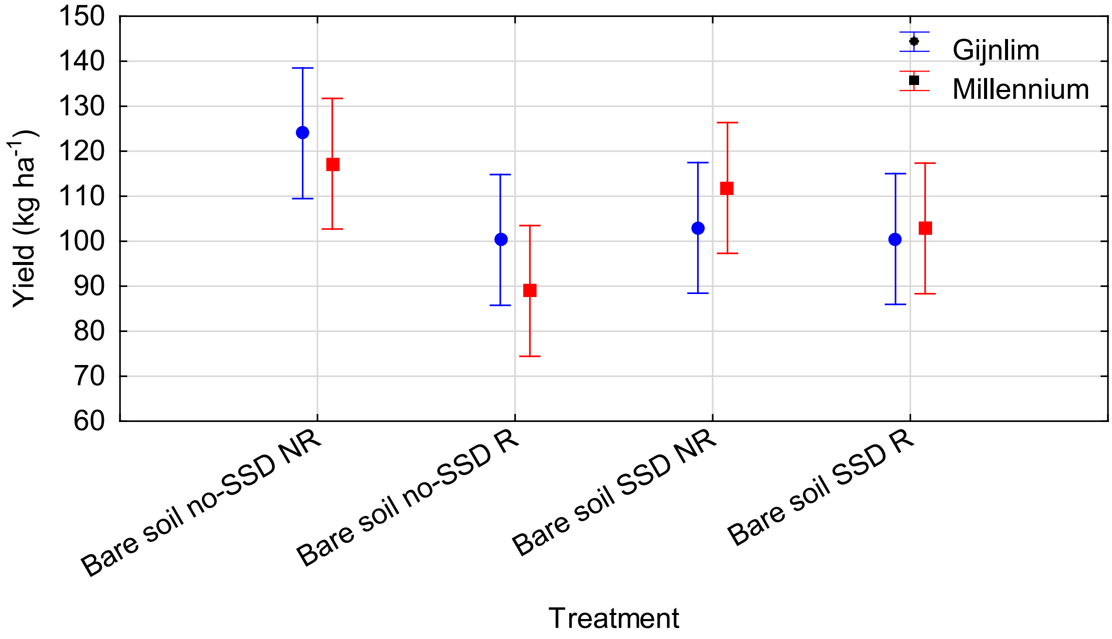


Figure 20. Varietal differences in 2019 Gijnlim and Guelph Millennium yield (kg ha^{-1}) between Experiment 2 BMP treatments. Vertical bars denote 0.95 confidence interval

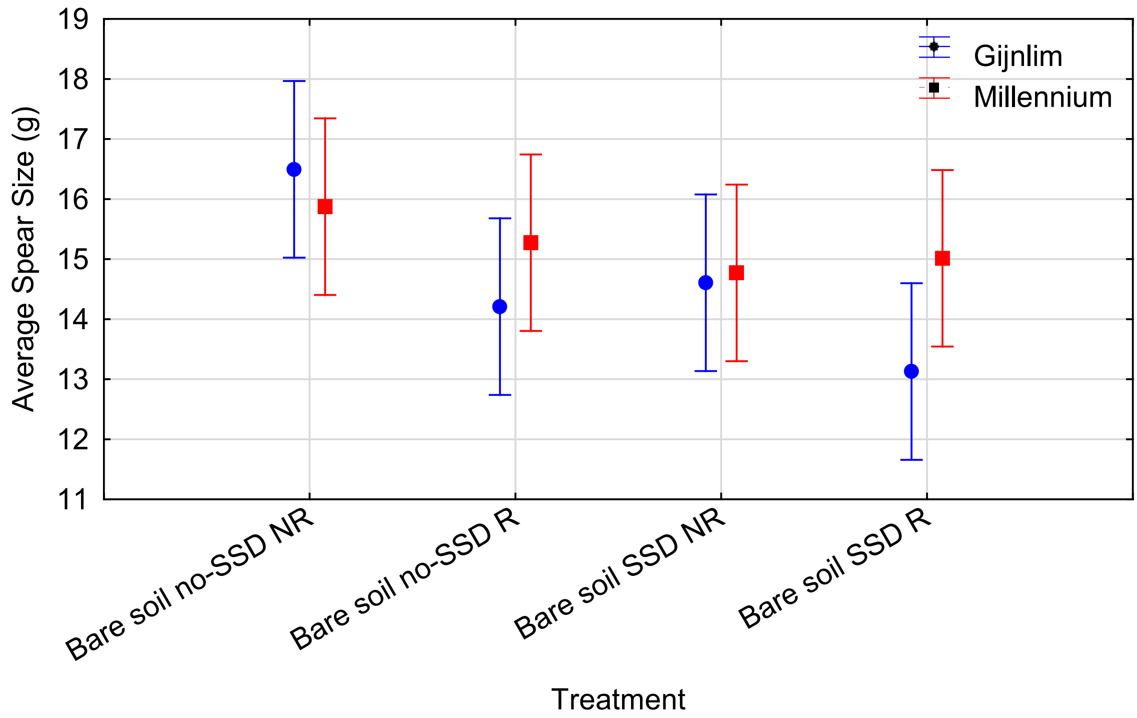
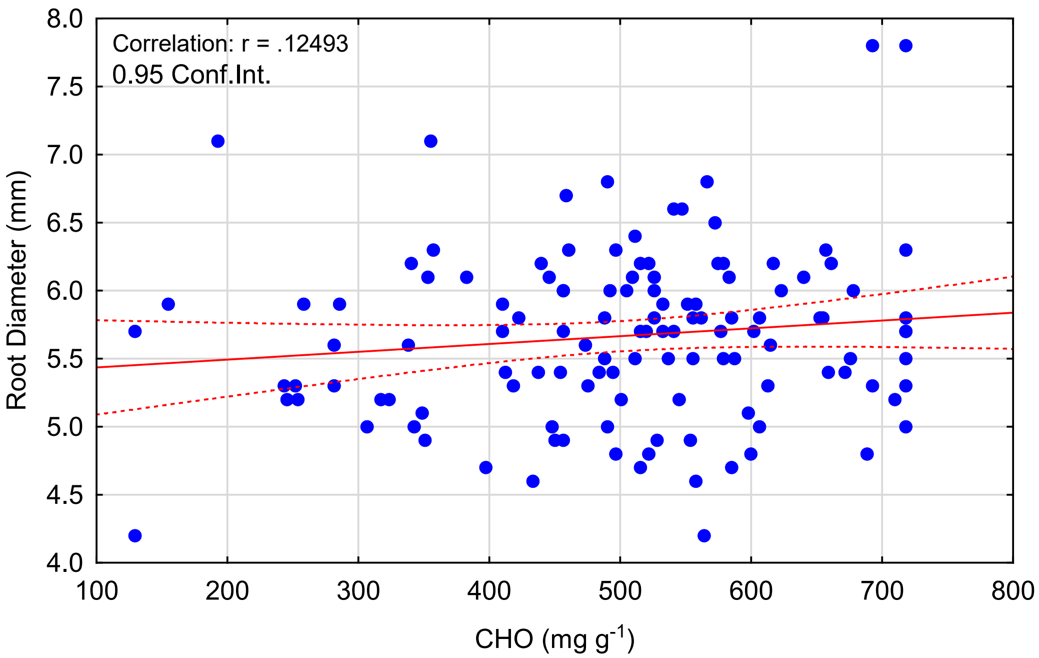


Figure 21. Varietal differences in 2019 Gijnlim and Guelph Millennium spear size (g) between Experiment 2 BMP treatments. Vertical bars denote 0.95 confidence interval.

Impact of FV 450 best management practices (BMPs) on 2020 asparagus soluble carbohydrate (CHO) levels.

In 2020, root samples for CHO analysis were taken from the Crown Zero Line, 0.15-0.30 m depth, which is the asparagus crown depth. In addition, roots of similar diameters (mm) were subject to the CHO analysis. Diameters of roots ranged from 4.20 and 7.80 mm. Data analysis indicates that root diameter is not correlated to the root CHO content (Figure 22).

Figure 22. Root CHO content correlation to the root diameter, following Pearson Correlation.



***2020: Impact of Experiment 1 (Gijnlim) BMPs on asparagus storage root* soluble carbohydrate (CHO) levels.**

Across all treatments mean pre-harvest storage root CHO values (in March 2020) at the Crown Zero Line (CZL) ranged from 377 – 525 mg g^{-1}. The majority of values are below the upper range of pre-harvest root CHO values observed during the AHDB FV 271 AspireUK project (AHDB, 2007) which reported mean values (dominated by Gijnlim) of 494 and 512 mg g^{-1} for 2005 and 2007. In addition, five BMP treatments (Table 8, Figure 23) were associated with CHO values below the target range of 450-550 mg g^{-1} outlined by Wilson et al., (2008) indicating inadequate CHO levels for optimum harvest.

For comparison (Table 8), the 2019 pre-harvest storage root CHO values (in March 2019) at the CZL ranged from 508 – 632 mg g^{-1}.

Table 8. Differences in 2020 and 2019 asparagus storage root CHO values (mg g^{-1}) between Experiment 1 BMPs at 0.15-0.3 m depth at the CZL.

Treatment	2020 CHO (mg g^{-1}) at CZL 0.15-0.30m depth	2019 CHO (mg g^{-1}) at CZL 0.15-0.30m depth
[1]Bare Soil No-SSD NR	*377 [a]	632[a]
[2]Bare Soil No-SSD R	506 [b]	508[a]
Bare Soil SSD NR	*418 [ab]	517[a]
Bare Soil SSD R	481 [ab]	555[a]
Mustard CC NR	*426 [ab]	525[a]
Mustard CC R	491 [ab]	592[a]
PAS 100 NR	502 [ab]	596[a]
PAS 100 R	*435 [ab]	540[a]
Rye CC NR	484 [ab]	513[a]
Rye CC R	*419 [ab]	547[a]
Straw Mulch NR	477 [ab]	565[a]
Straw Mulch R	525 [b]	566[a]

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. *Mean CHO values below the target range (450-550 mg g^{-1}) outlined by Wilson et al., (2008). [1]Zero-tillage treatment; [2]Conventional practice

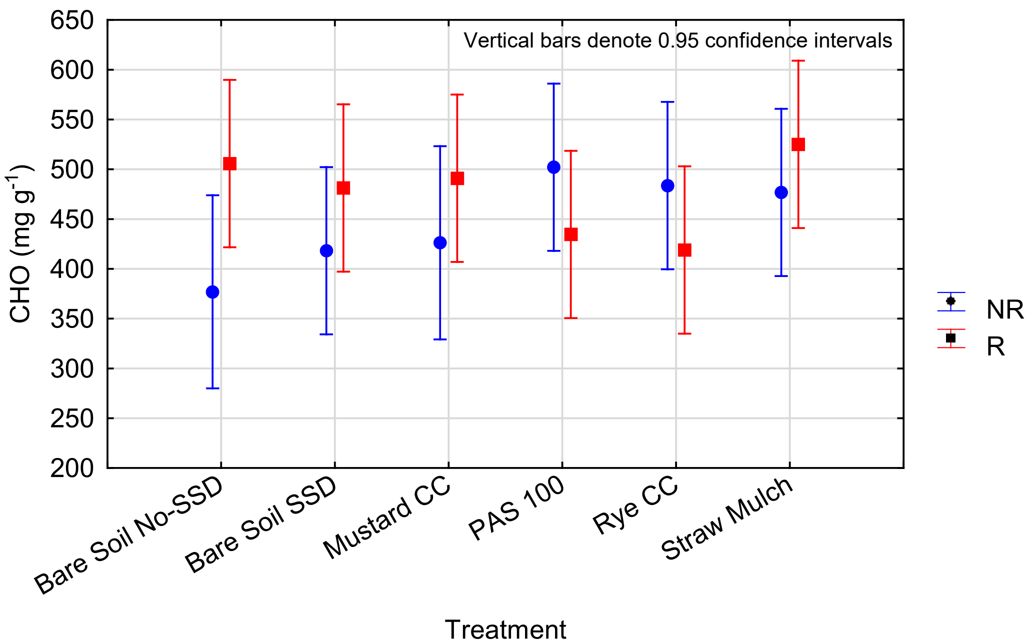


Figure 23. Differences in 2020 Gijnlim asparagus storage root CHO values (mg g^{-1}) between Experiment 1 BMP treatments at 0.15-0.3 m depth at the CZL. Vertical bars denote 0.95 confidence intervals.

2020: Impact of Experiment 2 BMPs on varietal differences (Gijnlim vs Guelph Millennium) in asparagus storage root soluble carbohydrate (CHO) levels.

The 2020 results indicate that as in 2018 and 2019, shallow soil disturbance (SSD) does not have any significant impact on asparagus storage root CHO values (Table 9). The 2018 and 2019 results (FV 450 2018 and 2019 Annual Reports) indicated significant differences in asparagus storage root CHO values between Gijnlim and Guelph Millennium. The 2020 results follow this trend with asparagus storage root CHO values for Guelph Millennium significantly ($p < 0.0001$) higher compared to the equivalent for Gijnlim Experiment 2 BMP treatments (Table 9). Mean asparagus storage root CHO values (across all Experiment 2 treatments) for Gijnlim and Guelph Millennium are 450 and 623 mg g^{-1}, respectively (Figure 24). Mean asparagus root CHO values at the CZL for Gijnlim and Guelph Millennium were just within or in excess of the target range (450-550 mg g^{-1}) outlined by Wilson et al., (2008) indicating adequate CHO levels for harvest.

Guelph Millennium results were not significantly different across the four Experiment 2 bare soil BMP treatments. However for Gijnlim unexpectedly, the zero-till (Bare soil No-SSD NR) asparagus storage root CHO values were significantly lower as compared to the conventional practice (Bare soil No-SSD R), with CHO values of 377 and 506 mg g^{-1}, respectively (Table 9).

Table 9. Varietal differences in 2020 Gijnlim and Guelph Millennium asparagus storage root CHO values (mg g^{-1}) between Experiment 2 BMPs at 0.15-0.3 m depth at the CZL.

Variety	Treatment	2020 CHO (mg g^{-1}) at CZL 0.15-0.30m depth
G^{A}	[1]Bare Soil No-SSD NR	*377 ^{a}
GM^{A}		695 ^{d}
G^{A}	[2]Bare Soil No-SSD R	506 ^{bc}
GM^{A}		603 ^{cd}
G^{A}	Bare Soil SSD NR	*418 ^{ab}
GM^{A}		613 ^{cd}
G^{A}	Bare Soil SSD R	481 ^{ab}
GM^{A}		598 ^{cd}

Within the column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. *Mean CHO values below the target range (450-550 mg g^{-1}) outlined by Wilson et al., (2008). [1]Zero-tillage treatment; [2]Conventional practice.

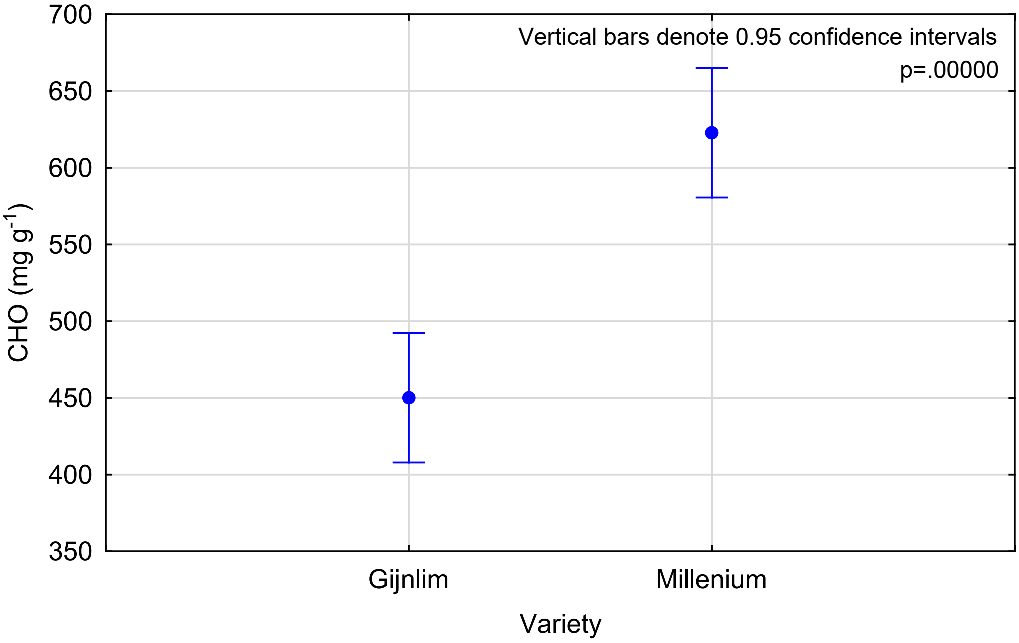


Figure 24. Varietal differences in 2020 Gijnlim and Guelph Millennium asparagus storage root CHO values (mg g^{-1}) across all Experiment 2 BMPs at 0.15-0.3 m depth at the CZL. Vertical bars denote 0.95 confidence intervals.

Impact of BMPs on 2019 and 2020 Soil structure assessments

Penetrative Resistance (PR)

In 2019, the shallow soil disturbance (SSD) application was not applied post-harvest. Consequently, SSD had no significant effect on PR in the wheelings. In the Bare Soil treatments (Figure 25a), zero-tillage (Bare soil No-SSD NR) was associated with a significantly lower whole profile mean (n= 12) PR value as compared to all other bare soil treatments. Companion cropping did not significantly affect PR as compared with the conventional practice (Bare soil No-SSD R) treatment (Figure 25b). Conversely, Straw Mulch NR, Straw Mulch R and PAS 100 NR were associated with a significantly lower whole profile mean (n= 12) PR as compared to the conventional practice treatment (Figure 25c). In 2020, SSD significantly reduced PR in the wheelings to 0.25 m depth for all SSD treatments (Figure 26a). The conventional practice was associated with significantly higher PR from 0.0-0.20 m depth as compared to all other Bare soil treatments (Figure 26a). Companion cropping did not significantly affect PR as compared with the conventional practice treatment (Figure 26b). However, all mulch treatments which are also subject to SSD were associated with significantly lower PR as compared to conventional practice from 0.0-0.40 m depth (Figure 26c).

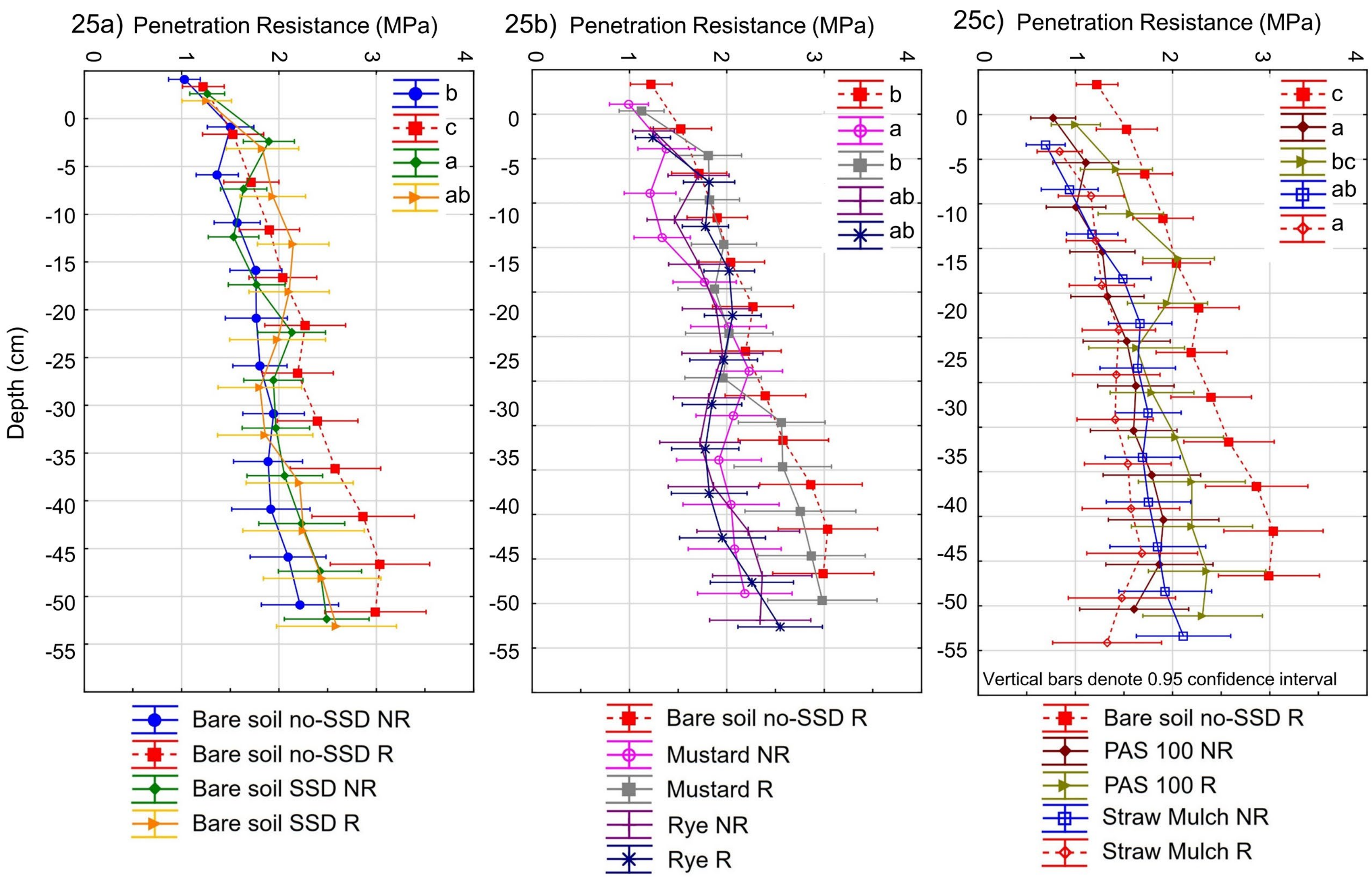


Figure 25. Differences in mean (n=12) 2019 PR values in interrow wheelings [0.0 – 0.5m depth] between Experiment 1 BMP treatments. Vertical bars denote 0.95 confidence intervals.

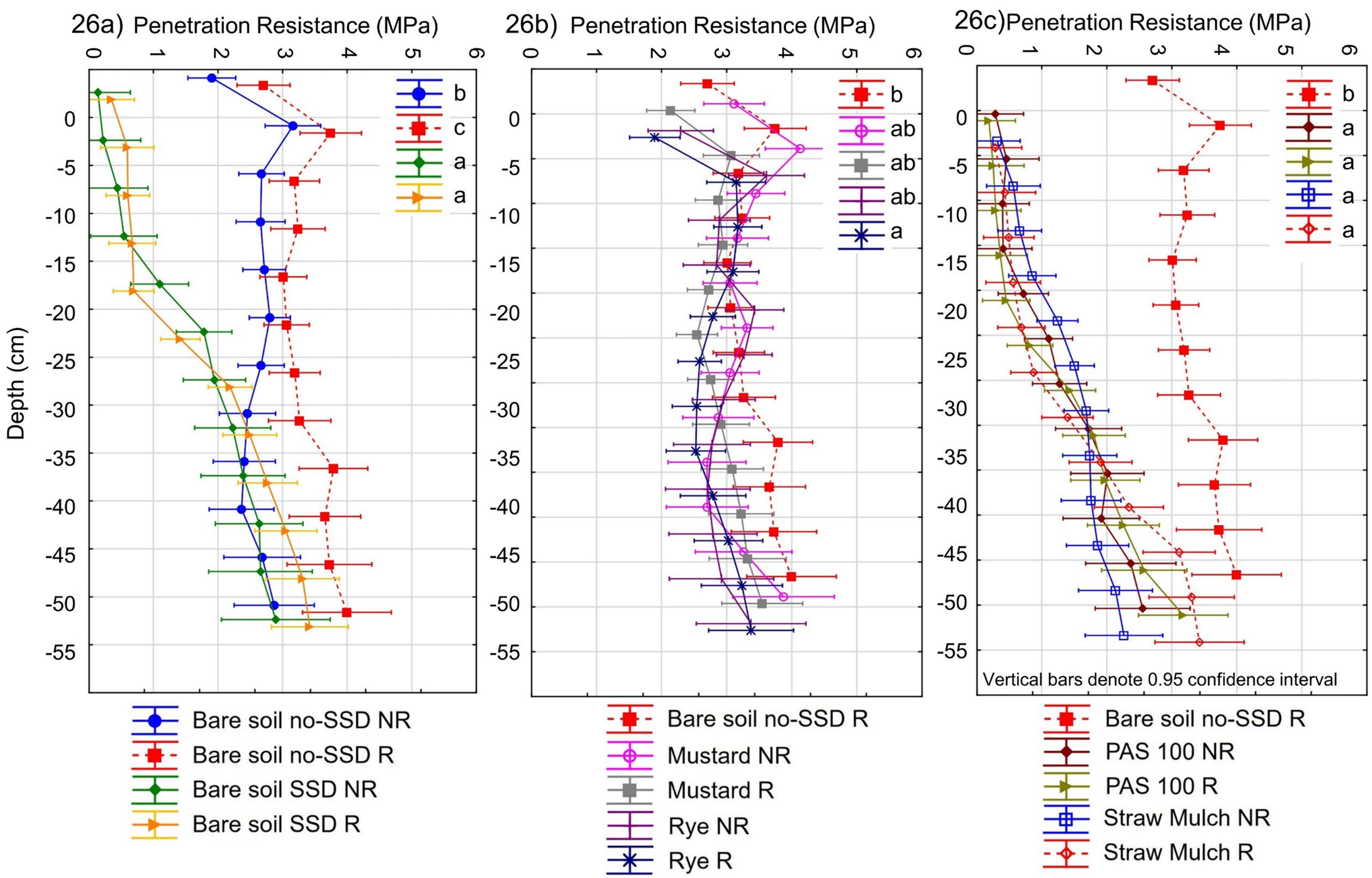


Figure 26. Differences in mean (n=12) 2020 PR values in interrow wheelings [0.0 – 0.5m depth] between Experiment 1 BMP treatments. Vertical bars denote 0.95 confidence intervals.

Infiltration rate and visual soil structure assessment (VESS)

The 2016 baseline mean infiltration rate was 102 mm h^{-1} (Moderately Rapid), with 62% of the measurements being classified as “Moderate” and “Relatively moderate” (AHDB, FV 450 Annual Report 2018).

In 2019, the SSD application was not applied post-harvest. Consequently, SSD had no significant effect on infiltration rate in the interrow wheelings. In 2019 (Table 10), the PAS 100 R (re-ridged) treatment was associated with a significantly higher infiltration rate (474 mm h^{-1} “Rapid”) as compared to all other treatments, with the exception of PAS 100 NR (non-ridged). All treatments ranged from “Moderate” to “Rapid” infiltration rate. In 2020 (Table 11), all treatments subject to SSD were classified as “Very Rapid” (>500 mm hr^{-1}) and had significantly higher infiltration rates as compared to the Conventional tillage practice (Bare soil No-SSD R) treatment which was classified as having a “Moderate” (23.2 mm h^{-1}) infiltration rate. All other treatments were classified as having a “Moderate” to “Rapid” infiltration rate (Table 11). No significant differences in infiltration rate were observed between the non-SSD companion crop or mulch treatments and the zero-till or Conventional practice treatments.

The 2019 the VESS results (Table 10) indicate that the Rye CC NR treatment is more compact (3.7) as compared to other companion crop treatments. Furthermore, Bare soil No-SSD NR (zero-tillage) had significantly better soil structure (2.5) compared to the Bare soil No-SSD R (Conventional tillage practice) treatment (3.3). 2020 Visual soil structure assessment results (Table 11) showed several significant differences between treatments. Most noticeable was the difference between PAS 100 R (2.5) and Rye NR (4.1). Furthermore, Bare soil No-SSD NR and PAS 100 R both had VESS scores lower than the baseline value (2016) of 3.1 indicating an improvement in soil structure.

Table 10. 2019 differences in infiltration rates and visual soil structure assessment (VESS) scores between Experiment 1 BMPs.

Treatment	Infiltration ($mm\ hr^{-1}$)	Infiltration rates category	VESS score
[1]Bare Soil No-SSD NR	129.6 ^{abcd}	moderately rapid	*2.5 ^{a}
[2]Bare Soil No-SSD R	51.5 ^{ab}	moderately rapid	3.3 ^{bc}
Bare Soil SSD NR	59.5 ^{ab}	moderately rapid	*3.0 ^{ab}
Bare Soil SSD R	24.4 ^{ab}	moderate	*3.0 ^{ab}
Mustard CC NR	136.6 ^{bcd}	moderately rapid	*2.9 ^{ab}
Mustard CC R	16.3 ^{a}	moderate	*3.0 ^{ab}
PAS 100 NR	234.2 ^{cd}	rapid	*3.0 ^{ab}
PAS 100 R	474.1 ^{d}	rapid	*3.0 ^{ab}
Rye CC NR	52.1 ^{ab}	moderately rapid	3.7 ^{c}
Rye CC R	22.5 ^{ab}	moderate	*3.0 ^{ab}
Straw Mulch NR	100.1 ^{abc}	moderately rapid	3.2 ^{bc}
Straw Mulch R	92.6 ^{a}	moderately rapid	3.2 ^{bc}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Infiltration rates categories are: impermeable (<0.4); very slow (0.4-1.5); slow (1.5-5 $mm\ hr^{-1}$); moderately slow (5-15 $mm\ hr^{-1}$); moderate (15-50 $mm\ hr^{-1}$); moderately rapid (50-150 $mm\ hr^{-1}$), rapid (150-500 $mm\ hr^{-1}$); very rapid (>500 $mm\ hr^{-1}$). *Treatments with VESS score values same or compared to the 2016 baseline value of 3.1. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.

Table 11. 2020 differences between BMPs in infiltration rates and visual soil structure assessment (VESS) scores.

Treatment	Infiltration ($mm\ hr^{-1}$)	Infiltration rates category	VESS score
[1]Bare Soil No-SSD NR	48.8 ^{ab}	moderate	*2.8 ^{ab}
[2]Bare Soil No-SSD R	23.2 ^{a}	moderate	*3.1 ^{abc}
Bare Soil SSD NR	10145.0 ^{d}	very rapid	3.4 ^{bc}
Bare Soil SSD R	39951.7 ^{d}	very rapid	3.3 ^{bc}
MustardCC NR	230.3 ^{c}	rapid	3.2 ^{bc}
MustardCC R	43.7 ^{ab}	moderate	3.6 ^{cd}
PAS 100 NR	39066.3 ^{d}	very rapid	3.3 ^{bc}
PAS 100 R	10064.3 ^{d}	very rapid	*2.5 ^{a}
RyeCC NR	128.7 ^{bc}	moderately rapid	4.1 ^{d}
RyeCC R	48.0 ^{abc}	moderate	3.7 ^{cd}
Straw Mulch NR	10334.4 ^{d}	very rapid	3.2 ^{bc}
Straw Mulch R	23146.7 ^{d}	very rapid	3.5 ^{cd}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Infiltration rates categories are: impermeable (<0.4); very slow (0.4-1.5); slow (1.5-5 $mm\ hr^{-1}$); moderately slow (5-15 $mm\ hr^{-1}$); moderate (15-50 $mm\ hr^{-1}$); moderately rapid (50-150 $mm\ hr^{-1}$), rapid (150-500 $mm\ hr^{-1}$); very rapid (>500 $mm\ hr^{-1}$). *Treatments with VESS score values same or compared to the 2016 baseline value of 3.1. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.

Impact of FV 450 best management practices (BMPs) on 2019 and 2020 asparagus root architecture.

2019: Impact of Experiment 1 BMPs (Gijnlim) on asparagus root architecture.

The 2019 root mass density (RMD) results indicate that negligible differences in whole profile RMD was observed between the FV 450 Experiment 1 treatments (Table 12). However, at 0.3, 0.6 and 0.9 m from the CZL, at 0.15 – 0.3 m depth, the Rye NR treatment is associated with significantly lower RMD values as compared with the conventional practice (Figure 27 a-c). In addition, for the PAS 100 NR treatment, there is a trend for increased RMD at 0.15 – 0.30 m and 0.30 – 0.45 m depth, 0.6 m from the CZL (Figure 17 e).

Table 12. 2019: Differences in mean whole profile[3] root mass density (RMD kg m^{-3}) between Experiment 1 (Gijnlim) BMPs.

Treatment	2019 RMD (kg m^{-3})
[1]Bare Soil No-SSD NR	0.84 [ab]
[2]Bare Soil No-SSD R	0.65 [ab]
Bare Soil SSD NR	0.69 [ab]
Bare Soil SSD R	0.65 [ab]
MustardCC NR	0.57 [ab]
MustardCC R	0.91 [a]
PAS 100 NR	0.89 [a]
PAS 100 R	0.67 [ab]
RyeCC NR	0.47 [b]
RyeCC R	0.80 [ab]
Straw Mulch NR	0.55 [ab]
Straw Mulch R	0.56 [ab]

Within the column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice. [3]Excludes the CZL 0-30cm depth.

2019: Impact of Experiment 2 BMPs on varietal differences (Gijnlim vs Guelph Millennium) in asparagus root architecture.

In 2019, no significant differences in whole profile RMD were observed between similar Gijnlim and Guelph Millennium treatments (Table 13). In addition, ridging had no significant effect on whole profile RMD or depth vs distance RMD values (Figure 28 a-f).

Table 13. 2019: Differences in Gijnlim and Guelph Millennium mean whole profile[3] root mass density RMD (kg m^{-3}) between Experiment 2 BMPs.

Variety	Treatment	RMD (kg m^{-3})
G^A	[1]Bare Soil No-SSD NR	0.84 ^{a}
GM^A		1.00 ^{a}
G^A	[2]Bare Soil No-SSD R	0.65 ^{a}
GM^A		0.77 ^{a}
G^A	Bare Soil SSD NR	0.69 ^{a}
GM^A		0.97 ^{a}
G^A	Bare Soil SSD R	0.65 ^{a}
GM^A		0.81 ^{a}

Within the column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Supercript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice. [3]Excludes the CZL 0-30cm depth.

Figure 27. Differences in 2019 root mass density (kg m^{-3}) profiles for Experiment 1 (Gijnlim) BMPs. Errors bars = +/- 1 STDEV.

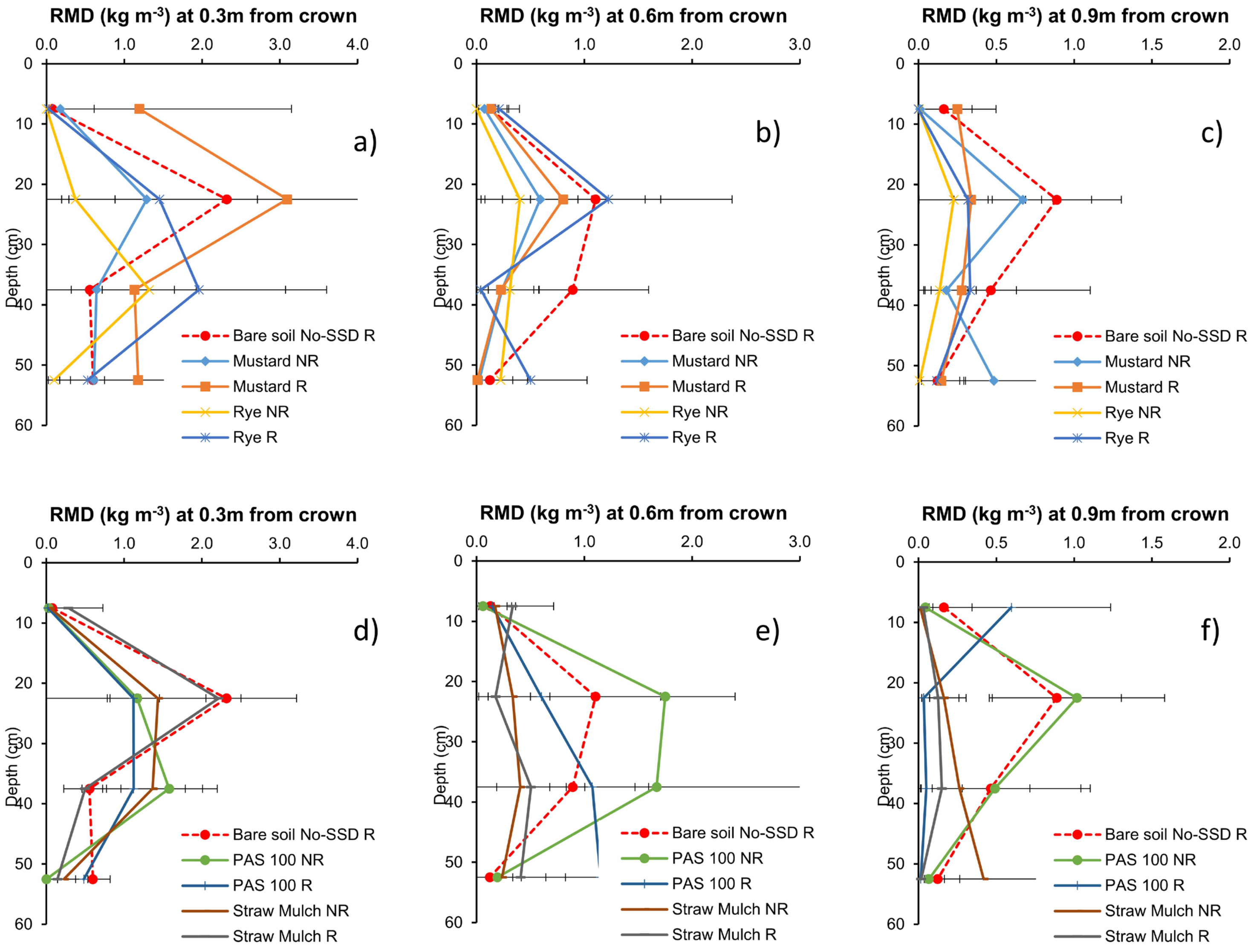
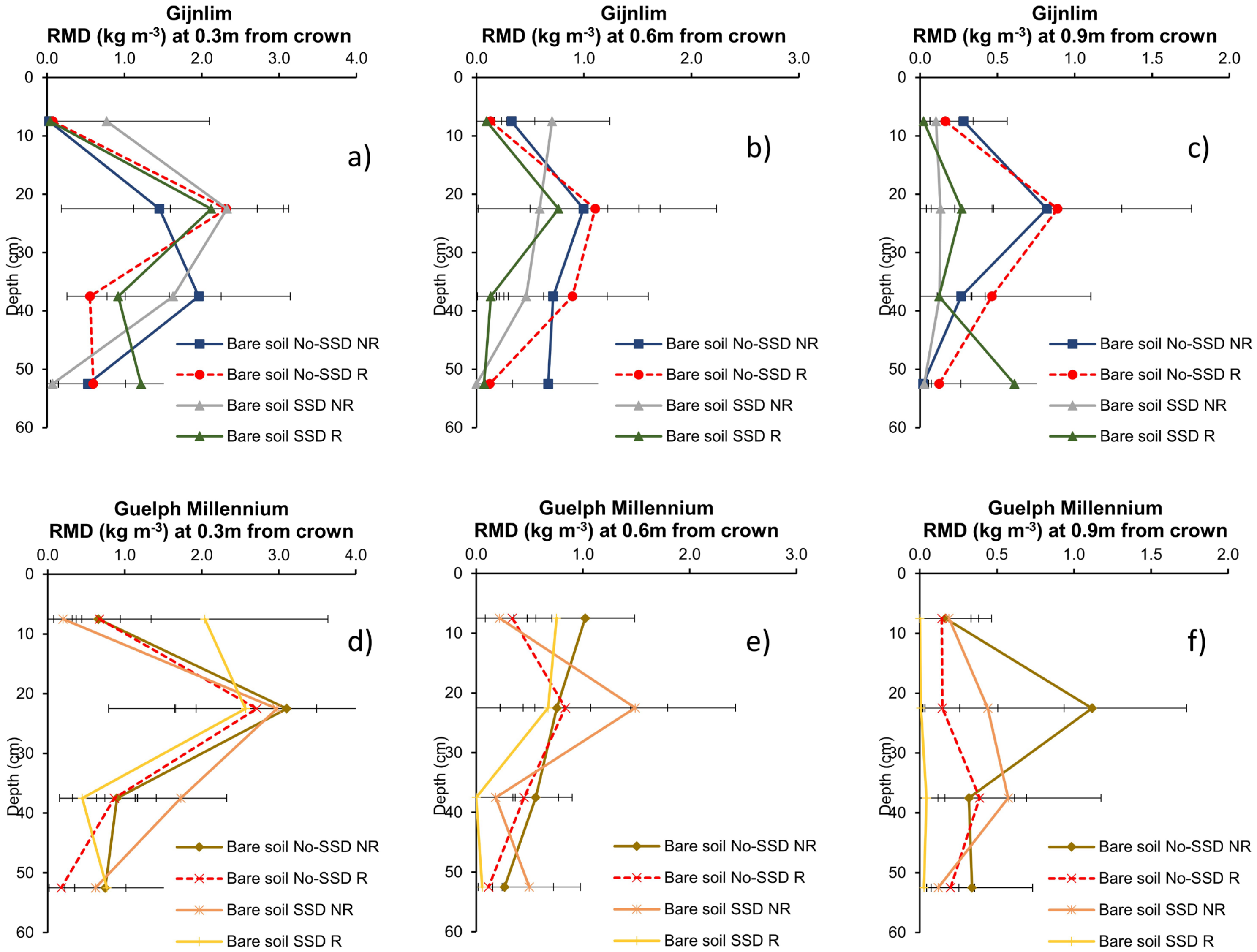


Figure 28. Differences in 2019 root mass density (kg m^{-3}) profiles for Experiment 2 (Gijnlim vs Guelph Millennium). Errors bars = +/- 1 STDEV.



2020: Impact of Experiment 1 BMPs (Gijnlim) on asparagus root architecture.

The 2020 significant differences in whole profile RMD was observed between the Bare Soil No-SSD NR (zero tillage) and Bare Soil No-SSD R (conventional practice) treatments (Table 14). This is due to significant differences in RMD at 0.15 – 0.30 m depth, 0.3, 0.6 and 0.9 m from the CZL (Figure 30 a-c) with values of 1.33 and 0.696, 0.925 and 0.017 and 0.547 and 0.027 kg m^{-3} for the Bare Soil No-SSD NR and Bare Soil No-SSD R treatments, respectively. This amounts to a 48-98% increase in RMD associated with the zero-tillage treatment. This supports the findings of (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) that annual re-ridging damages storage roots. However, to date no significant reduction in yield or increase in disease incidence has been observed.

In addition, a significant difference in whole profile RMD was observed between the PAS 100 NR and R treatments (Table 14). Specifically, this is due to a significant difference in RMD at 0.30 – 0.45m depth at the CZL with values of 4.24 and 2.35 kg m^{-3}, respectively. This amounts to a 55.4% increase in RMD associated with the PAS 100 NR treatment.

Table 14. 2020: Differences in mean whole profile[3] root mass density (RMD kg m^{-3}) between Experiment 1 (Gijnlim) BMPs.

Treatment	2020 RMD (kg m^{-3})
[1]Bare Soil No-SSD NR	0.57 [bc]
[2]Bare Soil No-SSD R	0.28 [a]
Bare Soil SSD NR	0.44 [ab]
Bare Soil SSD R	0.56 [bc]
MustardCC NR	0.52 [abc]
MustardCC R	0.35 [ab]
PAS 100 NR	0.73 [c]
PAS 100 R	0.48 [ab]
RyeCC NR	0.35 [ab]
RyeCC R	0.35 [ab]
Straw Mulch NR	0.46 [ab]
Straw Mulch R	0.50 [abc]

Within the column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice. [3]Excludes the CZL 0-30cm depth.

2020: Impact of Experiment 2 BMPs on varietal differences (Gijnlim vs Guelph Millennium) in asparagus root architecture.

In 2020, significant differences in RMD were observed between the Gijnlim and Guelph Millennium depth and distance from CZL RMD values (Tables 15-18 and Figure 30 a-f). This demonstrates the shallower rooting tendency of Guelph Millennium as compared with Gijnlim.

It is also of note that for all treatments, at 0.90 m from the CZL for all depths, no significant varietal differences in RMD were observed (Tables 15-18). In addition, at 0.60 m from the CZL for 0.30 – 0.60 depth, no significant varietal differences in RMD were observed.

For the Bare Soil No-SSD NR (zero-till) treatment Guelph Millennium is associated with significantly higher RMD at 0.0 – 0.15m depth at 0.3 and 0.6 m from the CZL as compared with Gijnlim with values of 1.25 and 0.0 and 1.52 and 0.52 (kg m^{-3}), respectively (Table 15). The amounts to a 100% and 66% increase in RMD associated with Guelph Millennium. In addition, Guelph Millennium is associated with significantly (45%) higher RMD at 0.3 – 0.45 m depth, 0.3 m from the CZL as compared with Gijnlim with values of 1.78 and 0.99 (kg m^{-3}), respectively.

Similarly, for the Bare Soil No-SSD R (Conventional practice) treatment Guelph Millennium is associated with significantly higher RMD at 0.0 – 0.15 m depth, 0.3 m from the CZL as compared with Gijnlim with values of 0.96 and 0.04 (kg m^{-3}), respectively (Table 16). In addition, Guelph Millennium is associated with significantly higher RMD at 0.15 – 0.30 m depth, 0.6 m from the CZL as compared with Gijnlim with values of 0.59 and 0.02 (kg m^{-3}).

For the variety treatments to which SSD was applied, significant differences were also observed between the Gijnlim and Guelph Millennium depth and distance from CZL RMD values (Tables 17-18 and Figure 30 a-f). For the Bare soil SSD NR treatment Guelph Millennium was again associated with significantly higher (87% increase) RMD at 0.0 – 0.15 m depth, 0.6 m from the CZL as compared with Gijnlim with values of 0.88 and 0.12 (kg m^{-3}), respectively (Table 17). Guelph Millennium is also associated with significantly higher (52% increase) RMD at 0.15 – 0.30 m depth, 0.3 m from the CZL as compared with Gijnlim with values of 2.33 and 1.18 (kg m^{-3}). Guelph Millennium is also associated with significantly higher (77% increase) RMD at 0.30 – 0.45 m depth at the CZL as compared with Gijnlim with values of 2.35 and 0.79 (kg m^{-3}), respectively (Table 17).

In contrast, for the Bare soil SSD R treatment no significant differences in RMD were observed between Guelph Millennium and Gijnlim at 0.0 – 0.15m depth at 0.3, 0.6 and 0.9 m from the CZL (Table 18 and Figure 30 a-c). In contrast to the other Experiment 2 varietal treatments, at 0.3 m from the CZL, at 0.15 – 0.30 m depth, Gijnlim was associated with significantly higher RMD than Guelph Millennium with values of 2.20 and 1.47 (kg m^{-3}), respectively (Table 18, Figure 30 a and d).

Table 15. 2020: Differences in Gijnlim and Guelph Millennium RMD (kg m^{-3}) for the Bare Soil No-SSD NR (zero-tillage) treatment.

Variety	Depth (m)	Distance from Crown Zero Line (m)			
		CZL	0.3	0.6	0.9
G^A	0.0 – 0.15		0.000*	0.517*	0.010
GM^A			1.247*	1.519*	0.421
G^A	0.15 – 0.30		1.326	0.925	0.547
GM^A			1.844	0.756	0.786
G^A	0.30 – 0.45	1.976	0.985*	0.564	0.282
GM^A		2.056	1.784*	0.398	0.298
G^A	0.45 – 0.60	0.116	0.179	0.325	0.169
GM^A		0.405	0.385	0.342	0.351

Within the column, values followed an apteryx are significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC).

Table 16. 2020: Differences in Gijnlim and Guelph Millennium RMD (kg m^{-3}) for the Bare Soil No-SSD R (Conventional practice) treatment.

Variety	Depth (m)	Distance from Crown Zero Line (m)			
		CZL	0.3	0.6	0.9
G^A	0.0 – 0.15		0.043*	0.109	0.040
GM^A			0.962*	0.607	0.219
G^A	0.15 – 0.30		0.696	0.017*	0.027
GM^A			1.141	0.587*	0.119
G^A	0.30 – 0.45	1.973	0.521	0.036	0.000
GM^A		1.492	0.773	0.103	0.196
G^A	0.45 – 0.60	0.076	0.342	0.040	0.000
GM^A		0.424	0.252	0.143	0.043

Within the column, values followed an apteryx are significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC).

Table 17. 2020: Differences in Gijnlim and Guelph Millennium RMD (kg m^{-3}) for the Bare Soil SSD NR treatment.

Variety	Depth (m)	Distance from Crown Zero Line (m)			
		CZL	0.3	0.6	0.9
G^{A}	0.0 – 0.15		0.129	0.116*	0.139
GM^{A}			0.235	0.875*	0.027
G^{A}	0.15 – 0.30		1.177*	0.371	0.209
GM^{A}			2.334*	0.448	0.239
G^{A}	0.30 – 0.45	0.792*	1.615*	0.312	0.239
GM^{A}		2.351*	0.683*	0.096	0.010
G^{A}	0.45 – 0.60	0.368	0.179	0.242	0.252
GM^{A}		0.345	0.305	0.000	0.000

Within the column, values followed an apteryx are significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC).

Table 18. 2020: Differences in Gijnlim and Guelph Millennium RMD (kg m^{-3}) for the Bare Soil SSD R treatment.

Variety	Depth (m)	Distance from Crown Zero Line (m)			
		CZL	0.3	0.6	0.9
G^{A}	0.0 – 0.15		0.189	0.123	0.007
GM^{A}			0.229	0.405	0.116
G^{A}	0.15 – 0.30		2.198*	0.484	0.080
GM^{A}			1.469*	0.550	0.315
G^{A}	0.30 – 0.45	2.606	1.509	0.199	0.166
GM^{A}		2.696	0.892	0.116	0.249
G^{A}	0.45 – 0.60	0.056*	0.106	0.106	0.043
GM^{A}		0.975*	0.043	0.431	0.050

Within the column, values followed an apteryx are significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. Superscript ^{A} = A Crown. GM = Guelph Millennium and G = Gijnlim. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC).

Figure 29. Differences in 2020 root mass density (kg m^{-3}) profiles for Experiment 1 (Gijnlim) BMPs. Errors bars = +/- 1 STDEV.

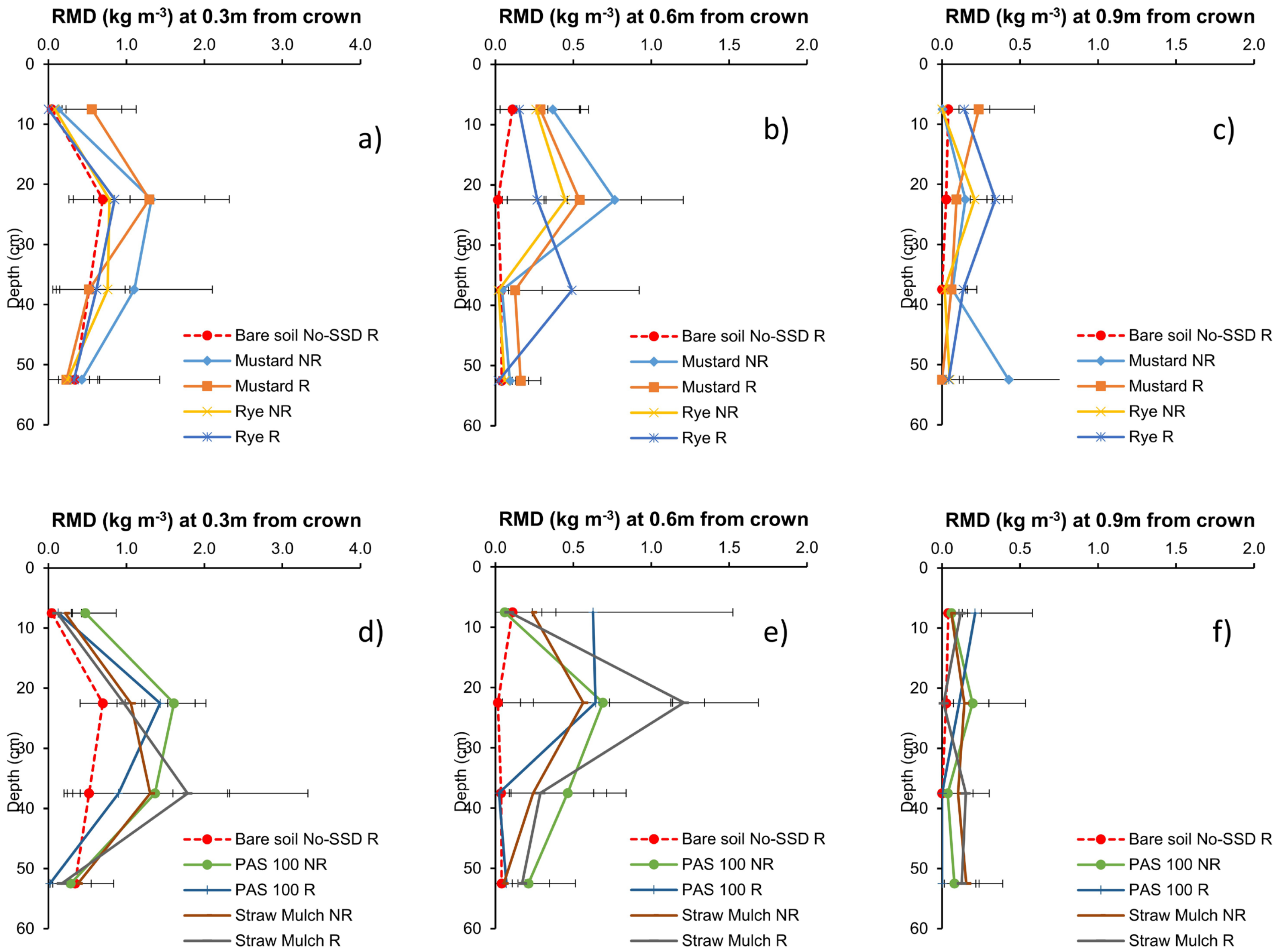
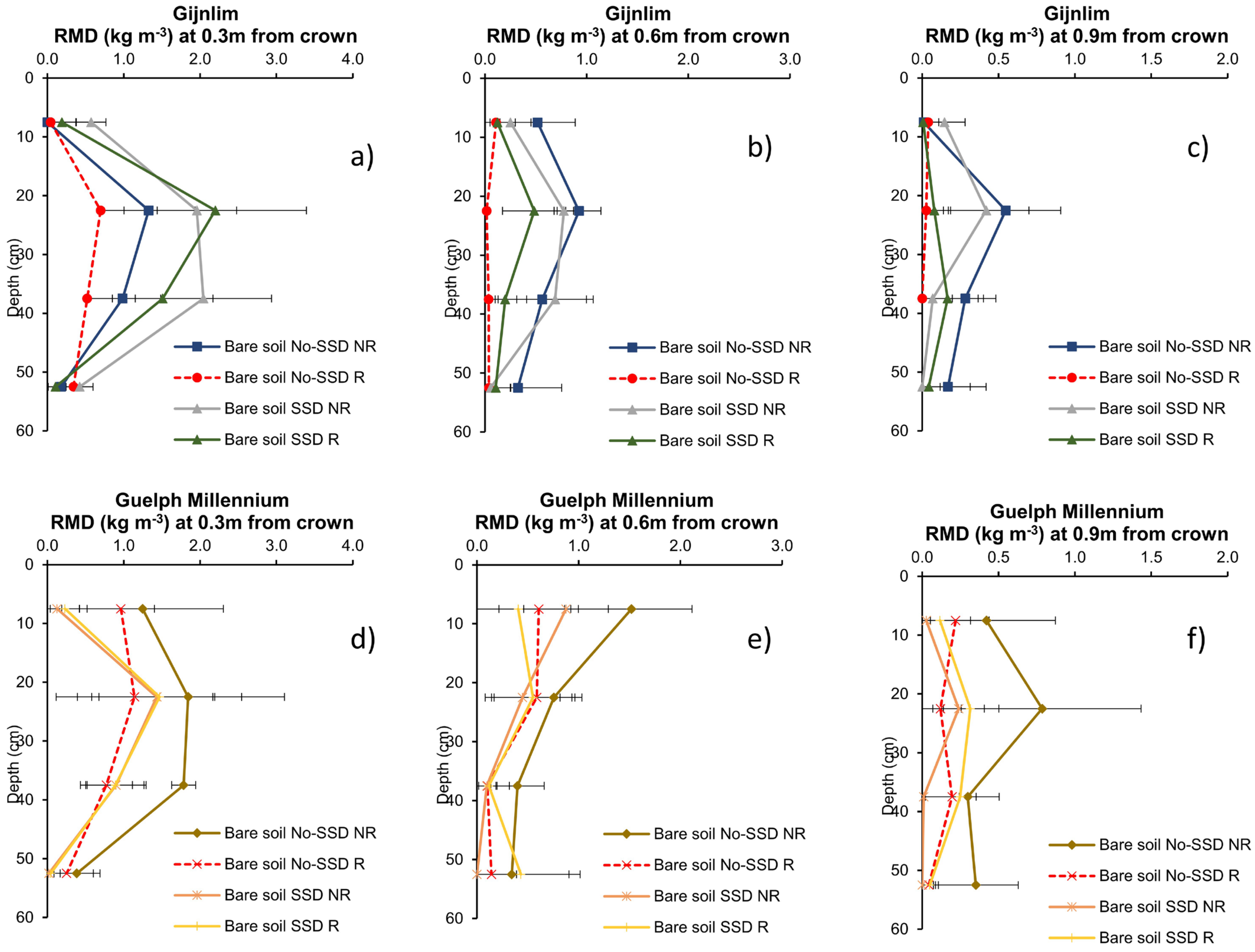


Figure 30. Differences in 2020 root mass density (kg m^{-3}) profiles for Experiment 2 (Gijnlim vs Guelph Millennium). Errors bars = +/- 1 STDEV



__Correlation of Penetrative Resistance (PR) and Root Mass Density (RMD)__

In 2020, additional PR transect measurements were taken post-harvest across the ridge profile (from CZL to centre of the interrow wheeling) in order to facilitate a direct correlation between soil PR and root mass density within the profile (Figure 31)

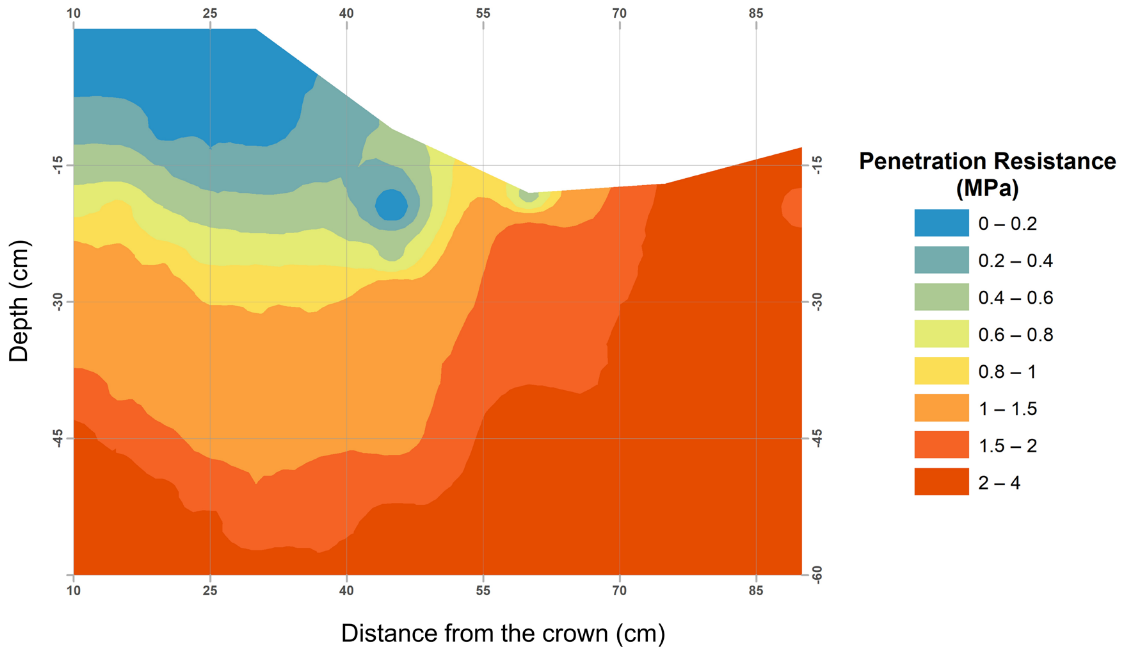


Figure 31. Penetrative resistance (PR) transect.

Across all treatments, (Tables 19 a-d) several locations were found to be positively correlated to Root Mass Density (RMD). At the CZL (Table 19 a), high PR at 0.15 – 0.30 m and 0.45 – 0.6 m depths was correlated to high RMD at 0.0 – 0.15 m depth. At 0.3 m from the CZL (Table 19 b), there were no significant correlations between the PR and RMD. At 6 m from the crown (Table 19 c), high PR at 0.45 – 0.60 m depth was correlated with low RMD at 0.15 - 0.30 m depth. Finally, at the 0.9 m from the CZL,(Table 19 d), high PR at 0.15 - 0.30 m depth was correlated with high RMD at 0.45 – 0.6 m depth, high PR at 0.45 – 0.6 m depth was further correlated to low RMDs at 0.15 – 0.30 m and at 0.30 – 0.45 m depths. It is recommended that concurrent root coring and PR transects are repeated on an annual basis as the FV 450 asparagus achieves commercial maturity (2021-2023). This is to enable the threshold PR value at which asparagus storage root elongation is restricted and identify which BMPs most effectively prevent this threshold being attained.

Table 19a. Correlation between Penetration Resistance (PR) and Root Mass Density (RMD) at the Crown Zero Line (CZL).

		Root Mass Density at specific root coring depths (m)			
	Root Coring depth (m)	0.0 – 0.15	0.15 – 0.3	0.30 – 0.45	0.45 – 0.60
Penetrative Resistance (PR)	0.15 – 0.3	ns	ns	ns	ns
	0.15 – 0.3	0.24*	ns	ns	ns
	0.30 – 0.45	ns	ns	ns	ns
	0.45 – 0.60	0.26*	ns	ns	ns

Correlation matrices following Kendall's Tau correlation; ns = not significant; *values significant at $p<0.05$. Positive correlation values indicate a positive relationship between PR and RMD. Negative correlation values indicate that PR has a negative relationship on RMD negative indicate negative relationship.

Table 19b. Correlation between Penetration Resistance (PR) and Root Mass Density (RMD) 0.30m from the CZL.

		Root Mass Density at specific root coring depths (m)			
	Root Coring depth (m)	0.0 – 0.15	0.15 – 0.3	0.30 – 0.45	0.45 – 0.60
Penetrative Resistance (PR)	0.15 – 0.3	ns	ns	ns	ns
	0.15 – 0.3	ns	ns	ns	ns
	0.30 – 0.45	ns	ns	ns	ns
	0.45 – 0.60	ns	ns	ns	ns

Correlation matrices following Kendall's Tau correlation; ns = not significant; *values significant at $p<0.05$. Positive correlation values indicate a positive relationship between PR and RMD. Negative correlation values indicate that PR has a negative relationship on RMD negative indicate negative relationship.

Table 19c. Correlation between Penetration Resistance (PR) and Root Mass Density (RMD) 0.60m from the CZL.

		Root Mass Density at specific root coring depths (m)			
	Root Coring depth (m)	0.0 – 0.15	0.15 – 0.3	0.30 – 0.45	0.45 – 0.60
Penetrative Resistance (PR)	0.15 – 0.3	ns	ns	ns	ns
	0.15 – 0.3	ns	ns	ns	ns
	0.30 – 0.45	ns	ns	ns	ns
	0.45 – 0.60	ns	-0.21*	ns	ns

Correlation matrices following Kendall's Tau correlation; ns = not significant; *values significant at $p<0.05$. Positive correlation values indicate a positive relationship between PR and RMD. Negative correlation values indicate that PR has a negative relationship on RMD negative indicate negative relationship.

Table 19d. Correlation between Penetration Resistance (PR) and Root Mass Density (RMD) 0.60m from the CZL.

		Root Mass Density at specific root coring depths (m)			
	Root Coring depth (m)	0.0 – 0.15	0.15 – 0.3	0.30 – 0.45	0.45 – 0.60
Penetrative Resistance (PR)	0.15 – 0.3	ns	ns	ns	ns
	0.15 – 0.3	ns	ns	ns	ns
	0.30 – 0.45	ns	ns	ns	ns
	0.45 – 0.60	ns	-0.21*	ns	ns

Correlation matrices following Kendall's Tau correlation; ns = not significant; *values significant at $p<0.05$. Positive correlation values indicate a positive relationship between PR and RMD. Negative correlation values indicate that PR has a negative relationship on RMD negative indicate negative relationship.

Asparagus Root Architecture: Wider Grower Landbank

In 2019 and 2020, spatial distribution of asparagus storage roots was investigated for sixteen fields from two UK growers adopting conventional crop management practice, i.e. annual re-ridging (Table 3). The total number of grower fields sampled to date under the FV 450a project is 30: 14 fields were sampled in 2018, 8 sampled from Grower E in September 2019 and a further 8 in February 2020 from Grower F.

Norfolk and Suffolk: Grower E: 1.8 m and 1.5 m row spacings.

The 7 out of 8 fields sampled in Norfolk and Suffolk (Table 3 – Grower E, Figure 32 a-f) had a row spacing of 1.8 m and were planted to Gijnlim. The remaining field had a row spacing of 1.5 m and was planted to Guelph Millennium. Planting densities ranged from 24,000 to 34,000 plants ha^{-1} and planting method was A crowns for both varieties. Figures 32a, 32b and 32c are fields grown under polytunnels. Figures 32d, 32e and 32f are open fields.

Root mass density associated with asparagus cultivated under Polytunnels

At 0.3 m distance from the CZL at 0.15 – 0.3 m sampling depth RMD values were in the order, 2 yr old < 5 yr old < 4 yr old < 3 yr old < 6 yr old Gijnlim (Figures 32 a-c). The highest RMD was observed for 6 yr old Gijnlim. As expected, significantly lower RMD was observed at the 2 yr old Gijnlim. At 0.6 m distance from the CZL 6 yr old Gijnlim was associated with significantly highest RMD at the 0.30 – 0.45 m sampling depth as compared with 5 yr and 2 yr old Gijnlim (Figures 32 a-c). 6 yr old Gijnlim grown under polytunnels had significantly higher RMD values at 0.30 – 0.45 m sampling depth compared to 6 yr old Open Field Gijnlim.

RMD values for the 5 yr and 2 yr old Gijnlim were not significantly different across all sampling depths (Figures 32 a-c). At 0.9 m distance from the CZL, 6 yr old Gijnlim had significantly highest RMD at 0.15 – 0.60 m sampling depths as compared with all other stand ages (Figure 32 a-c). However, 2 yr old Gijnlim was associated with the highest RMD value at the 0.0 – 0.15 m sampling depth. This may be due to lower number of interrow wheeling foot and vehicular trafficking events associated with the 2 yr old stand limiting compaction which facilitates root elongation to the centre of the interrow wheeling. This may also be due to reduced damage due to repeated annual ridging operations. Elongation of storage roots in the interrow wheeling at the 0.0 – 0.15 m depth increases the risk of root damage associated with re-ridging operations. In addition, at 0.9 m distance from the CZL, 6 yr old Gijnlim under polytunnels was associated with significantly higher RMD values at 0.15 – 0.60 m sampling depths compared to 6 yr old Gijnlim grown under open field conditions.

Root mass density associated with Open Field asparagus

In contrast to the polytunnel RMD values, for the Open Field asparagus at 0.3 m distance from the CZL at 0.15 – 0.3 m depth, no significant differences in RMD were observed between the 4 yr and the 6 yr old Gijnlim. However, at 0.6 m from the CZL, 6 yr old Gijnlim was associated with significantly higher RMD values at 0.30 – 0.60 m sampling depths as compared to the 4 yr old Gijnlim. Further, at 0.9 m distance from the CZL, 6 yr old Gijnlim had significantly higher RMD values at 0.15 – 0.45 m sampling depths compared to the 4 yr old Gijnlim (Figure 32 d-f).

Warwickshire: Grower F: 1.83m row spacings.

In total 8 fields were sampled in Warwickshire (Table 3 – Grower F, Figures 33 a-f). These had a row spacing of 1.83 m and were planted to Gijnlim and Guelph Millennium. Planting density was 21,500 plants ha^{-1}; planting methods were A Crowns and B Crowns.

At 0.3 m distance from the CZL at 0.15 – 0.3 m sampling depth at 0.3 m distance from the CZL, RMD values for Gijnlim were in the order, 4 yr old < 2 yr old < 2 yr old < 4 yr old < 5 yr old Gijnlim. The 5 yr old Gijnlim field had significantly highest RMD values at the 0.30 – 0.45 m sampling depth than all other field sampled (Figure 33 a-c). At 0.15 – 0.3 m sampling depth at 0.3 m distance from the CZL, RMD values for Guelph Millennium were in the order 4 yr old < 2 yr old < 5 yr old Guelph Millennium with the 5 yr stand having significantly higher RMD values at 0.15 – 0.60 m sampling depths.

At 0.6 m distance from the crown at 0.15 – 0.3 m sampling depth RMD values for Gijnlim were as expected in the order, 2 yr old < 4 yr old < 4 yr old < 5 yr old. 5 yr old Gijnlim is associated with significantly highest RMD values at the 0.15 – 0.30 m sampling depth as compared with all other stand ages (Figure 33 b).

5 yr old Guelph Millennium had significantly highest RMD values at 0 – 0.45 m sampling depths. High RMD values at the 0 – 0.15 m depth Guelph Millennium imply greater risk of root damage associated with re-ridging operations in asparagus. The significantly higher RMD associated with the 5 yr old Guelph Millennium as compared with 5 yr old Gijnlim at 0.0 – 0.15m depth 0.6m from the CZL (Figure 33 b and e) reflects the findings from the FV 450 field trials indicating a shallower rooting tendency.

At 0.9 m distance from the CZL 5 yr old Gijnlim was associated with significantly higher RMD values from 0.0 – 0.30 m depths as compared with all other Gijnlim stands (Figure 33 c). At 0.15 – 0.3 m sampling depth, 0.9 m distance from the CZL, RMD values for Gijnlim were in the order, 4 yr old < 2 yr old < 2 yr old < 4 yr old < 5 yr old.

For Guelph Millennium, at 0.9 m distance from the CZL, the 2 yr old stand was associated with significantly higher RMD values at the 0.0 – 0.15 m depth (Figure 33 f), This may in large part be due to lower number of interrow wheeling foot and vehicular trafficking events associated with the 2 yr old stand limiting compaction which facilitates root elongation to the centre of the interrow wheeling. This may also be due to reduced damage due to repeated annual ridging operations. Elongation of storage roots in the interrow wheeling at the 0.0 – 0.15 m depth increases the risk of root damage associated with re-ridging operations.

Figure 32. Root mass density (kg m^{-3}) profiles for Grower E on 1.8 m row spacing's Gijnlim.

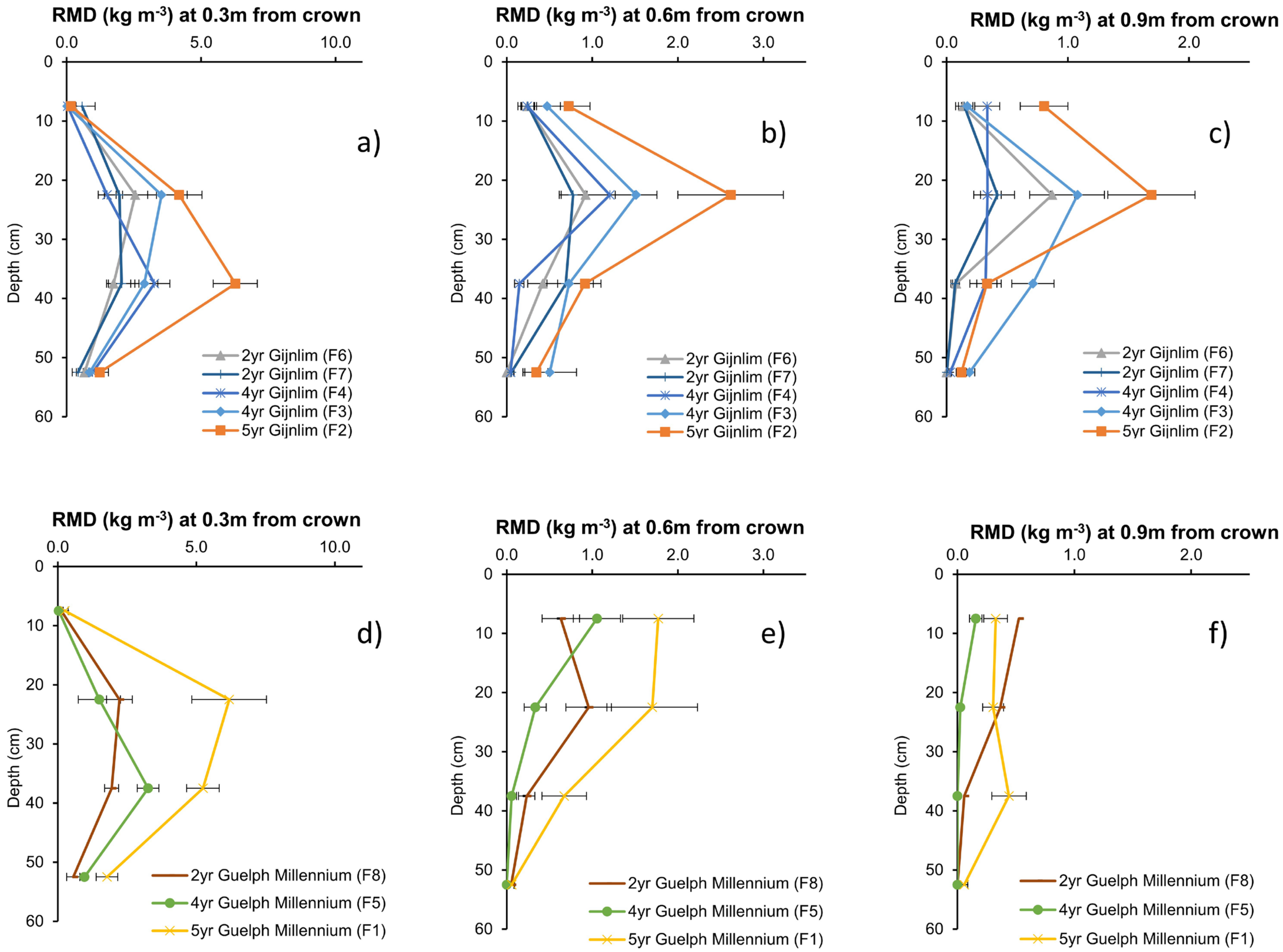
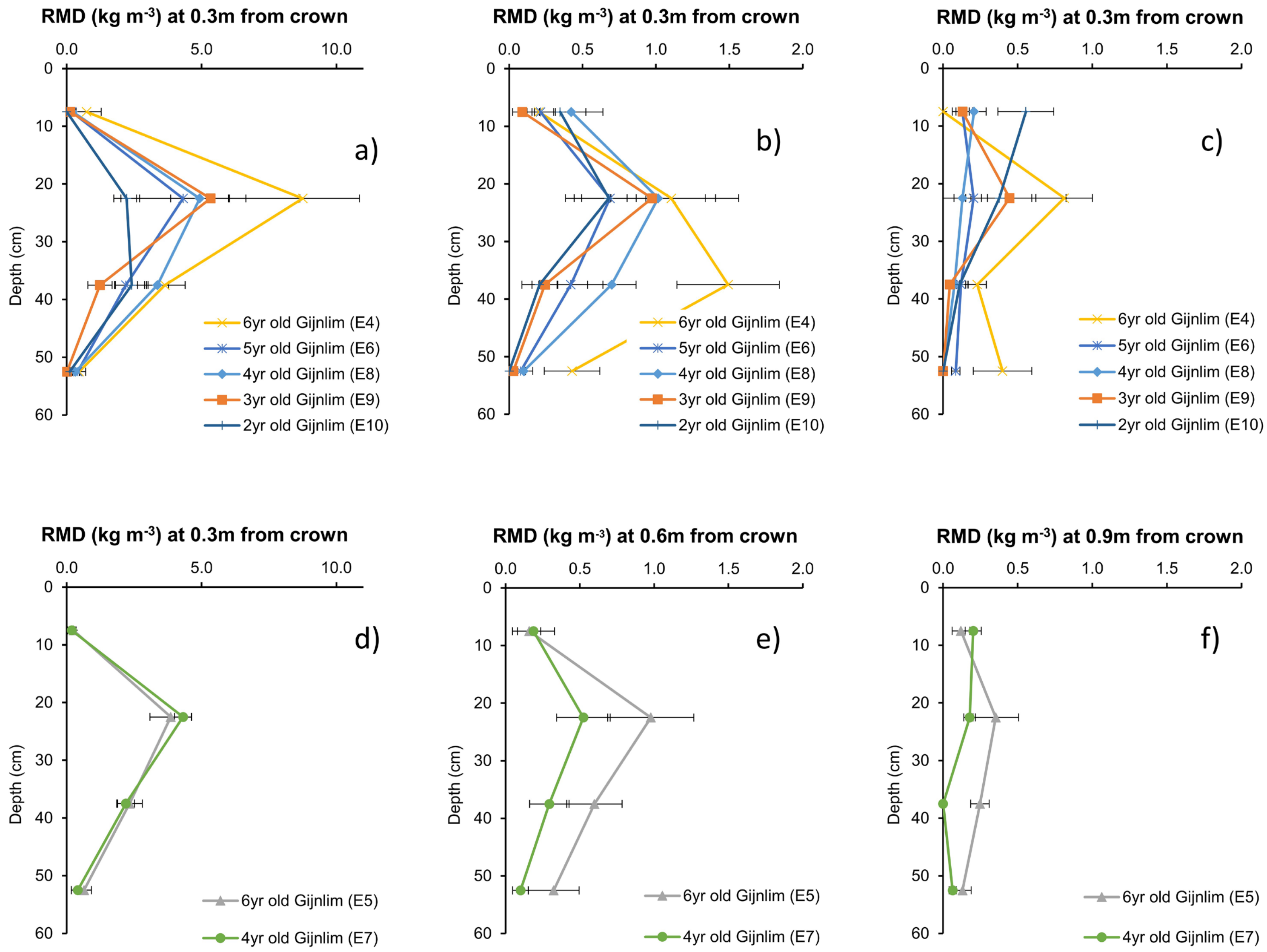


Figure 33. Root mass density (kg m^{-3}) profiles for Grower F on 1.83 m row spacing's Gijnlim and Guelph Millennium



Discussion

Root architecture across the wider grower landbank: Implications for damaging roots during sub-soiling and ridging operations

2020: Norfolk and Suffolk: Grower E: 1.8 m and 1.5 m row spacings.

The results indicate that for 11 yr old Guelph Millennium on 1.5m centres there is a potential for 8-11% of storage root Total Root Biomass (TRB) to be damaged when using the winged with shallow leading tine, winged tine and modified para-plough to 300 mm operating depth (Appendix 1 Figure 34). Approximately, 2-5 % of TRB could potentially be damaged using the narrow tine and narrow with shallow leading tine configurations investigated by Niziolomski, et al., (2016). Gijnlim planted as A crowns grown on 1.80 m centres, aged 2-6 yr old (planted from 2014-2018) would be associated with damage to <2% of TRB (Table 20) under all tine configurations investigated by Niziolomski, et al. (2016) to an operating depth of 300 mm.

Table 20. 2020: Potential damage to storage roots expressed as % of Total Root Biomass (%TRB) for Grower E.

			Potential damage to storage roots expressed as % of Total Root Biomass (%TRB)					
Variety	Year Planted	Row spacing (m)	[1]Winged with shallow leading tine	[1]Narrow tine	[1]Winged tine	[1]Narrow with shallow leading tine	[1]Modified para-plough	[2]Annual ridging operation
GM[A]	2009	1.5	8-11%	2-5%	8-11%	2-5%	8-11%	11-14%
G[A]	2014	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	5-8%
G[A]	2014	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	5-8%
G[A]	2015	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	5-8%
G[A]	2016	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	2-5%
G[A]	2016	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	5-8%
G[A]	2017	1.8	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
G[A]	2018	1.8	2-5%	0-2%	2-5%	0-2%	2-5%	5-8%

Superscript [A] = A Crown. GM = Guelph Millennium and G = Gijnlim

[1]After, Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52. (Ref. Figures 34-41 in Appendix 1)

[2]Assuming that the ridger used by Grower E has a similar disturbance pattern as that adopted by Cobrey Farms (Ref. Figures 50-65 in Appendix 2).

The interrow wheeling zones of the 2-6 yr old Gijnlim grown in Norfolk and Suffolk are largely devoid of storage roots creating a ‘dead-zone’ (Appendix 1 Figures 35-41). This may in part be due to severe compaction restricting storage root expansion into this zone as the interrow wheelings are not regularly sub-soiled (Table 3). This has major implications for infiltration, run-off and erosion and soil moisture recharge.

The lack of storage roots observed within wheelings in 2-6 yr old Gijnlim grown in Norfolk and Suffolk indicates that SSD operations to 300 mm depth using all tine configurations investigated by Niziolomski, (2016) can be undertaken. (Appendix 1 Figures 35-41).

With regards to re-ridging operations, for the 2-6 yr old Gijnlim on 1.8m row spacing, the root heat maps (Appendix 1 Figures 35-41) suggest that ridging has the potential to damage on average 5-8% of TRB (Table 20 and Appendix 1 Figures 35-41). For 11 yr old Guelph Millennium grown on 1.5 m centres there is the potential to damage 11-14% of TRB due to both the age of stand and shallower rooting habit of Guelph Millennium.

Warwickshire: Grower F: 1.83 row spacings.

The results indicate that in general, for both Gijnlim and Guelph Millennium, for stands aged 2-5 yrs, planted either as A or B crowns there is the potential for 2-5% of storage roots to be damaged when using all tine configurations investigated by Niziolomski, et al., (2016) operated to 300 mm depth (Table 21 and Appendix 1 Figures 42-49). With regards to re-ridging operations, for both Gijnlim and Guelph Millennium, planted either as A or B crowns there is the potential to damage on average 5-9% of storage roots (Appendix 1 Figures 42-49).

Table 21. 2020: Potential damage to storage roots expressed as % of Total Root Biomass (%TRB) for Grower F.

			Potential damage to storage roots expressed as % of Total Root Biomass (%TRB)					
Variety	Year Planted	Row spacing (m)	[1]Winged with shallow leading tine	[1]Narrow tine	[1]Winged tine	[1]Narrow with shallow leading tine	[1]Modified para-plough	[2]Annual ridging operation
GM^B	2014	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	5-9%
G^B	2014	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	2-5%
G^A	2015	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	5-9%
G^B	2015	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	5-9%
GM^B	2015	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	5-9%
G^A	2017	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	2-5%
G^B	2017	1.83	0-2%	0-2%	0-2%	0-2%	2-5%	2-5%
GM^A	2017	1.83	2-5%	2-5%	2-5%	2-5%	2-5%	5-9%

Superscript ^{A} = A Crown. Superscript ^{B} = B Crown. GM = Guelph Millennium and G = Gijnlim
[1]After, Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52. (Ref. Figures 41-49 in Appendix 1)
[2]Assuming that the ridger used by Grower F has a similar disturbance pattern as that adopted by Cobrey Farms (Ref. Figures 50-65 in Appendix 2).

For both Grower E and F, it is recommended that SSD is undertaken in conjunction with straw or compost mulch application which has been shown to reduced run-off by >80% (Niziolomski et al., 2020) and to significantly improve infiltration and reduce PR in the interrow wheelings (FV450 Field Trials).

FV 450 field trials: Implications for damaging roots during sub-soiling and ridging operations

Across all FV 450 Experiment 1 BMP treatments, sub-soiling (SSD) in interrow wheelings would result in damage to up to 5% of TRB (Table 22) under all tine configurations investigated by Niziolomski, et al. (2016) to an operating depth of 300 mm (Appendix 2 Figures 50-61). Similarly, annual ridging operations have the potential to damage up to 5% of TRB (Table 22 and Appendix 2 Figures 50-61).

Table 22. 2020: Potential damage to storage roots expressed as % of Total Root Biomass (%TRB) associated with Experiment 1 (Gijnlim) BMPs.

	Potential damage to storage roots expressed as % of Total Root Biomass (%TRB)					
Treatment	[3]Winged with shallow leading tine	[3]Narrow tine	[3]Winged tine	[3]Narrow with shallow leading tine	[3]Modified para-plough	[4]Annual ridging operation
[1]Bare Soil No-SSD NR	2-5%	2-5%	2-5%	2-5%	2-5%	2-5%
[2]Bare Soil No-SSD R	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
Bare Soil SSD NR	0-2%	0-2%	0-2%	0-2%	0-2%	2-5%
Bare Soil SSD R	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
MustardCC NR	2-5%	0-2%	2-5%	0-2%	2-5%	2-5%
MustardCC R	0-2%	0-2%	0-2%	0-2%	2-5%	2-5%
PAS 100 NR	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
PAS 100 R	2-5%	0-2%	2-5%	0-2%	2-5%	2-5%
RyeCC NR	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
RyeCC R	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
Straw Mulch NR	0-2%	0-2%	0-2%	0-2%	0-2%	2-5%
Straw Mulch R	2-5%	0-2%	2-5%	0-2%	2-5%	2-5%

Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD.
[1]Zero-tillage treatment; [2]Conventional practice.
[3]After, Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
[4]Based on the operating depth and specifications of the ridger used by Cobrey Farms (Appendix 2 Figures 50-61).

Table 23. 2020: Potential damage to storage roots expressed as % of Total Root Biomass (%TRB) associated with Experiment 2 varietal (Gijnlim vs Guelph Millennium) BMPs.

		Potential damage to storage roots expressed as % of Total Root Biomass (%TRB)					
Variety	Treatment	[3]Winged with shallow leading tine	[3]Narrow tine	[3]Winged tine	[3]Narrow with shallow leading tine	[3]Modified para-plough	[4]Annual ridging operation
G^A	[1]Bare Soil No-SSD NR	2-5%	2-5%	2-5%	2-5%	2-5%	2-5%
GM^A		0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
G^A	[2]Bare Soil No-SSD R	0-2%	0-2%	0-2%	0-2%	0-2%	2-5%
GM^A		0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
G^A	Bare Soil SSD NR	2-5%	0-2%	2-5%	0-2%	2-5%	2-5%
GM^A		0-2%	0-2%	0-2%	0-2%	2-5%	2-5%
G^A	Bare Soil SSD R	0-2%	0-2%	0-2%	0-2%	0-2%	0-2%
GM^A		2-5%	0-2%	2-5%	0-2%	2-5%	2-5%

Annual re-ridging (R) or No-ridging (NR). GM = Guelph Millennium and G = Gijnlim. Superscript ^{A} = A Crown. Shallow soil disturbance (SSD) or No-SSD. [1]Zero-tillage treatment; [2]Conventional practice.
[3]After, Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
[4]Based on the operating depth and specifications of the ridger used by Cobrey Farms (Appendix 2 Figures 50-53 and 62-65).

Similarly, across the FV 450 Experiment 2 treatments, sub-soiling (SSD) in interrow wheelings would result in damage to up to 5% of TRB (Table 23) under all tine configurations investigated by Niziolomski, et al., (2016) to an operating depth of 300 mm (Appendix 2 Figures 50-53 and 62-65). Similarly, annual ridging operations have the potential to damage up to 5% of TRB (Table 23 and Appendix 2 Figures 50-53 and 62-65).

Conclusions

Impact of FV 450 Best Management Practice treatments on asparagus yield.

2019:

- With the exception of the rye ridged and non-ridged treatments, ridging had no significant impact on yield or spear size.
- The Rye non-ridged treatment was associated with a 20% reduction in yield compared to the Rye ridged treatment. This is in large part due to the significantly 19% lower spear weight associated with the Rye non-ridged as compared to the Rye ridged treatment.

Varietal Differences:

- A significant >20% reduction in yield was observed between the Gijnlim and Guelph Millennium zero-till (non-ridged) treatments and the Gijnlim and Guelph Millennium conventional practice (ridged) treatments with values of 163 and 118 kg ha^{-1} and 138 and 111 kg ha^{-1}, respectively.
- In contrast no significant differences in yield were observed between the Gijnlim and Guelph Millennium treatments which received shallow soil disturbance (SSD).

2020:

- The PAS 100 ridged (R) and PAS 100 non-ridged (NR) treatments were associated with a 20% uplift in asparagus yield as compared to the conventional practice, bare soil SSD ridged and non-ridged treatments and Rye non-ridged treatments.
- The Rye non-ridged treatment continues to be associated with a 23% reduction in yield as compared to Rye ridged treatment.

Varietal Differences:

- In contrast to the 2018 and 2019 yield data, in 2020 no significant difference in yield was observed between the comparable Gijnlim and Guelph Millennium treatments.
- As observed in 2019, for both Gijnlim and Guelph Millennium, annual re-ridging associated with conventional practice was associated with a 20-24% reduction in yield as compared with the equivalent zero-tillage treatments. This may in part corroborate the findings of (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) that annual re-ridging causes root damage and yield reductions.

Impact of FV 450 Best Management Practice treatments on storage root soluble carbohydrate (CHO) levels

- Across all FV 450 BMP treatments, mean pre-harvest storage root CHO values (in March 2020) at the Crown Zero Line (CZL) ranged from 377 – 525 mg g^{-1}. The majority of values are below the upper range of pre-harvest root CHO values observed during the AHDB FV 271 AspireUK project (AHDB, 2007) which reported mean values (dominated by Gijnlim) of 494 and 512 mg g^{-1} (2005 and 2007).

Varietal Differences:

- The 2020 results follow the 2018 and 2019 findings that asparagus storage root CHO values for Guelph Millennium are significantly higher than the equivalent for Gijnlim Experiment 2 BMP treatments. Mean asparagus storage root CHO values (across all Experiment 2 treatments) for Gijnlim and Guelph Millennium were 450 and 623 mg g^{-1}, respectively.

Impact of FV 450 Best Management Practice treatments on mitigating interrow wheeling compaction

- Conventional practice was associated with significantly higher penetrative resistance from 0.0-0.20 m depth as compared to all other bare soil treatments. In contrast, the Zero-tillage treatment, was associated with a significantly lower whole profile penetrative resistance as compared to all other bare soil treatments.
- In both 2019 and 2020, companion cropping did not significantly affect penetrative resistance as compared with conventional practice.
- In 2020, shallow soil disturbance (SSD) significantly reduced penetrative resistance in the interrow wheelings to 0.25 m depth for all SSD treatments. Further, the straw mulch and PAS 100 compost treatments which were applied in conjunction with SSD were associated with significantly lower whole profile mean penetrative resistance as compared to the conventional practice from 0.0-0.40 m depth.
- In 2020 infiltration rate in all treatments subject to SSD were classified as “Very Rapid” (>500 mm h^{-1}) and had significantly higher infiltration rates as compared to the conventional tillage practice (classified as having a “Moderate” (23.2 mm h^{-1}). This has major implications for the control of surface run-off and soil moisture re-charge.

Impact of FV 450 Best Management Practice treatments on root architecture

2019:

- Negligible differences in whole profile root mass density (RMD) were observed between the FV 450 Experiment 1 (Gijnlim) treatments.
- However, at 0.3, 0.6 and 0.9 m from the crown zero line (CZL), at 0.15 – 0.3 m depth, the Rye non-ridged treatment was associated with significantly lower RMD values as compared with the conventional practice.

Varietal Differences:

- No significant differences in whole profile RMD were observed between similar Gijnlim and Guelph Millennium treatments. In addition, ridging had no significant effect on whole profile RMD or depth vs distance RMD values.

2020:

- Significant differences in whole profile RMD were observed between the zero tillage and conventional practice treatments. This was due to significant differences in RMD at 0.15 – 0.30 m depth, 0.3, 0.6 and 0.9 m from the CZL. These differences amount to between a 48-98% increase in RMD associated with the zero-tillage treatment.
- This supports the findings of (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) that annual re-ridging damages storage roots. However, to date no significant reduction in yield or increase in disease incidence has been observed.
- A significant difference in whole profile RMD was observed between the PAS 100 non-ridged and ridged treatments. This was due to a 55.4% increase in RMD associated with the PAS 100 non-ridged treatment at 0.30 – 0.45 m depth at the CZL.

Varietal Differences:

- In 2020, significant differences in RMD were observed between Gijnlim and Guelph Millennium that demonstrate the shallower rooting tendency of Guelph Millennium as compared with Gijnlim.
- For the zero-till treatment Guelph Millennium is associated with 66-100% higher RMD at 0.0 – 0.15m depth at 0.3 and 0.6 m from the CZL as compared with Gijnlim. In addition, Guelph Millennium is associated with 45% higher RMD at 0.3 – 0.45 m depth, 0.3 m from the CZL as compared with Gijnlim.

Potential root damage associated with sub-soiling and ridging operations

FV 450 Trials

- Across all FV 450 BMPs for both Experiment 1 (Gijnlim) and Experiment 2 (Gijnlim vs Guelph Millennium), sub-soiling (SSD) in interrow wheelings could potentially damage up to 5% of the total root biomass (TRB) under all tine configurations investigated by Niziolomski, et al., (2016) used at an operating depth of 300 mm.
- Annual ridging operations have the potential to damage up to 5% of TRB.

Wider grower landbank:

Grower E.

- Gijnlim planted as A crowns grown on 1.80 m centres, aged 2-6 yr old (planted from 2014-2018) would be associated with damage to <2% of TRB under all tine configurations investigated by Niziolomski, et al., (2016) to an operating depth of 300 mm.
- With regards to re-ridging operations, for the 2-6 yr old Gijnlim on 1.8 m row spacing, the root heat maps suggest that ridging has the potential to damage on average 5-8% of TRB.
- In contrast, for the 11 yr old Guelph Millennium planted on 1.5m centres there is a potential for 8-11% of storage root TRB to be damaged when using the winged with shallow leading tine, winged tine and modified para-plough investigated by Niziolomski, et al., (2016) to a 300 mm operating depth. Approximately 2-5 % of TRB could potentially be damaged using the narrow tine and narrow with shallow leading tine configurations investigated by Niziolomski, et al., (2016).
- With regards to re-ridging operations, for the 11 yr old Guelph Millennium grown on 1.5 m centres there is the potential to damage 11-14% of TRB. This is due to both the age of stand and shallower rooting habit of Guelph Millennium.

Grower F.

- For both Gijnlim and Guelph Millennium, for stands aged 2-5 yrs, planted either as A or B crowns there is the potential for 2-5% of storage roots to be damaged when using all tine configurations investigated by Niziolomski, et al., (2016) operated to 300 mm.
- With regards to re-ridging operations, for both Gijnlim and Guelph Millennium, planted either as A or B crowns there is the potential to damage on average 5-9% of storage roots.

Knowledge and Technology Transfer

The following knowledge and technology transfer activities have been undertaken in the reporting period.

Engagement Activities

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

- 4th June 2019 CHAP Soils Forum 2019 Asparagus field trial demonstration
- 16th July 2019 – The Asparagus Growers Association Biennial Conference in York – Field demonstration.
- 30th - 31st January 2020 AHDB Crops PhD Conference poster presentation.

- March 2020 Article published in the Asparagus World Magazine N°2 https://www.eurofresh-distribution.com/asparagus-world/asparagus-world-2
- 6th July 2020 Cranfield and FERA SBSH joint meeting

Glossary

BMPs	Best Management Practices
MPP	Modified Para-plough
NSLT	Narrow tine with shallow leading tines
NT	Narrow tine
PAG	Project Advisory Group
PR	Penetrative resistance
PSD	Particle size distribution
RMD	Root Mass Density
%TRB	Percentage Total Root Biomass
VESS	Visual Evaluation of Soil Structure
VSA	Visual Soil Assessment
WSLT	Winged tine with shallow leading tines
WT	Winged tine
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

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Appendices

Appendix 1:

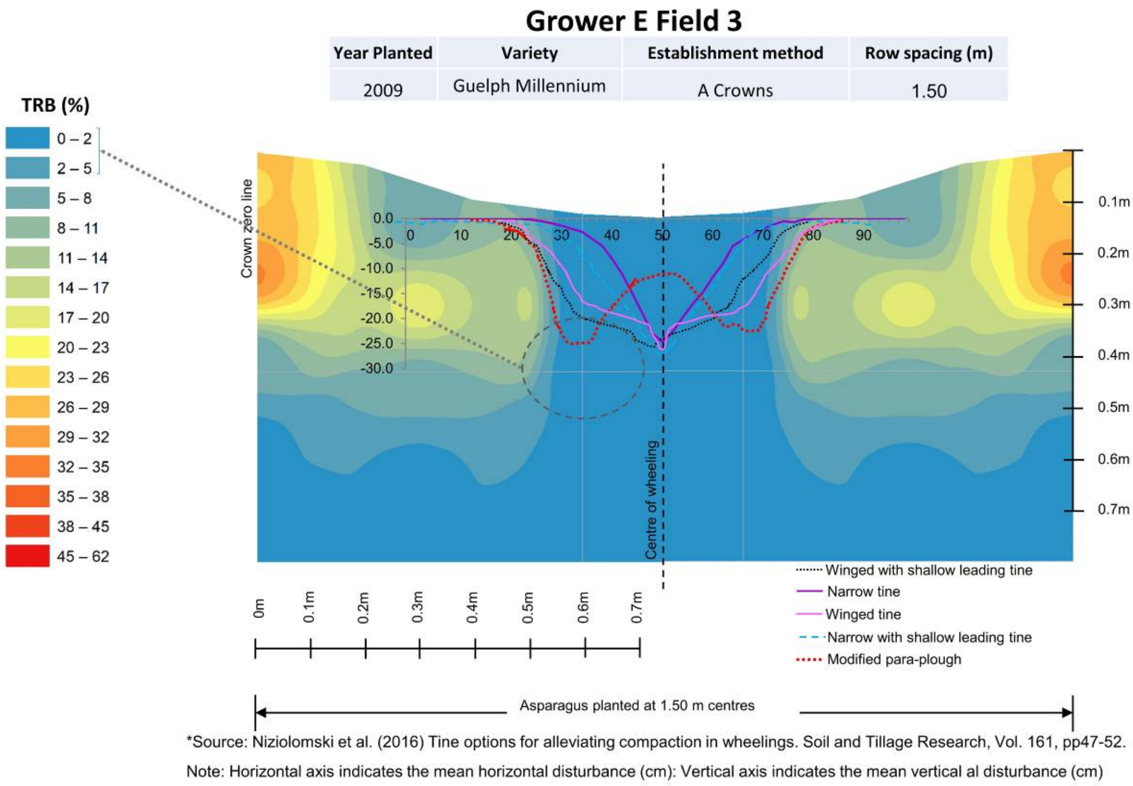


Figure 34. Grower E total root biomass (TRB%) root map for 11yr old Guelph Millennium A-Crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

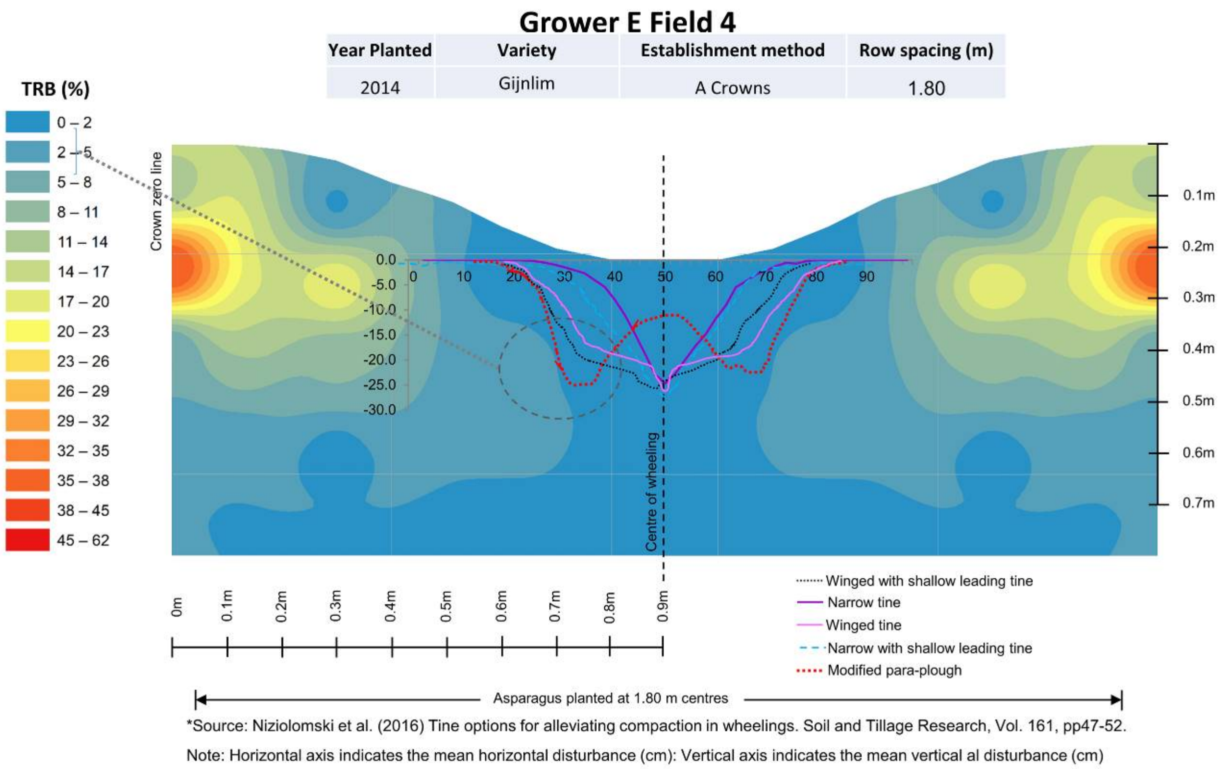


Figure 35. Grower E total root biomass (TRB%) root map for 6yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

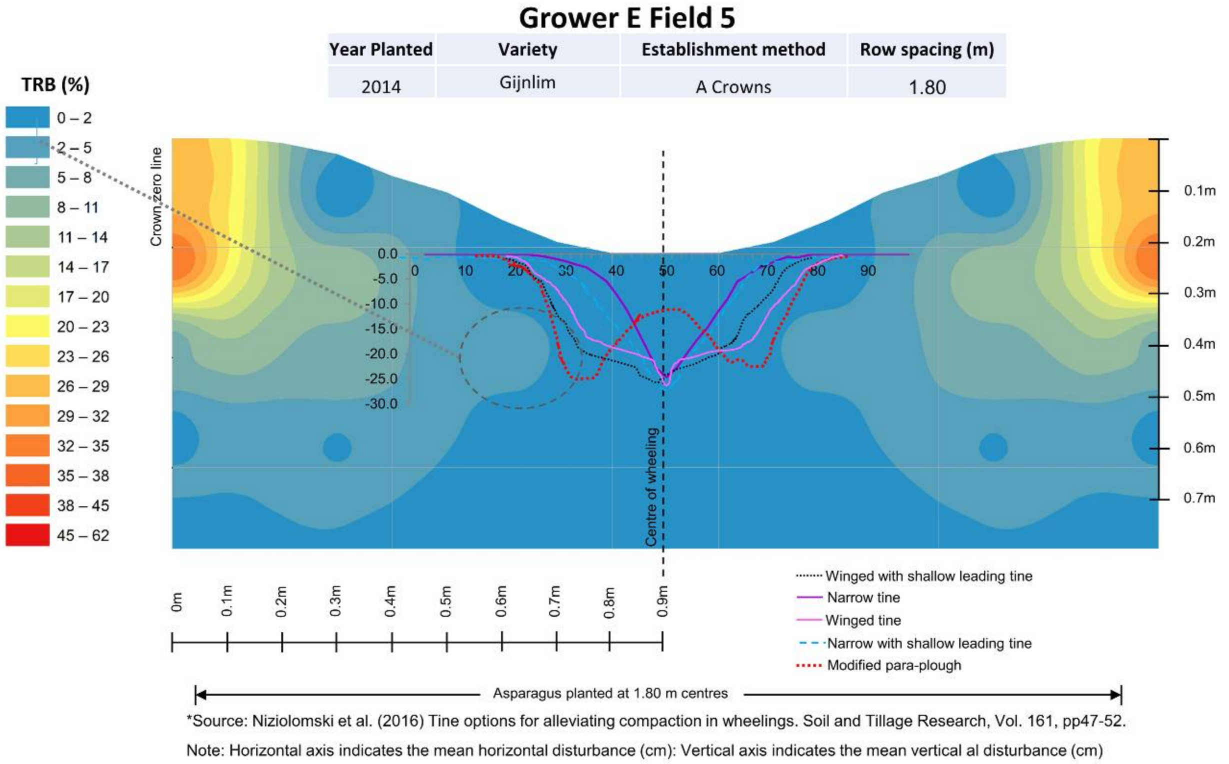


Figure 36. Grower E total root biomass (TRB%) root map for 6yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

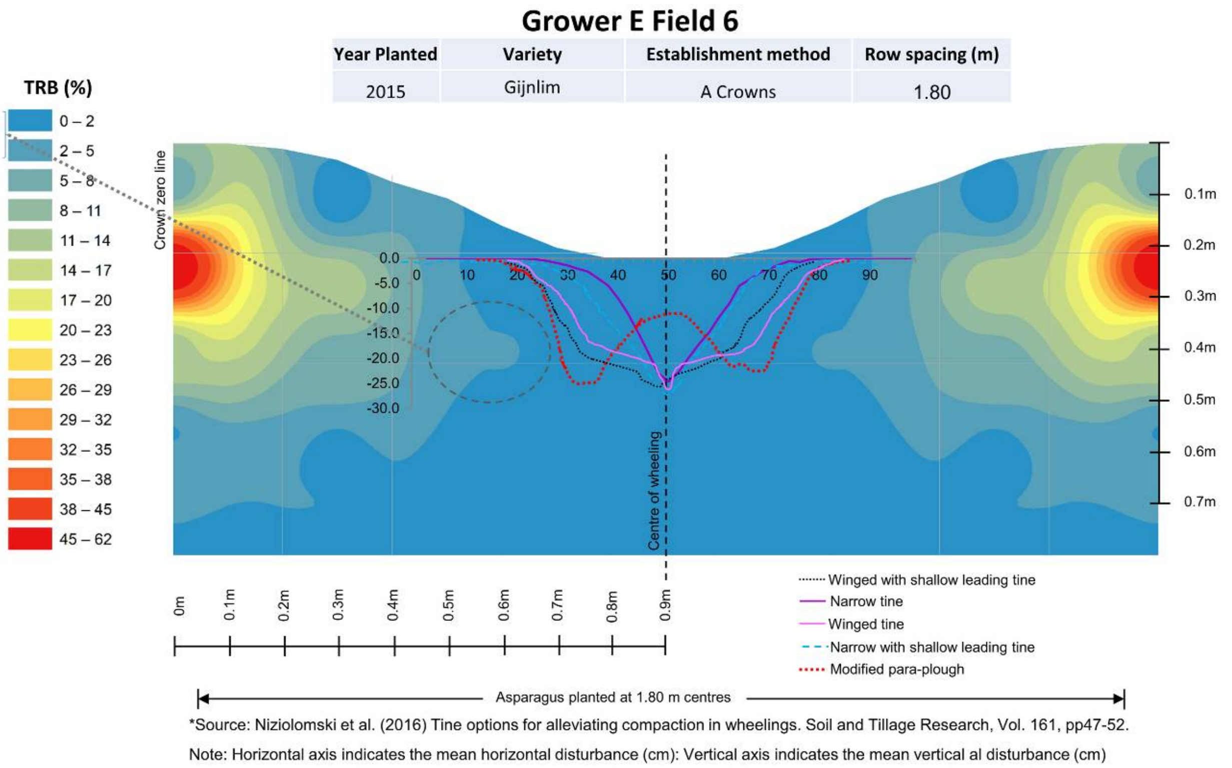
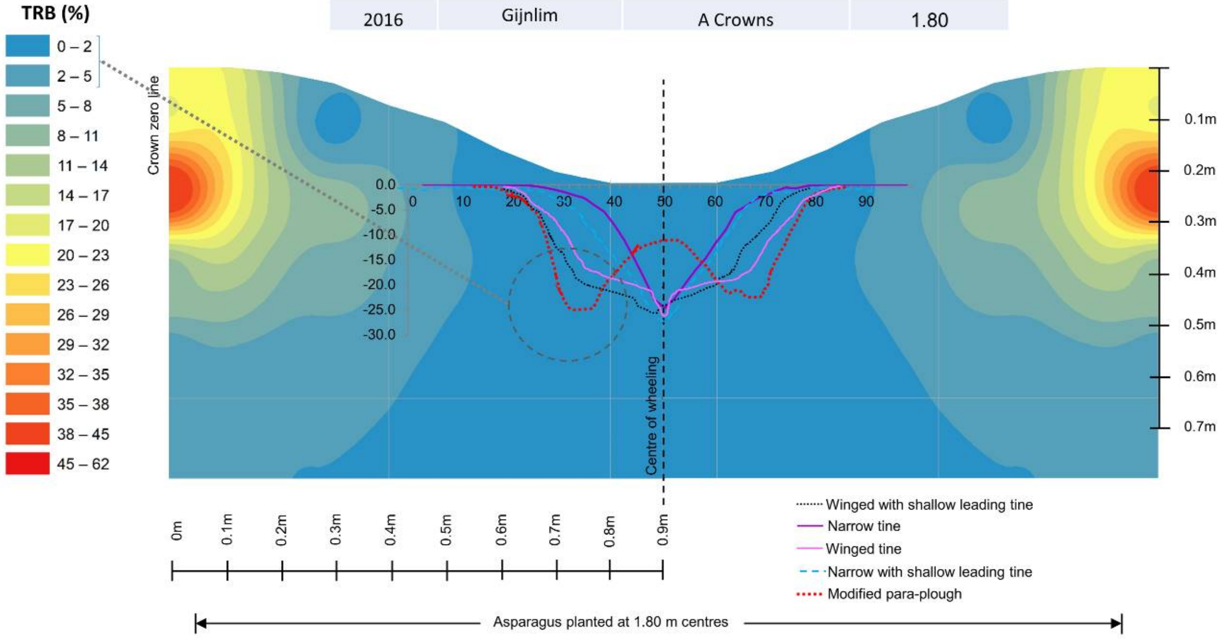


Figure 37. Grower E total root biomass (TRB%) root map for 5yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower E Field 7

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	1.80



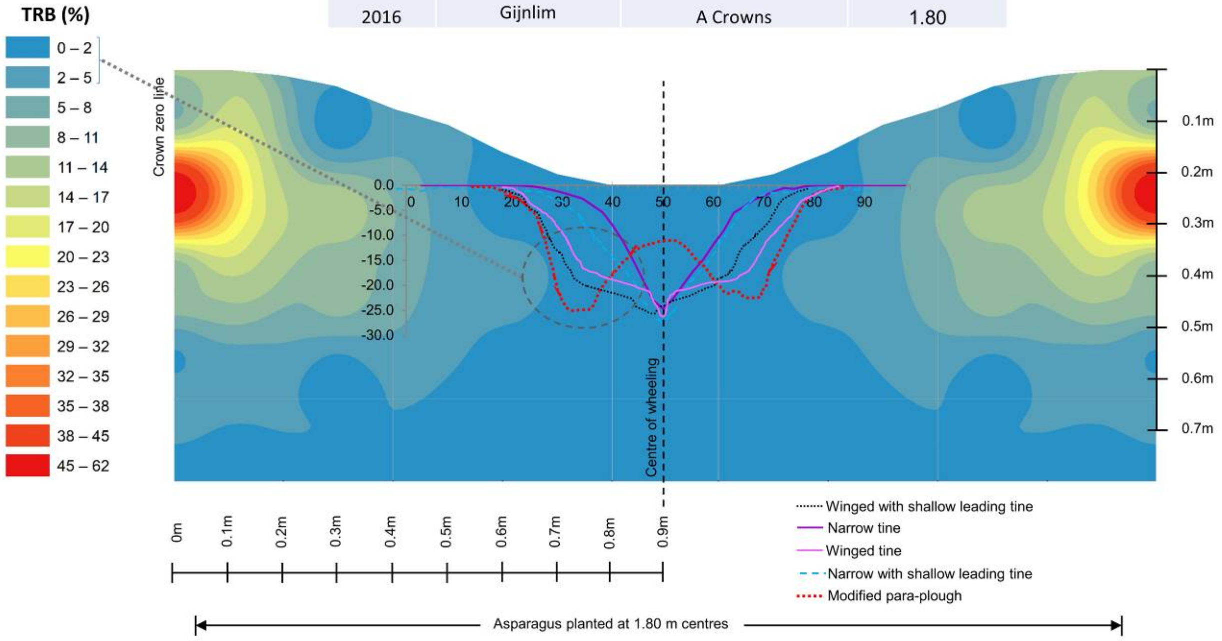
*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 38. Grower E total root biomass (TRB%) root map for 4yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower E Field 8

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	1.80



*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 39. Grower E total root biomass (TRB%) root map for 4yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

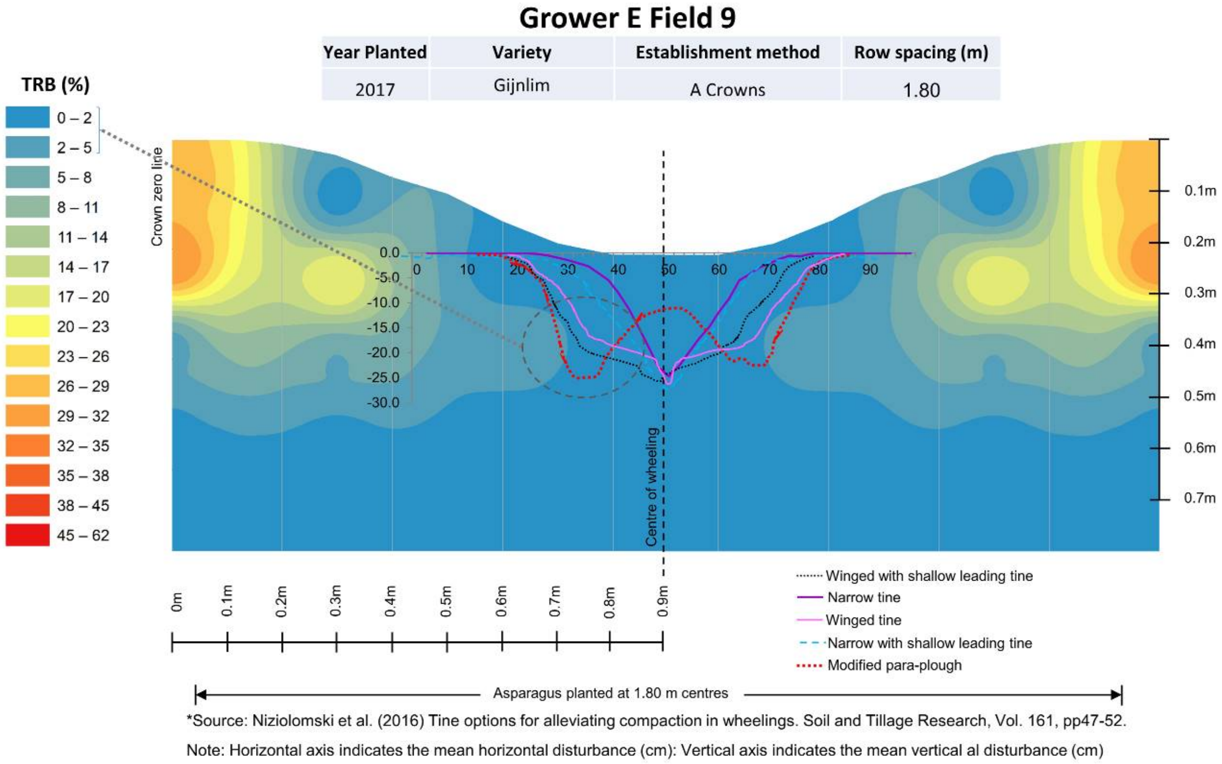


Figure 40. Grower E total root biomass (TRB%) root map for 3yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

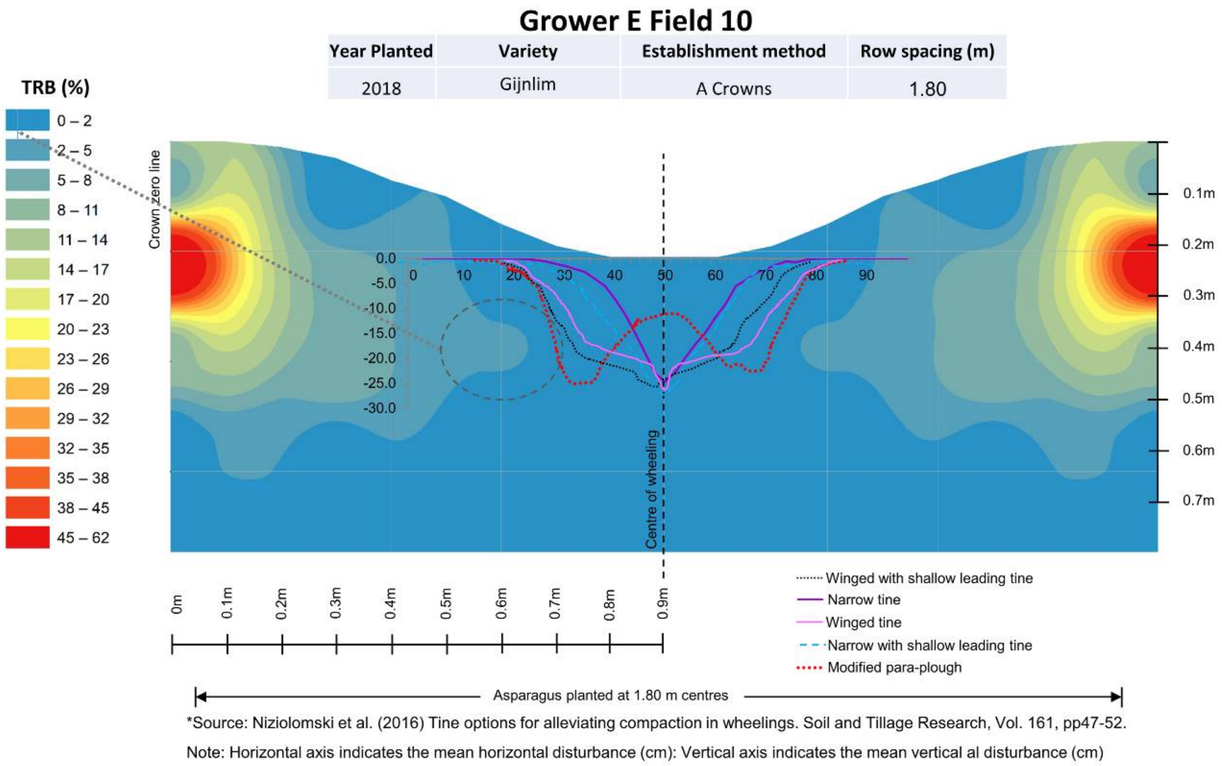


Figure 41. Grower E total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

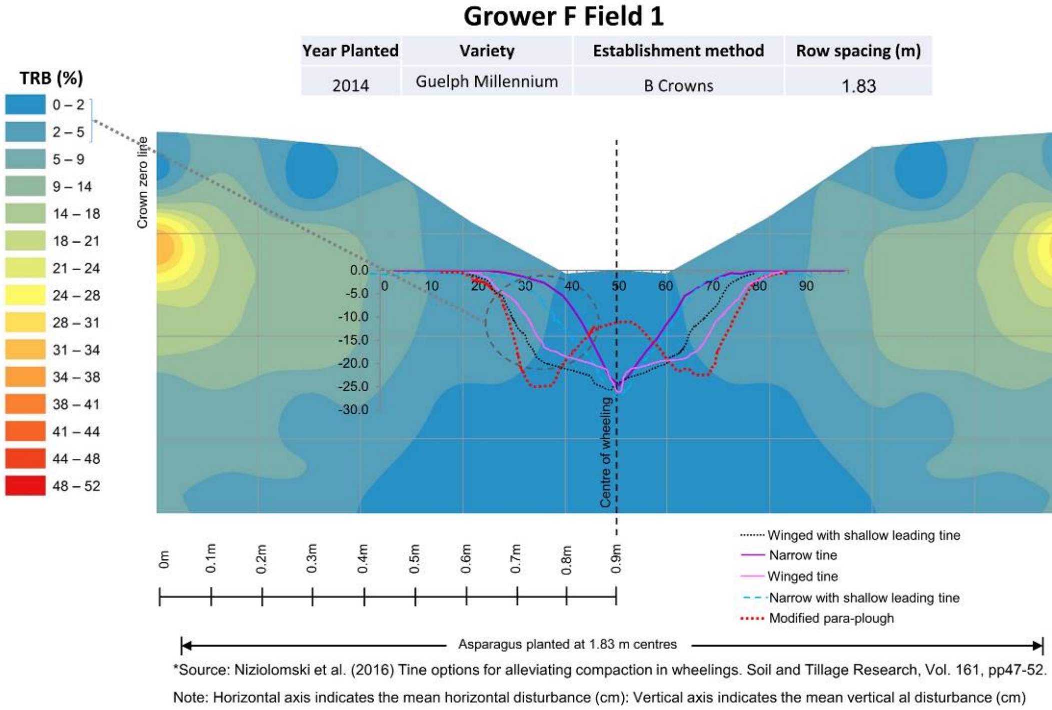


Figure 42. Grower F total root biomass (TRB%) root map for 5yr old Guelph Millennium B-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

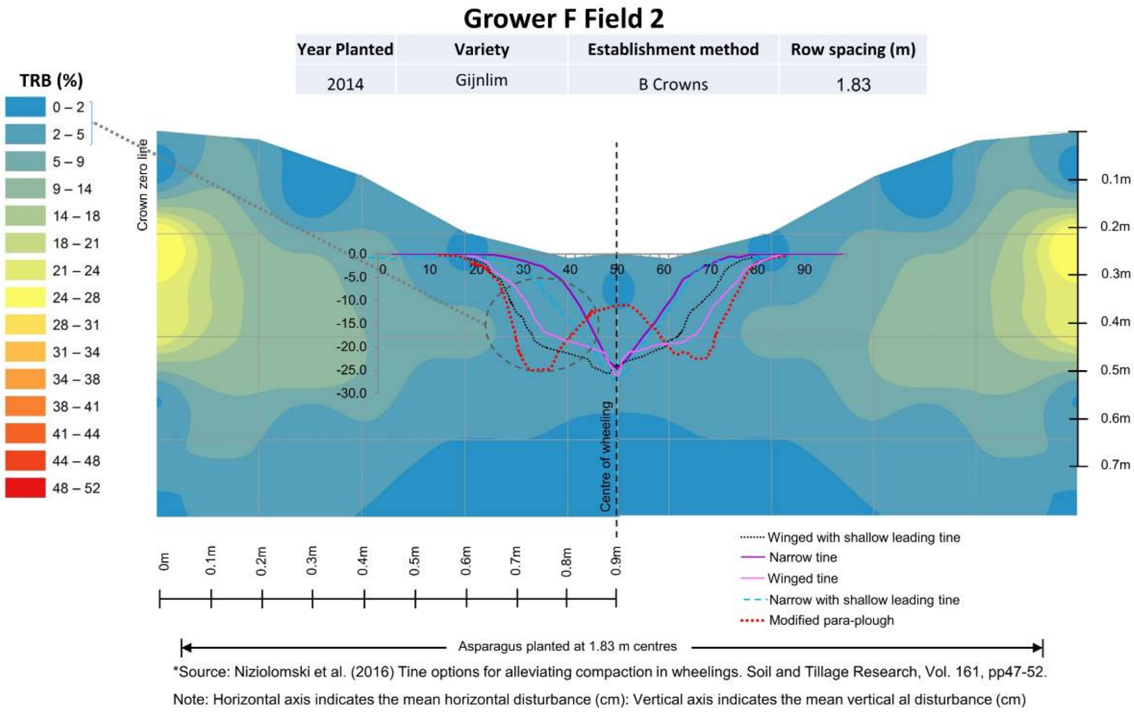


Figure 43. Grower F total root biomass (TRB%) root map for 5yr old Gijnlim B-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

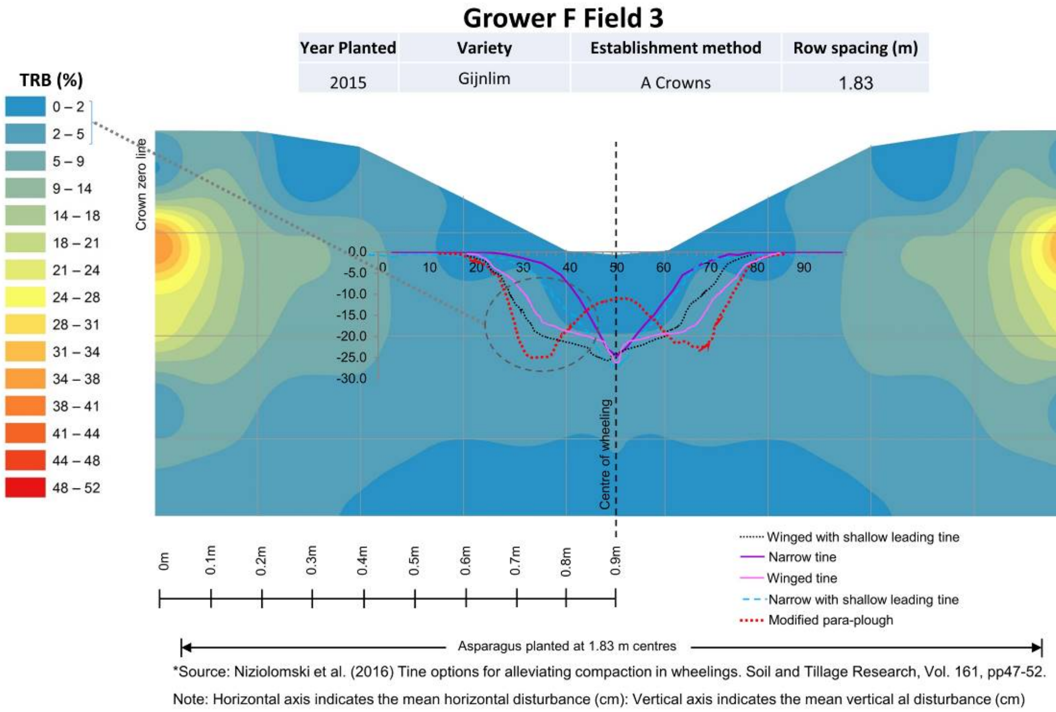


Figure 44. Grower F total root biomass (TRB%) root map for 4yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

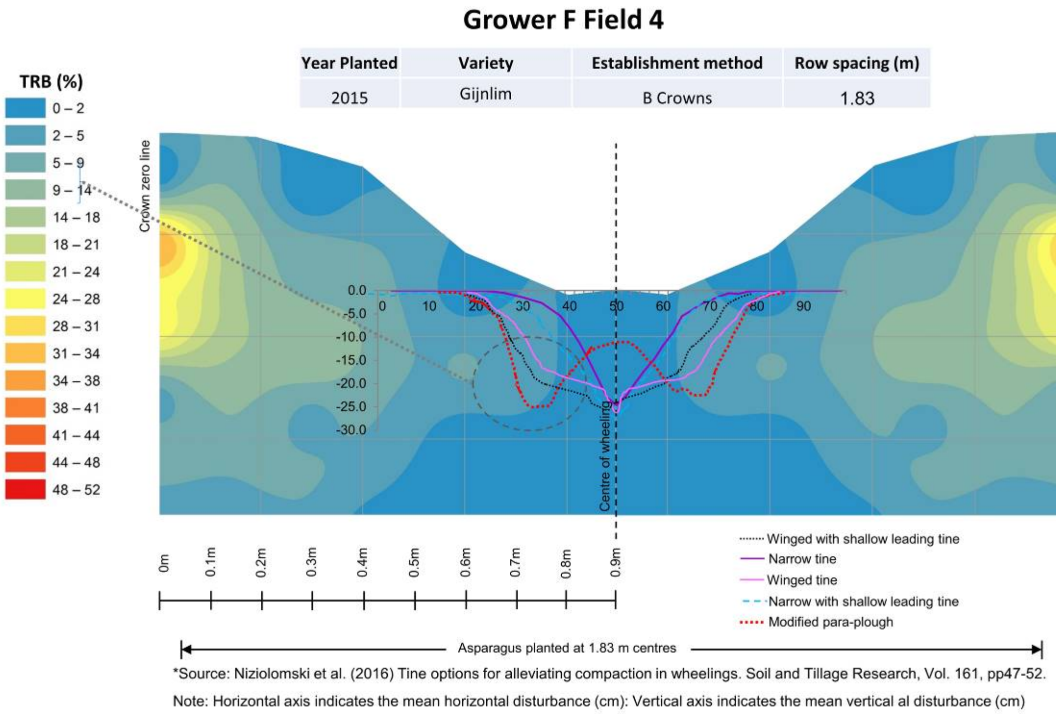


Figure 45. Grower F total root biomass (TRB%) root map for 4yr old Gijnlim B-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

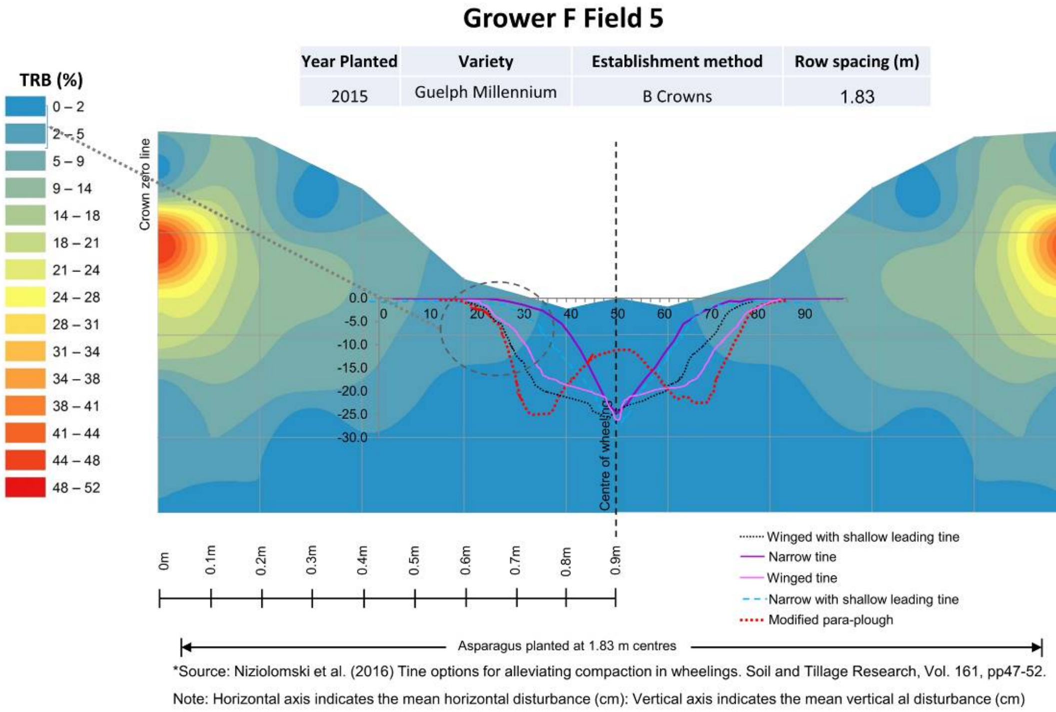


Figure 46. Grower F total root biomass (TRB%) root map for 4yr old Guelph Millennium B-crowns. Potential root damage associated with sub-soiling operations to 300mm depth.

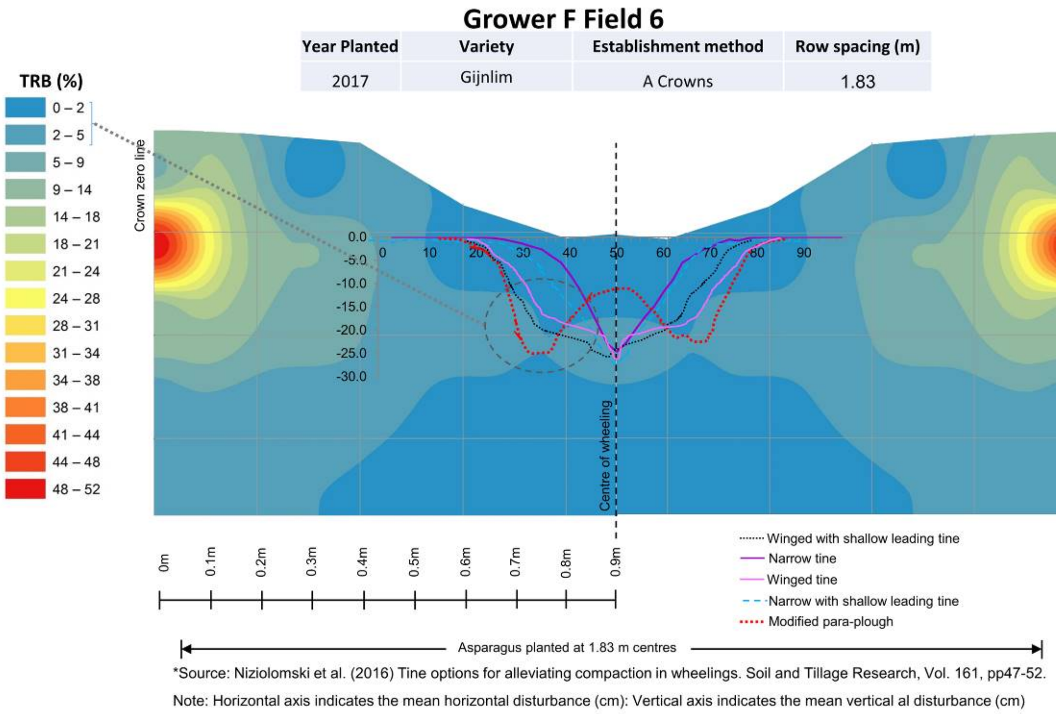


Figure 47. Grower F total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

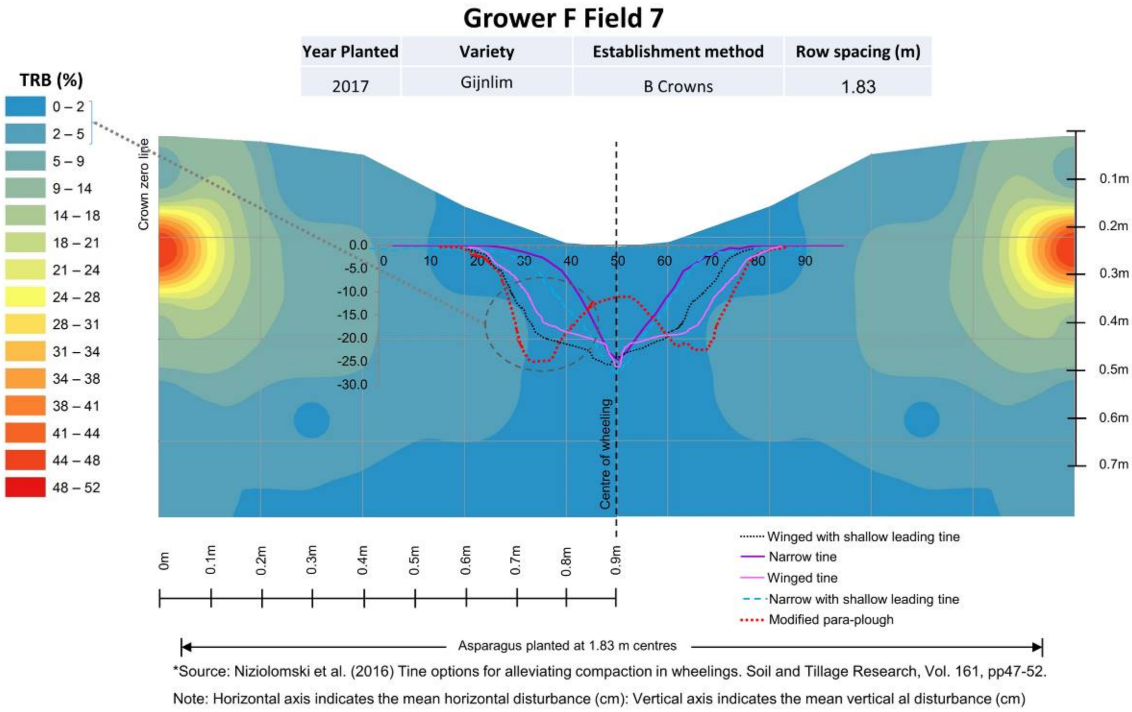


Figure 48. Grower F total root biomass (TRB%) root map for 2yr old Gijnlim B-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

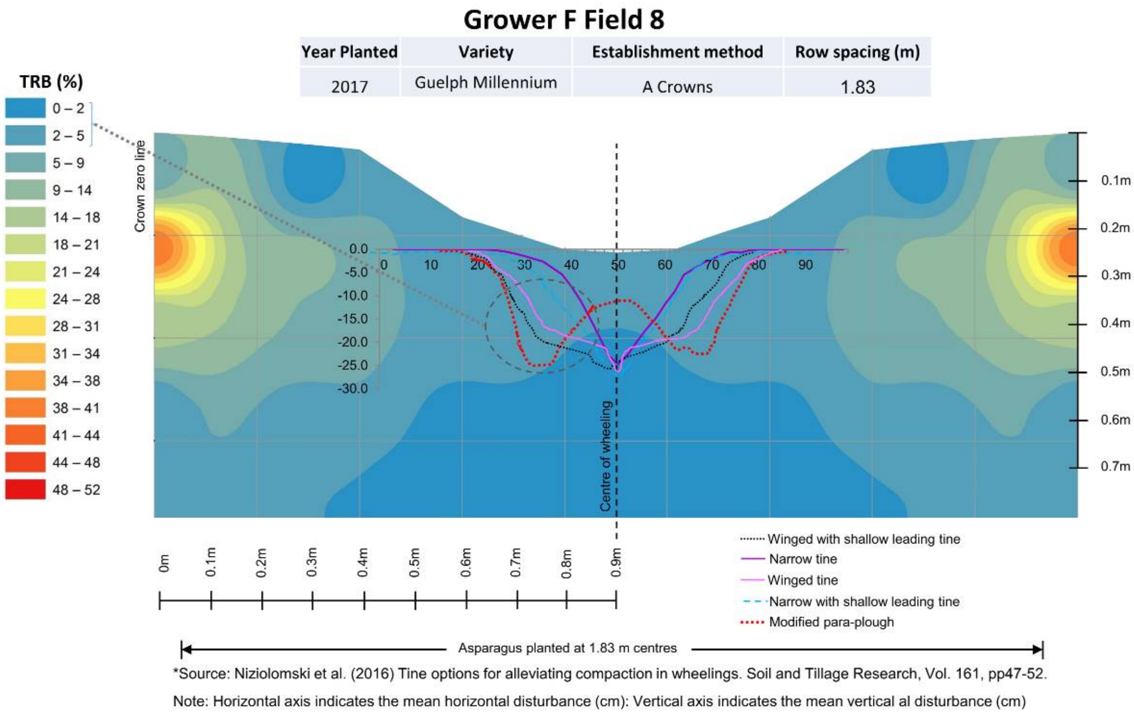


Figure 49. Grower F total root biomass (TRB%) root map for 2yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Appendix 2

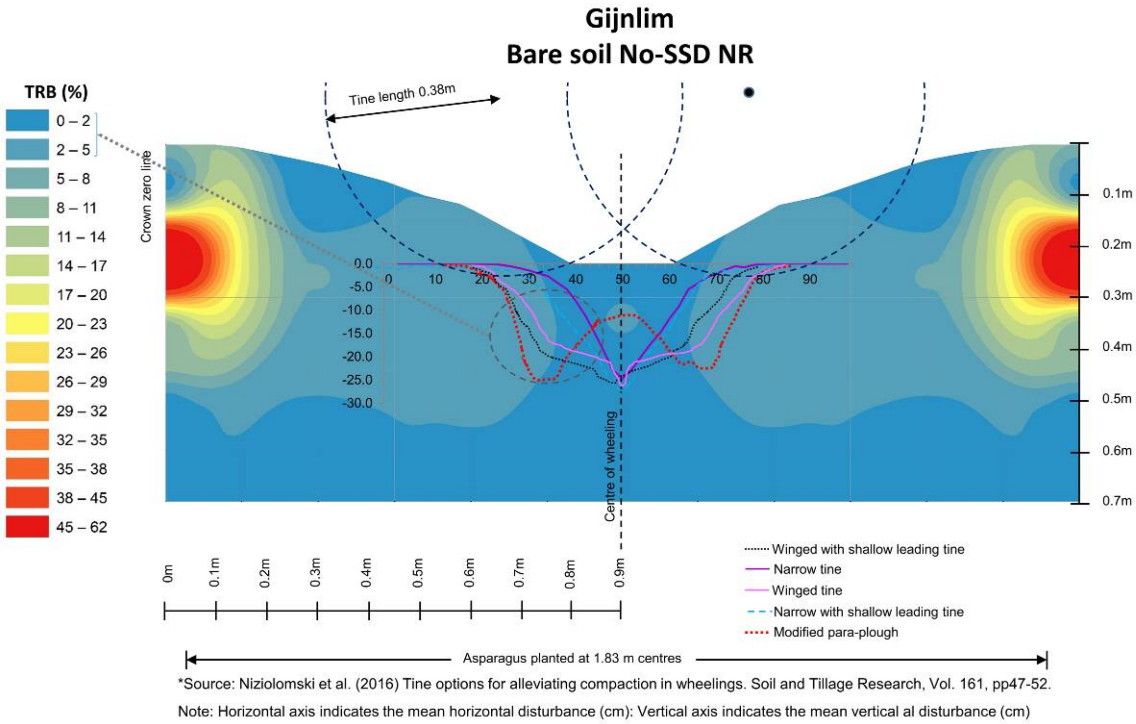


Figure 50. FV 450a trial total root biomass (TRB%) root map for Bare soil No-SSD NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

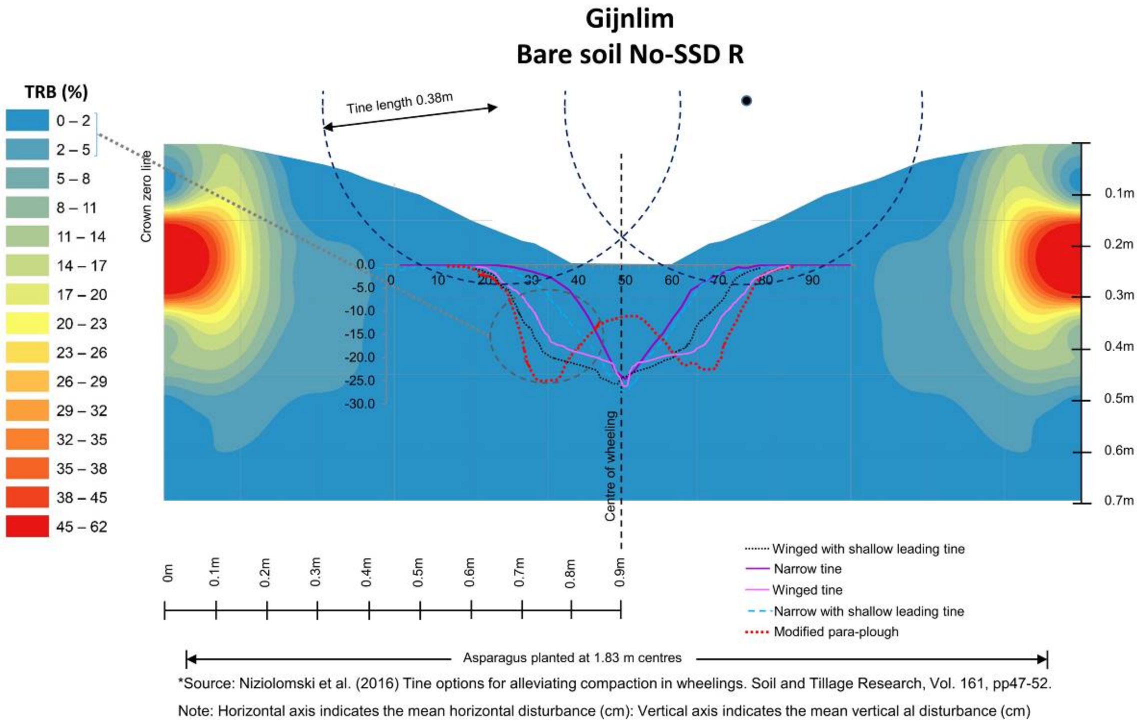


Figure 51. FV 450a trial total root biomass (TRB%) root map for Bare soil No-SSD R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

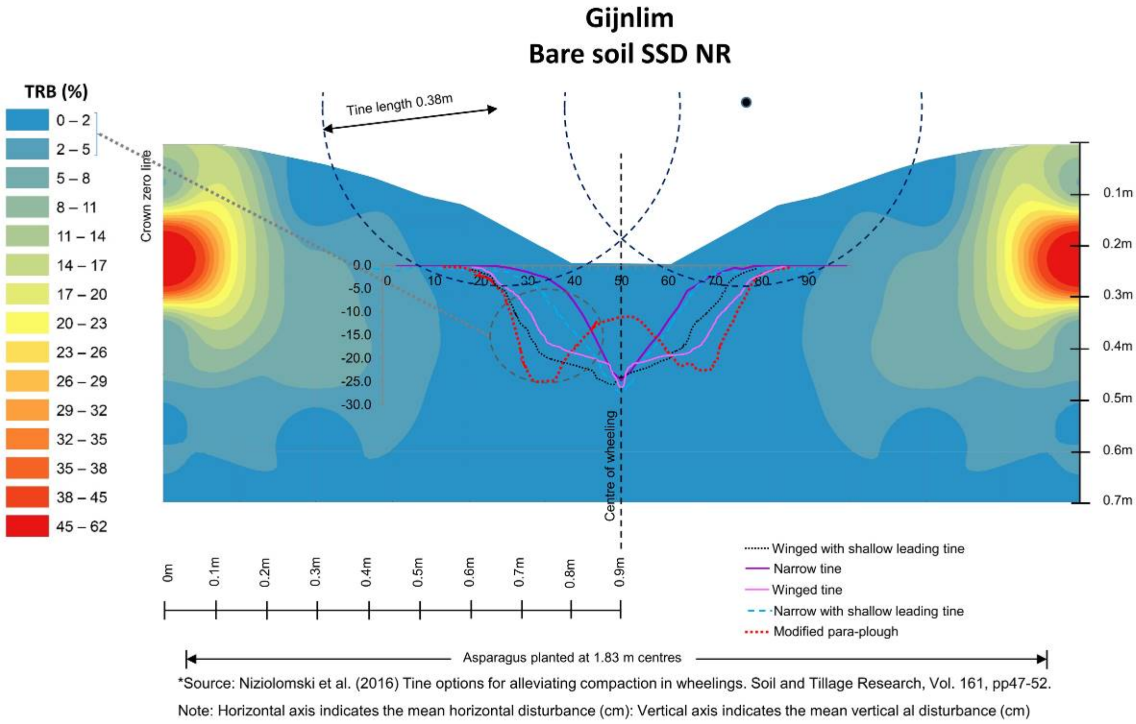


Figure 52. FV 450a trial total root biomass (TRB%) root map for Bare soil SSD NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

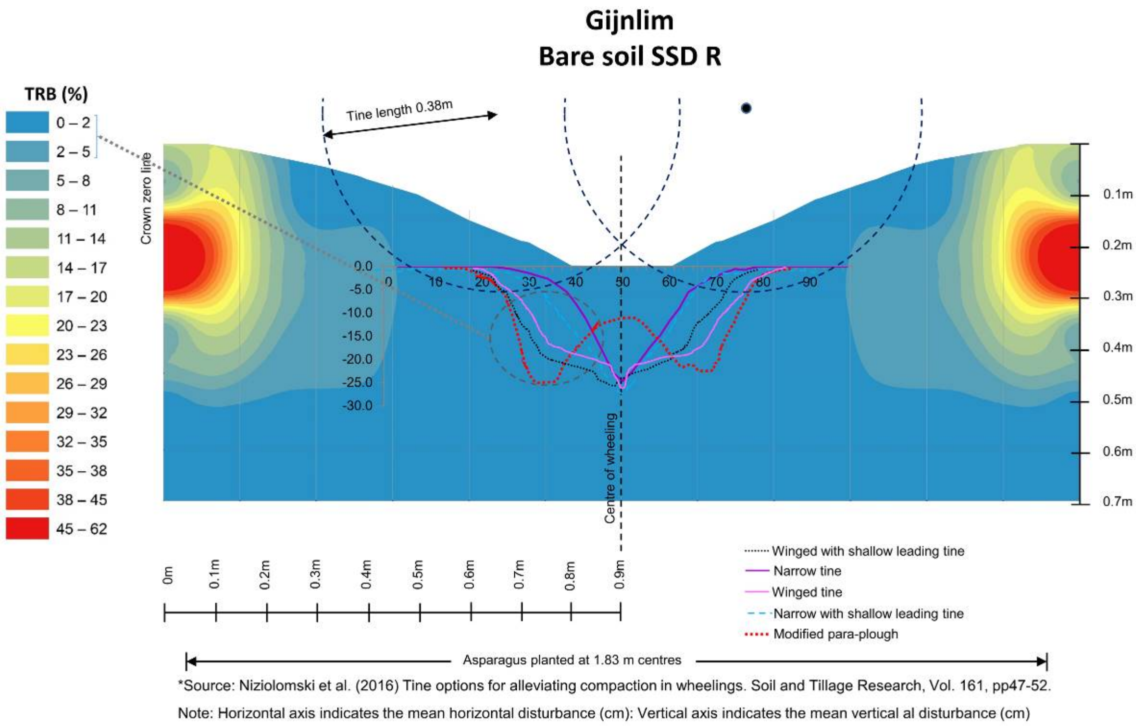


Figure 53. FV 450a trial total root biomass (TRB%) root map for Bare soil SSD R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

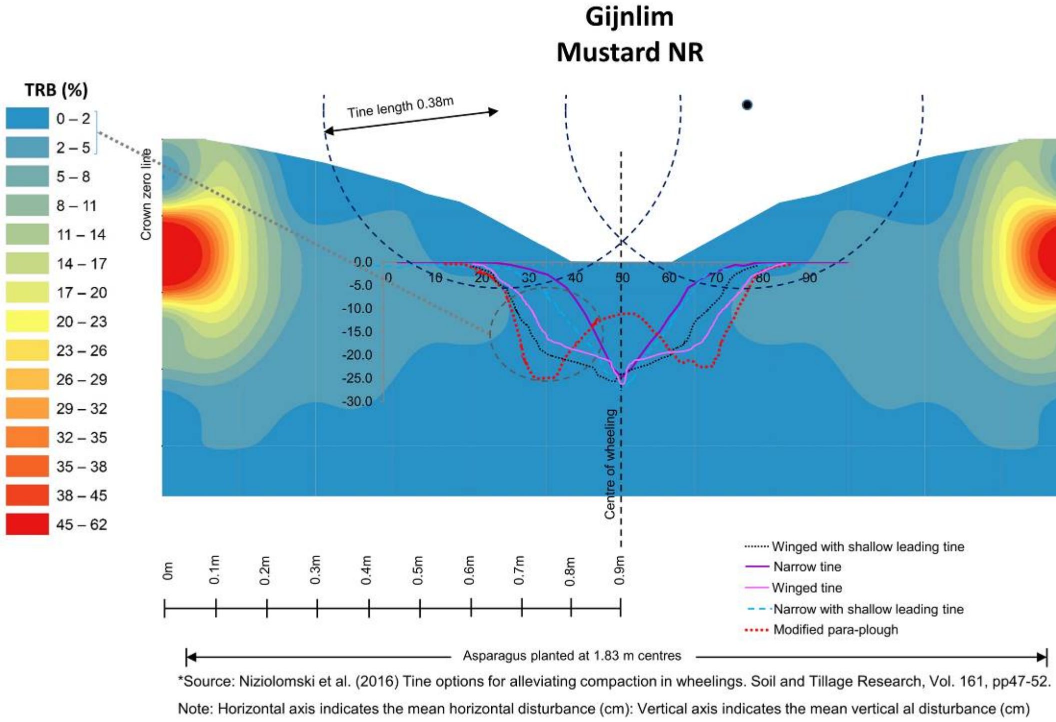


Figure 54. FV 450a trial total root biomass (TRB%) root map for Mustard NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

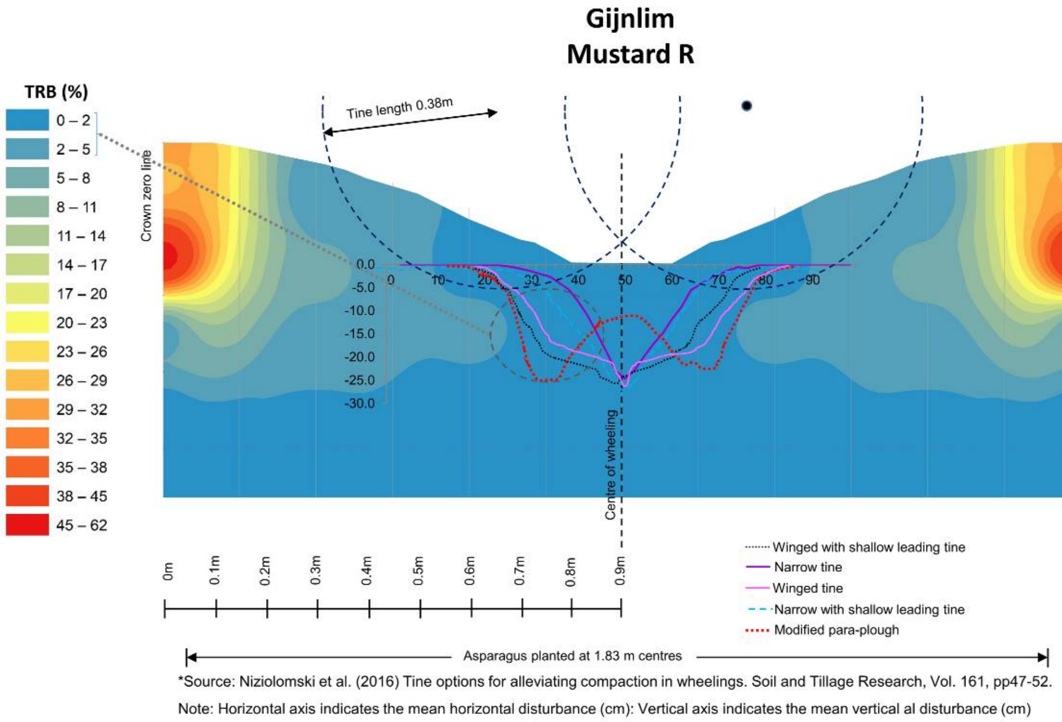


Figure 55. FV 450a trial total root biomass (TRB%) root map for Mustard R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

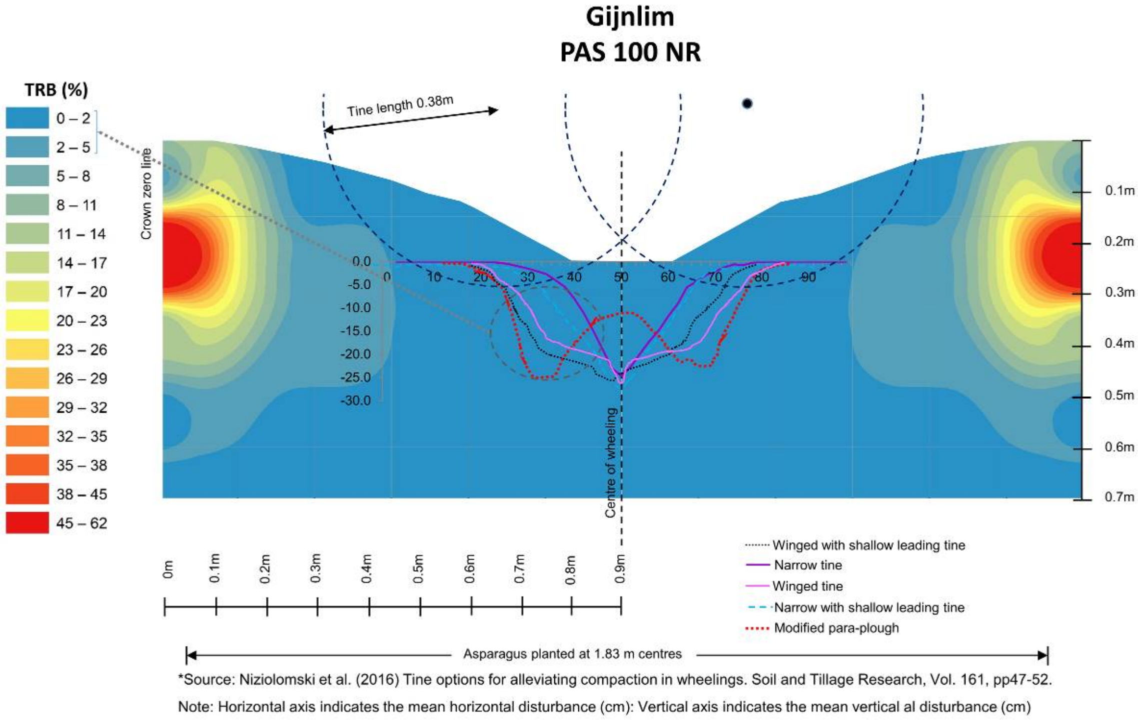


Figure 56. FV 450a trial total root biomass (TRB%) root map for PAS 100 NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

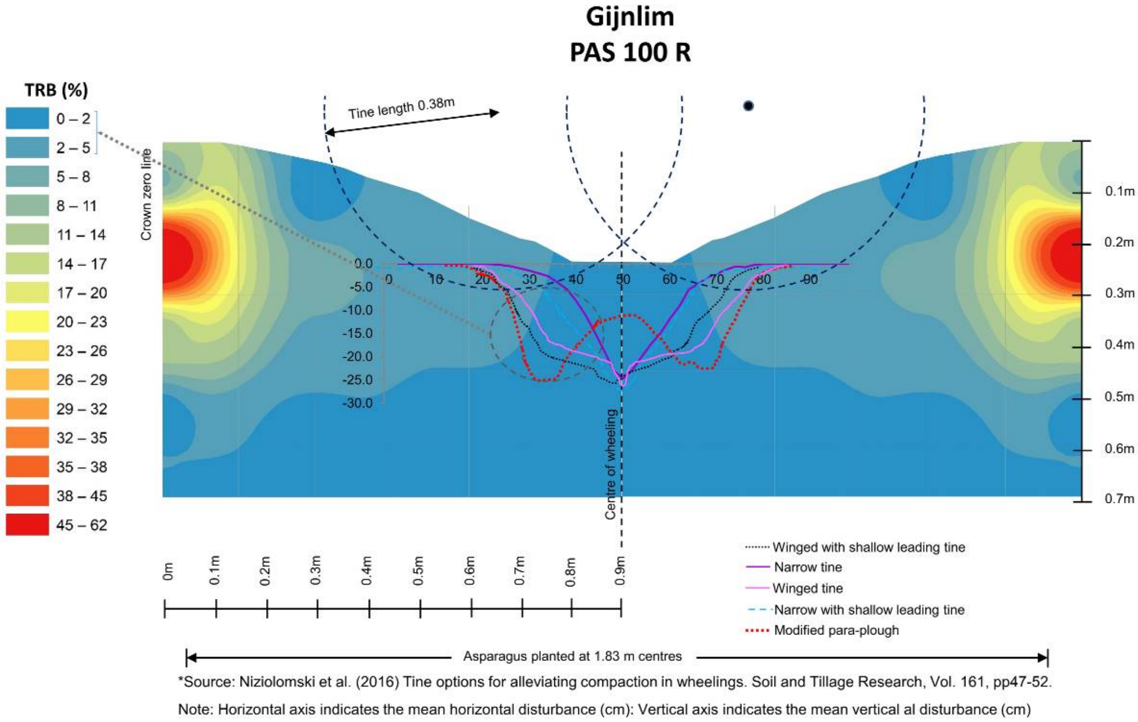


Figure 57. FV 450a trial total root biomass (TRB%) root map for PAS 100 R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

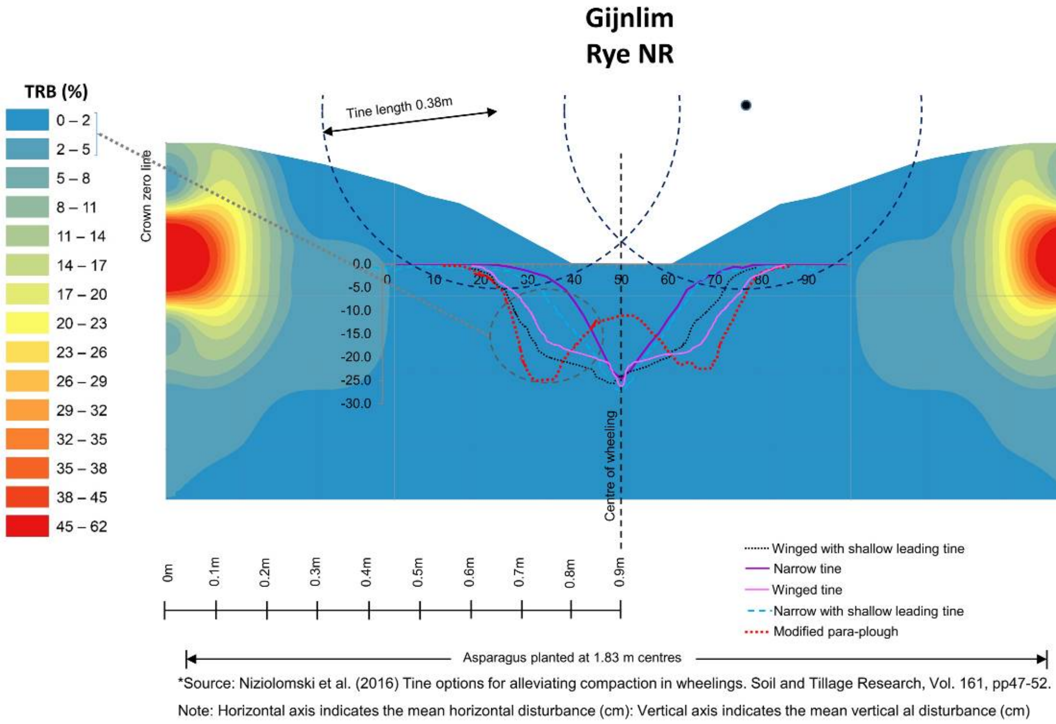


Figure 58. FV 450a trial total root biomass (TRB%) root map for Rye NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

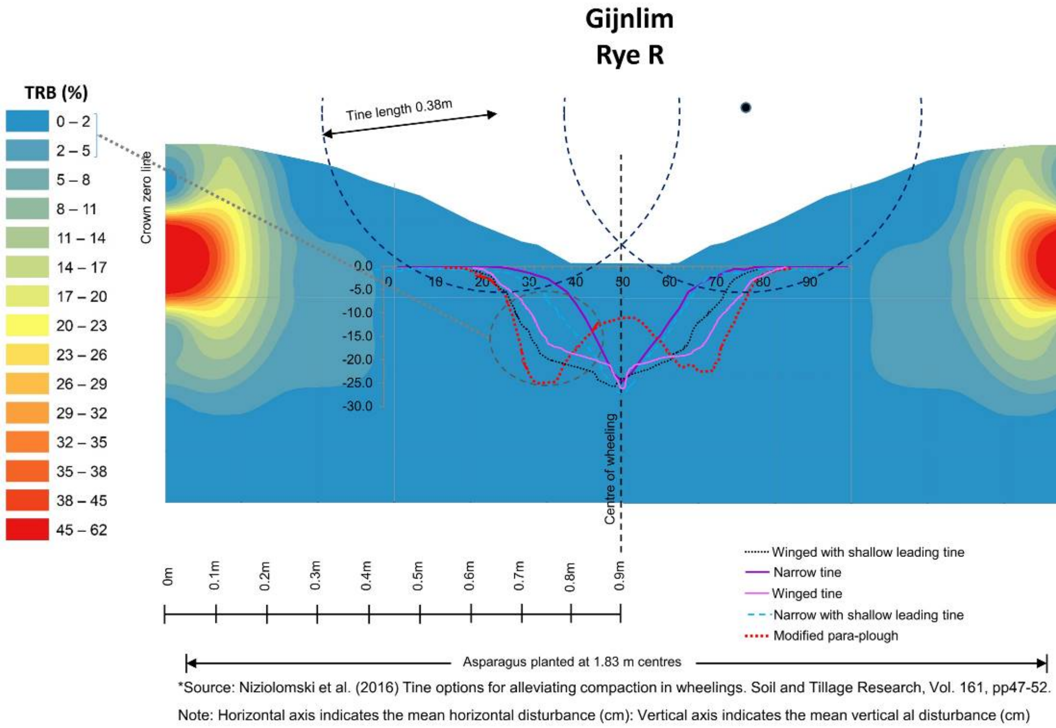


Figure 59. FV 450a trial total root biomass (TRB%) root map for Rye R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

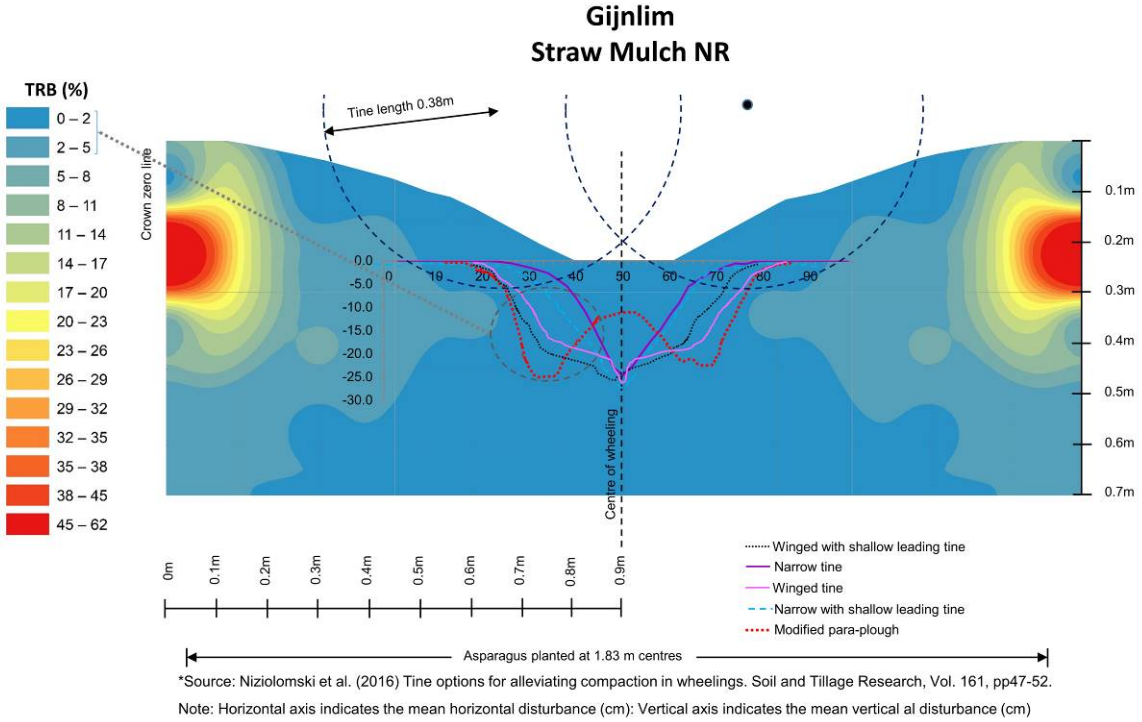


Figure 60. FV 450a trial total root biomass (TRB%) root map for Straw Mulch NR Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

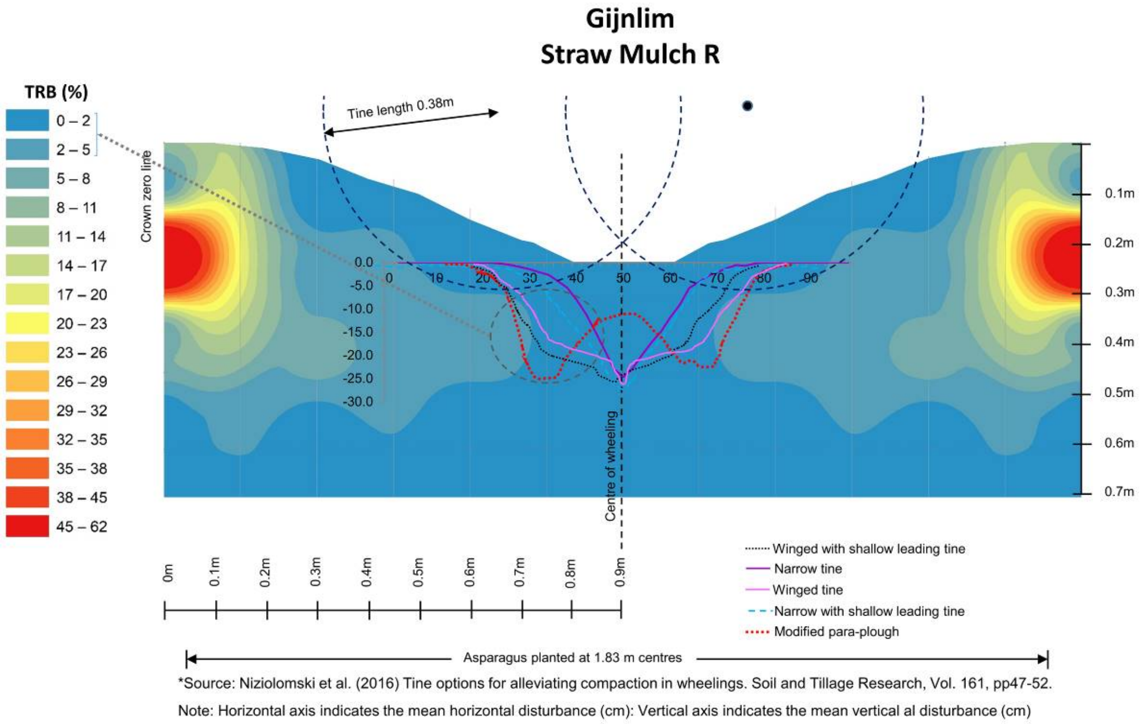


Figure 61. FV 450a trial total root biomass (TRB%) root map for Straw Mulch R Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

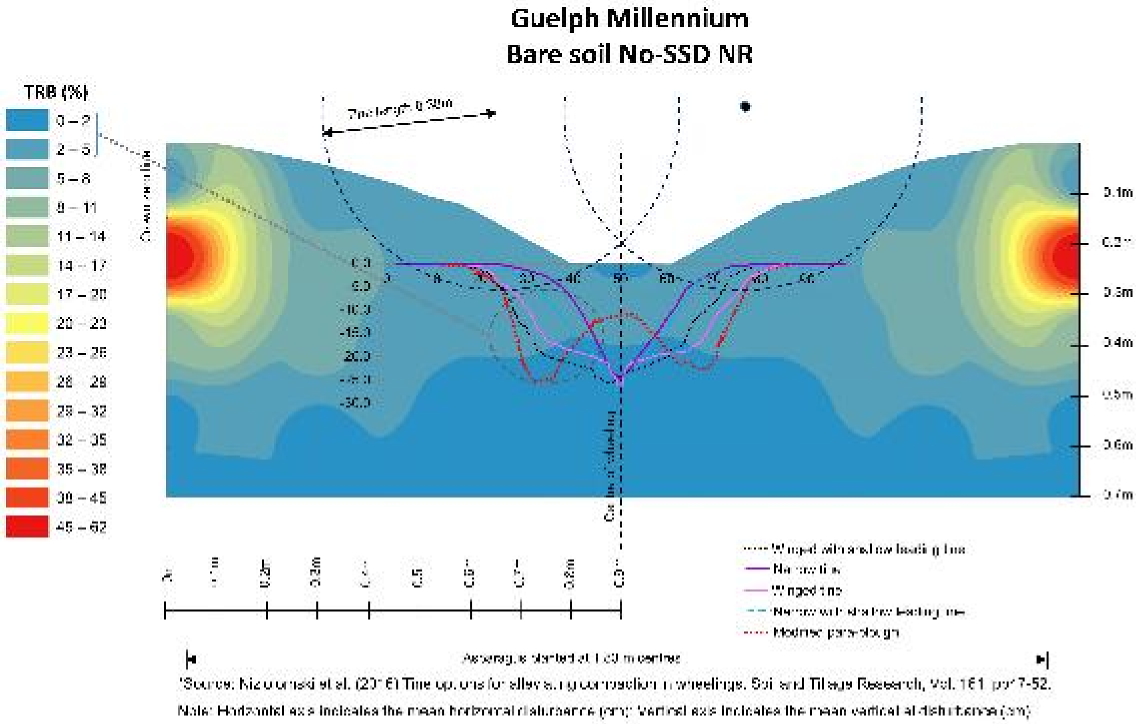


Figure 62. FV 450a trial total root biomass (TRB%) root map for Bare soil No-SSD NR Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

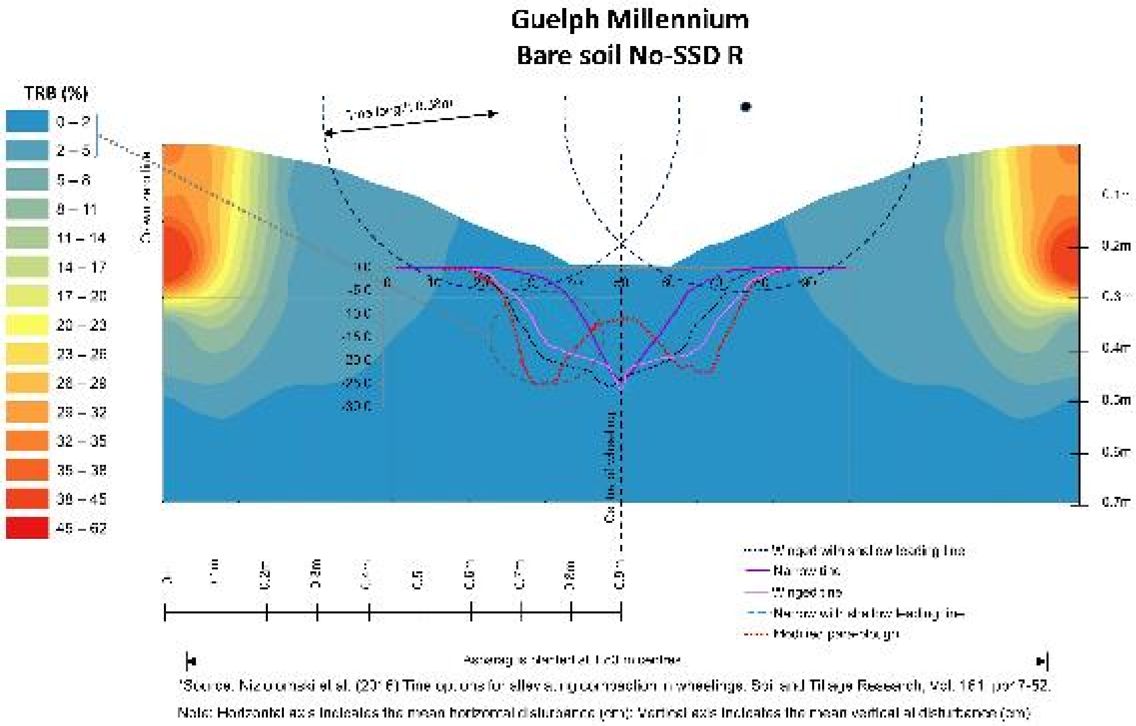


Figure 63. FV 450a trial total root biomass (TRB%) root map for Bare soil No-SSD R Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

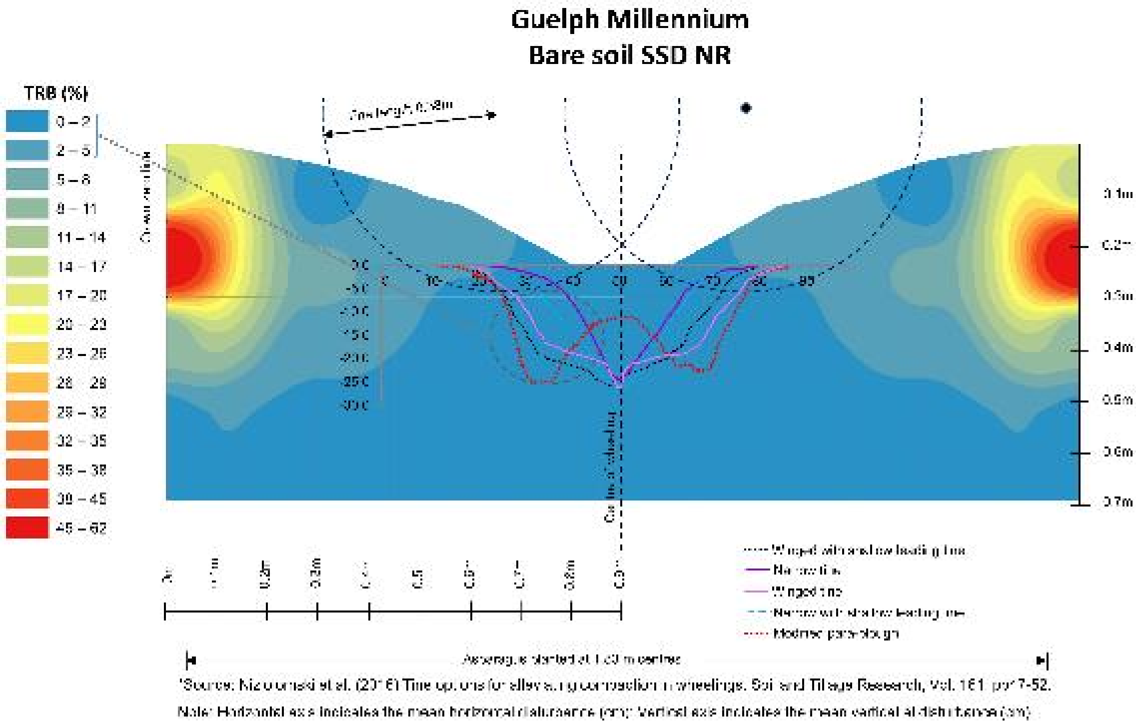


Figure 64. FV 450a trial total root biomass (TRB%) root map for Bare soil SSD NR Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

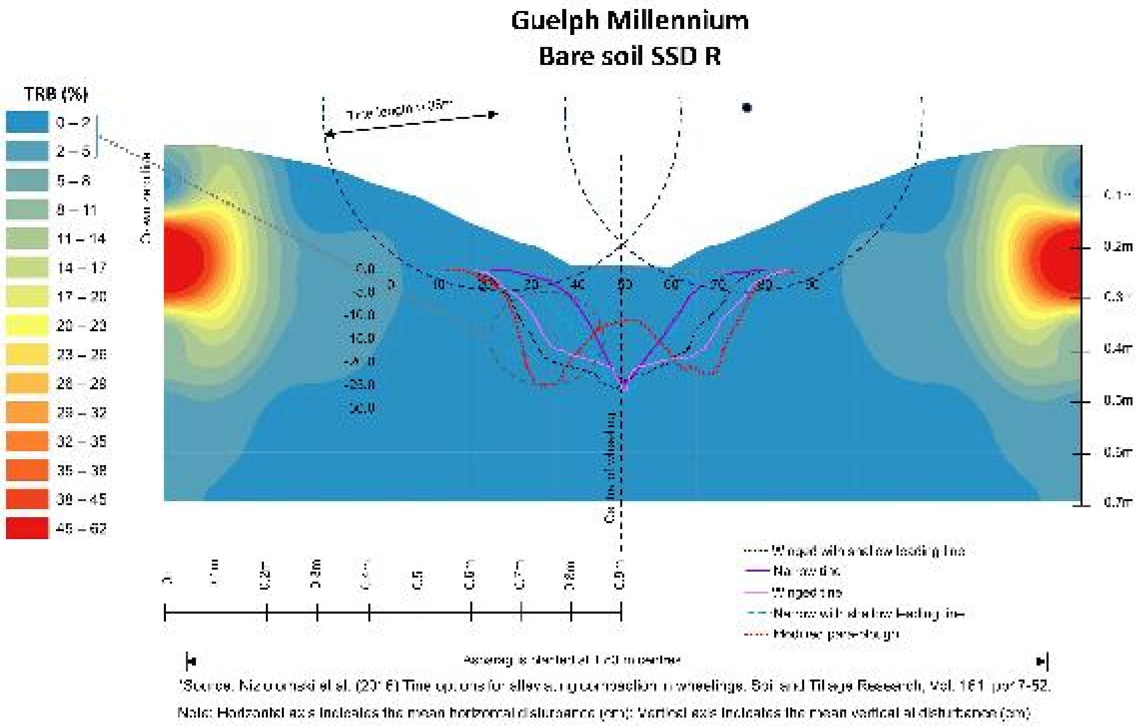


Figure 65. FV 450a trial total root biomass (TRB%) root map for Bare soil SSD R Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

43.

