Project title:	**Asparagus: Sustainable soil management for stand longevity and yield optimization**
Project number:	FV 450a
Project leader:	Dr Rob Simmons, Cranfield University
Report:	Annual Report, April 2019
Previous report:	Final Report FV 450, 2018
Key staff:	Dr Sarah De Baets and Lucie Maskova
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):	28/02/2021

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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

- In long-term field trials (planted 2016), there were no significant differences in pre-harvest asparagus root carbohydrate levels from different soil management treatments in 2019. Significantly higher root carbohydrate levels were observed for variety Gijnlim as compared with Guelph Millennium treatments.
- Findings from a survey of root architecture in UK asparagus fields showed that annual re-ridging has the potential to damage between 5-14% of the total root biomass annually, with implications for increased disease risk and reduced stand longevity.
- Using data from twelve asparagus fields, preliminary guidelines have been developed to relate sub-soiling operations with potential risk of root damage for different asparagus varieties, soil depths and row spacings.

Background

Conventional operations associated with UK asparagus production, i.e. tillage operations, such as ridging and sub-soiling, spray operations and harvesting, can result in progressive and severe compaction of all inter-bed wheelings. In addition, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and productivity, and increases the susceptibility to crown and root rots caused by *Phytophthora* and *Fusarium* species. Both root damage and crown and root rots significantly contribute 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, while 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 will evaluate 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 non-till 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 cropping practices.

Summary

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 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 full detail of the 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.

Experiment 1: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	Companion Crop - rye	R
Gijnlim	Companion Crop – rye	Non-R
Gijnlim	Companion Crop – mustard	R
Gijnlim	Companion Crop – mustard	Non-R
Gijnlim	PAS 100_SSD	R
Gijnlim	PAS 100_SSD	Non-R
Gijnlim	Straw Mulch_SSD	R
Gijnlim	Straw Mulch_SSD	Non-R
Gijnlim	Bare soil_SSD	R
Gijnlim	Bare soil_SSD	Non-R
Gijnlim	Bare soil_No-SSD	R
Gijnlim	Bare soil_No-SSD	Non-R

Annual re-ridging (R) or Zero-ridging (Non-R). 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	Non-R
Gijnlim	Bare soil_No-SSD	R
Gijnlim	Bare soil_No-SSD	Non-R
Millennium	Bare soil_SSD	R
Millennium	Bare soil_SSD	Non-R
Millennium	Bare soil_No-SSD	R
Millennium	Bare soil_No-SSD	Non-R

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

Mulch treatments

In April 2018, PAS 100 compost and straw were applied to three wheelings per treatment (central wheeling and guard rows) at a rate of 25 t ha^{-1} and 6 t ha^{-1}, respectively. Shallow soil disturbance (SSD) was applied using a winged tine. In 2019, the same mulch treatments were re-applied on 19th March 2019.

Shallow soil disturbance (SSD) treatments

In April 2018 SSD was applied using a winged tine at 0.25 - 0.3 m depth with occasional asparagus root damage observed behind the tine. In 2019, SSD treatments will be applied post-harvest in *circa* June.

Companion Crop treatments

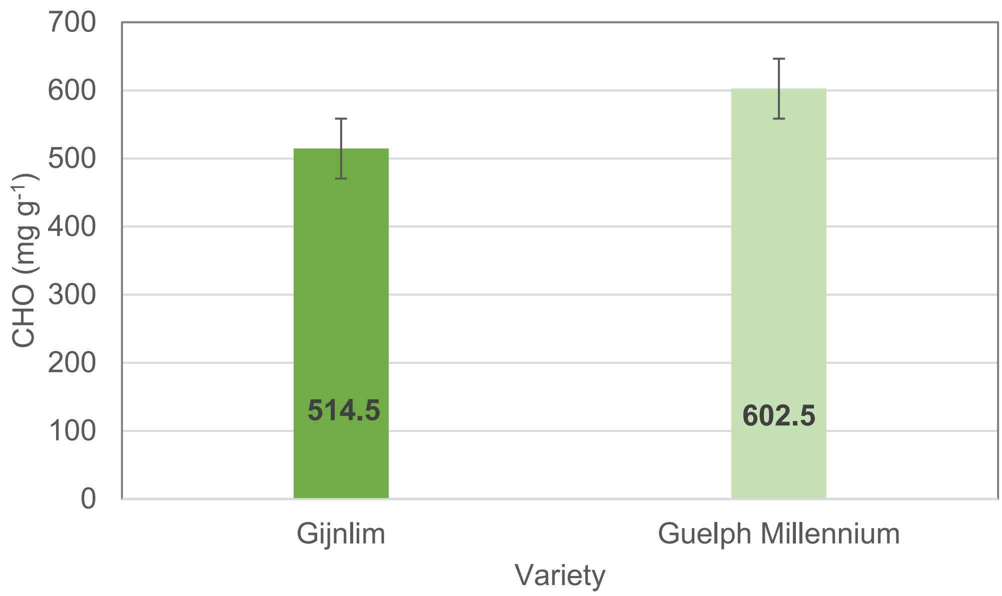
In August 2018, companion crops rye (*Cereale secale* L var. Protector) and mustard (*Sinapis alba* L. var. Severka).were sown at rates of 150 kg ha^{-1} and 19 kg ha^{-1}, respectively to three wheelings (central wheeling and guard rows). However, the dry summer of 2018 limited emergence and establishment of both companion crops. Consequently, they were re-applied in late September 2018. A field survey in November 2018 indicated spatially sporadic but good establishment in treated plots.

Annual re-ridging treatments

In 2018, re-ridging treatments were applied in April 2018. In 2019, re-ridging treatments were applied on the 15th of March 2019. In both 2018 and 2019 minor root damage was observed during re-ridging.

Impact of best management practices (BMPs) on root soluble carbohydrate (CHO) levels, 2019.

- No significant differences in asparagus storage root CHO (mg g^{-1}) were observed between treatments. Across all treatments mean pre-harvest storage root CHO values at the Crown Zero Line ranged from 507 – 631 mg g^{-1}. This is within the upper target range outlined from previous research, indicating adequate CHO levels for optimum harvest. Yield implications for the 2019 harvest will be reported in the next annual report.
- CHO values obtained from Guelph Millennium treatments at the 0.3 m distance from the crown were significantly ($p < 0.01$) higher as compared to the equivalent for Gijnlim with mean values of 514.5 and 602.5 mg g^{-1}, respectively. For Guelph Millennium, this exceeds the mean CHO values reported under FV 271 (AHDB, 2007) which were dominated by Gijnlim. The implications of this will be investigated under the PhD of Lucie Maskova.



Soil structure assessments

- The 2018 soil structural assessments indicate that significant differences in penetrative resistance (PR) are emerging between treatments. Specifically, at both 0-5 and 5-10 cm depth, the two companion crop treatments and the bare soil_No-SSD treatment, both ridged or non-ridged, were associated with significantly higher penetrative resistance (PR) as compared with 2016 baseline measurements. The implication of this is that the companion crop treatments are negatively affecting soil structure. However, no significant difference in bulk density (BD) in the mid-topsoil depth was observed between treatments and the 2016 Baseline. The higher PR values observed for the two companion crop treatments is likely to be due to lower soil moisture content.

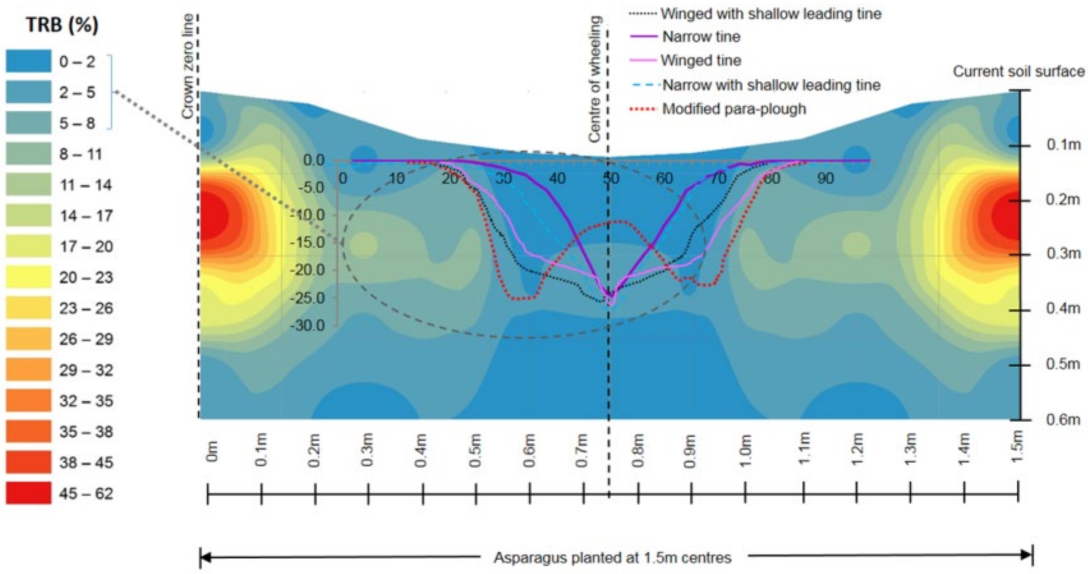
Wider Grower Landbank: *Potential impact of sub-soiling and ridging operations on root damage.*

In February 2018, an online questionnaire 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 a wider grower root architecture survey. A wide range of detailed information was gathered on cropping and soil management practices. The questionnaire was completed by 14 AGA members and included 187 fields (>1100 ha) with a geographical spread that covers Yorkshire, Warwickshire, Hampshire, Lincolnshire, Kent, Worcestershire, Suffolk, Oxfordshire, Shropshire, Norfolk, Gloucestershire and Herefordshire. To date a total of twelve fields have been sampled from three growers. A larger sampling campaign with the support of several growers will be undertaken in spring 2019.

- Across all row spacings, age of stand, varieties, and planting method sampled, annual re-ridging operations if undertaken within 0.3 – 0.4 m of the crown zero line to depths of 0.15 m have the potential to damage between 5-14% of the Total Root Biomass (TRB). This has significant implications with regards increasing the risk of crown and root rot caused by *Phytophthora* and *Fusarium* species. This has wider significance to CHO storage potential as it is truncating root length to <0.4m.
- For asparagus grown on 1.5-1.52 m row spacings, across all ages of stand, varieties, and planting method sampled, sub-soiling operations undertaken in the centre of the wheeling at 150 mm depth using a modified para-plough risk damaging up to 8-11% of TRB (See example below).

Grower A Field 5

Year Planted	Variety	Establishment method	Row spacing (m)
2013	Guelph Millennium	A Crowns	1.5



*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

- For asparagus grown on 1.5-1.52 m row spacings, across all ages of stand, varieties, and planting method sampled, sub-soiling operations undertaken in the centre of the wheeling at 150 mm depth using a winged with shallow leading tine, narrow tine, winged tine and narrow shallow leading tines of configurations investigated by Niziolomski et al. (2016) are in general associated with <2% damage to TRB.
- For asparagus grown on 2.0 m row spacings, for 2-year old Guelph Millennium and Gijnlim and 1-year old Mondeo planted as modules, sub-soiling operations can be undertaken in

the centre of the wheeling from 150-300 mm depth using the tines configurations investigated by Niziolomski et al. (2016) with the risk of damaging <2% damage to TRB.

- For Gijnlim planted as A-crowns, on 2.0 m row spacing, sub-soiling operations undertaken in the centre of the wheeling from 150-300 mm depth using the tines configurations investigated by Niziolomski et al. (2016) risk damaging 2-5% of TRB.

Financial Benefits

During 2005 – 2017 the area under asparagus cultivation in the UK increased from 890 – 2479 ha (>270%). In addition, during 2005 – 2015 British asparagus production during the traditional growing season (April-June) increased by >260% (2,050 t to 5,434 t). The ex-farm value of British asparagus in 2005 was circa £5.7 Million and in 2014, £27.6 Million. UK imports during the British season (April to June 2015) of 2,396 t, is valued at £8.4 million. Annual asparagus imports to the UK in 2014 amounted to 14,200 t, valued at £46.8 million. The potential for UK grown asparagus production to expand is significant.

However, 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 per annum. A 10% reduction in yield losses due to asparagus decline would amount to a saving of >£1.6M to UK asparagus growers per year. There would also be an improved ability of UK growers to meet customer (supermarket) demand during the British asparagus season.

Action Points

This is only the 3rd year of this long-term replicated field trial now continued under FV 450a. 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.

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. Further, 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) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2001; 2015) which leads to yield decline and direct economic losses to the grower. In the UK, the effect of annual re-ridging on asparagus root architectural development, root damage and the impact that this has on stand longevity is unknown.

Compaction of wheelings leads to a significant reduction in infiltration resulting in an increased risk of surface water ponding and on sloping land, runoff generation and erosion. In turn surface water ponding and/or erosion compromises field operations impacting on both foot and vehicular traffic. In addition, water ponding in furrows increases the risk of crown and root rot. Research undertaken by Cranfield University in collaboration with Cobrey Farms to *Optimise soil disturbance and mulch attenuation for erosion and runoff control in row crops* demonstrated that shallow soil disturbance (SSD) in association with straw or PAS 100 compost application reduces runoff and erosion by >80% (Niziolomski 2011, 2015).

However, the 3D root profile architecture of UK asparagus varieties is unknown. Consequently, potential root damage associated with the use of SSD to control runoff and erosion has not been assessed.

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, 2010; 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 et al. 2010). These biota improve the architecture of the soil by mechanisms including adhesion, kinetic restructuring and filamentous binding (Miransari, 2014). Residues from the aboveground plant parts, if deposited to the soil, also provide an energy-rich substrate which can be utilised by the biota to drive structural genesis. Further the role of crop canopies, stems and root architecture to reduce soil erosion are well documented (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 as well as to increase harvested yield (Wilcox-Lee & Drost 1991). To date cover/companion crops have not been adopted within UK asparagus systems.

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. The extent to which wheeling compaction dictates 3D asparagus root architecture and root profile distribution is currently under-researched and will be assessed under Experiments 1 and 2 (Objective 2 and 4).

Reduced tillage describes a continuum of tillage practices which minimise the mechanical disruption to physical, biological and chemical soil properties, whilst producing a viable seedbed favourable to crop establishment, development and high marketable yields (Bhaskar et al., 2014; Holland, 2004; Morris et al., 2010; Soane et al., 2012).

A better structured soil requires less draught to cultivate it (associated with reduction in fuel requirements, number of tractor hours and passes to prepare and size of tractor and implements). Conventional practice is to re-ridge asparagus beds annually. This has fuel and hence economic implications to the grower.

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 would have profound implications to the longevity and profitability of UK asparagus stands. This project will investigate the implications of annual re-ridging vs zero tillage on soil compaction and structural status and more specifically, on the efficacy of the Best Management Practices (BMPs) investigated in the study on Key Performance Indicators (KPIs).

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	Non-R
Gijnlim	Companion Crop – mustard	R
Gijnlim	Companion Crop – mustard	Non-R
Gijnlim	PAS 100_SSD	R
Gijnlim	PAS 100_SSD	Non-R
Gijnlim	Straw Mulch_SSD	R
Gijnlim	Straw Mulch_SSD	Non-R
Gijnlim	Bare soil_SSD	R
Gijnlim	Bare soil_SSD	Non-R
Gijnlim	Bare soil_No SSD	R
Gijnlim	Bare soil_No SSD	Non-R

Annual re-ridging (R) or Zero-ridging (Non-R). 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 (Non-R) (Table 2).

Table 2: Experiment 2: Treatment descriptions

Variety	Treatment description	Re-ridging
Gijnlim	Bare soil_SSD	R
Gijnlim	Bare soil_SSD	Non-R
Gijnlim	Bare soil_No-SSD	R
Gijnlim	Bare soil_No-SSD	Non-R
Millennium	Bare soil_SSD	R
Millennium	Bare soil_SSD	Non-R
Millennium	Bare soil_No-SSD	R
Millennium	Bare soil_No-SSD	Non-R

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

Mulch treatments

In 2018, mulch treatments were applied on 20th April 2018. PAS 100 compost was applied to three wheelings per treatment (central wheeling and guard rows) at a rate of 25 t ha^{-1}. Straw was applied to three wheelings per treatment (central wheeling and guard rows) at 6 t ha^{-1}. Further, SSD was applied using a winged tine.

In 2019, mulch treatments were applied (by Cobrey Farms team) on 19th March 2019. PAS 100 compost was applied to three wheelings per treatment (central wheeling and guard rows) at a rate of 25 t ha^{-1}. Straw was applied to three wheelings per treatment (central wheeling and guard rows) at 6 t ha^{-1}.

Shallow soil disturbance (SSD) treatments

Shallow soil disturbance (SSD) was applied on 20th April 2018 using a winged tine (Niziolomski et al., 2016) at 0.25 - 0.3 m depth with occasional asparagus root damage observed behind the tine. Shallow soil disturbance is included in those treatments to which mulch (PAS 100 compost or straw) was applied. The principle behind this is that the mulch-SSD treatments are intended to replicate the cover (mulch) and 'bio-drilling' (tillage-SSD) associated with the companion crops. In 2019, SSD treatments will be applied post-harvest in *circa* June (as agreed by PAG 13th February, 2019).

Companion Crop treatments

Companion crops included in this trial were rye (*Cereale secale* L var. Protector) and mustard (*Sinapis alba* L. var. Severka). In 2017, these 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.

Annual re-ridging treatments

In 2018, re-ridging treatments were applied in April 2018. In 2019, re-ridging treatments were applied on the 15th of March 2019. In both 2018 and 2019 minor root damage was observed during re-ridging.

Soil structural assessments:

Metrics to assess changes in soil structure between treatments included Penetrative resistance (PR), Bulk density (BD), Visual Evaluation of Soil Structure (VESS) and Infiltration Rate (IR). Baseline sampling took place in April 2016. The 2018 assessment was carried out between the 19th to 22nd of June 2018 within the central wheeling of two randomly selected plots per treatment. 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 0.03m depth x 0.05m internal diameter and further processed to obtain Loss on Ignition (Schulte, et al., 1991; Arshad MA et al., 1996). Infiltration was sampled using a single 0.12 m diameter PVC cylinder and classified following the Cranfield Methodology. The VESS was appraised from 0 to 0.3 m depth, using the BSSS standard (Guimares, 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 1). For fields sampled from the wider grower landbank, this spacing will vary as a function of wheeling centres (Figures 2 and 3). 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.

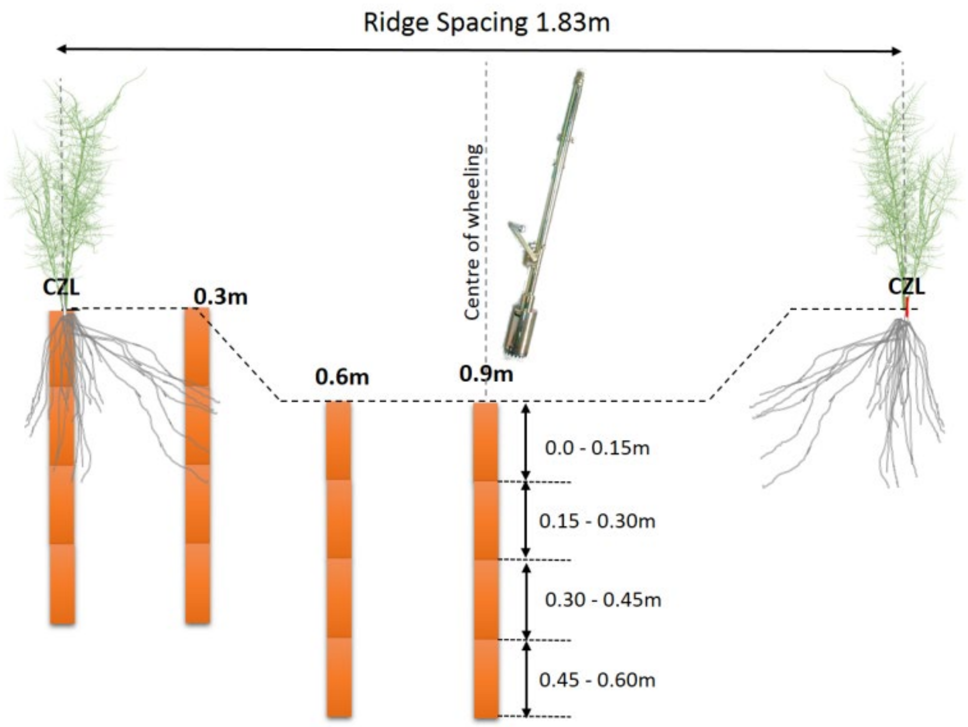


Figure 1. Root coring protocol adopted at the FV 450/FV 450a trial site.

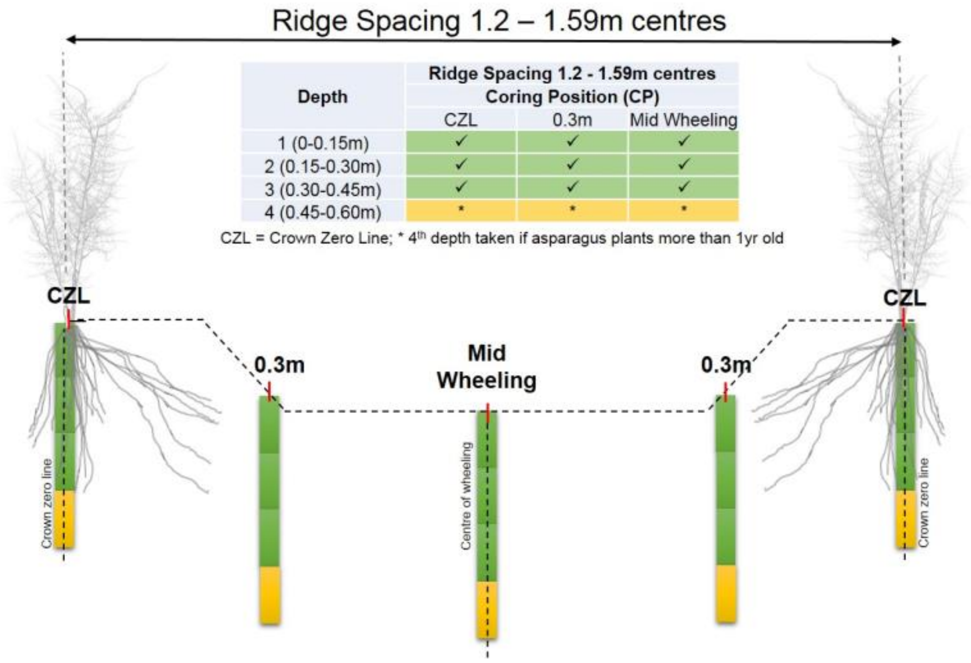


Figure 2: Root coring positions for asparagus cultivated on ridges with 1.2 – 1.59 m centres

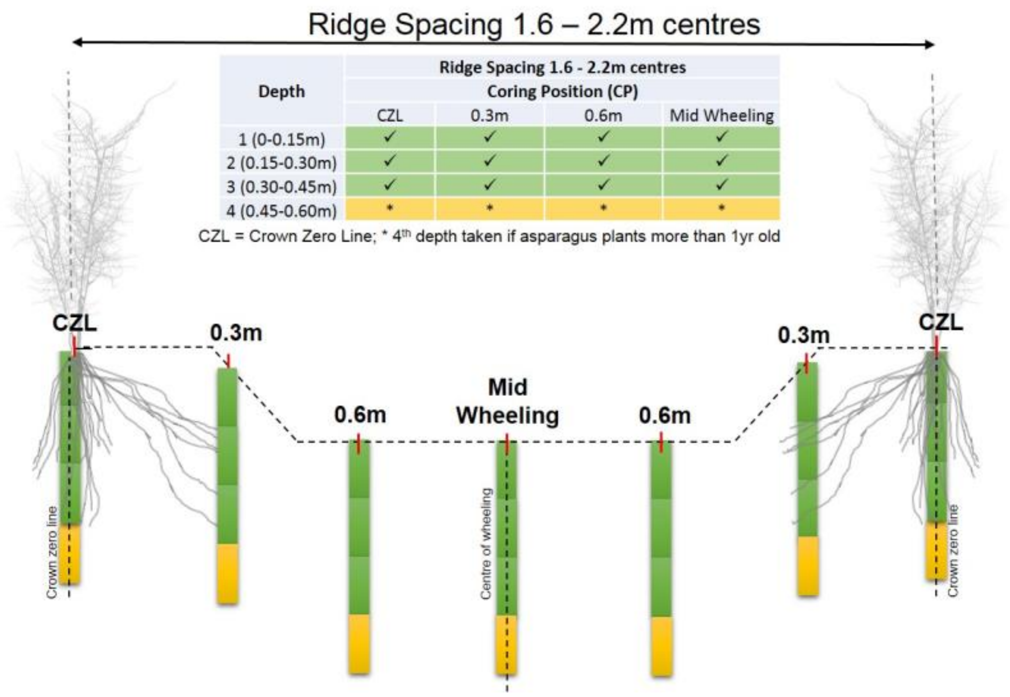


Figure 3: Root coring positions for asparagus cultivated on ridges with 1.6 – 2.2 m centres

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).

Image capture and preparation of Rootsnap interpolation maps

To map the spatial distribution of roots, root mass density (RMD), root length density (RLD) or Root Biomass as a percentage of total root biomass (TRB%) can be used. To assess RLD, roots are imaged per sample and analysed for total root length using RootSnap software (CID Bio-Science) to generate root length density (RLD) information. In RootSnap, roots are digitized used a touch screen technology and by setting the size of the image, root length is then automatically generated for each image. RLD is calculated as follows: RLD= RL /V, where RL (km) is total length of the roots in a sample and V (m^3) is the volume of the root core (m^3).

All root core samples are then 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 RLD. These x, y, z values are then used to construct interpolated root mass/length density maps in ARC-GIS using a geo-statistical technique called Krigging (Figure 4).

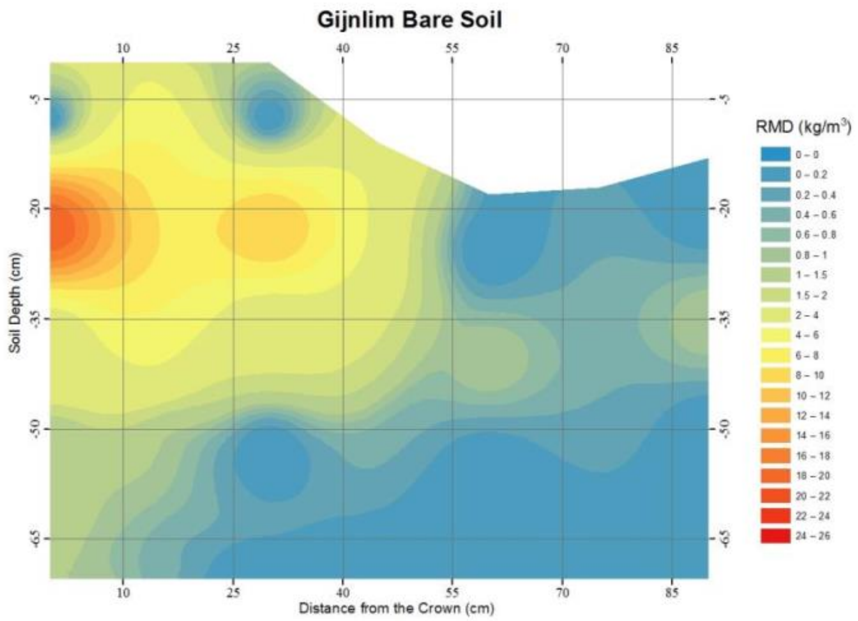


Figure 4. Interpolated root mass density (RMD) map generated in ARC-GIS using the Krigging geo-statistical technique.

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 5).

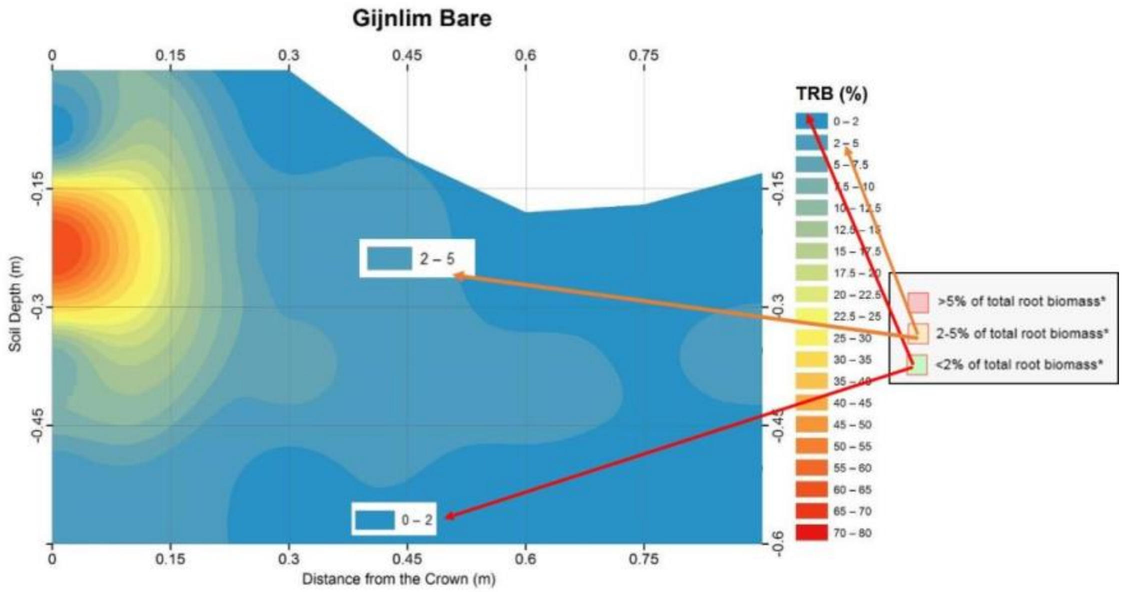


Figure 5. Interpolated total plant root biomass (TRB%) map generated in ARC-GIS using the Krigging geo-statistical technique.

Crop performance indicators

It is important to critically evaluate the effect of BMPs on root architecture as well as root carbohydrate (CHO) content (pre-harvest) and yield and crop performance. It is envisaged that several of those crop performance indicators measured in FV 271 will be adopted in this study. For the FV 450/FV 450a trials plots these will include Harvest length (days), yield per cut (kg $plot^{-1}$), yield per plot (kg), spears count per plot and spear weight. Root CHO will also be determined. As with FV 271, participating growers will be ask to record this data.

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. For the 2019 harvest, it is envisage that *Stemphylium* and *Phytopthora* will be monitored during the spear stage through an assessment of harvested yield. During the fern stage, the incidence of ferns exhibiting symptoms of *Stemphylium*, *Fusarium* and *Phytophthora* will be recorded.

Quantifying the efficacy of BMPs to reduce runoff from asparagus wheelings

The role of crop canopies, stems and root architecture to reduce soil erosion are well documented (Finney 1984, De Baets et al. 2007). The MMF model (Morgan and Duzant, 2008) is a validated erosion model that incorporates above-ground 'vegetation effects' (VE) parameters to derive values for soil detachment, runoff generation, sediment transport and deposition. However, there are currently no values available for the VE parameters of cover crops and hence, the effectiveness of cover crops to mitigate erosion cannot be accurately quantified. These VE parameters include stem diameter, stem density, plant height, canopy cover and ground cover and have been measured on FV 450. For the cover crops investigated as BMPs in the FV 450 trials these VE parameters will be measured. The measured VE parameters will be input into the MMF model to assess their effect on erosion and runoff as compared with a bare soil control. This will be assessed for a range of soil type, slope and rainfall scenarios. The surface cover associated with the mulch BMPs will also be evaluated an input into the MMF model. Other model parameters that are effected by the BMPs such as bulk density (BD) and effective hydrological depth (EHD) will be measured and modified in the MMF model. In addition, infiltration using a single ring infiltrometer will be assessed in triplicate on each FV 450 experimental plots. It is envisaged that this will take the form of an MSc Thesis in 2019 or 2020.

Cover crop selection and seeding rates:

Companion crops included in this trial are rye (*Cereale secale* L) and mustard (*Sinapis alba* L). Rye is applied at 150 kg ha^{-1} and White mustard applied at 19 kg ha^{-1}.

One of the main reasons for selecting rye as a companion crop in asparagus stands is 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 (*Secale cereal* L.) produces a number of allelochemicals including benzoxazinone, phenolicacids, beta-hydroxybutyric acid, hydroxamic acids (Kruse et al. 2000). 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 an host of arbuscular mycorrhizal fungi (AMF), known to increase mycorrhizal fungus colonisation of the subsequent crop (Kabir and Koide 2002) and promote yields. AMF form a symbiotic relationship with the roots of most agricultural crops and aid acquisition of soil phosphorus as well as promoting soil aggregation, and carbon sequestration. In addition, AMF have been shown to increase plant resistance to biotic and abiotic stresses (Smith and Read 2008). Asparagus is strongly mycorrhizal, with root colonization reaching up to 70% (Matsubara et al., 2014). Many species of the AMF glomus are associated with reduced crown and root rot damage from Fusarium infection and improved root health of asparagus (Matsubara et al., 2001, 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* sp. 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 is to evaluate the potential for the synergistic enhancement of multiple soil functions such as runoff and erosion mitigation, weed suppression, improving soil structure, promoting AMF and mitigating crown and root rots associated with Fusarium.

Selection of fields for wider asparagus root architecture survey

As agreed by the PAG (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), annual yield (kg ha^{-1}), 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, planting depth, fern management mowed and/or incorporated and date operation completed. 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 14 AGA members and included 187 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 6a). Row spacing's (Figure 6a) 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 6c), 66%, 31% and 3% of fields were planted as A Crowns, B Crowns and Modules, respectively. Further, 86% of fields were ridged on an annual basis with 14% non-ridged. In addition, only 16% of fields were regularly sub-soiled. Age of stand (Figure 6d) 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 that will be incorporated 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).

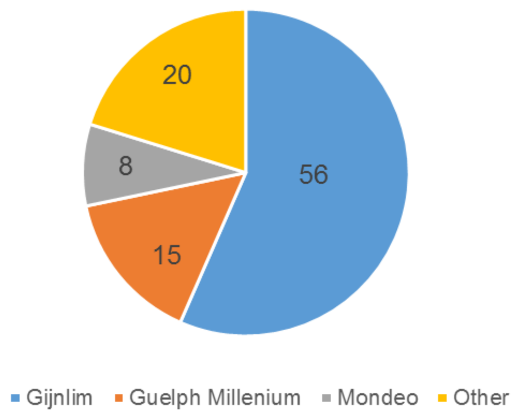


Figure 6a. Dominant asparagus varieties cultivated

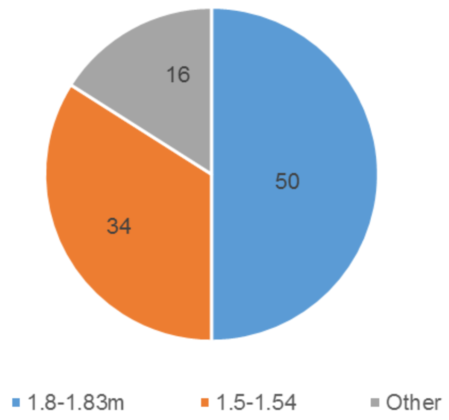


Figure 6b. Dominant row spacing's

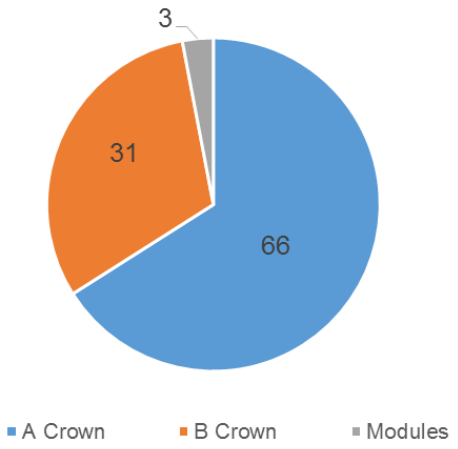


Figure 6c. Dominant planting method

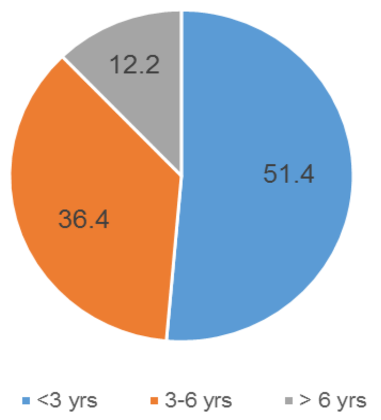


Figure 6d. Dominant age of stand

Table 3. Summary characteristics of fields sampled from the wider grower landbank

Grower	Field	Year Planted	Variety	Cropped area (ha)	Establishment method	Planting depth of crowns/modules from natural soil surface (cm)	Planting density (plants per ha)	Row spacing (m)	In-row spacing (m)	Year of first harvest	Is the field ridged?	Frequency of ridging	Wheelings sub-soiled	Interested in root coring training
A	1	2010	Gijnlim	1.6	B Crowns	10	25000	1.5	0.26	2012	Yes	Annually	Yes	Yes
	2	2011	Guelph Millennium	1.3	A Crowns	10	25000	1.5	0.26	2012	Yes	Annually	Yes	Yes
	3	2011	Guelph Millennium	0.75	A Crowns	10	25000	1.5	0.26	2012	Yes	Annually	Yes	Yes
	4	2012	Guelph Millennium	1.1	A Crowns	10	25000	1.5	0.26	2013	Yes	Annually	Yes	Yes
	5	2013	Guelph Millennium	1.2	A Crowns	10	35000	1.5	0.19	2014	Yes	Annually	Yes	Yes
	6	2014	Guelph Millennium	1.1	A Crowns	10	31000	1.5	0.22	2015	Yes	Annually	Yes	Yes
	7	2015	Mondeo	2.7	A Crowns	10	30000	1.5	0.22	2016	Yes	Annually	Yes	Yes
	8	2016	Guelph Millennium	1.75	A Crowns	10	40000	1.5	0.17	2017	Yes	Annually	Yes	Yes
	9	2017	Mondeo	2.44	Modules	4	40000	1.5	0.17		No	TBC	Yes	Yes
B	1	2016	Gijnlim	12.84	A Crowns	12-14 CM	30000	1.52	0.2	2018	Yes	Annually	No	Yes
	2	2014	Gijnlim	1.15	A Crowns	12-14 CM	30000	1.52	0.2	2016	Yes	Annually	No	Yes
	3	2008	Gijnlim	8.55	A Crowns	12-14 CM	30000	1.52	0.2	2010	Yes	Annually	No	Yes
	4	2011	Gijnlim	3.24	A Crowns	12-14 CM	30000	1.52	0.2	2011	Yes	Annually	No	Yes
	5	2011	Gijnlim	5.42	A Crowns	12-14 CM	30000	1.52	0.2	2013	Yes	Annually	No	Yes
	6	2008	Gijnlim	4.66	A Crowns	12-14 CM	30000	1.52	0.2	2010	Yes	Annually	No	Yes
C	1	2010	Gijnlim	2	B Crowns	20	21500	1.2	0.25	2013	Yes	Annually	No	Yes
	2	2010	Guelph Millennium	0.6	B Crowns	20	21500	1.2	0.25	2013	Yes	Annually	No	Yes
	3	2011	Guelph Millennium	2.6	B Crowns	20	21500	1.6	0.25	2013	Yes	Annually	No	Yes
	4	2012	Gijnlim	2.6	B Crowns	20	21500	1.6	0.25	2015	Yes	Annually	No	Yes
	5	2015	Gijnlim	2.5	A Crowns	20	21500	1.6	0.25	2017	No	small ridge due 2018	No	Yes
	6	2015	Portlim	0.3	A Crowns	20	21500	1.6	0.25	2017	No	small ridge due 2018	No	Yes
	7	2016	Portlim	0.8	A Crowns	20	21500	1.6	0.25	2018	No	small ridge due 2018	No	Yes
D	1	2016	NJ1021	13.1	Modules	10	33000	2	0.3	2018	No	Annually	No	Yes
	2	2016	Guelph Millennium	7.82	Modules	10	33000	2	0.3	2018	No	Annually	No	Yes
	3	2017	NJ1021	4.85	Modules	10	33000	2	0.3	2019	No	Annually	No	Yes
	4	2016	Gijnlim	21.1	A Crowns	20	28500	2	0.35	2017	No		No	Yes
	5	2016	Gijnlim	4.94	Modules	10	28500	2	0.35	2018	No	Annually	No	Yes
	6	2017	Mondeo	14.15	A Crowns	20	28500	2	0.35	2018	No		No	Yes
E	1	2014	Gijnlim	17.18	A crowns	12	24000	1.80	0.02	2015	Yes	depends on need and conditions	No	maybe
	2	2016	Gijnlim	9.11	A crowns	12	24000	1.80	0.02	2018	Yes	depends on need and conditions	No	maybe

Sampled in Autumn 2018
Sampled in Summer 2018
Root data received in May 2018 (Fresh root mass)
Grower to self-core in Spring 2019

Results

FV 450 Trial 2018 Carbohydrate levels – Impact of BMPs

In 2018, due to subsoiling and ridging operations taking place in April 2018 post-root sampling (March 2018), storage root samples were only taken from Guelph Millennium and Gijnlim Bare soil_No-SSD_NR treatments and from Gijnlim RyeCC_NR and MustardCC_NR treatments (Table 4). No significant difference in root CHO values was observed between the Gijnlim RyeCC_NR, Gijnlim MustardCC_NR and Guelph Millennium Bare soil_No-SSD_NR treatments (Table 4). However, a significant (p <0.1) difference in root CHO was observed between the Guelph Millennium and Gijnlim Bare soil_No-SSD_NR treatments with values of 319 and 464 mg g^{-1}, respectively.

It is of note that across all treatments, mean 2018 root CHO values at the 0.3 m distance from the CZL were below the target range outlined by Wilson et al., (2008) indicating inadequate CHO levels for harvest. Similarly, these 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 of 494 and 512 mg g^{-1} for 2005 and 2007, respectively.

Table 4. Treatment and varietal differences in 2018 asparagus storage root CHO values (mg g^{-1}) between treatments at 0.15-0.3 m depth at 0.3 m distance from the CZL.

Variety	Treatment	CHO (mg g^{-1}) at 0.3 m distance from the CZL 0.15-0.30 m depth
Gijnlim	Bare soil_No-SSD_NR	319^{b}
	Rye CC_NR	387^{ab}
	Mustard CC_NR	456^{a}
Guelph Millennium	Bare soil_No-SSD_NR	464^{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 0.90 confidence interval. Cover crop (CC). No-ridging (NR). No Shallow soil disturbance (SSD) = No-SSD.

FV 450 a Trial 2019 Carbohydrate levels – Impact of BMPs

In 2019, asparagus storage root sub-samples for CHO determination were taken from the 0.15-0.30 m depth at two distances namely at the CZL and 0.3 m from the CZL.

Experiment 1: Gijnlim

Across all treatments mean pre-harvest storage root CHO values at the CZL ranged from 507 – 631 mg g^{-1}. This is within the upper target range outlined by Wilson et al., (2008) indicating adequate CHO levels for harvest. Similarly, this is within the upper range of pre-harvest root CHO values observed during the AHDB FV271 *AspireUK* project (AHDB, 2007) which reported mean values of 494 and 512 mg g^{-1} for 2005 and 2007, respectively. It is of note that the asparagus fields sampled under FV 271 were dominated by Gijnlim. No significant differences in asparagus storage root CHO (mg g^{-1}) were observed between treatments (Table 5).

However, across all treatments, a significant difference in root CHO value was observed between coring positions, where CHO at the CZL was significantly ($p < 0.1$) higher as compared to 0.3 m from the CZL with mean values of 555 and 493 mg g^{-1}, respectively (Figure 7). It is of note that mean pre-harvest storage root CHO values 0.3 m from the CZL ranged from 440 – 549 mg g^{-1}. This is still within the upper target range outlined by Wilson et al., (2008) indicating adequate CHO levels for harvest.

In addition, this is comparable to the pre-harvest root CHO values observed during the AHDB FV 271 Aspire project (AHDB, 2007) where mean values of 494 and 512 mg g^{-1} were reported for 2005 and 2007, respectively.

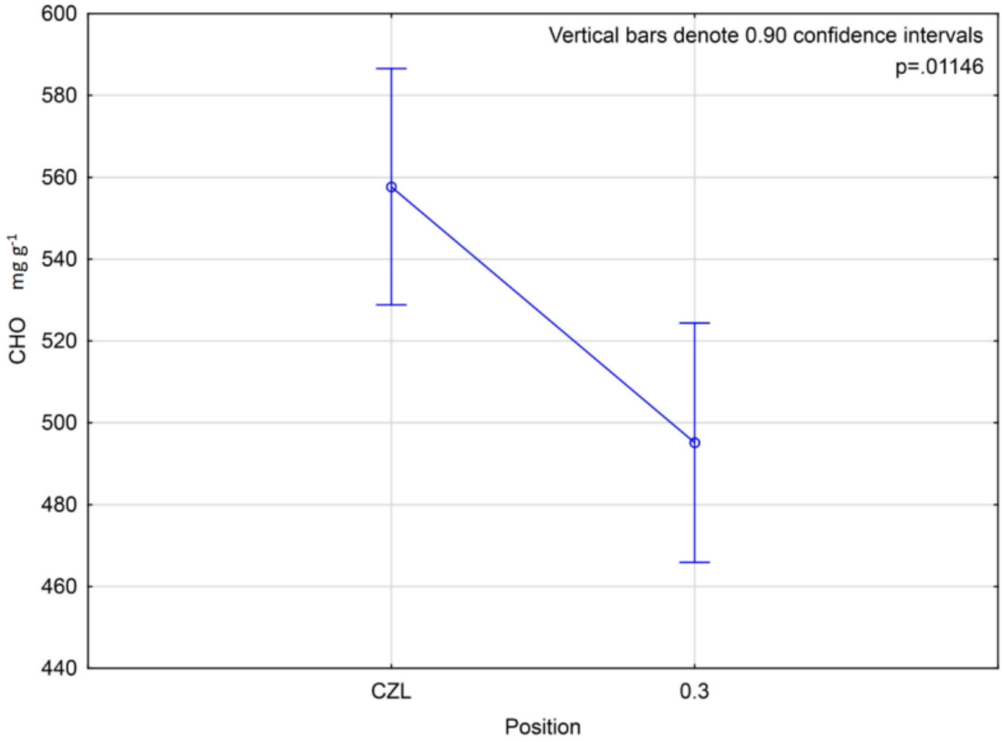


Figure 7. Effects of coring position on asparagus storage root CHO (mg g^{-1}).

Table 5. Differences in 2019 asparagus storage root CHO values (mg g^{-1}) between treatments at 0.15-0.3 m depth at the CZL and 0.3 m from the CZL.

Treatment	CHO (mg g^{-1}) at CZL 0.15-0.30 m depth	CHO (mg g^{-1}) 0.3m from CZL 0.15-0.30 m depth
Mustard CC_R	591.5[a]	468.6[a]
Mustard CC_NR	525.0[a]	523.0[a]
Rye CC_R	546.7[a]	479.7[a]
Rye CC_NR	513.4[a]	490.9[a]
PAS 100_SSD_R	540.3[a]	523.5[a]
PAS 100_SSD_NR	596.3[a]	549.8[a]
Straw Mulch_SSD_R	566.2[a]	538.2[a]
Straw Mulch_SSD_NR	565.1[a]	440.1[a]
Bare soil_SSD_R	554.6[a]	522.9[a]
Bare soil_SSD_NR	516.6[a]	501.8[a]
Bare soil_No-SSD_R	507.6[a]	428.5[a]
Bare soil_No-SSD_NR	631.6[a]	452.2[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 0.90 confidence interval. Annual re-ridging (R) or No-ridging (NR). Cover crop (CC). Shallow soil disturbance (SSD) or No-SSD.

Experiment 2: Varietal differences between Gijnlim and Guelph Millennium

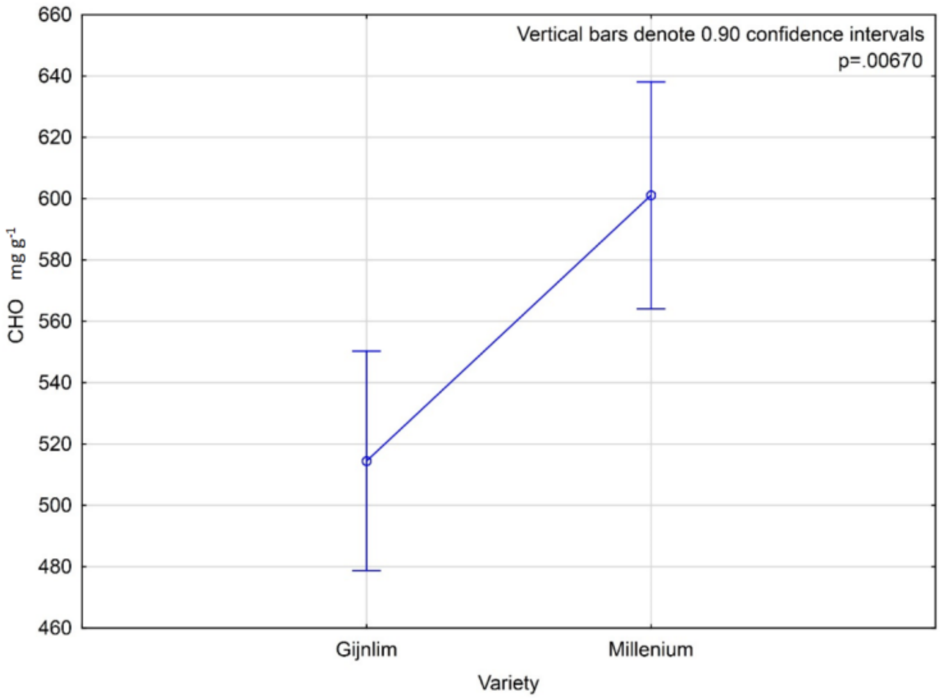
The results indicate that with the exception of the Guelph Millennium Bare soil_No-SSD_R and Bare soil_No-SSD_R neither shallow soil disturbance (SSD) or annual re-ridging resulted in significant differences in storage root CHO values (Table 6). However, across all treatments, CHO values obtained from Guelph Millennium treatments were significantly ($p < 0.01$) higher as compared to the equivalent for Gijnlim with mean values of 602 and 514 mg g^{-1}, respectively (Figure 8). For Guelph Millennium, this exceeds the mean CHO values of 494 and 512 mg g^{-1} reported under FV 271 for 2005 and 2007 which were dominated by Gijnlim which reiterates the varietal differences in CHO levels.

Table 6. Varietal differences in 2019 asparagus storage root CHO values (mg g^{-1}) between treatments at 0.15-0.3 m depth at the CZL and 0.3 m from the CZL.

Variety	Treatment	CHO (mg g^{-1}) at CZL 0.15-0.30 m depth	CHO (mg g^{-1}) 0.3m from CZL 0.15-0.30 m depth
Gijnlim	Bare soil_SSD_R	554.6^{ab}	522.9^{ab}
	Bare soil_SSD_NR	516.6^{ab}	501.8^{ab}
	Bare soil_No-SSD_R	507.6^{ab}	428.5^{a}
	Bare soil_No-SSD_NR	631.6^{ac}	452.2^{a}
Guelph Millennium	Bare soil_SSD_R	629.0^{ac}	535.6^{ab}
	Bare soil_SSD_NR	510.6^{ab}	586.6^{ab}
	Bare soil_No-SSD_R	481.8^{a}	647.8^{b}
	Bare soil_No-SSD_NR	688.0^{c}	643.7^{b}

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 0.90 confidence interval. Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD.

Figure 8. Varietal differences in asparagus storage root CHO (mg g^{-1}).



2018 Year 3: Soil structure assessments

The 2018 soil structural assessments were undertaken as an MSc thesis project (Arpano, 2018). The summarised results are presented here.

Penetrative Resistance

The 2018 soil structural assessments indicate that significant differences in penetrative resistance (PR) are emerging between treatments (Table 7). Specifically, at both 0-5 and 5-10 cm depth, the two CC treatments and Bare soil_No-SSD treatment both ridged or non-ridged are associated with significantly higher PR as compared with the 2016 Baseline (Table 7 and Figure 9).

0-5 cm depth: Despite registering the lowest mean PR values, PAS 100 Compost_SSD and both ridged and non-ridged Straw Mulch_SSD and Bare Soil_no-SSD showed no significant difference in PR as compared with the 2016 baseline observations (Table 7). Conversely, Bare Soil_SSD_R, CC Mustard and CC Rye ridged and non-ridged treatments, and the Bare Soil_No-SSD ridged and non-ridged were associated with significantly higher PR values as compared with the 2016 baseline (Table 7).

5-10 cm depth: CC Mustard (non-ridged 2.48, ridged 2.25 MPa), CC Rye (non-ridged 2.76, non-ridged 2.68 MPa) and No-SSD Bare Soil (non-ridged 2.88, re-ridged 2.91 MPa) – regardless of the re-ridging practice- were all associated with significantly higher PR values as compared with the 2016 baseline (1.01 MPa). Further, Bare Soil SSD, Mulch and Compost treatments regardless of the re-ridging practice showed no significant difference in PR as compared with the 2016 baseline.

10-15 cm depth: Bare Soil_No-SSD (re-ridged 2.96, non-ridged 2.66 MPa) were found to be significantly different from the 2016 baseline (1.39 MPa). In addition, CC Mustard_NR, CC Rye_NR, CC Rye_R were also associated with PR values high than 1.8 MPa. All other treatments did not show any significant improvement or worsening of the compaction associated with the plough pan reported in the 2016 baseline (AHDB, 2017).

15-20 cm: The only treatment significantly different from the 2016 baseline, is the Bare Soil_No-SSD_NR treatment with a mean PR value of 2.8 MPa. The PAS 100_SSD_R and PAS 100_SSD_NR (1.15 and 1.24 MPa) were associated with significantly lower PR values as compared with the Bare Soil_No-SSD_NR (2.38 MPa) absolute control.

Bulk density

In contrast, to the PR values, no significant difference in BD mid-topsoil depth was observed between the 2018 sampling and the 2016 Baseline (Table 7).

Table 7. Differences in PR (KPa) and BD (g cm^{-3}) between treatments at specific soil depth (cm) as compared with 2016 Baseline.

Treatment	PR 0-5cm	PR 5-10cm	PR 10-15cm	PR 15-20cm	BD
Mustard CC_R	*1.66^{cdef}	*2.25^{bcde}	1.91^{abcd}	1.97^{abcde}	1.55^{ab}
Mustard CC_NR	*1.91^{ef}	*2.48^{cde}	2,21^{bcd}	2.26^{bcde}	1.51^{ab}
Rye CC_R	*1.68^{cdef}	*2.68^{de}	2.35^{bcd}	2.02^{abcde}	1.68^{a}
Rye CC_NR	*2.28^{f}	*2.76^{e}	2.31^{bcd}	2.55^{de}	1.70^{a}
PAS 100_SSD_R	0.60^{abc}	0.91^{a}	0.96^{ab}	1.15^{ab}	1.51^{ab}
PAS 100_SSD_NR	0.96^{abcd}	1.52^{abc}	1.52^{ab}	1.24^{a}	1.81^{ab}
Straw Mulch_SSD_R	0.97^{abcd}	1.50^{abc}	1.40^{ab}	1.43^{abc}	1.82^{ab}
Straw Mulch_SSD_NR	1.24^{bcde}	1.22^{ab}	1.50^{ab}	1.46^{abcd}	1.51^{ab}
Bare soil_SSD_R	*1.31^{cde}	1.66^{abcd}	1.99^{abcd}	1.80^{abcde}	1.44^{b}
Bare soil_SSD_NR	0.93^{abcd}	0.94^{a}	1.99^{abcd}	1.90^{abcde}	1.55^{ab}
Bare soil_No-SSD_R	*2.34^{f}	*2.91^{e}	*2.96^{d}	*2.82^{e}	1.52^{ab}
Bare soil_No-SSD_NR	*2.00^{ef}	*2.88^{e}	*2.66^{cd}	2.38^{cde}	1.49^{ab}
2016 Baseline	0.42^{ab}	1.01^{a}	1.39^{ab}	1.58^{abcd}	1.48^{ab}

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and post-hoc Turkey LSD analysis at 0.95 confidence interval. *Treatments with PR values significantly higher than the 2016 baseline value.

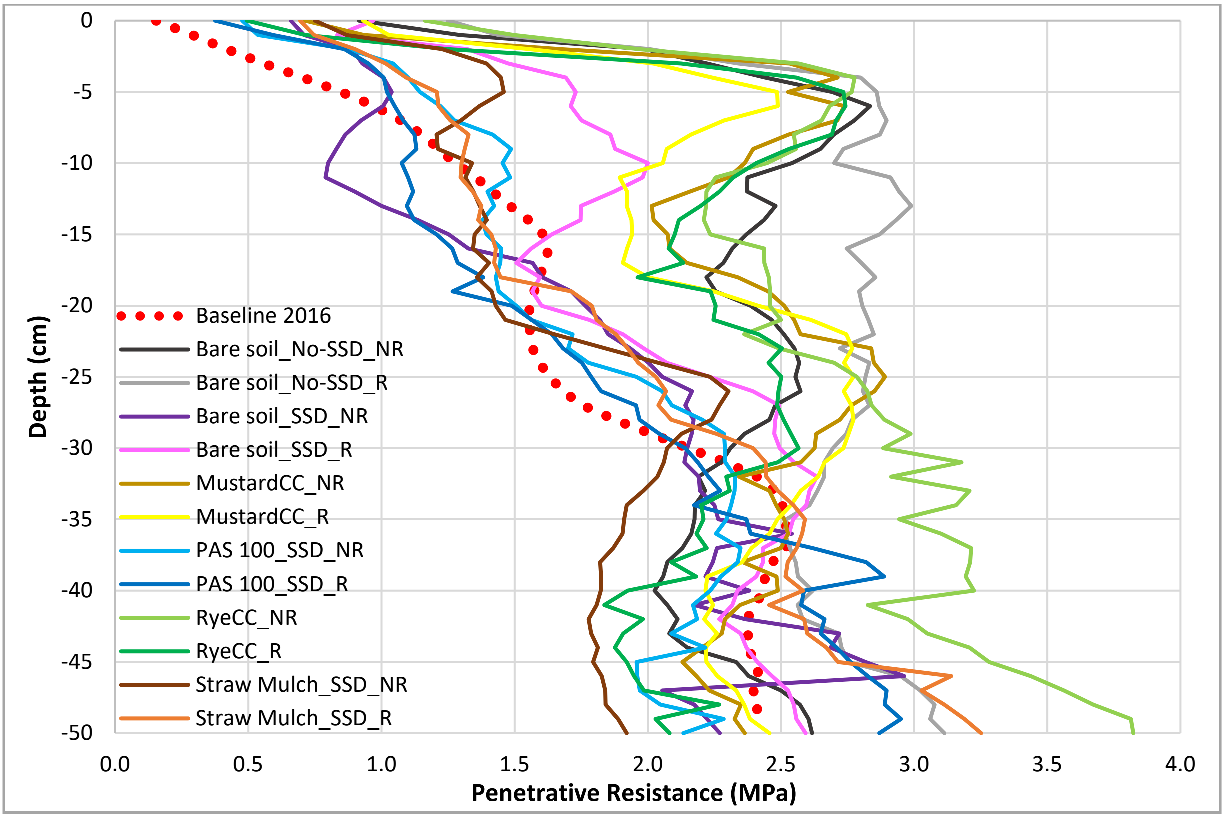


Figure 9. Differences in mean (n=6) PR values between treatments.

Infiltration

The 2016 baseline mean infiltration rate was 102 mm hr^{-1} (Moderately Rapid), with 62% of the measurements being classified as moderate and relatively moderate (AHDB, 2018).

In the 2018 sampling (Figure 10), the only treatment classified as “moderately rapid” (50 - 150 mm hr^{-1}) is Bare Soil_no-SSD_NR, with a mean (n=6) infiltration rate of 94.6 mm hr^{-1}. All other treatments are classified as “Rapid” or “Very Rapid” (150-500 and >500 mm hr^{-1} respectively). The highest infiltration rates were recorded for the Straw Mulch_SSD_NR and PAS 100_SSD_NR with values of 11,881 mm hr^{-1} and 5,724 mm hr^{-1}, respectively. All cover crop treatments irrespective of ridging practice were associated with infiltration rates of between 175 - 578 mm h^{-1}. No significant difference was observed between the CC Mustard or CC Rye treatments.

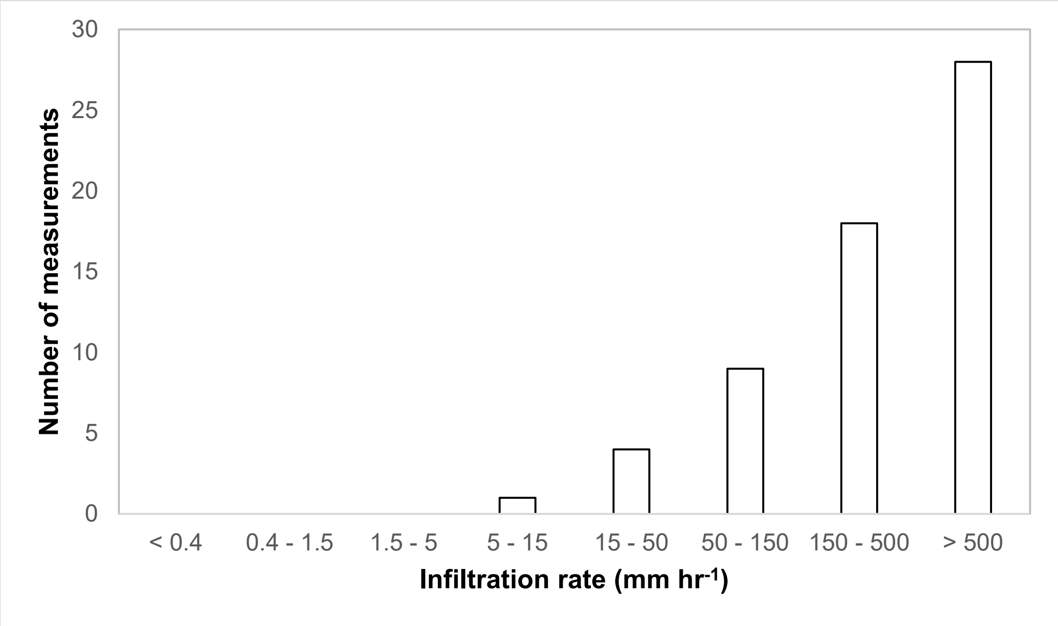


Figure 10. 2018 infiltration rate measurements (mm hr^{-1}). Infiltration rates categories are: impermeable (<0.4); very slow (0.4-1.5); slow (1.5-5); moderately slow (5-15); moderate (15-50); moderately rapid (50-150), rapid (150-500); very rapid (>500).

Asparagus Root Architecture: Wider Grower Landbank

An MSc thesis project (Rodriguez, 2018) investigated the spatial distribution of asparagus storage roots for six fields from two UK growers adopting different crop management practices, i.e. conventional tillage versus conservation tillage practices. In addition, to the six fields sampled by (Rodriguez, 2018) a further six fields were sampled by the FV 450a team in autumn 2018.

Lincolnshire: Grower A: 1.5 m row spacing.

The 5 fields sampled in Lincolnshire (Table 3 – Grower A) had a row spacing of 1.5 m and planting densities of ranging from 30,000 - 40,000 plants ha^{-1} depending on variety and planting method (crown vs module).

At 0.0 – 0.15 m depth at the CZL, there is no significant difference in RMD between fields sampled (Figure 11). In contrast, at 0.15 – 0.3 m sampling depth at the CZL, RMD values are in the order, 5yr old Guelph Millennium A-crowns > 3yr old Mondeo A-crowns = 4yr old Guelph Millennium A-crowns > 2yr old Guelph Millennium A-crowns > 1yr old Mondeo modules.

At 0.15 – 0.30 m depth at the CZL, the highest RMD was observed for 5yr old Guelph Millennium A-crowns. Further, no significant difference in RMD was observed between the 3yr old Mondeo A-crowns, 4yr old Guelph Millennium A-crowns and 2yr old Guelph Millennium A-crowns between fields sampled (Figure 11). As expected, significantly lower RMD was observed 1yr old Mondeo modules than all other fields.

At 0.0 – 0.15 m depth 0.3 m from the CZL, there is negligible difference in RMD between fields sampled (Figure 11). In contrast, at 0.15 – 0.3m sampling depth 0.3m from the CZL significantly higher RMD is associated with the 5yr and 4yr old Guelph Millennium A-crowns as compared with the other fields. This implies greater risk of root damage associated with re-ridging operations as compared with the 3yr old Mondeo and 2yr old Guelph Millennium A-crowns and 1yr old Mondeo modules. In the centre of the wheeling (0.75m from CZL) RMDs are an order of magnitude lower that at the CZL. However, there continues to be a trend for greater RMD associated with the 5yr and 4yr old Guelph Millennium A-crowns. This has implications for potential root damage associated with sub-soiling operations to alleviate compaction in wheelings. These root profile distributions are also visualized as %TRB root profile diagrams (Figures A-1 – A-5 Appendix 1).

Kent: Grower B: 1.52m row spacing.

The 2 fields sampled to date in Kent (Table 3 – Grower B) had a row spacing of 1.52m and planting densities of 30,000 plants ha^{-1}. Root mass density (kg m^{-3}) distributions are shown in Figure 15. The results indicate that there is no significant difference in RMD between the 2yr old and 4yr old Gijnlim Crowns, at the CZL or at 0.3m from the CZL for both the 0.0 – 0.15m and 0.15 – 0.3m sampling depths. However, for both the 0.3m – 0.45m and 0.45 – 0.6m sampling depths at both the CZL and at 0.3m from the CZL the 2yr old Gijnlim Crowns are associated with significantly higher RMD values as compared with the 4yr old Gijnlim Crowns (Figure 15). In contrast, in the centre of the wheeling (0.76m from CZL), across all sampling depths, the 2yr old Gijnlim Crowns are associated with significantly higher RMD values as compared with the 4yr old Gijnlim Crowns (Figure 15). These root profile distributions are visualized as %TRB root profile diagrams (Figures A-6 and A-7 Appendix 1).

Suffolk: Grower D: 2.0m row spacing.

The 4 fields sampled in Suffolk (Table 3 – Grower D) had a row spacing of 2.0m and planting densities ranging between 28500 – 33000 plants ha^{-1}. Root mass density (kg m^{-3}) distributions are shown in Figure 13. The results indicate that for all sampling depths, there is no significant difference in RMD between the 2yr old Guelph Millennium Crowns, Gijnlim modules and 1yr old Mondeo Crowns at the CZL or at 0.3m from the CZL. However, at both 0.0 – 0.15m and 0.15 – 0.3m sampling depths, the 2yr old Guelph Millennium modules are associated with significantly lower RMD at both the CZL and 0.3m from the CZL as compared with the other varieties and planting method sampled. At 0.7m from the CZL and in the centre of the wheeling (1.0m from CZL), Gijnlim crowns are associated with significantly greater RMD at both the 0.15 – 0.3m and 0.3m – 0.45m sampling depths as compared with the other varieties and planting methods sampled (Figure X). At the centre of the wheeling, (1.0m from CZL), 2yr old Gijnlim crowns are associated with significantly greater RMD at both the 0.15 – 0.3m sampling depth as compared with the other varieties and planting method sampled (Figure 13). These root profile distributions are visualized on %TRB root profile diagrams (Figures A-8 – A11 Appendix 1).

Figure 11. Root mass density (kg m^{-3}) profiles for Grower A on 1.5 m row spacing's.

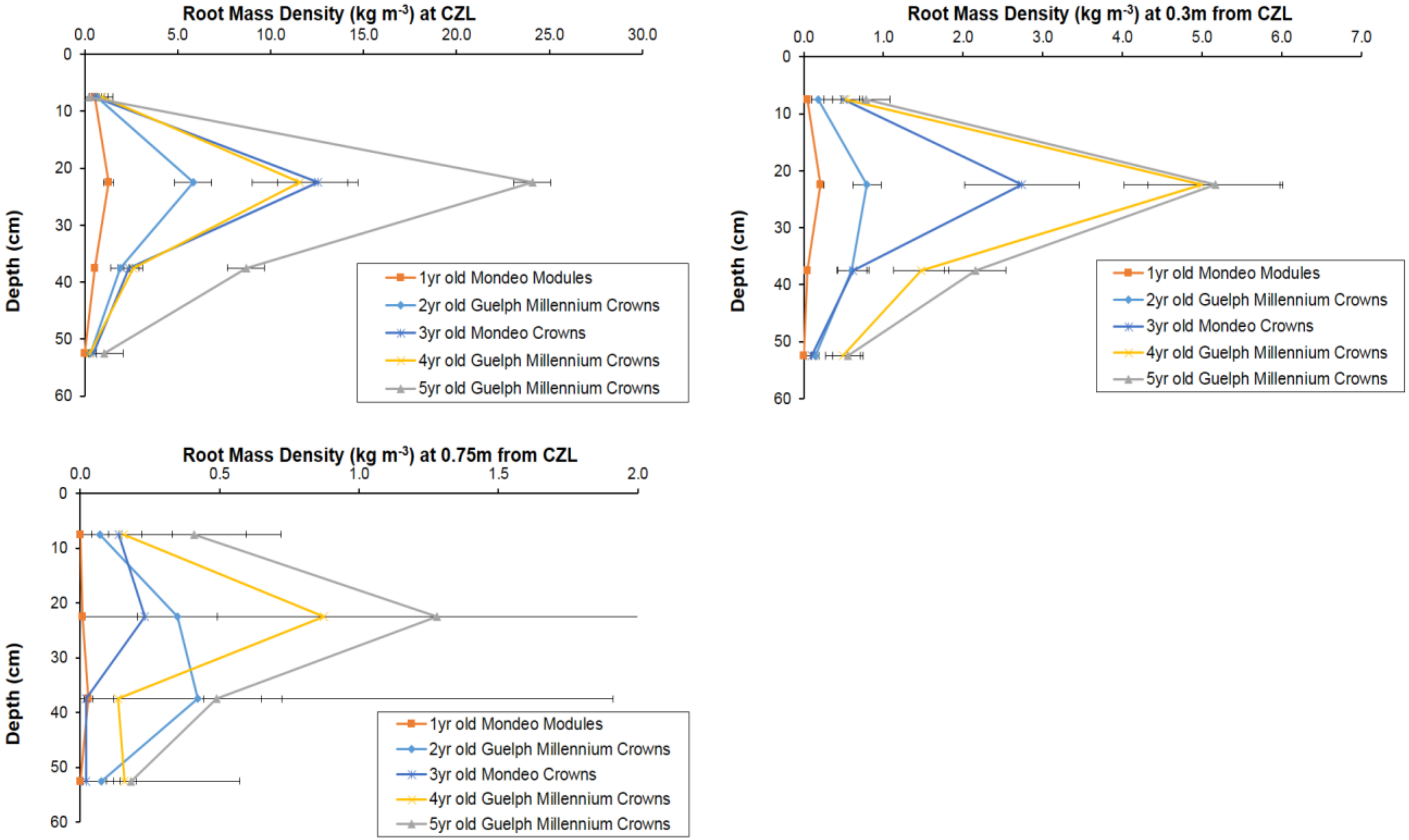


Figure 12. Root mass density (kg m^{-3}) profiles for Grower B on 1.52 m row spacing's.

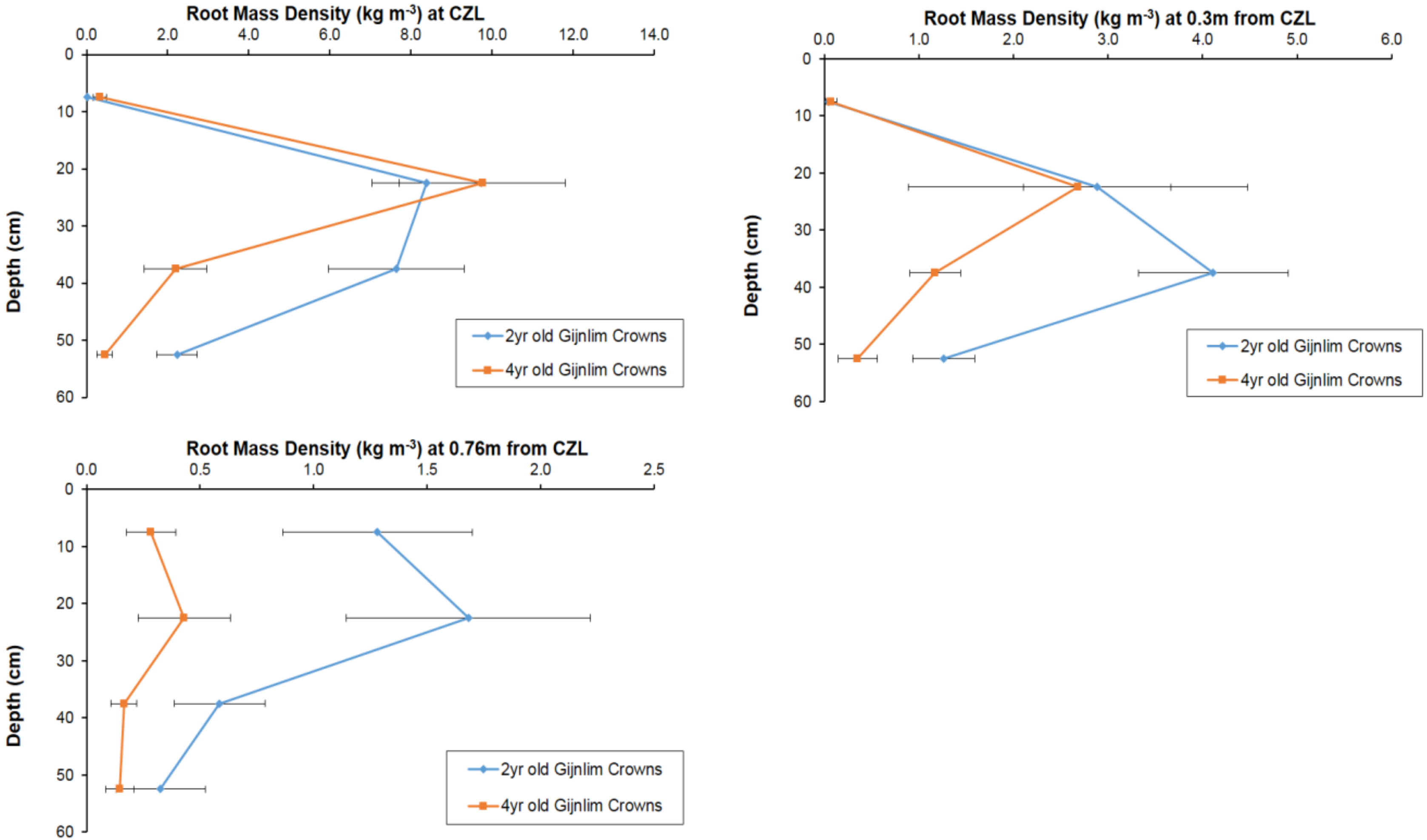
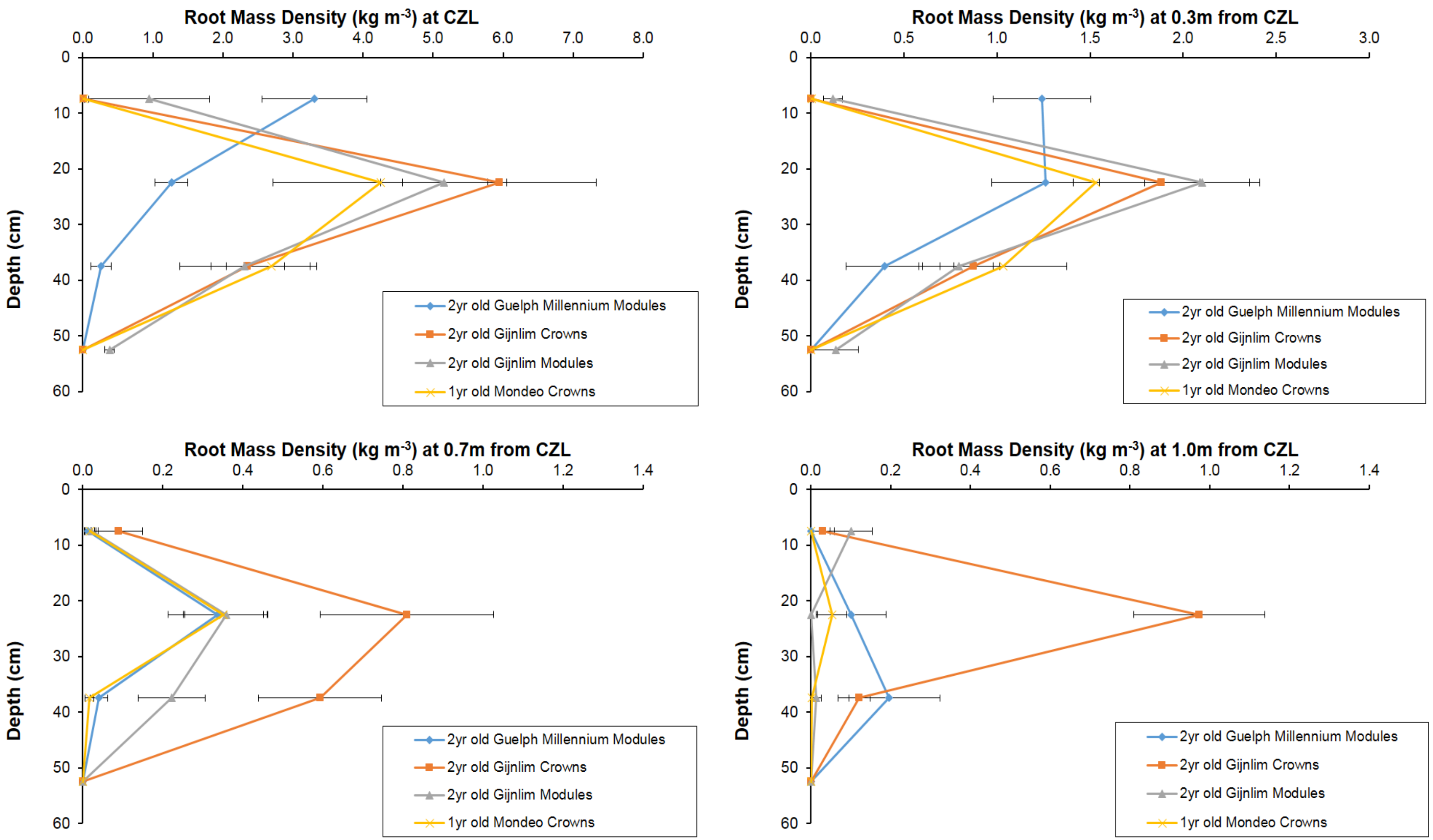


Figure 13. Root mass density (kg m^{-3}) profiles for Grower D on 2.0 m row spacing's.



Discussion

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

Grower A: Lincolnshire: 1.5m row spacing

Results indicate that for both the 4 and 5yr old Guelph Millennium A-crowns there is the potential for 2-8% of storage roots to be damaged when using a modified para-plough to 150mm operating depth (Figures 14 and 16). Negligible root damage (<2% of TRB) would be associated with the use of all other tine configurations investigated by Niziolomski, (2016). In contrast, at an operating depth of 300mm, all tine configurations have the potential for damaging 2-8% of TRB. For 2yr old Guelph Millennium A-crowns there is the potential for 2-11% of storage roots to be damaged when using a modified para-plough to 150mm operating depth (Figure 20). Negligible root damage <2% would be associated with the use of the other tine configurations investigated by Niziolomski, (2016). At an operating depth of 300mm, all tine configurations have the potential for damaging 2-8% of storage roots. For 3yr old Mondeo A-crowns <2% of storage roots have extended >0.5m from the CZL. Therefore, centre of the wheeling is essentially devoid of storage roots at all sampling depths. However, there is the potential for 2-8% of storage roots to be damaged when using a modified para-plough to 150mm operating depth (Figure 18). For all other tine configurations investigated by Niziolomski, (2016) there is negligible risk (<2% TRB) of root damage. At an operating depth of 300mm, both the winged shallow leading tine and the winged tine all tine configurations have the potential for damaging 2-8% of storage roots. In contrast at an operating depth of 300mm, the narrow tine and narrow with shallow leading tine are associated with <2.0% potential damage to storage roots.

For 1yr old Mondeo modules, sub-soiling with a modified para-plough has the potential to damage up to 8% of storage roots (Figure 22). Further, up to 5% of root damage could be expected when sub-soiling with all other tine configurations investigated by Niziolomski, (2016). At an operating depth of 300mm, all tine configurations have the potential for damaging 2-8% of storage roots. For both the 4 and 5yr old Guelph Millennium A-crowns annual ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage 5-11% of the TRB. This increases the risk of crown and root rot (CRR) caused by Phytophthora megasperma (Falloon & Grogan 1991) and Fusarium oxysporum f. sp. Asparagi (Elmer, 2001; 2015). For the 2yr old Guelph Millennium A-crowns, 3yr old Mondeo A-crowns and 1yr old Mondeo modules, annual ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage 5-8% of the TRB and increase risk of CRR.

Grower A Field 5

Year Planted	Variety	Establishment method	Row spacing (m)
2013	Guelph Millennium	A Crowns	1.5

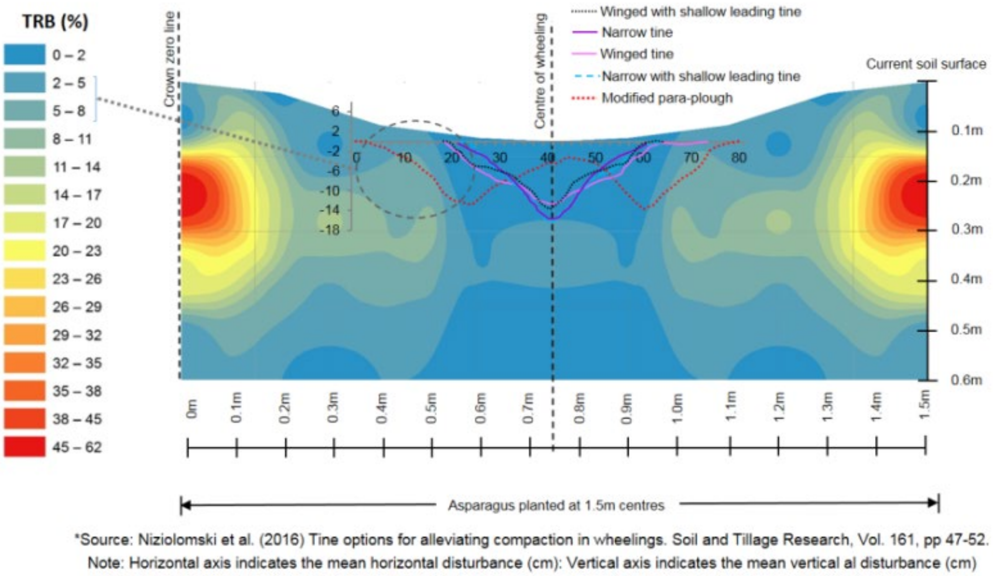


Figure 14. Grower A total root biomass (TRB%) root map for 5yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower A Field 5

Year Planted	Variety	Establishment method	Row spacing (m)
2013	Guelph Millennium	A Crowns	1.5

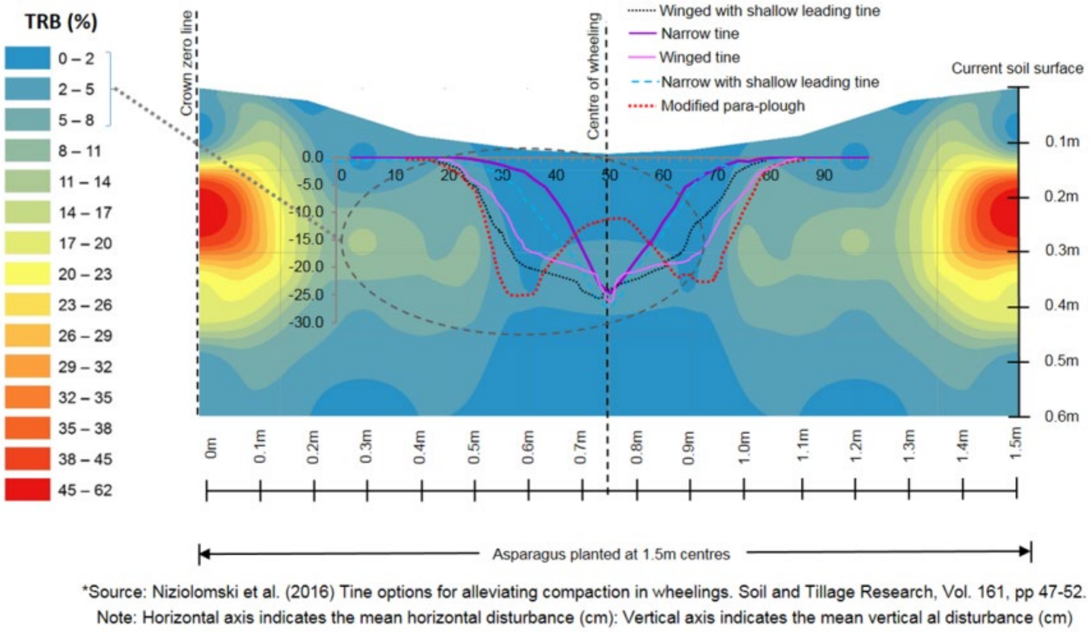
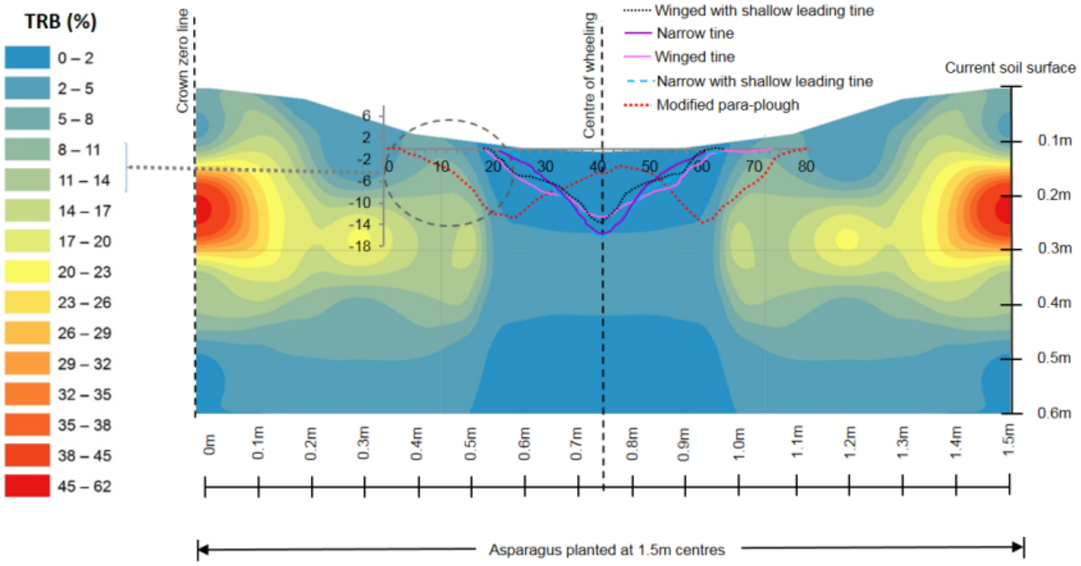


Figure 15. Grower A total root biomass (TRB%) root map for 5yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower A Field 6

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Guelph Millennium	A Crowns	1.5

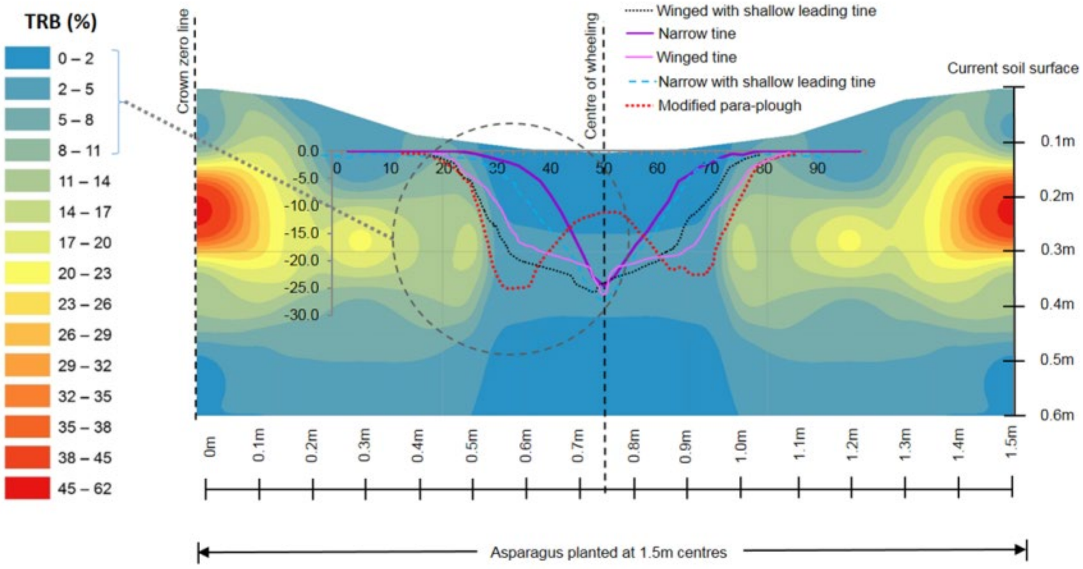


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 16. Grower A total root biomass (TRB%) root map for 4yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower A Field 6

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Guelph Millennium	A Crowns	1.5

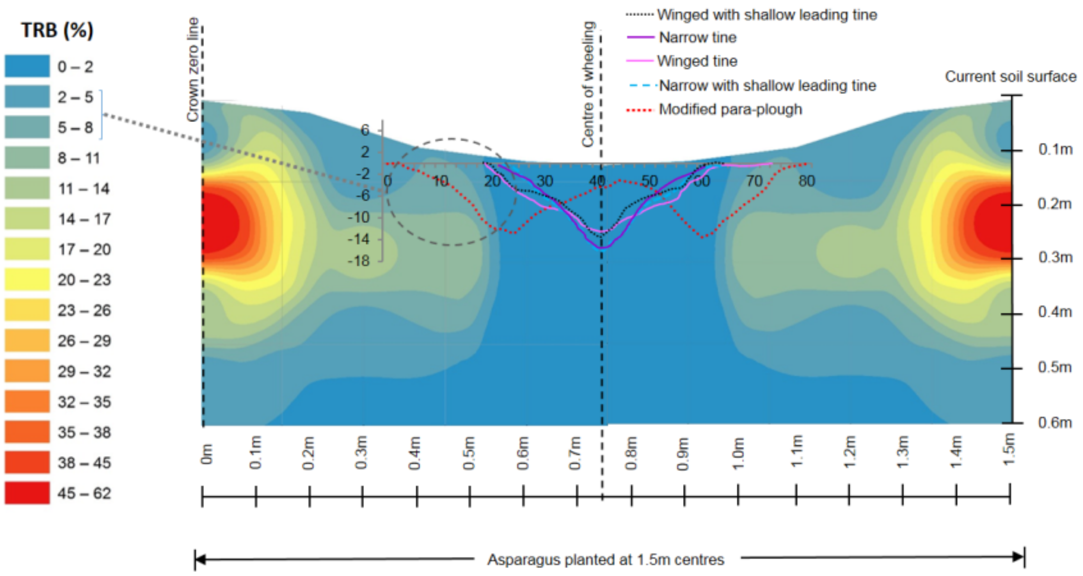


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 17. Grower A total root biomass (TRB%) root map for 4yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower A Field 7

Year Planted	Variety	Establishment method	Row spacing (m)
2015	Mondeo	A Crowns	1.5

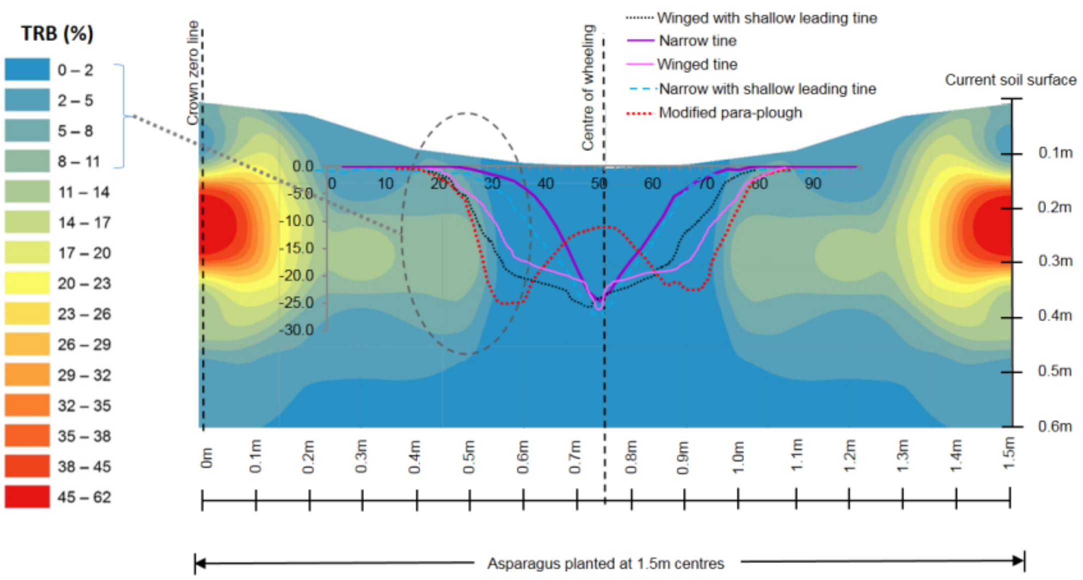


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 18. Grower A total root biomass (TRB%) root map for 3yr old Mondeo A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower A Field 7

Year Planted	Variety	Establishment method	Row spacing (m)
2015	Mondeo	A Crowns	1.5

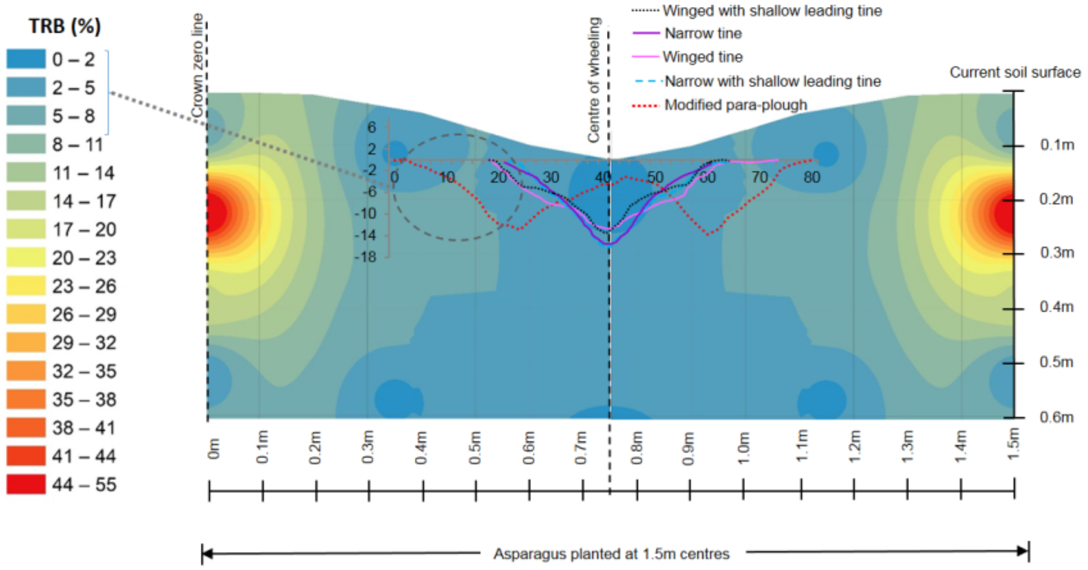


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 19. Grower A total root biomass (TRB%) root map for 3yr old Mondeo A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower A Field 8

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Guelph Millennium	A Crowns	1.5

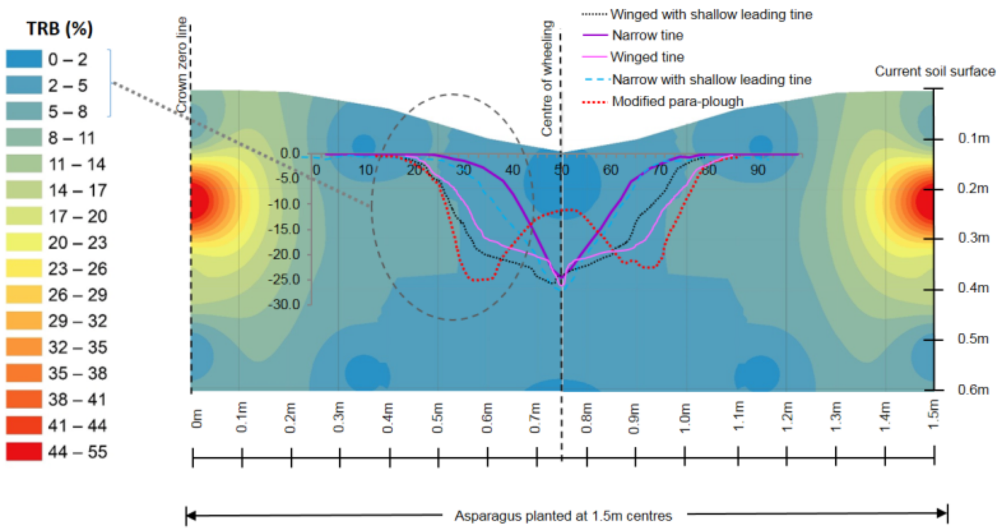


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 20. Grower A total root biomass (TRB%) root map for 2yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower A Field 8

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Guelph Millennium	A Crowns	1.5

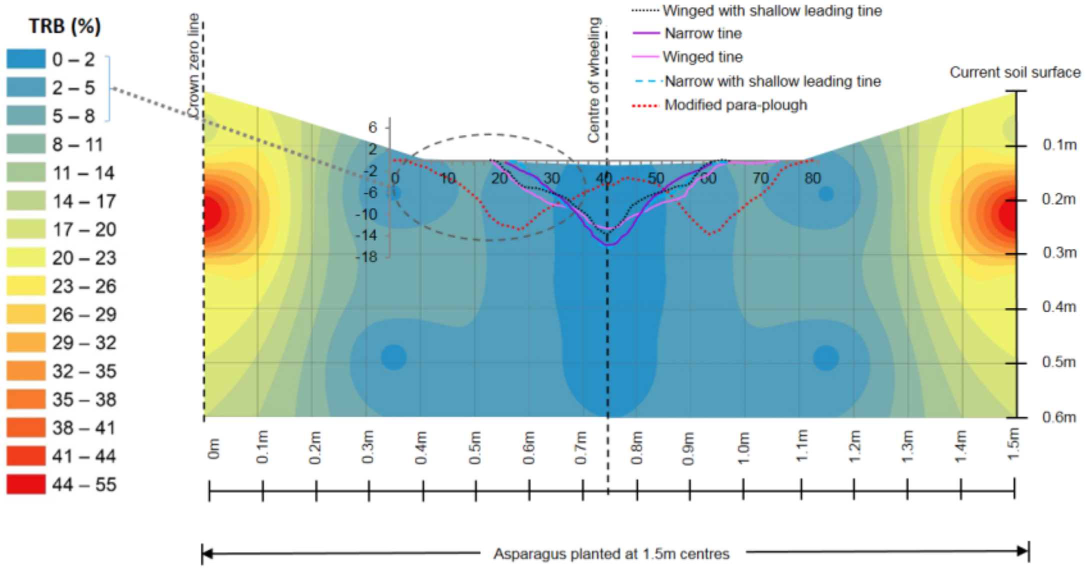


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 21. Grower A total root biomass (TRB%) root map for 2yr old Guelph Millennium A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower A Field 9

Year Planted	Variety	Establishment method	Row spacing (m)
2017	Mondeo	Modules	1.5

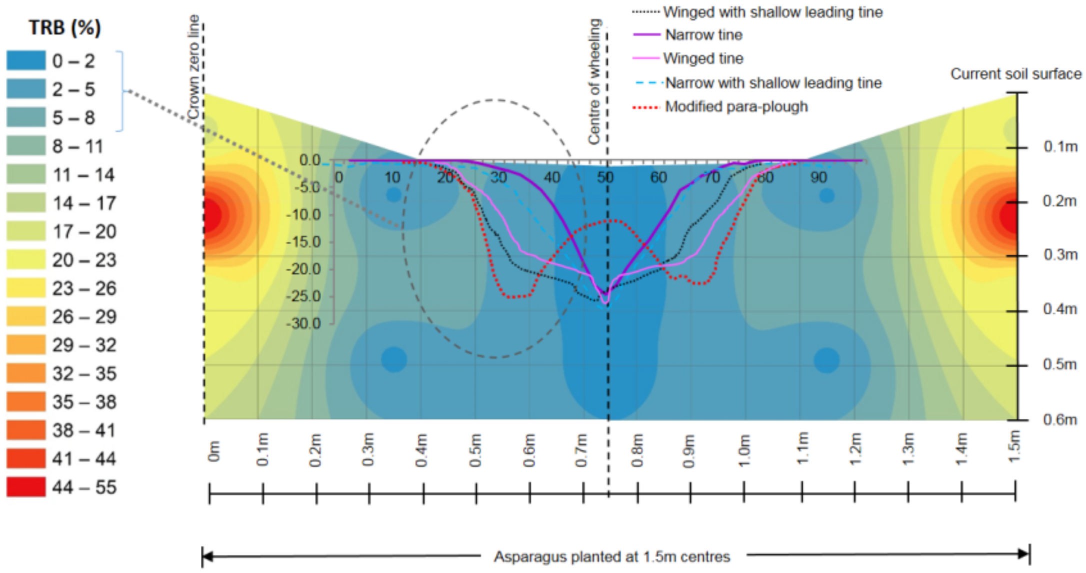


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 22. Grower A total root biomass (TRB%) root map for 1yr old Mondeo modules. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower A Field 9

Year Planted	Variety	Establishment method	Row spacing (m)
2017	Mondeo	Modules	1.5



*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 23. Grower A total root biomass (TRB%) root map for 1yr old Mondeo modules. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower B: Kent: 1.52m row spacing

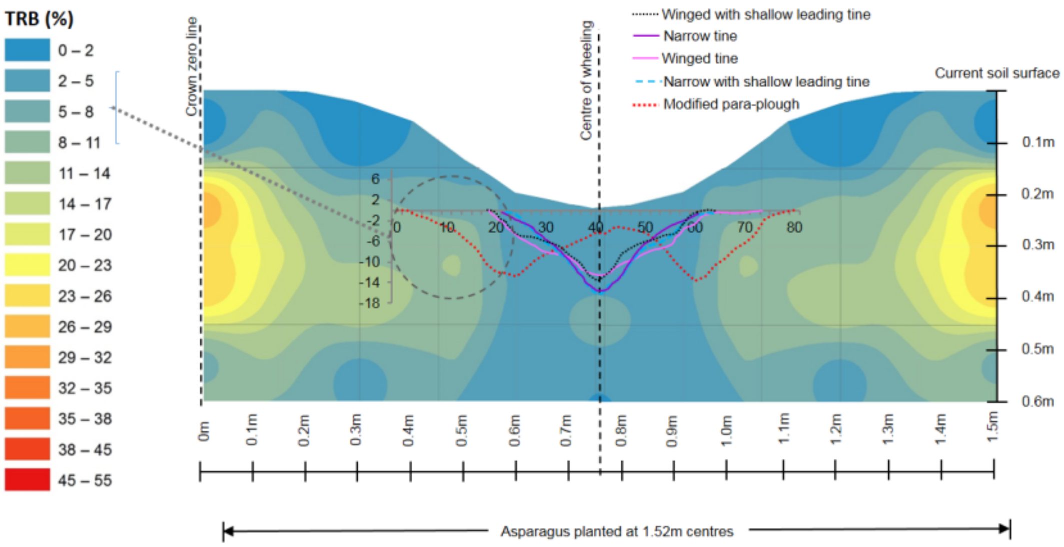
For the 2yr old Gijnlim A-crowns there is the potential for 8-11% of storage roots to be damaged when using a modified para-plough to 150mm operating depth (Figure 24). Further, between 2-5% root damage would be associated with the use of the other tine configurations investigated by Niziolomski, (2016). In contrast, the wheeling of the 4yr old Gijnlim A-crowns is largely devoid of storage roots creating a ‘dead-zone’ (Figure 26). This may in part be due to compaction restricting storage root expansion into this zone as the wheelings are not regularly sub-soiled (Table 3). This also has implications for infiltration, runoff and soil moisture recharge. The lack of storage roots observed within the wheeling in the 4yr old Gijnlim stand indicates that sub-soiling operations to 150mm depth using a winged with shallow leading tine, narrow tine, winged tine or narrow with shallow leading tine could be undertaken (Figure 26).

For the 2yr old Gijnlim A-crowns, at an operating depth of 300mm, all tine configurations have the potential for damaging 2-8% of storage roots (Figure 25). In contrast, for the 4yr old Gijnlim A-crowns there is a lower risk of causing root damage when undertaking sub-soiling operations using a narrow tine or narrow with shallow-leading tine (Figure 27).

Further, both the 2 and 4yr old Gijnlim A-crowns circa 5-11% of the storage roots are at 0.15 – 0.30m depth 0.3 – 0.5m from the CZL at the shoulder of the ridge (Figures 25 and 27). Annual re-ridging operations have the potential therefore to damage up to 11% of storage roots reducing the CHO storage capacity and increasing risk of CRR.

Grower B Field 1

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	1.52

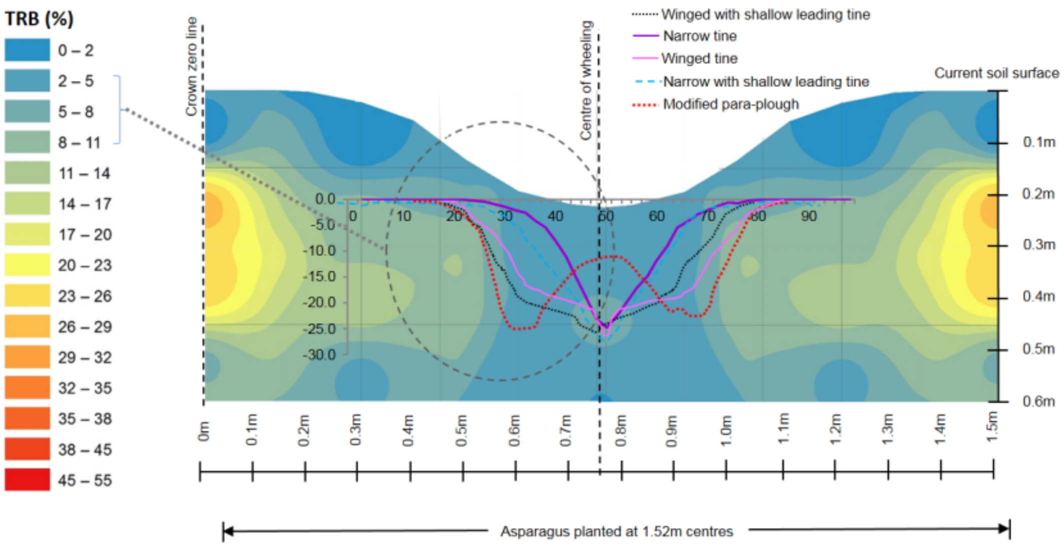


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 24. Grower B total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower B Field 1

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	1.52

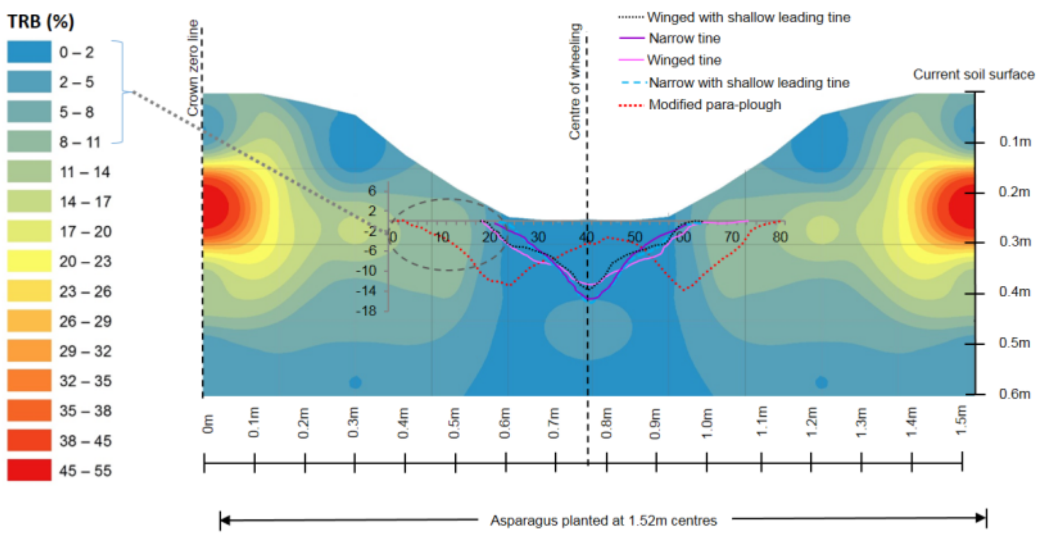


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 25. Grower B total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower B Field 2

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Gijnlim	A Crowns	1.52

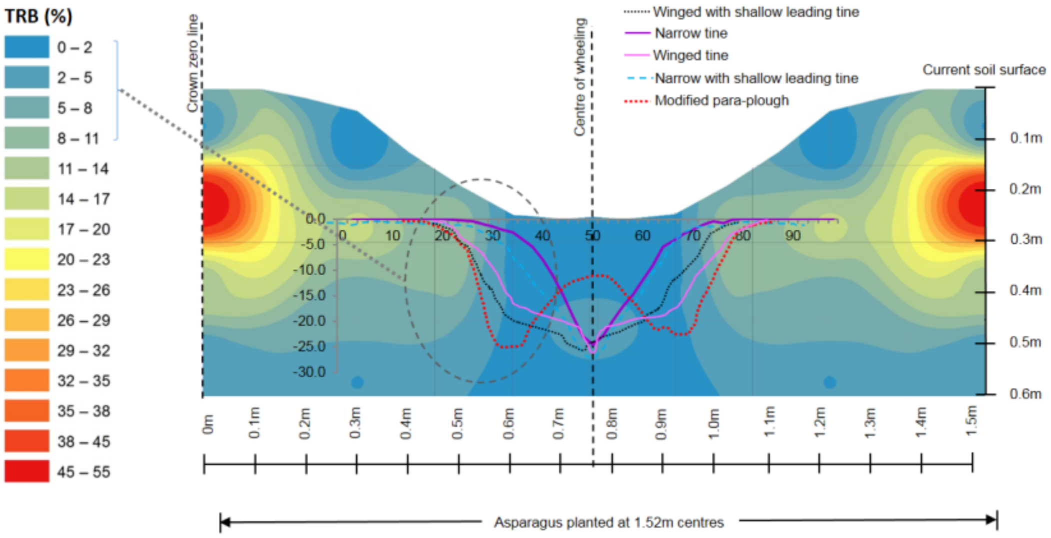


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 26. Grower B total root biomass (TRB%) root map for 4yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower B Field 2

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Gijnlim	A Crowns	1.52



*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp 47-52.
Note: Horizontal axis indicates the mean horizontal disturbance (cm): Vertical axis indicates the mean vertical al disturbance (cm)

Figure 27. Grower B total root biomass (TRB%) root map for 4yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower D: Suffolk: 2.0m row spacing

Results indicate that for 2yr old Guelph Millennium modules (grown on the flat at time of sampling), sub-soiling operations in the centre of the wheeling can be undertaken at both 150 and 300mm operating depths (Figures 28 and 29) with negligible (<2%) risk of root damage for all tine configurations investigated by Niziolomski, (2016). The only exception is for the modified para-plough at 300mm operating depth that has the potential to damaging 2-8% of storage roots.

Critically ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage 11-14% of the TRB increasing the risk of crown and root rot (CRR) caused by *Phytophthora megasperma* (Falloon & Grogan 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2001; 2015).

In contrast, for 2yr old Gijnlim A-crowns all tine configurations investigated by Niziolomski, (2016) have the potential to damaged up to 2-5% of TRB at both 150mm and 300mm operating depths (Figures 30 and 31). Annual ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage 2-5% of the TRB.

For 2yr old Gijnlim modules sub-soiling operations in the centre of the wheeling can be undertaken at both 150 and 300mm operating depths (Figures 32 and 33) with negligible (<2%) risk of root damage for all tine configurations investigated by Niziolomski, (2016). Annual ridging operations if undertaken within 0.3 – 0.6m of the CZL to depths of 0.15m have the potential to damage 5-8% of the TRB.

Similarly, for 1yr old Mondeo A-crowns (grown on the flat at time of sampling) sub-soiling operations in the centre of the wheeling can be undertaken at both 150 and 300mm operating depths (Figures 34 and 35) with negligible (<2% of TRB) risk of root damage for all tine configurations investigated by Niziolomski, (2016).

Critically ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage 5-8% of the TRB increases the risk of CRR.

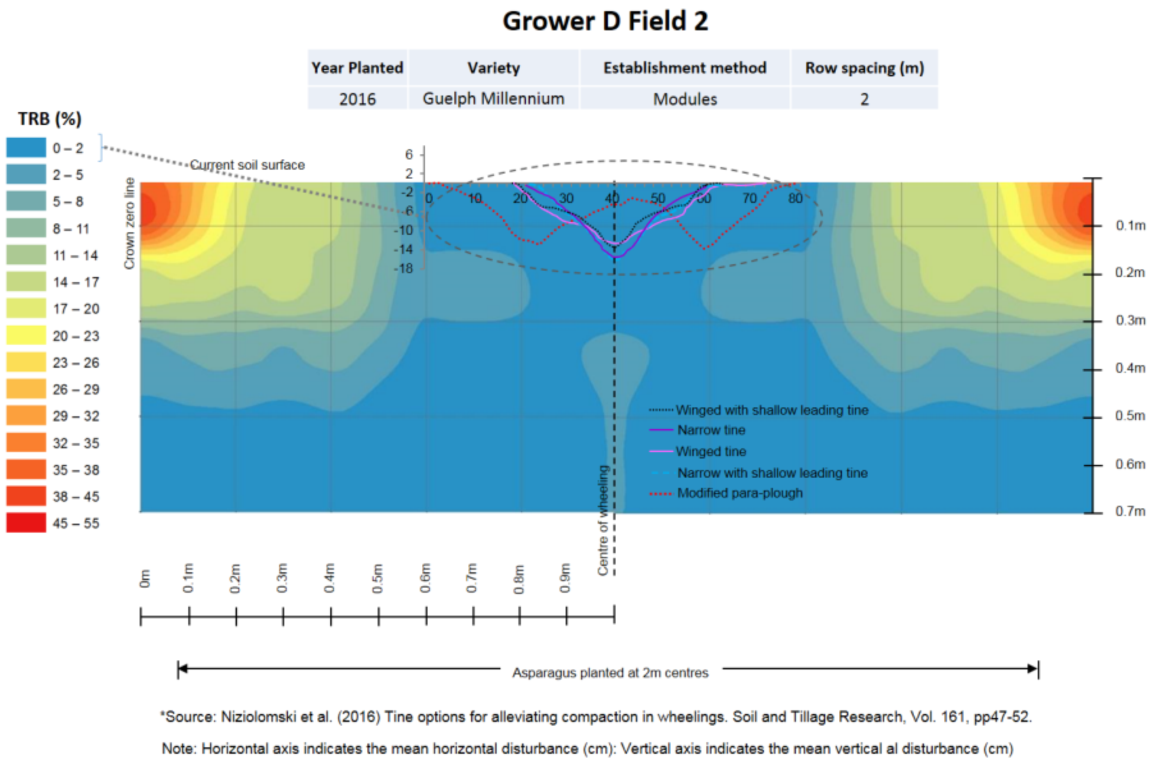
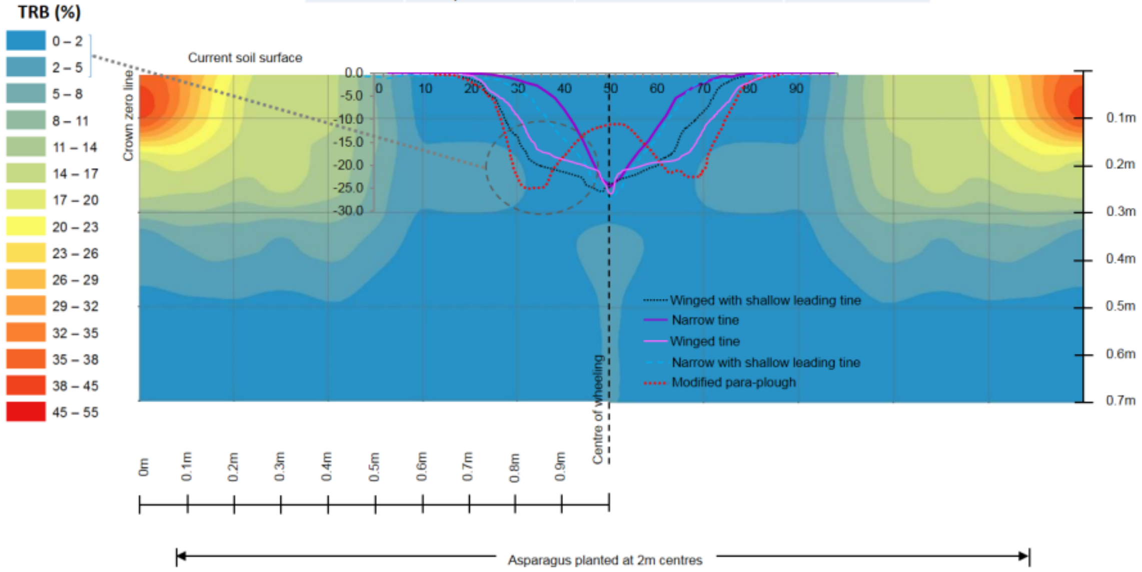


Figure 28. Grower D total root biomass (TRB%) root map for 2yr old Guelph Millennium modules. Potential root damage associated with sub-soiling operations at 150mm depth.

Grower D Field 2

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Guelph Millennium	Modules	2



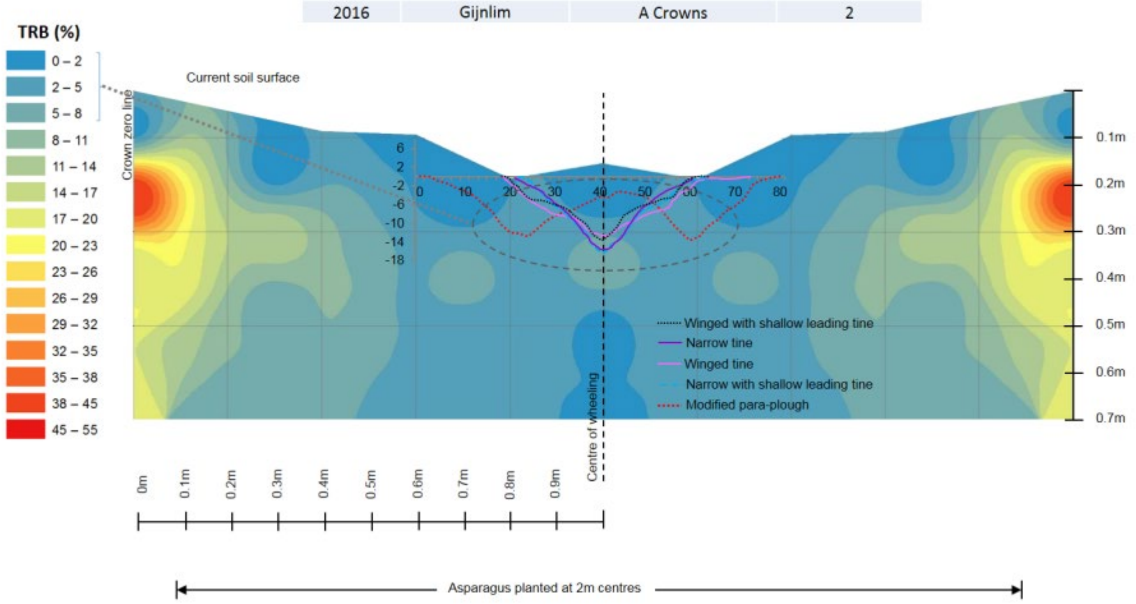
*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

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

Figure 29. Grower D total root biomass (TRB%) root map for 2yr old Guelph Millennium modules. Potential root damage associated with sub-soiling operations at 300mm depth.

Grower D Field 4

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	2



*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 30. Grower D total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

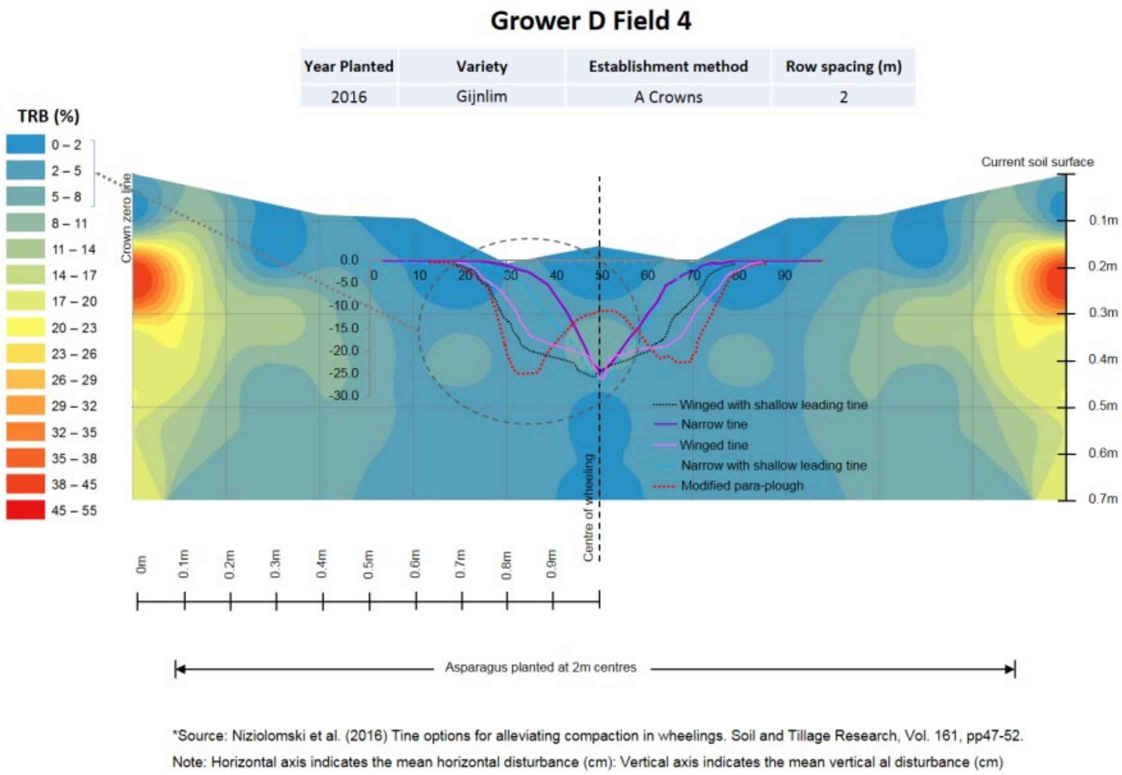


Figure 31. Grower D total root biomass (TRB%) root map for 2yr old Gijnlim A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

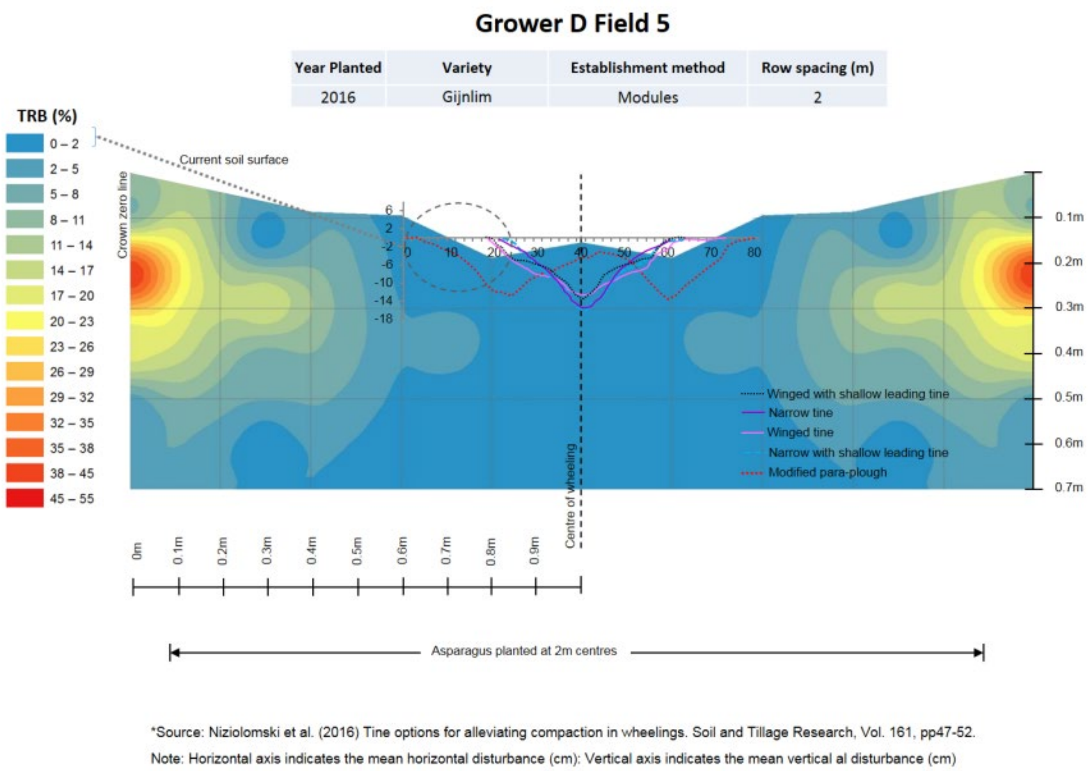


Figure 32. Grower D total root biomass (TRB%) root map for 2yr old Gijnlim modules. Potential root damage associated with sub-soiling operations at 150mm depth.

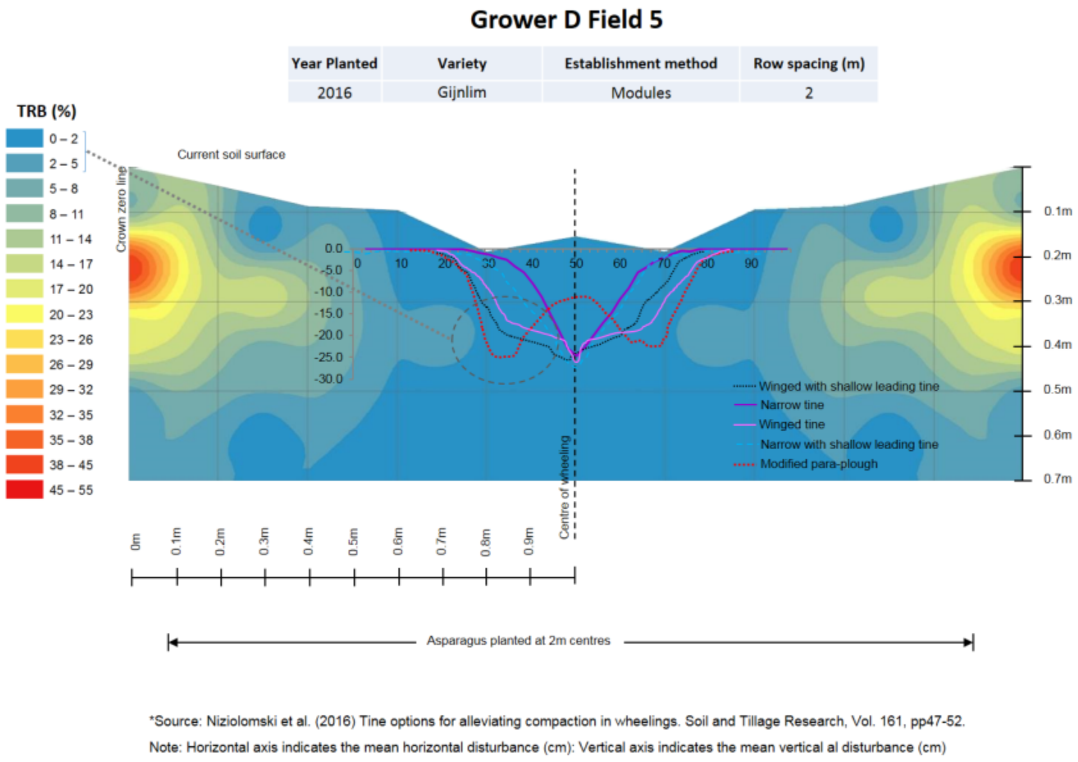


Figure 33. Grower D total root biomass (TRB%) root map for 2yr old Gijnlim modules. Potential root damage associated with sub-soiling operations at 300mm depth.

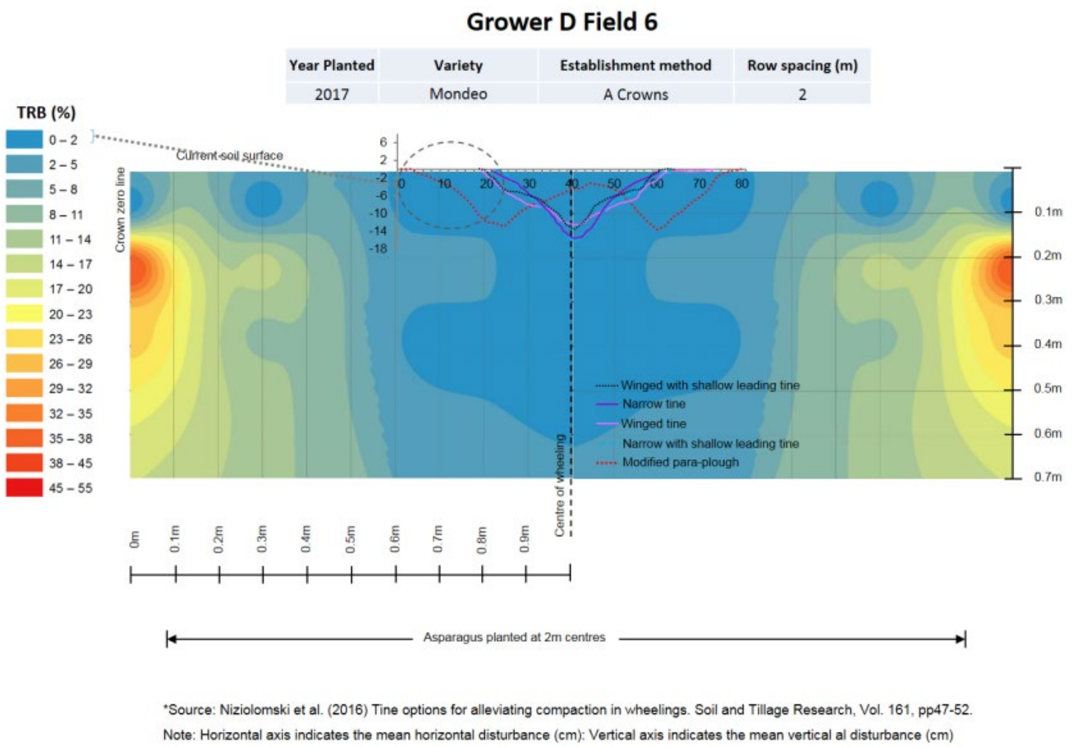


Figure 34. Grower D total root biomass (TRB%) root map for 1yr old Mondeo A-crowns. Potential root damage associated with sub-soiling operations at 150mm depth.

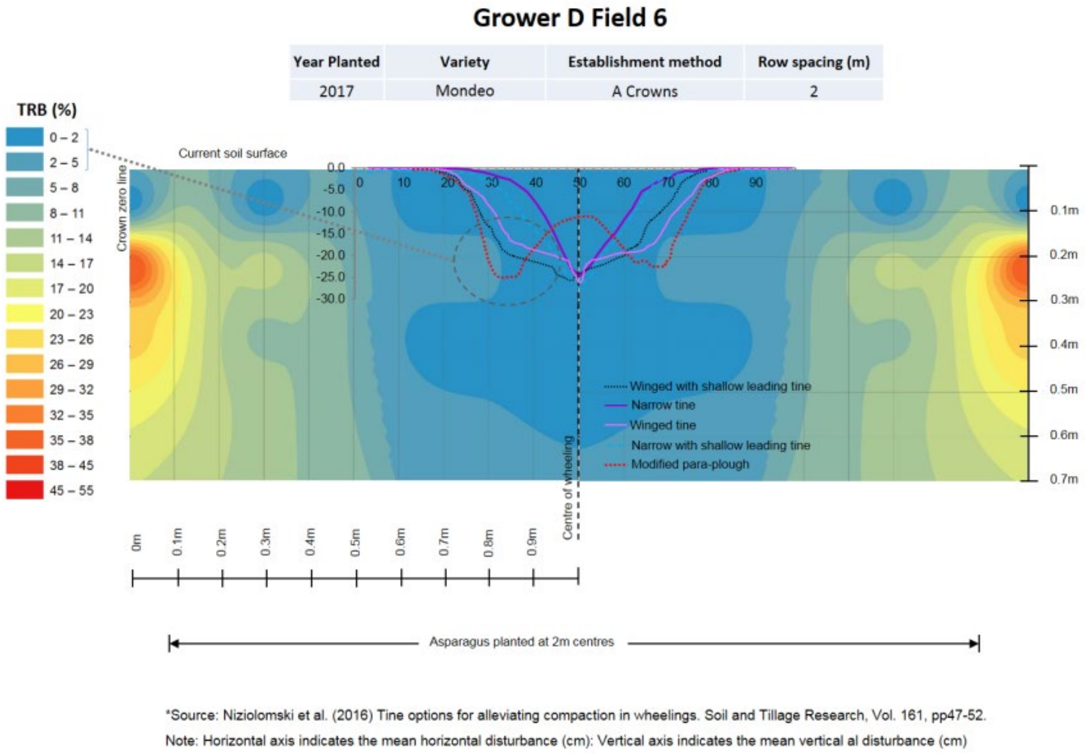


Figure 35. Grower D total root biomass (TRB%) root map for 1yr old Mondeo A-crowns. Potential root damage associated with sub-soiling operations at 300mm depth.

Conclusions

FV 450 Trial 2018 root soluble carbohydrate (CHO) levels – Impact of BMPs

- No significant difference in storage root CHO values was observed between the Gijnlim RyeCC_NR, Gijnlim MustardCC_NR and Guelph Millennium Bare soil_No-SSD_NR treatments (Table 4).
- However, a highly significant ($p < 0.01$) difference in varietal root CHO was observed between the Guelph Millennium and Gijnlim Bare soil_No-SSD_NR treatments with values of 319 and 464 mg g^{-1}, respectively. These 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 of 494 and 512 mg g^{-1} for 2005 and 2007, respectively.

FV 450a Trial 2019 root soluble carbohydrate (CHO) levels – Impact of BMPs:

- No significant differences in asparagus storage root CHO (mg g^{-1}) were observed between BMP treatments. Across all treatments mean pre-harvest storage root CHO values at the CZL ranged from 507 – 631 mg g^{-1}. This is within the upper target range outlined by Wilson et al., (2008) and AHDB (2017) indicating adequate CHO levels for optimum harvest.
- CHO values obtained from Guelph Millennium treatments were significantly ($p < 0.01$) higher as compared to the equivalent for Gijnlim with mean values of 518 and 600 mg g^{-1}, respectively (Table 6). For Guelph Millennium, this exceeds the mean CHO values reported under FV 271 (AHDB, 2007) which were dominated by Gijnlim.

2018 Year 3: Soil structure assessments

- The 2018 soil structural assessments indicate that significant differences in penetrative resistance (PR) are emerging between treatments (Table 7). Specifically, at both 0-5 and 5-10cm depth, the two Cover Crop BMP treatments and the Bare soil_No-SSD treatment both ridged or non-ridged were associated with significantly higher PR as compared with the 2016 Baseline (Table 7 and Figure 9).
- In contrast, to the PR values, no significant difference in bulk density (BD) in the mid-topsoil depth was observed between the 2018 sampling and the 2016 Baseline (Table 7).

Wider Grower Landbank: *Potential impact of sub-soiling and ridging operations on root damage.*

- Across all row spacings, age of stand, varieties, and planting method sampled, annual re-ridging operations if undertaken within 0.3 – 0.4m of the CZL to depths of 0.15m have the potential to damage between 5-14% of the TRB. This has significant implications with regards increasing the risk of crown and root rot (CRR) caused by *Phytophthora megasperma* and *Fusarium oxysporum f. sp. asparagi*. This has wider significance to CHO storage potential as it is truncating root length to <0.4m.

- For asparagus grown on 1.5-1.52m row spacings, across all ages of stand, varieties, and planting method sampled, sub-soiling operations [*to reduce compaction, improve infiltration and enhance green water use efficiency*] undertaken in the centre of the wheeling at 150mm depth using a modified para-plough risk damaging up to 8-11% of the TRB.

- For asparagus grown on 1.5-1.52m row spacings, across all ages of stand, varieties, and planting method sampled, sub-soiling operations undertaken in the centre of the wheeling at 150mm depth using a winged with shallow leading tine, narrow tine, winged tine and narrow shallow leading tines of configurations investigated by Niziolomski et al., (2016) are in general associated with <2% damage to TRB.

- For asparagus grown on 2.0m row spacings, for 2yr old Guelph Millennium and Gijnlim and 1yr old Mondeo planted as modules, sub-soiling operations can be undertaken in the centre of the wheeling from 150-300mm depth using the tines configurations investigated by Niziolomski et al., (2016) with the risk of damaging <2% damage of TRB.

- For Gijnlim planted as A-crowns, on 2.0m row spacing sub-soiling operations e undertaken in the centre of the wheeling from 150-300mm depth using the tines configurations investigated by Niziolomski et al., (2016) risk of damaging 2-5% of TRB.

Knowledge and Technology Transfer

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

1. Project Advisory Group (PAG) Meeting was held (13th February 2019) in order to update and received feedback from PAG members as well as AHDB representatives.

2. Year 2 results were presented at the Asparagus Innovation Day 2018 on the 20th September 2018. Feedback was extremely positive with x3 groups of participants fully engaged around a pre-prepared soil profile. Visualising asparagus roots and discussing the implications of tillage and ridging on root damage and crown and root rots resulted in several growers agreeing to participate in the FV 450a wider grower based root coring programme.

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

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

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

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


AHDB

Asparagus root growth patterns

Glossary

BD	Bulk density
BMPs	Best Management Practices
MPP	Modified Para-plough
NSLT	Narrow tine with shallow leading tines
NT	Narrow tine
PAG	Principal Asparagus Growers
PR	Penetrative resistance
PSD	Particle size distribution
RMD	Root Mass Density
%TRB	Percentage Total Root Biomass
SOM	Soil organic matter
TOC	Total organic carbon
VESS	Visual Evaluation of Soil Structure
VSA	Visual Soil Assessment
WSLT	Winged tine with shallow leading tines
WT	Winged tine

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Appendices

Appendix 1: Total Root Biomass (TRB%) root maps.

Appendix 1

Grower A Field 9

Year Planted	Variety	Establishment method	Row spacing (m)
2017	Mondeo	Modules	1.5

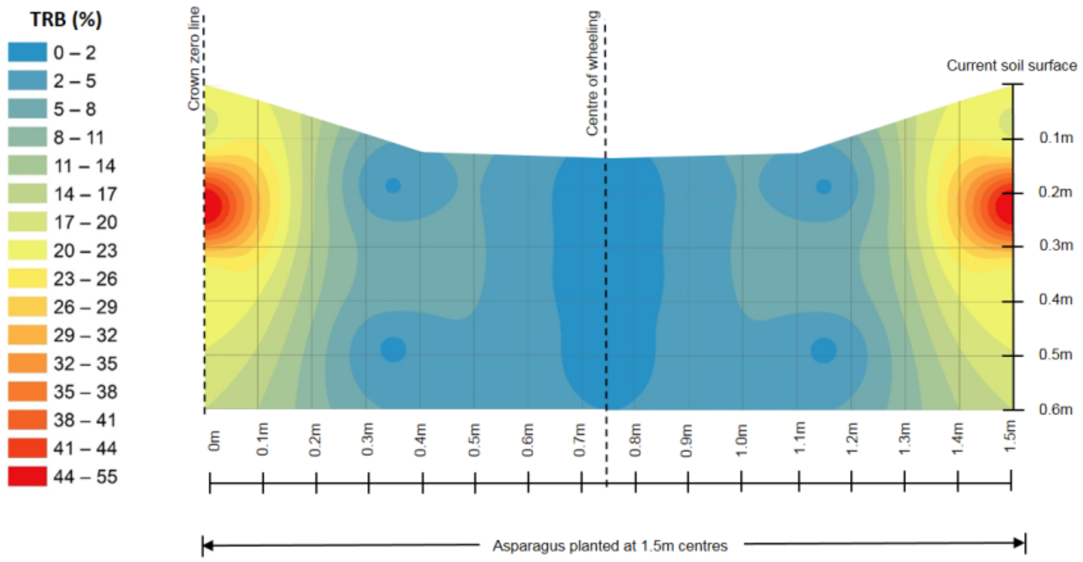

Figure A-1. Grower A total root biomass (TRB%) root map for 1yr old Mondeo planted as Modules at a planting density of 40,000 crowns ha^{-1}, on 1.5m row spacing.

Grower A Field 8

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Guelph Millennium	A Crowns	1.5

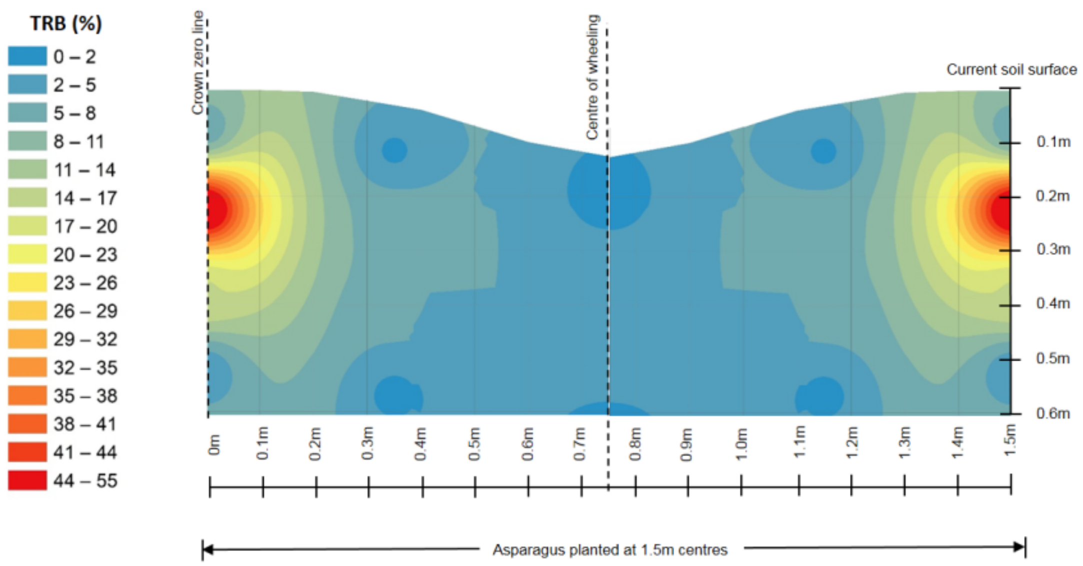

Figure A-2. Grower A total root biomass (TRB%) root map for 2yr old Guelph Millennium planted as A-crowns at a planting density of 40,000 crowns ha^{-1}, on 1.5m row spacing.

Grower A Field 7

Year Planted	Variety	Establishment method	Row spacing (m)
2015	Mondeo	A Crowns	1.5

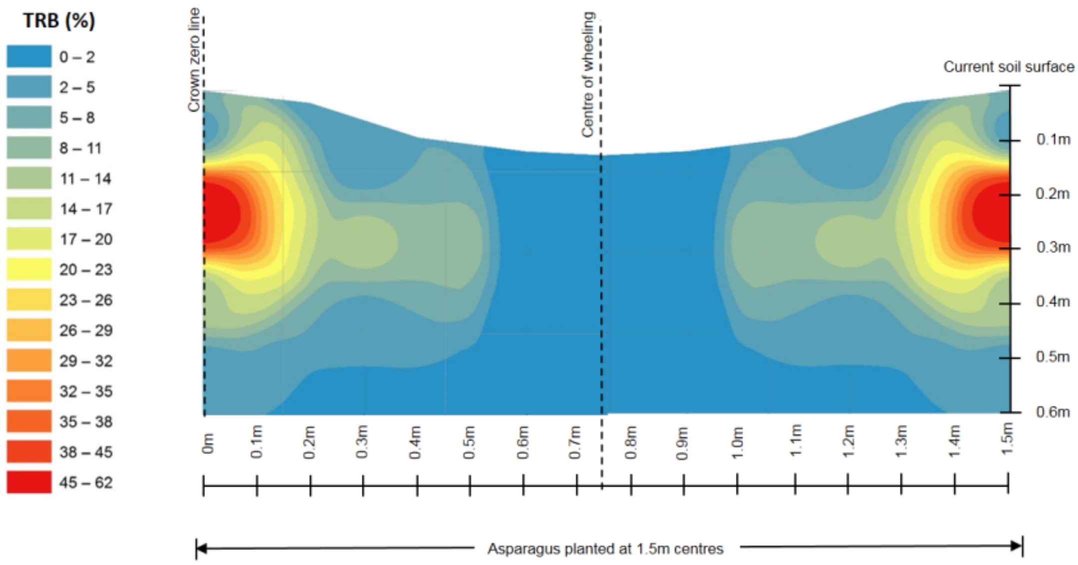

Figure A-3. Grower A total root biomass (TRB%) root map for 3yr old Mondeo planted as A-crowns at a planting density of 30,000 crowns ha^{-1}, on 1.5m row spacing.

Grower A Field 6

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Guelph Millennium	A Crowns	1.5

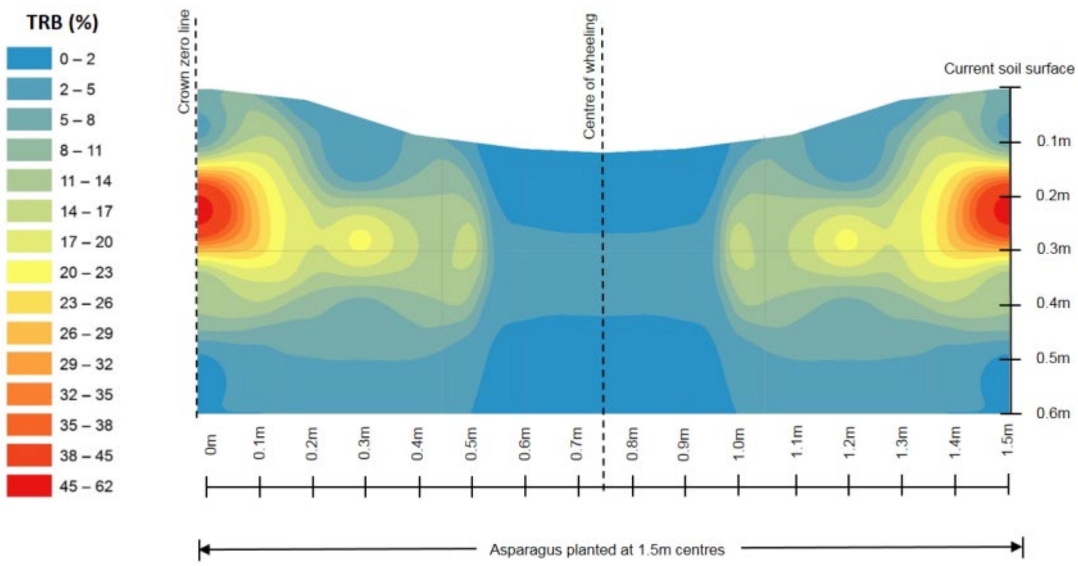

Figure A-4. Grower A total root biomass (TRB%) root map for 4yr old Guelph Millennium planted as A-crowns at a planting density of 31,000 crowns ha^{-1}, on 1.5m row spacing.

Grower A Field 5

Year Planted	Variety	Establishment method	Row spacing (m)
2013	Guelph Millennium	A Crowns	1.5

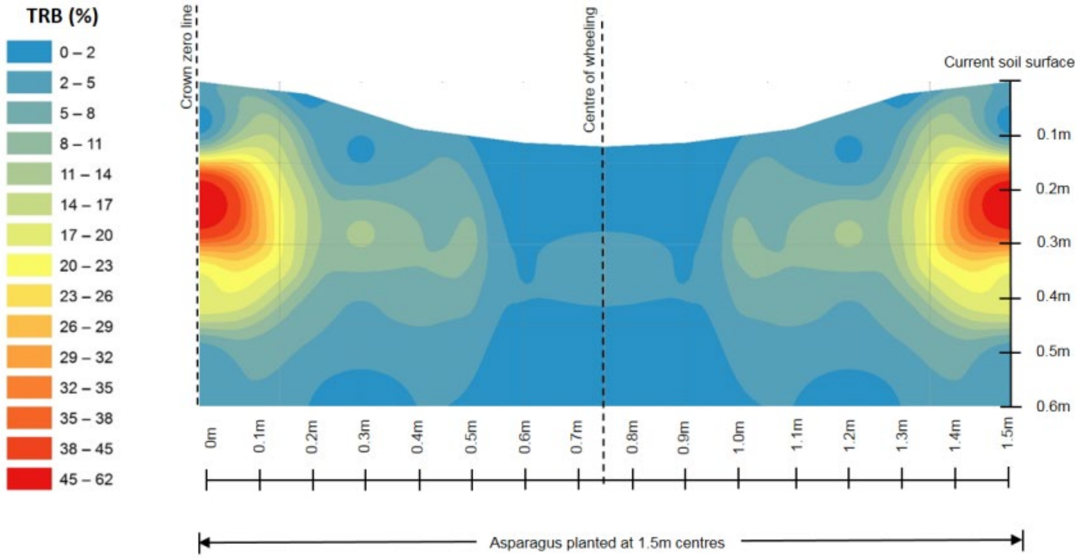

Figure A-5. Grower A total root biomass (TRB%) root map for 5yr old Guelph Millennium planted as A-crowns at a planting density of 35,000 crowns ha^{-1}, on 1.5m row spacing.

Grower B Field 1

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Gijnlim	A Crowns	1.52

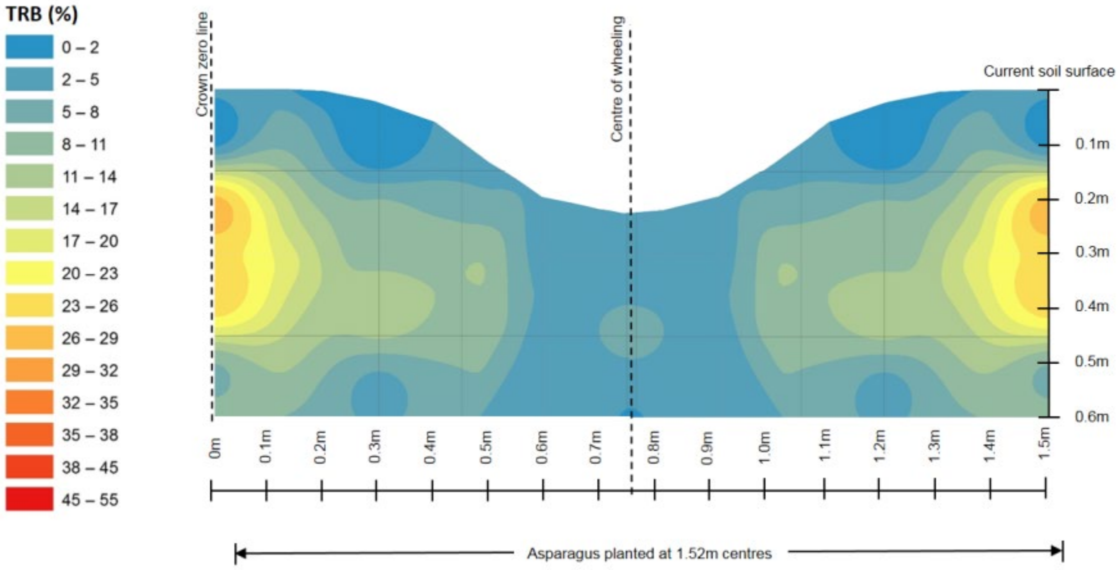

Figure A-6. Grower B total root biomass (TRB%) root map for 2yr old Gijnlim planted as A-crowns at a planting density of 30,000 crowns ha^{-1}, on 1.52m row spacing.

Grower B Field 2

Year Planted	Variety	Establishment method	Row spacing (m)
2014	Gijnlim	A Crowns	1.52

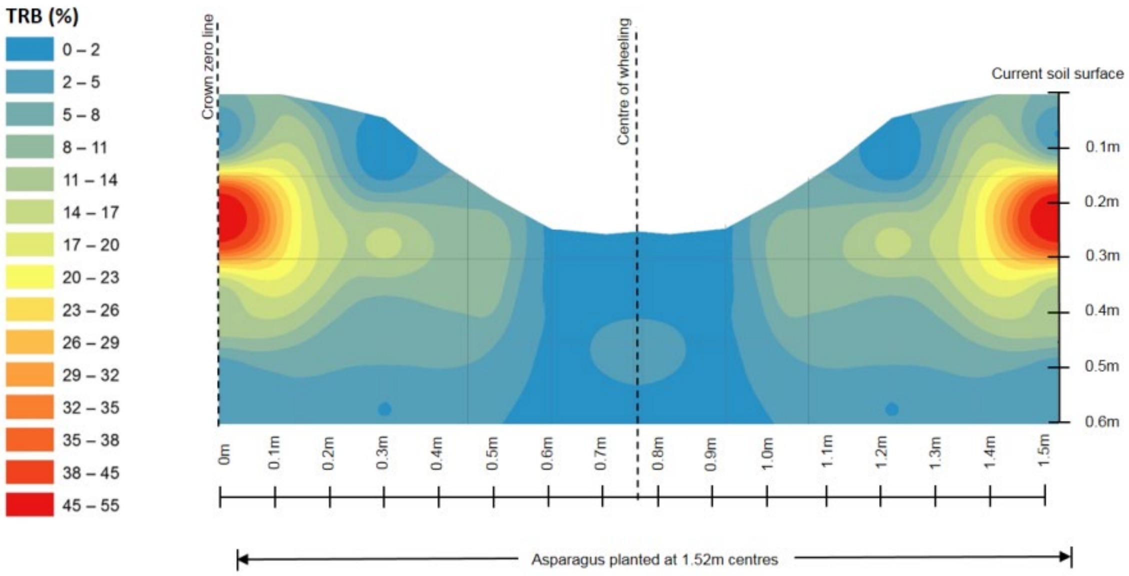

Figure A-7. Grower B total root biomass (TRB%) root map for 4yr old Gijnlim planted as A-crowns at a planting density of 30,000 crowns ha^{-1}, on 1.52m row spacing.

Grower D Field 2

Year Planted	Variety	Establishment method	Row spacing (m)
2016	Guelph Millennium	Modules	2

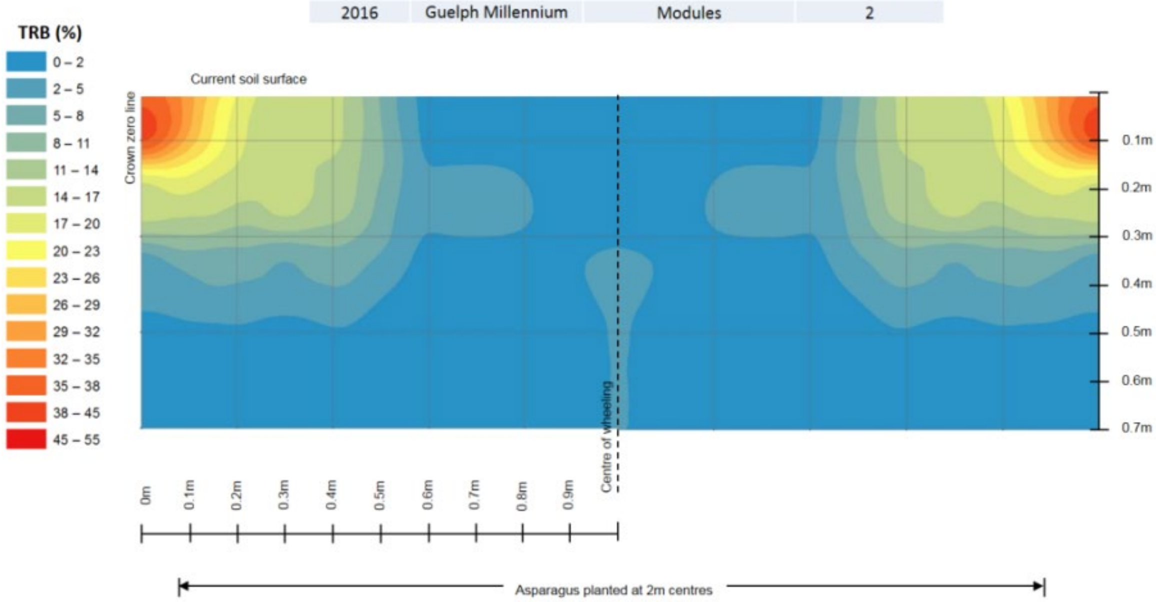

Figure A-8. Grower D total root biomass (TRB%) root map for 2yr old Guelph Millennium planted as modules at a planting density of 33,000 modules ha^{-1}, on 2.0m row spacing.

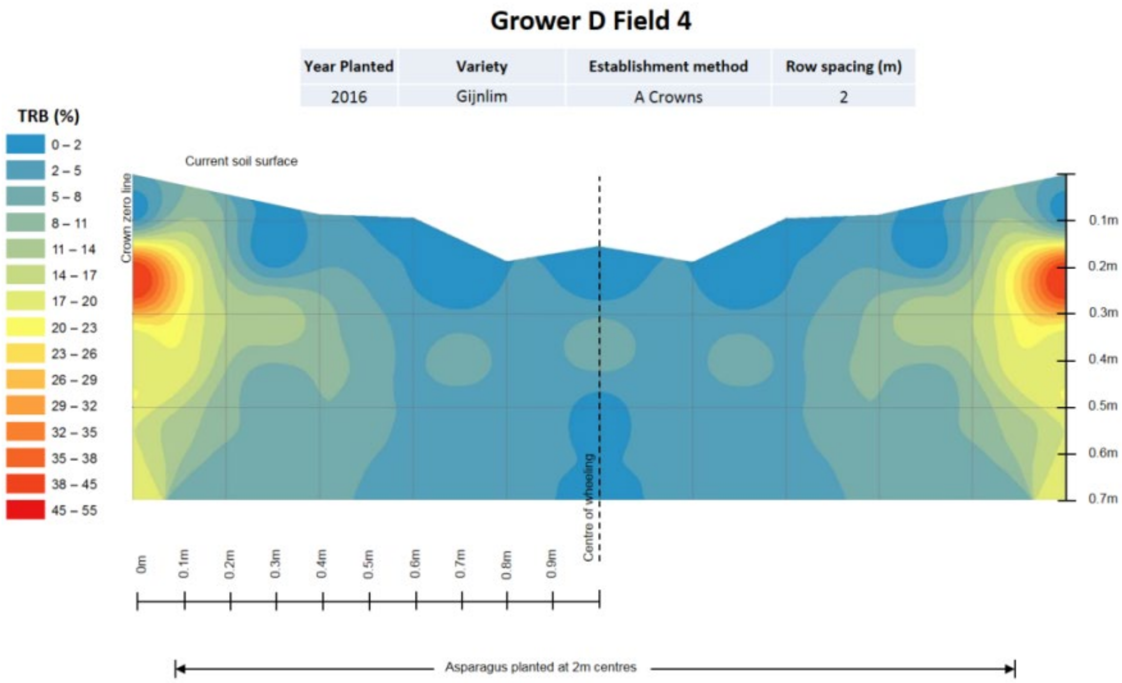

Figure A-9. Grower D total root biomass (TRB%) profile for 2yr old Gijnlim planted as A-crowns at a planting density of 28,500 crowns ha^{-1}, on 2.0m row spacing.

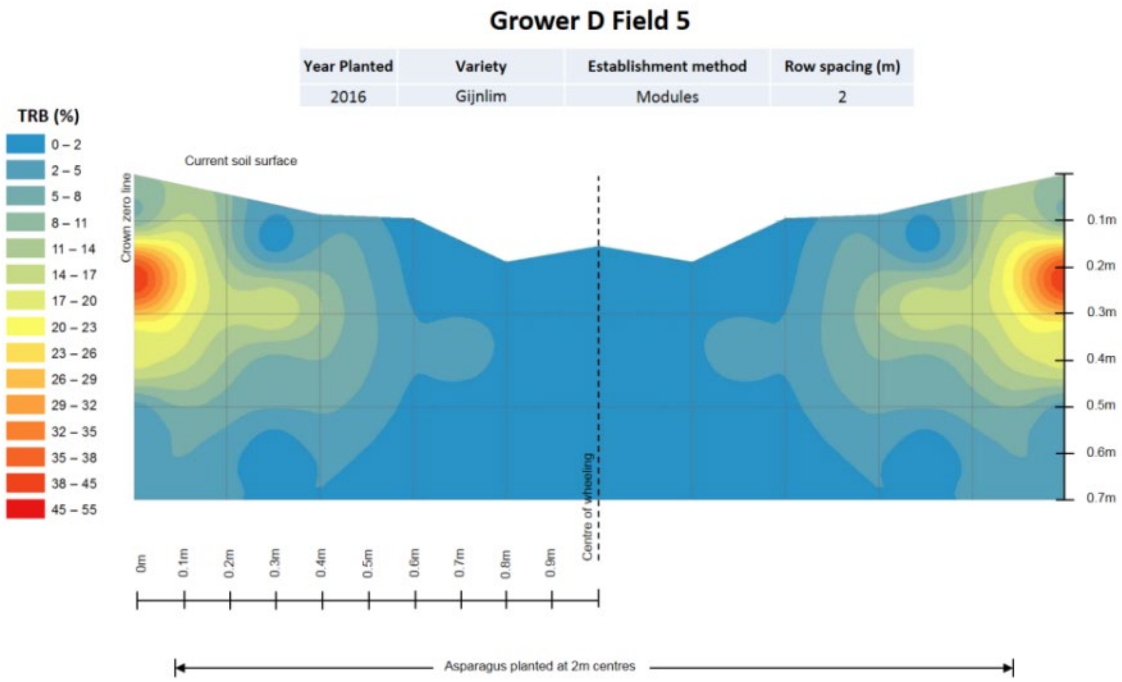

Figure A-10. Grower D total root biomass (TRB%) profile for 2yr old Gijnlim planted as modules at a planting density of 28,500 modules ha^{-1}, on 2.0m row spacing.

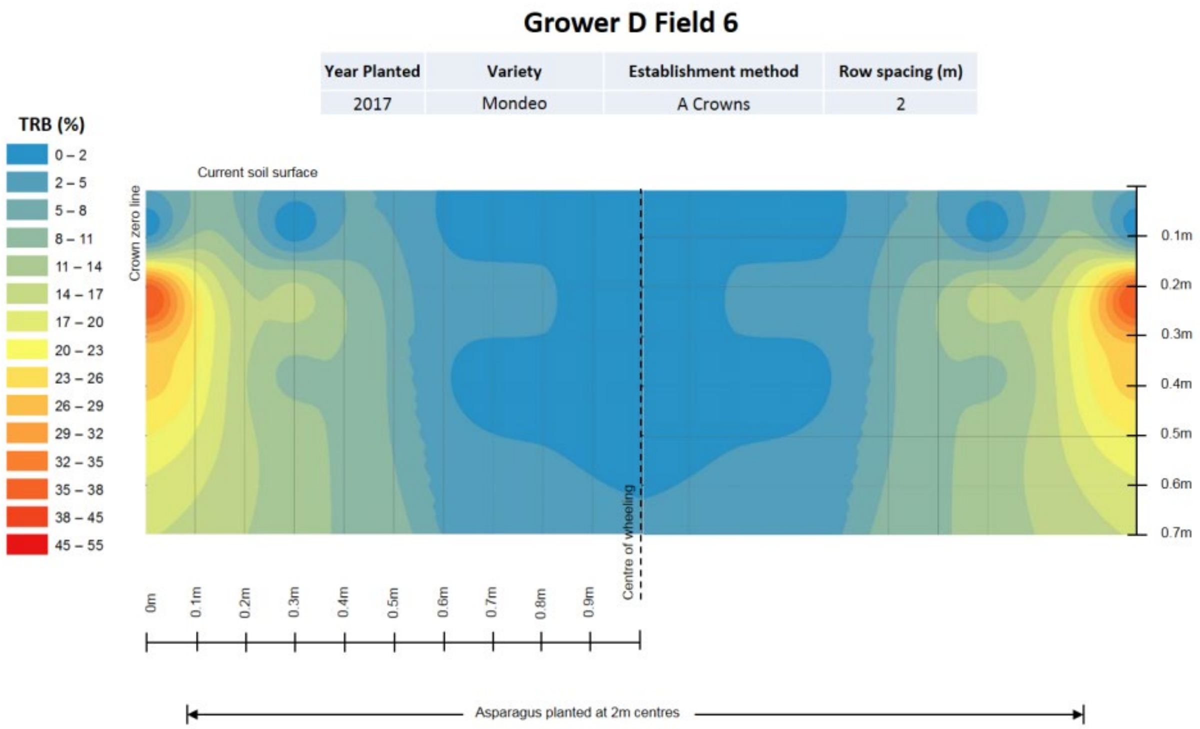

Figure A-11. Grower D total root biomass (TRB%) profile for 1yr old Mondeo planted as A-crowns at a planting density of 28,500 crowns ha^{-1}, on 2.0m row spacing.

