Project title:	**Asparagus: Sustainable soil management for stand longevity and yield optimization**
Project number:	FV 450
Project leader:	Dr Rob Simmons, Cranfield University
Report:	Final Report, April 2018
Previous report:	Year 1 Annual Report, May 2017
Key staff:	Dr Sarah De Baets and Dr Joanna Niziolomski, Cranfield University
Location of project:	Gatsford, Ross-on-Wye
Industry Representative:	Neil Cairns, Barfoots of Botley Ltd Sefter Farm, Pagham Road Bognor Regis, West Sussex PO21 3PX
Date project commenced:	01 May 2016
Date project completed (or expected completion date):	30 April 2018

DISCLAIMER

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.

Dr Robert Simmons

Senior Lecturer Sustainable Soil Management

Cranfield University

Signature .... Date ....30-04-18............

Dr Sarah De Baets

Lecturer in Plant Systems

Cranfield University

Signature .... Date ....30-04-18................

Report authorised by:

Prof. Andrew Thompson

Head of Cranfield Soil and Agrifood Institute

Cranfield University

Signature .... Date ....28th Nov. 2018................

CONTENTS

GROWER SUMMARY

Headlines

- Findings indicate a strong trend for Gijnlim roots to expand more into the wheeling than Guelph Millennium. However, no significant differences in the spatial distribution of root mass densities were observed between Gijnlim and Guelph Millennium varieties in a two-year old asparagus stand.
- Although yield data indicates that re-ridging does not reduce yield for either variety, growers are strongly advised to undertake exploratory root profile distribution surveys before undertaking tillage operations. Results suggest that for wheelings on 1.83 m centres, subsoiling operations to 0.3 m depth are safe to undertake where either rye or mustard companion crops are grown. However, in a two-year old asparagus stand there is a risk of damaging 2-5% of the total root mass when sub-soiling in the wheelings at 0.175 cm depth for Guelph Millennium and at 0.3 m depth for Gijnlim.
- Rye or mustard companion crops seem to restrict the development of asparagus storage roots to the ridge zone, with less root growth in the surface (< 0.15 m) of wheelings. The rye/no-Shallow Soil Disturbance (SSD) / non-ridged treatment yielded significantly lower (18.9 – 28.5%) than the mustard/no-SSD/ridged, PAS 100 compost/SSD and straw mulch/SSD, both ridged and non-ridged, bare soil/SSD/non-ridged and bare soil/no-SSD/non-ridged treatments, respectively. The reduction in yield associated with the non-ridged rye no-SSD treatment contrasts strongly with findings of North America asparagus growers and warrants further investigation under FV 450a.

Background

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

In addition, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and productivity (Drost & Wilcox-Lee, 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) and increases the susceptibility to crown and root rots caused by *Phytophthora megasperma* (Falloon & Grogan 1991) and *Fusarium oxysporum* f.sp. *asparagi* (Elmer, 2001). 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, 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 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 will compare shallow soil disturbance (SSD) and mulch attenuation options, cover/companion cropping, and non-till options against conventional practice.

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.

Experiment 1 (48 experimental plots) is restricted to Gijnlim which represents 70% of UK field grown asparagus. Shallow soil disturbance (SSD) was applied on 20 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) will be 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.

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). Treatments highlighted in green will be included in Experiment 2.

The mulch treatments were also applied on 20 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. Companion crops included in this trial were rye (*Cereale secale* L var. Protector) and mustard (*Sinapis alba* L. var. Severka) seeded on 10 August 2017 at rates of 150 kg ha^{-1} and 19 kg ha^{-1}, respectively. Companion crops were applied to the central wheeling only. The efficacy of these rates for run-off and erosion mitigation were confirmed by an MSc project linked to this research (Órpez Milán, 2017). 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: 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). Treatments highlighted in green are included from Experiment 1.

Re-ridging versus non-ridging (zero) treatments were applied to both Experiment 1 and Experiment 2 in April 2018 and will be evaluated in project FV 450a. Baseline soil sampling undertaken during 17th – 21st October and 1st – 3rd November 2016 indicated that there was no significant difference in the parameters tested (Reference page 7-8) between experimental plots. This is critical as it means that any differences observed can in future, be attributed to the best management practice treatments applied.

Comparison of root architecture for two asparagus varieties

Baseline root coring in Year 1 indicated that root mass densities (RMD) are generally higher for Gijnlim as compared to Guelph Millennium for most soil depths and sample locations. However, no significant differences between varieties were detected in the overall spatial distribution of storage roots. For both varieties, one year after planting, about 65% of the total measured plant root mass is found at the crown zero line (central line of ridge Figure A) near the surface at 0 - 0.15 m depth. Very few roots have explored the soil at 0.3 m, 0.6 m and 0.9 m away from the crown zero line. Further away from the crown zero line, roots tend to be mostly in the 0.15 – 0.30 m and 0.3 - 0.45 m soil layers and avoid the topsoil (0.0 - 0.15 m).

For both varieties, no roots were detected in any of the root cores (0 – 0.45m depth) taken 0.9 m away from the crown zero line. When the dimensions of the re-ridged bed-form are superimposed on the baseline varietal root distribution, the results indicate that for both Guelph Millennium and Gijnlim after 1-year of growth, there is a risk of damaging 7-9% of total root biomass if the rotating tines of the bed-former used were to till soil in the 0.15 - 0.3 m depth zone within 0.3 m of the crown zero line. In addition, for Guelph Millennium there is a risk of damaging 2% of total plant root biomass if the rotating tines of the bed-former till soil in the 0.0 - 0.15 m depth zone within 0.3 m of the crown zero line. The year-one field trial results indicate that due to the absence of storage roots for both Gijnlim and Guelph Millennium, sub-soiling operations (for the control of run-off and erosion) could be undertaken at operating depths of 0.175 – 0.3 m, where crowns are planted on 1.83 m centres.

It is of note that the high Penetrative Resistance measurements (PR value >3 MPa) observed in the upper sub-soil during the baseline sampling could impact asparagus root development. The observed high Bulk Density (BD) measurements (>1.45 g cm^{-3}) in the mid top-soil and more notably in the upper sub-soil are likely to impede root growth (Jones, 1983). Historically, asparagus roots have been observed in soils with PR values of 1.96 MPa and 2.9 MPa (Reijerink, 1973). However, the limiting values of PR and BD for the expansion of the asparagus storage root system and hence ability to store total carbohydrates (COH) is unknown.

Results from Year 2 root sampling showed that for both Gijnlim and Guelph Millennium, the average root mass densities (RMD) at the crown zero line for the 0.15 – 0.3 m depth increased significantly from 8-12 kg m^{-3} in Year 1 up to ca. 20 kg m^{-3} in Year 2.

Year 2 results continue to indicate that Gijnlim roots expand more into the wheeling as compared to Guelph Millennium, although Guelph Millennium roots are found closest to the surface in the inter-row zone. These observed varietal differences are not, however, statistically significant. This trend will be further monitored under FV540a.

Year 2 root maps comparing the spatial distribution of the root mass for Gijnlim crops grown with and without companion crops in the wheelings indicate that the presence of the companion crop seems to restrict the asparagus storage roots to the ridge zone (crown zero line). This is particularly apparent 0.6-0.9 m from the zero crown line at 0.15 – 0.3 m depth. With companion crops growing in the wheeling the wheeling zone shows lower densities of asparagus roots. The results indicate that on average the Gijnlim without companion crops had greater RMD at 0.6 m and 0.9 m from the crown zero line as compared to the companion crop treatments. This trend will continue to be monitored under FV 450a.

Year 2 varietal root distributions indicate that for Gijnlim there is a risk of damaging <2% of total plant root biomass if the rotating tines of the bed-former till soil to 0.15 m depth within 0.3 m and 0.6 m of the crown zero line. For Gijnlim, if ridging tines disturb soil at 0.15 – 0.30 m depth, 0.3 and 0.6 m from the crown zero line there is a risk of damaging *circa* 6% and 2-5% of total plant root biomass respectively (Figure A).

For Guelph Millennium there is also a risk of damaging <2% and 2.2% of total plant root biomass if the rotating tines of the bed-former till soil to <0.15 m depth within 0.3 m and 0.6 m of the crown zero line. If ridging tines disturb soil at 0.15 – 0.30 m depth, 0.3 and 0.6 m from the crown zero line there is a risk of damaging *circa* 5% and 2-5% of total plant root biomass respectively.

The Year 2 results indicate that for Gijnlim, sub-soiling operations to 0.175 m depth with a full range of tine configuration options (Niziolomski et al. 2016) can continue to be undertaken with potential to damage <2.0% of total plant root biomass. In contrast, the root profile distribution of Guelph Millennium suggests that a modified para-plough (Niziolomski et al. 2016) should not be utilised at 0.175 m depth as this has the potential to damage 2-5% of roots at 0-0.15 m depth 0.6 m from the crown zero line.

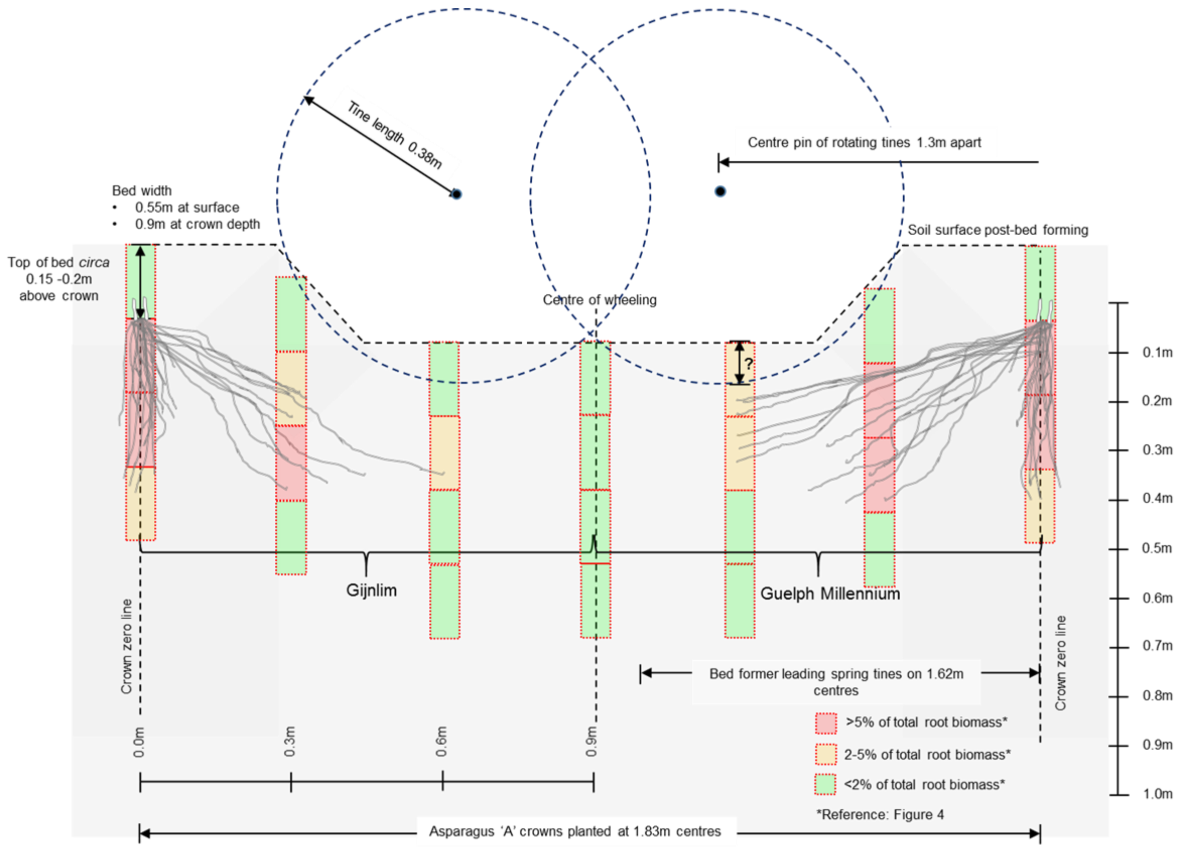


Figure A. Potential root damage associated with annual re-ridging operations, 2 years after planting

At a sub-soiling depth of 0.3 m, neither the modified para-plough or a winged tine of dimensions/configuration investigated by Niziolomski et al. (2016) should be utilised as the below ground disturbance patterns intersect roots within the 0.15-0.30 m depth 0.6 m from the crown zero line suggesting damage to 2-5% of total plant root biomass, both for Gijnlim and for Guelph Millennium.

As stated above, Year 2 root maps comparing the spatial distribution of the root mass for Gijnlim crops grown with and without companion crops in the wheelings show that the presence of the companion crop appears to restrict the asparagus storage roots to the ridge zone (crown zero line- 0.3 m). This is particularly apparent 0.6-0.9 m from the zero crown line at 0.15 – 0.3 m depth. At 0.6 m and 0.9 m away from the crown, the proportions of total root mass stay below 2% for the plots with companion crops, whereas the plots without cover had 2-5% of total root mass present in some of these wheeling positions.

For Gijnlim, this has implications in terms of reducing potential root damage associated with subsoiling (to reduce erosion risk through improved infiltration, surface roughness and surface depression storage) at both 0.175 and 0.3 m depth as root development in the 0-0.15 m and 0.15-0.30 m depth 0.6m from the crown zero line is reduced.

This also implies that when asparagus is undersown with either rye or mustard companion crops sub-soiling operations to 0.3 m depth with a full range of tine configuration options (Niziolomski et al. 2016) can be undertaken with the potential to damage <2.0% of total plant root biomass.

However, it is still strongly recommended that growers undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations. Training in root sampling will be provided to growers under FV 450a.

The results of the MSc Thesis (Lee, 2017) indicate that root growth is inhibited under the wheeling due to compaction and probably also due to tillage operations. Correlation analysis showed that there was a significant ($p<0.05$) negative but weak correlation between root mass distribution and soil PR data integrated for the same soil depth intervals and positions; r^2=-0.183. This was a pioneer study, only based on 5 fields. More work is needed to provide a more robust picture of root mass density distribution for different asparagus varieties, stand ages, management practices and soil types. This will be a core objective in FV 450a.

In 2018 a short 4-week (April 24th to May 21st) harvest from 19-cuts was taken from the experimental plots by George Nairn (Cobrey Farms). For Experiment 1 (Gijnlim), Mean (n=19) spear count, Total Harvest (kg per plot^{-1}) and Estimated Yield (kg ha^{-1}) were recorded. For the varietal component of the FV 450 trial (Experiment 2), average spear weight, Total Harvest and Estimated Yield were recorded for both Gijnlim and Guelph Millennium.

With the exception of the rye No-SSD ridged as compared with the non-ridged treatment, ridging did not result in any significant difference ($p > 0.1$) in yield for the BMPs evaluated in this trial. However, it is of note that rye No-SSD ridged and non-ridged Total Harvest and Estimated Yield values are 43.0 and 33.5 (kg per plot^{-1}) and 2984 and 2327 (kg ha^{-1}), respectively. This equates to a 22% reduction in yield for the non-ridged as compared with ridged rye No-SSD treatments.

Further, and critically, the rye No-SSD non-ridged Estimated Yield (kg ha^{-1}) is significantly, 18.9%, 23.3%, 28.5%, 25.3%, 19.0%, 19.5% and 24.7% lower than the mustard No-SSD ridged, PAS 100 Compost_SSD and Straw Mulch_SSD ridged and non-ridged, Bare soil_SSD non-ridged and Bare soil_No-SSD non-ridged treatments, respectively (Table Y).

This reduction in yield associated with the non-ridged rye No-SSD treatment is contrary to findings of North America asparagus growers (Personal Communication: Prof. Dan Drost) and may in part be due to the continued release of allelopathic exudates from non-ridged rye roots in wheelings not destroyed by the action of re-ridging. This will require further investigation.

PAS 100 compost SSD non-ridged total harvest (kg per plot^{-1}) and estimated yield (kg ha^{-1}) values of 46.9 kg per plot^{-1} and 3255 kg ha^{-1} are significantly ($p < 0.1$) higher compared to the mustard no-SSD non-ridged, rye no-SSD non-ridged, bare soil SSD ridged and bare soil no-SSD ridged treatments respectively.

Varietal yield results for the two year stand indicate that Guelph Millennium yields significantly lower (16 – 31%) than equivalent Gijnlim treatments. The Guelph Millennium, bare soil no-SSD ridged, bare soil no-SSD non-ridged, bare soil-SSD ridged, Bare soil SSD non-ridged treatments are associated with 16%, 31%, 23% and 27.3% lower Total Harvest and Estimated Yield (kg ha^{-1}) as compared with the equivalent Gijnlim treatments. However, growers consulted state that it is normal for Guelph Millennium to be associated with significantly lower yields than Gijnlim in early establishment years and that yields catch up in later years.

It is expected that the continuation of the long-term trials under FV 450a will form an evidence base for a paradigm shift in the way asparagus is cultivated in the UK, particularly the need for, and intensity of, annual re-ridging operations and the efficacy of a suite of BMPs to remediate compaction and their selection to avoid root damage. Minimizing root damage is known to contribute to stand longevity and productivity and decreases the susceptibility to crown and root rot.

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 (an important consideration for growers considering GAEC greening rules, the needs of assurance schemes, environmental audits and demonstrating sustainable soil management).

- During 2005 – 2015 the area under asparagus cultivation in the UK increased from 890 – 2235 ha (>250%). 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* 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.
- Improved ability of UK growers to meet customer (supermarket) demand during the British asparagus season.

Action Points

This is only the 2nd year of this long-term replicated field trial now continued under FV 450a. The results support the recommendation that in order to prevent storage root damage through re-ridging operations or SSD, growers should undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations.

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 yrs 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 there 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 BMPs investigated in the study on Key Performance Indicators (KPIs).

Materials and methods

Establishment of 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. Prior to trial establishment, during the 17-18th of April 2016, Poultry Manure, PAS 100 Compost and Limex 70 were applied to the whole field at rates of 25 t ha^{-1}, 28.5 t ha^{-1} and 5.5 t ha^{-1}, respectively. Subsequently, the field was rotovated, ploughed, and sub-soiled to a depth of 0.14m, 0.3m and 0.45m, respectively. Immediately prior to planting the asparagus, the plots were power-harrowed to a depth of 0.15m. Asparagus 'A' crowns were planted on 20-21st of April 2016 on the flat at an anticipated depth of 0.14m with a 0.16m spacing between crowns on 1.83m wide bed centres.

In both experiments, experimental plots are 40 m long and comprise of two asparagus beds equating to a field trial of approximately 0.5 ha [not including guard rows/areas between treatments and the main crop]. Conventional pesticide treatments have been applied to all trial plots in 2016, 2017 and 2018.

Following a visit by the PAG to the field trial in December 2016, it was agreed that due to the shallow depth (circa 0.06m) of soil above crown and not the anticipated 0.14m that all treatments would be re-ridged in the spring of 2017. This was carried out on the 22nd of April 2017. Consequently, it was agreed that the Zero non-ridging (non-R) treatment would be implemented from Spring 2018 onwards. The Non-R treatment was implemented in April 2018. The Mulch and SSD treatments (Table 1) were applied on the 20th of April 2018. Images of the treatment imposed in April 2018 are shown in Figure 1.

- PAS 100 QP compliant compost was applied to 3 wheelings per treatment (central wheeling and guard rows) at a rate of 25 t ha^{-1}.

- Straw applied to 3 wheelings per treatment (central wheeling and guard rows) at 6 t ha^{-1}.
- SSD was applied using a winged tine to 250-300mm depth (Niziolomski et al., 2016) with occasional asparagus root damage observed behind the tine.
- Details of the companion crops treatments are outlined in the *Cover crop selection and seeding rates* section below

As noted in the Year 1 FV 450 Annual Report, Experiment 1 could not be established as a full factorial design as the number of factorial combinations and subsequent experimental replicates would be prohibitive. Consequently, a General Liner Model based on a nested design was adopted. Experiment 1 is restricted to Gijnlim variety which represents 70% of UK field grown asparagus. SSD is included in those treatments to which mulch (PAS 100 Compost or Straw) will be applied. The principal 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. A total of 48 experimental replicates (replicated in quadruplicate) have been established under the main experiment (Table 1).

Table 1. Experiment 1: Treatments to be included in field trials

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 non-ridging (Non-R). Treatments highlighted in green will be included in Experiment 2. These treatments were confirmed during the PAG Meeting on 6th December 2016.

Figure 1: Mulch and SSD treatments applied on the 20th of April 2018.

Bare soil_No-SSD Annual Re-ridging (R)

Bare soil_SSD Annual Re-ridging (R)

PAS 100_SSD Annual re-ridging (R)

PAS 100_SSD Zero re-ridging (Non-R)

Figure 1 Cont. Mulch and SSD treatments applied on the 20th of April 2018.

 Companion crop: rye Annual re-ridging (R)	 Companion crop: rye Zero re-ridging (Non-R)
 Straw Mulch_SSD Zero re-ridging (Non-R)	 Companion crop: Mustard (Non-R)

Experiment 1: *Critical evaluation of BMPs (48 experimental plots)*

Sub-objectives:

1. Critically investigate and quantify the efficacy of selected BMPs to prevent and/or remediate compaction in asparagus wheelings.
2. Quantify the effect of BMPs on asparagus root architecture and root profile distribution.
3. Quantify the efficacy of BMPs to reduce runoff and erosion from asparagus wheelings and asses policy implications.
4. Quantify the effect of BMPs on asparagus yield and spear size

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). Experiment 2 is established adjacent to Experiment 1 and is a cost effective way (16 additional experimental plots) of incorporating two experimental programmes within a single field trial.

Table 2. Proposed experimental treatments to be included in field trials

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 non-ridging (Non-R). Treatments in green will be included in Experiment 2. These treatments were confirmed during the PAG Meeting on 6th December 2016.

Experiment 2: *Varietal trials (16 additional experimental plots)*

Sub-objective:

5. *Critically evaluate varietal differences in root response to annual re-ridging vs zero tillage and SSD.*

Under both experiments, Key Performance Indicators (KPIs) are sub-divided into i) Soil compaction and structural status [bulk density, penetrative resistance, soil structural assessment (VSA/VESS), infiltration rate]; ii) Crop Response [root development/architecture and root profile distribution]; iii) Asparagus yield and spear size**; iv) Environmental Impacts [time to runoff initiation, runoff rate, runoff volume and soil loss]*

*Note: *At the PAG meeting in December 2016, it was agreed that due to the topography of the field site, rainfall/runoff will not be measured directly. This will be replaced by replicated measures of infiltration**. Further, it was agreed that asparagus yield and yield quality indicators will evaluated from 2018 harvest onwards. The 2018 yield and yield quality data will be presented as an addendum to this Final Report.*

Baseline soil sampling

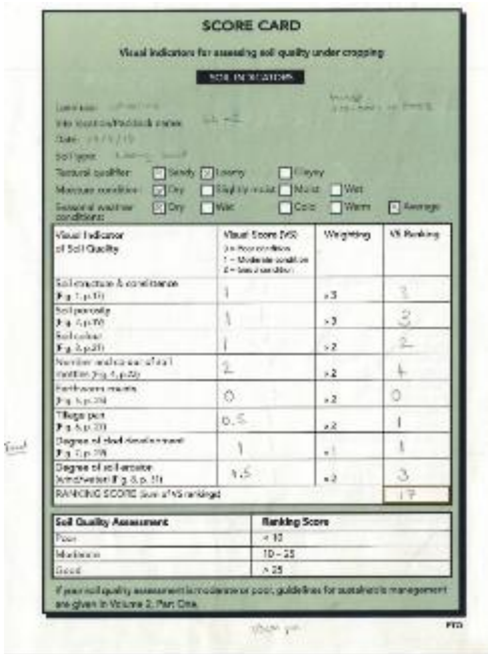
To ensure close alignment with CP 107a: Soils - Improved Sustainable Management for Horticultural Crops the method to assess soil compaction and structural status will largely follow the CP107a methodology. However, in contrast to the CP107a methodology field sampling will be carried out in wheelings. This differentiation is critical in order to understand the effect of wheeling compaction on asparagus root architecture and the 3D distribution of roots within wheelings as affected by the BMPs imposed in this long-term trial (Objective 3).

Baseline soil sampling was undertaken during 17th – 21st October and 1st – 3rd November 2016. A digital Eijkelkamp Penetrologger with a 1.2 cm^2 30° internal angle cone was used to determine penetrative resistance (PR). For each of the 64 experimental plots, six PR profile measurements (at 0.01m intervals to a depth of 0.5m) were taken along the centre of the wheeling along the length of the treatments (at 5.0m intervals). Subsequently, for each plot, BD cores (0.05m depth x 0.05m internal diameter) were taken at two depths mid-topsoil (0.20 - 0.25m) and upper sub-soil (0.45 - 0.50m). Topsoil and subsoil were defined following a soil survey undertaken at the trial site. For each experimental plot, BD cores were taken at the location of the minimum, maximum and median profile PR.

In addition, for each experimental plot, a 6 point (0 – 0.2m) 2.0 kg composite soil sample was collected for subsequent determination of (Total-N, available-P, pH, Soil Organic Matter (SOM), Total Carbon and particle size distribution (PSD)). The results of the baseline soil sampling were presented in the Year 1 Report and will not be repeated here. (https://horticulture.ahdb.org.uk/project/asparagus-sustainable-soil-management-stand-longevity-and-yield-optimization).

Baseline soil structural assessments

Baseline soil structural surveys were undertaken between the 19th -21st July 2017 on 12 randomly selected baseline plots, representing 19 % of the trial plots. At each of the selected plots, soil structure was assessed at 2, 7 and 12 m from the Northern edge of the treatment plot. Top soil structure (0-0.3 m) was assessed using both the Visual Soil Assessment (VSA; Shepherd, 2000) and the Visual Evaluation of Soil Structure (VESS; Guimarães et al., 2011). Subsoil structure (0.3-0.5 m) was assessed using SubVESS (Ball et al., 2015).


SCORE CARD

Visual indicators for assessing soil quality under cropping

Visual Indicator of Soil Quality	Visual Score (VS)	Weighting	VS Ranking
Soil structure & consistence	1	x3	3
Soil porosity	1	x3	3
Soil colour	1	x2	2
	2	x2	4
	0	x2	0
Tillage pan	0.5	x2	1
	1	x1	1
Degree of soil erosion	1.5	x2	3
RANKING SCORE (Sum of VS rankings)			17

Soil Quality Assessment	Ranking Score
Poor	< 10
Moderate	10 – 25
Good	> 25

Baseline infiltration rates.

In addition, the PAG agreed that infiltration would be used as a proxy for potential runoff generation risk and to evaluate the effect of BMPs on improving soil structure. Infiltration testing was carried out on the same plots as the soil structure survey, using a simple single ring infiltration method (Soil Survey Staff, 2014). This required inserting a 12cm section of PVC drainpipe (20 cm internal diameter) 2 cm deep into the furrow. Internal and external edges were subsequently sealed to ensure no leakages. A plastic sheet was then put on top of the pipe to protect the soil surface, and water poured in until it reached the top of the pipe. Infiltration was calculated based on the time taken for the water level to drop 2.0 cm, marked 3.0 cm from the top of the infiltration ring.

Assessment of root architecture and root profile distribution (Objectives 2 and 4)

A detailed understanding of the spatial profile distribution of asparagus roots is critical to successful, long-term productivity. The selection of appropriate BMPs to alleviate/mitigate soil compaction achieves two goals namely, to minimize root damage which contributes to stand longevity and productivity (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) and to decrease the susceptibility to crown and root rots.

Root architecture is determined following the procedure of Drost and Wilson (2003). In Year 1, the first set of baseline (pre-ridging) cores was taken on the crown zero line from between two plants and subsequently in line with the crown at distances of 0.3m, 0.6m and 0.9m (Figure 2). Root cores were extracted with an Eijkelkamp bi-partite hand held root auger (internal diameter: 0.06m, volume: 754 cm^3) at the following soil depths: 0.00 - 0.15m, 0.15 - 0.30m and 0.30 - 0.45m. Baseline root coring was carried out during the 7-9th of March 2017. In total 16 plants were sampled per variety from eight randomly selected plots.

Year 2 root coring (prior to re-ridging and mulch and SSD treatment implementation) was carried out during the 7-9th of March 2018. In total 6 plants were sampled from randomly selected treatment plots. Treatments sampled were Gijnlim with rye companion crop; Gijnlim with mustard companion crop; Gijnlim Bare soil; Guelph Bare soil. The first set of cores was taken on the crown zero line from between two plants and subsequently in line with the crown at distances of 0.3m, 0.6m and 0.9m (Figure 3).

Root cores at the crown zero line and 0.3m distance were extracted with an Eijkelkamp bi-partite hand held root auger (internal diameter: 0.06m, volume: 754 cm^3) at the following soil depths: 0.00 - 0.15m, 0.15 - 0.30m, 0.30 - 0.45m and 0.45 – 0.6m. Root cores within the wheeling (0.6m and 0.9m from the crown zero line) were extracted using an Eijkelkamp Soil Column Cylinder Auger (internal diameter: 0.1m with a volume for each 0.15m depth of 1,178 cm^3). This was driven into the soil using a Cobra TT petrol-driven percussion hammer.

Determination of root mass density

Both Year 1 and 2 root samples asparagus storage roots were separated from the soil by dry selection and stored at <4.0ºC before further assessment. Fresh storage roots were washed with tap water in the laboratory to remove soil remnants and spread out on white paper with scale bar and photographed for further root length analysis.

The roots, already dead (hollow), were then grouped away from the fleshy (live) storage roots. Subsequently, the roots were weighed and oven dried at 60-65 ˚C for 48h, and in some cases 72h until constant mass was attained. The weight of dry roots was recorded immediately after the drying process. The dry weight of already dead roots was recorded separately. From the root mass data, root mass density (RMD) values were calculated as follows: RMD = RM /V, where RM is total dry root mass (kg) and V is volume of the root core (m^3). A subset of fresh roots where then stored at -30 ^{0}C for subsequent carbohydrate analysis. Carbohydrates in root sap are a proxy for yield that can be expected from the plants (Shelton and Lacy, 1980; Wilson et al. 2008).

From an economic and stand longevity perspective understanding the effect of BMPs on the distribution and volume of the main storage root system is critical. Root coring focuses on investigating storage root distributions through measuring root mass density (RMD).

Root data has been analysed by standard analysis of variance (ANCOVA) to determine main effects and interactions of BMP's, sampling depths and location. Root distribution graphs will be generated from these data.

Visualization of root architecture and root profile distribution:

In order to assess the risk of roots being cut during tillage operations such as sub-soiling and ridging, spatial root distribution have been visualised in two ways. The first uses a traffic light colouring scheme. The critical thresholds for root mass are presented as follows:

>5% of total root biomass in core: **Red**

2-5% of total root biomass in core: **Amber**

<2% of total root biomass in core: **Green**

For all treatments at each coring position, the mean (Year 1 n=16 and Year 2 n=6) value of the percentage (%) of total root mass was used (Figure x-x).

The second approach uses Arc-GIS to generate 2-D interpolation maps. All root core samples were given x, y coordinates according to the position from the row (x-value) and soil depth (y-value) they were sampled at and given a corresponding z-value for RMD. These x, y, z values are then used to construct interpolated RMD maps in Arc-GIS using a geo-statistical technique called Krigging using Inverse Distance Weighting as the interpolation method.

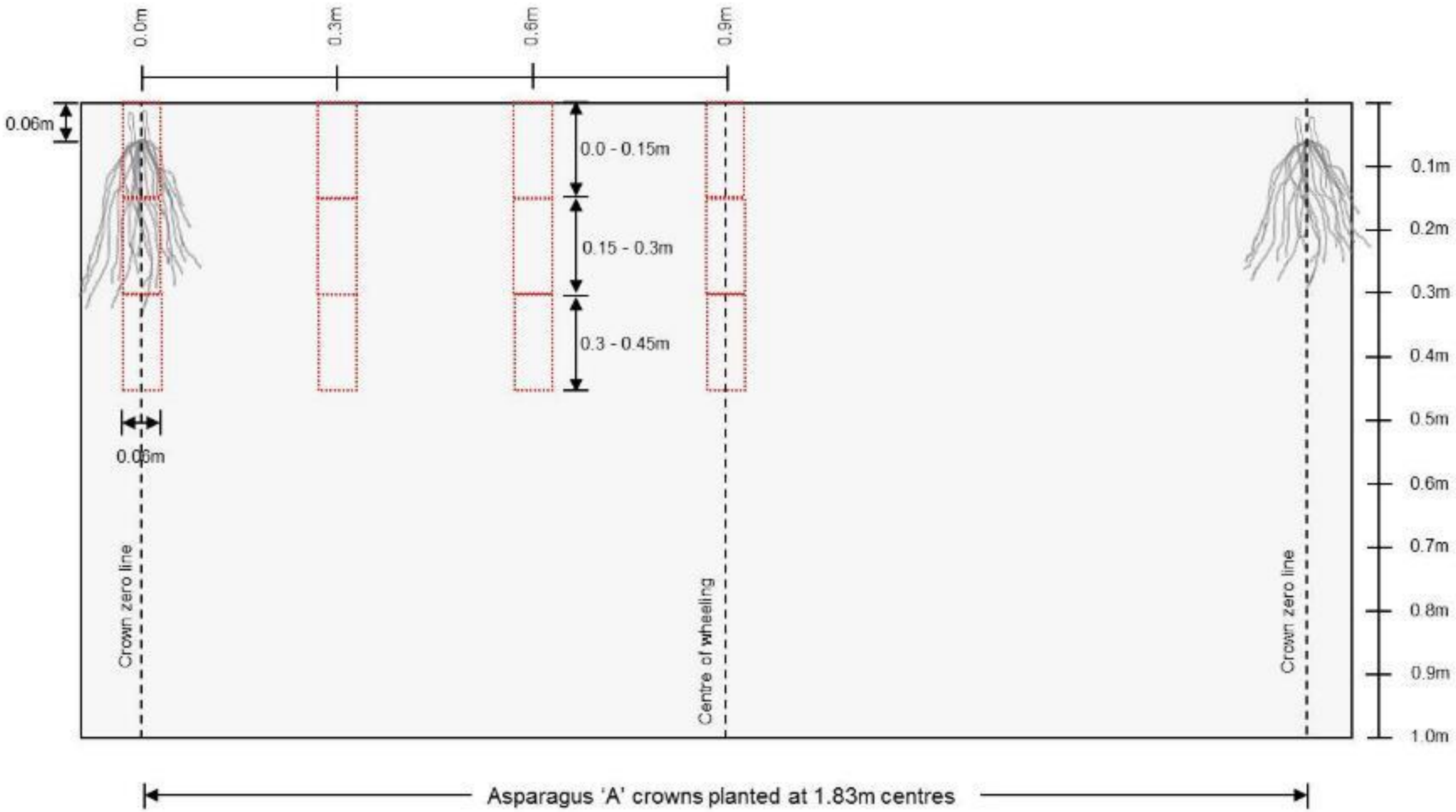


Figure 2. Root coring protocol adopted in Year 1 of this study.

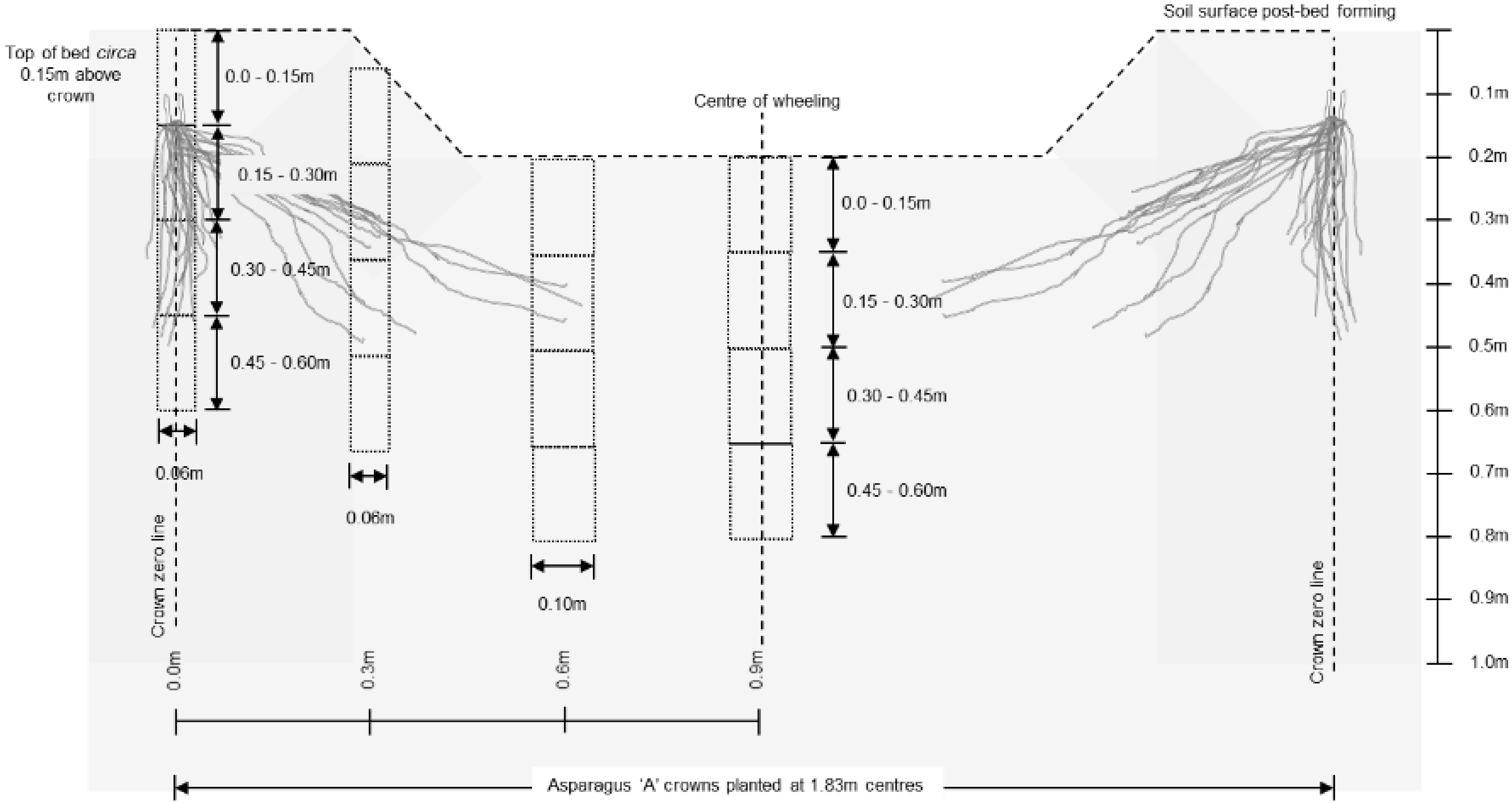


Figure 3. Root coring protocol adopted in Year 2 of this study.

Cover crop selection and seeding rates:

As agreed by the PAG (17th May 2017) companion crops included in this trial are rye (*Cereale secale* L) and mustard (*Sinapis alba* L).

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 1996a). In addition, rye is an AMF host, known to increase mycorrhizal fungus colonisation of the subsequent crop (Kabir and Koide 2002) and promote yields. Arbuscular mycorrhizal fungi (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.

To identify an appropriate seeding rate from an erosion control perspective, an MSc student thesis (Órpez Milán, 2017) was undertaken at Cranfield during May – August 2017. Ten treatments were investigated namely rye applied at rates of 220, 150 and 60 kg ha^{-1}, mustard applied at 28, 19 and 10 kg ha^{-1} and rye:mustard mixes at ratios of 90:10, 80:20 and 65:35 applied at 60 kg ha^{-1}. All treatments were compared with a bare soil un-seed Control. Seeds were supplied by Frontier Agriculture.

The test soil derived from the field trial was packed in 0.5m long x 0.25m wide x 0.085m deep stainless steel erosion trays fitted with leachate collecting trays at a bulk density (BD) of 1.5 Mg m^{-}3, to replicate BD values observed in the FV 450 field wheelings. Three design storm events were simulated namely 80 mm hr^{-1} intensity for 5, 18 and 20 mins which represent the 5 yr, 18 yr and 75 yr return period storm events for the study area (NERC, 1975). Treatment performance was assessed after 3 and 5 weeks of growth in terms of time to runoff initiation, runoff volume (ml), runoff rate (ml min^{-1}) sediment concentration (g l^{-1}), total soil loss (g) and leachate volume (ml). For brevity, the results indicated that the rye applied at 150 kg ha^{-1} and White mustard applied at 19 kg ha^{-1} were the most cost effective treatments in terms of the performance indicators evaluated (Órpez Milán, 2017).

White mustard (Sinapis alba L. var. Severka): 17th Sept. 2017

Consequently, in the FV 450 field trials on August 10th 2017, companion crop treatments rye (Cereale secale L var. Protector) and White mustard (Sinapis alba L. var. Severka) were broadcast by hand to all companion crop treatments (Table 1: n=16) with seed distributed above head height in a semi-circular motion whilst pacing backwards between asparagus rows.

Rye (Cereale secale L var. Protector): 17th Sept. 2017

Results

Baseline soil sampling

The baseline soil analyses indicated that there is no significant difference in the parameters tested (texture, SOM, pH, Olsen-P, Total-C and Total-N) between experimental plots. This is critical as it means that any differences observed can in future, be attributed to the BMP treatments applied. Baseline PR measurements to 0.5m revealed increasing resistance from the mid top-soil to the upper sub-soil (Ref: Year 1 Annual Report). Measurements in the upper sub-soil (45-50 cm) exceed 3.0 MPa, considered to be highly restrictive to plant roots (Reijmerink, 1973). Bulk density also increased with depth with less variation in the upper sub-soil zone. Current BD levels at both depths are classified as restrictive to root growth to some extent (Jones, 1983), most notably within the upper sub-soil. It is of note that the high baseline PR (>3 MPa) measurements observed in the upper sub-soil could impact asparagus root development. Further, the observed high BD measurements (>1.45 Mg m^{-3}) in the mid top-soil and more notably in the upper sub-soil are likely to impede root growth (Jones, 1983). Historically, asparagus roots have been observed in soils with PR values of 1.96 MPa and 2.9 MPa (Reijerink, 1973). However, currently the limiting values of PR and BD for the unhindered expansion of asparagus storage roots are unknown. This project aims to address this knowledge gap, through the longer-term monitoring of this trial and in FV 450a through investigation of the wider grower base.

Baseline soil structure assessments

Top soil structure (0-0.3 m) was classed as moderate under VSA, with a mean site score of 18.2 (+/-1.1). With VESS assessment, top soil structure was most commonly assigned a score of 3 indicating a firm structure although scores ranged between 2-3 (intact-firm) and 4 (compact) (Figure 4). Subsoil quality (0.3-0.5 m) was most commonly assessed as a 3 indicating some compaction, although overall scores ranged between 2-3 (firm-some compaction) and a 5 (massive or structureless) (Figure 5).

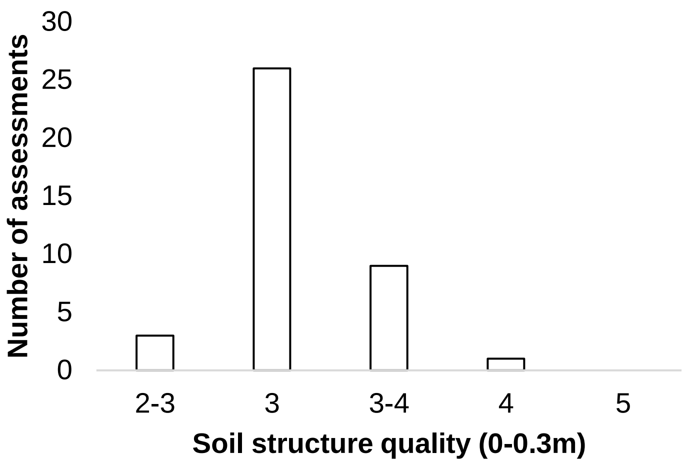


Figure 4. Baseline assessments of VESS in topsoil 0-0.3m. Soil structure quality classes are friable (1), intact (2), firm (3), compact (4) and very compact (5).

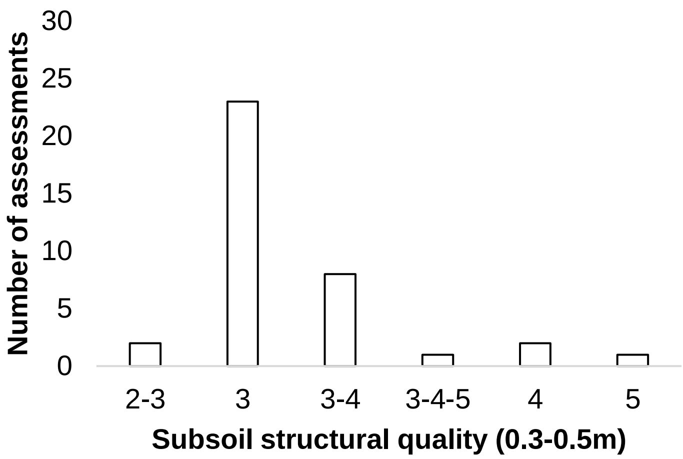


Figure 5: Baseline assessments of subVESS (0.3-0.5m). Subsoil structural quality classes are: friable (1); firm (2); some compaction (3); compact or large scale structures (4); massive or structureless (5).

Baseline infiltration

The mean infiltration rate equalled 99.8 mm hr^{-1}, and can be classified as moderately rapid, with a median of 65.4 mm hr^{-1} – also classed as moderately rapid. Infiltration rates ranged from impermeable to very rapid (Figure 6).

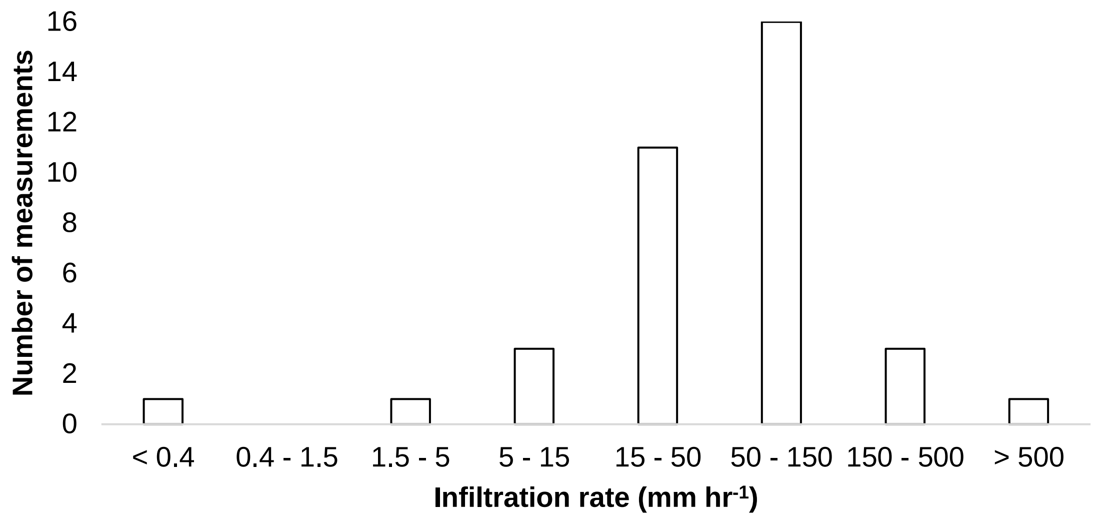


Figure 6: Infiltration rate measurements (mm hr^{-1}). Infiltration rates categories are: impermeable (<0.4); very slow (0.4-1.5); slow (1.5-5); moderately slow (5-15); moderate (15-50); moderately rapid (50-150), rapid (150-500); very rapid (>500).

Year 1 baseline root coring results summary and discussion

Root mass density (RMD) values were generally higher for Gijnlim as compared to Guelph Millennium for most soil depths and sample locations. However, no significant differences were detected. The Year 1 results suggest that roots of both varieties are exploring the soil profile in a similar way. One year after planting the asparagus plants, most roots are near the crown (ca. 65% of the total measured plant root mass is found at the crown zero line, near the surface at 0.0 - 0.15 m depth). Very few roots have explored the soil at 0.3m, 0.6m and 0.9m away from the crown zero line.

Further away from the crown zero line, roots tend to be mostly in the 0.15 – 0.30 m and 0.3-0.45m soil layers and avoid the topsoil (0.0-0.15 m). There were no roots detected (RMD values <0.1 kg m^{-3}) in any of the root cores taken 0.9m away from the crown zero line (Ref Year 1 Annual Report: https://horticulture.ahdb.org.uk/project/asparagus-sustainable-soil-management-stand-longevity-and-yield-optimization).

Potential root damage associated with ridging operations:

Conventional practice is to re-ridge in the second year post planting in order to achieve circa 0.14m of soil above the crown to promote the generation of spears of suitable quality. Ridging is also undertaken, to incorporate the residues of the previous season's fern into the soil to control *Pleospora herbarum* (sexual stage of *Stemphylium vesicarium*). Consequently, on 22nd April 2017 the experimental trials were re-ridged. A target ridge depth of 0.2m soil above the crown was required in order to facilitate the zero tillage treatments associated with this long-term experimental trial. The bed-former achieved bed dimensions of 0.55m at the bed-surface and 0.9m at the base. Rotating 0.38m tines were on 1.3m centres (above the crown zero line) with leading spring tines at 1.62m centres (Appendix 1).

When the dimensions of the bed-form were superimposed on the baseline varietal root distribution this indicated that for both Guelph Millennium and Gijnlim there is a risk of damaging 7-9% of total root biomass if the rotating tines of the bed-former till soil to 0.15 - 0.3m depth within 0.3m of the crown zero line. In addition, for Guelph Millennium there is a risk of damaging 2% of total plant root biomass if the rotating tines of the bed-former till soil to 0.0 - 0.15m depth within 0.3m of the crown zero line (Ref: Year 1 Annual Report).

Potential root damage associated with sub-soiling operations:

The tillage of wheelings to alleviate compaction and facilitate infiltration is a conventional practice amongst UK asparagus growers as a mitigation measure to control runoff and erosion. Niziolomski et al. (2016) investigated the draught efficiency of different tine options at various depths to alleviate compaction in asparagus wheelings. The results demonstrated that the Modified Para-Plough (MPP) at 175 mm depth had significantly lower specific draught as compared with Winged Tine (WT), Winged with Shallow Leading Tines (WSLT), and Narrow with Shallow Leading Tines (NSLT). No significant difference in specific draught was observed between the MPP and a Narrow Tine (NT). At 300 mm, no significant difference between specific draught was observed.

The below ground disturbance profiles of the tines investigated by Niziolomski et al. (2016) at 0.175m and 0.3m operating depths were superimposed on the Year 1 root profile distributions (Ref Year 1 Annual Report: https://horticulture.ahdb.org.uk/project/asparagus-sustainable-soil-management-stand-longevity-and-yield-optimization). The results indicated that in Year 1, for both Gijnlim and Guelph Millennium varieties at both operating depths, with crowns planted on 1.83m centres SSD operations could be undertaken to alleviate compaction without the risk of damaging asparagus roots.

Year 2: Asparagus root coring results

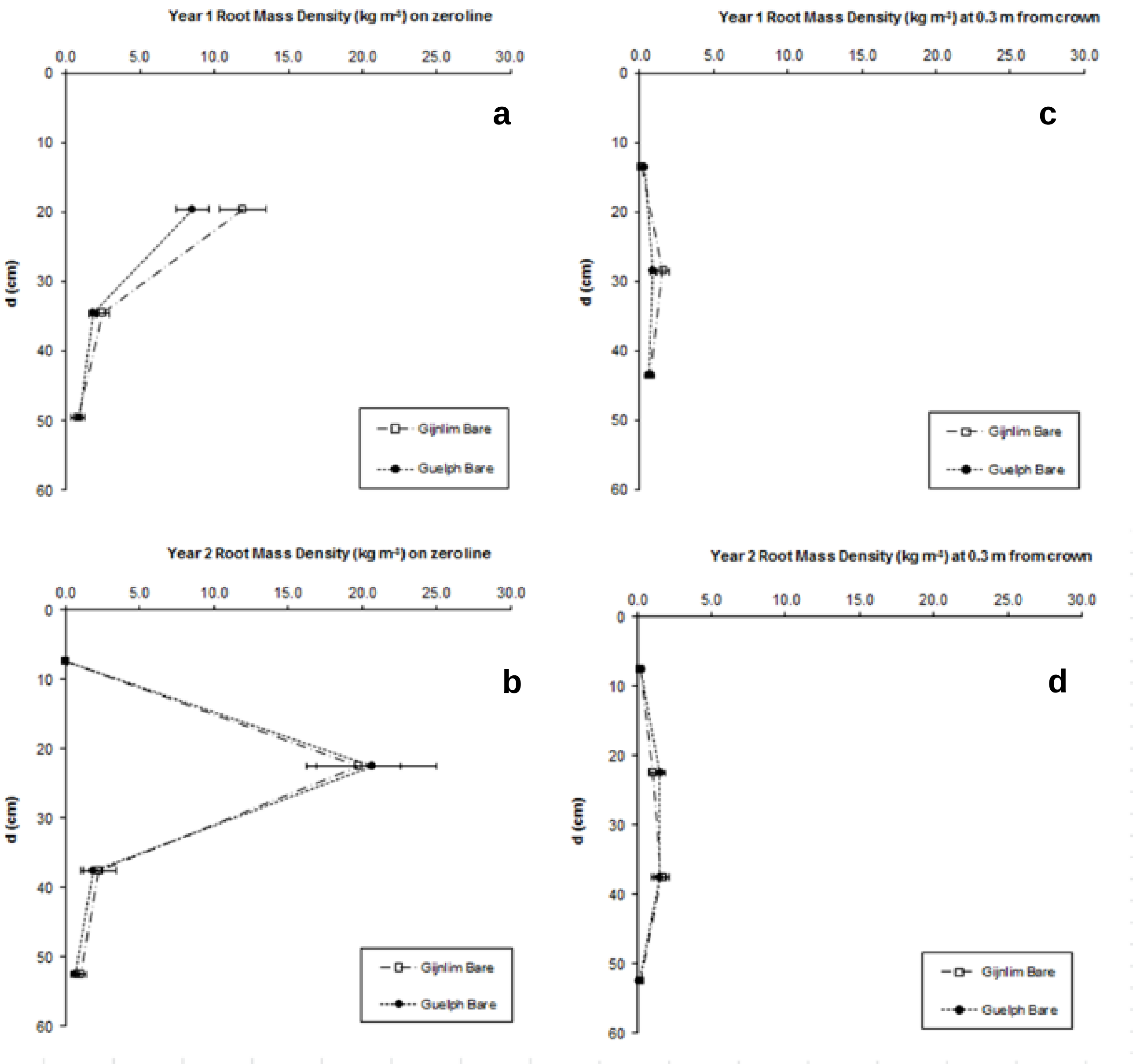
The results from the Year 2 root sampling campaign show that for both Gijnlim and Guelph Millennium, the average RMD at the crown zero line for the 0.15 – 0.3m depth increased from 8-12 kg m^{-3} in Year 1 up to ca. 20 kg m^{-3} in Year 2 (Figure 7a and 7b). No significant differences in the spatial distribution of RMD are observed between varieties (p=0.870).

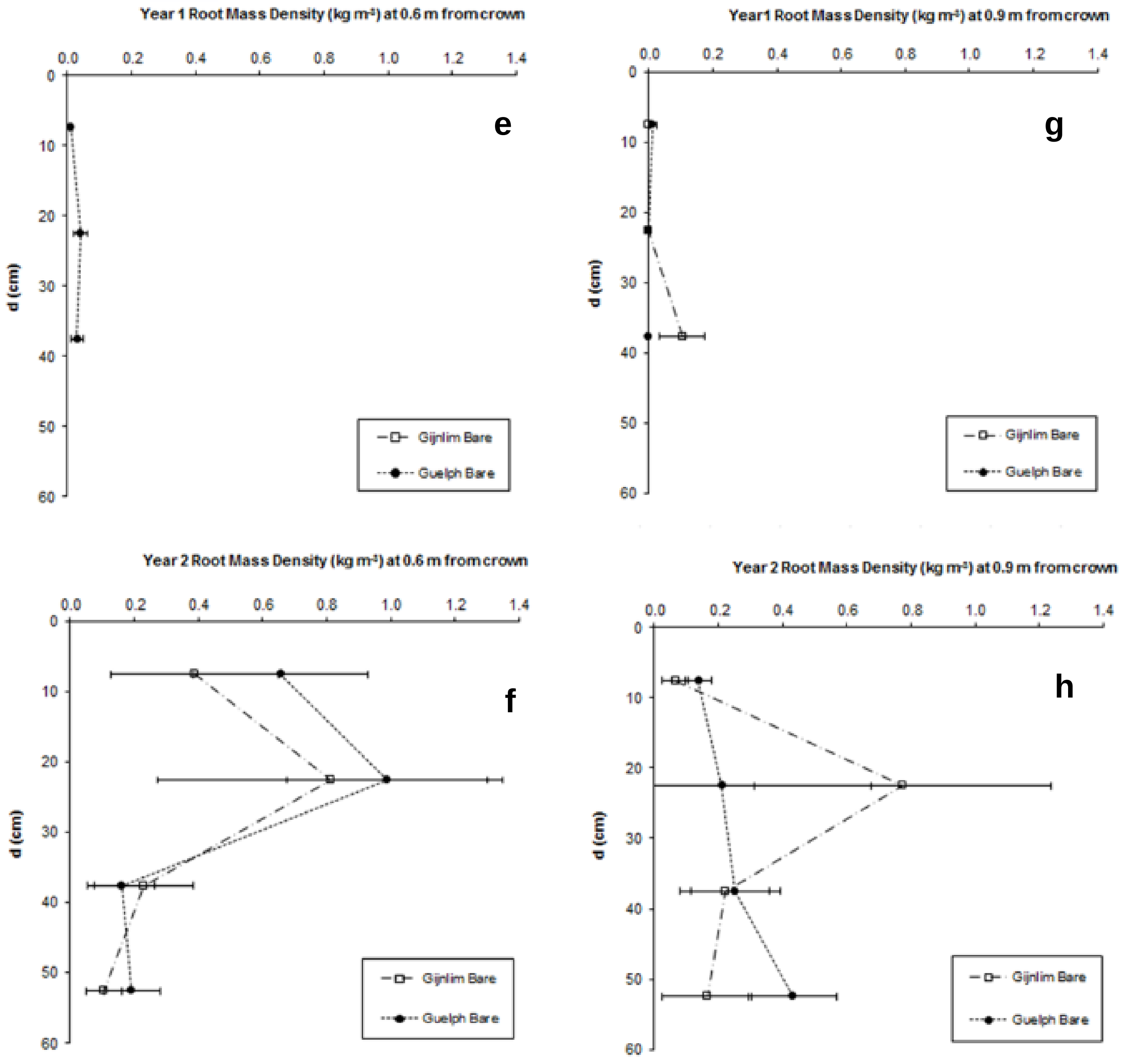
The year 2 root mass densities were significantly higher as compared to the year 1 root mass densities (p=0.03). Soil depth and distance away from the crown also significantly affected root mass densities (p< 0.0001). The results of the year 2 root data show that Gijnlim seems to expand more into the wheeling, compared to Guelph Millennium (Fig. 7c-h), However this is not significant (p=0.205). No significant differences in RMD at this location and depth were observed between varieties.

Further, at 0.3m distance from the crown zero line, the results indicate that for both Gijnlim and Guelph Millennium at 0.15 – 0.3m depth the average RMD remained at <2.0 kg m^{-3} in Year 1 and Year 2 (Figure 7c and 7d). For Guelph Millennium no significant differences in RMD 0.3m distance from the crown zero line at 0.15 – 0.3m depth were observed.

At 0.6 m from the crown zero line, the results indicate a significant expansion of root biomass into the wheeling in Year 2 as compared with Year 1 primarily at 0.15 – 0.3m depth (Fig 7e and 7f). The results further indicate that there is a trend for Gijnlim storage roots to expand more into the wheeling (Figure 7g and 7h) as compared to Guelph Millennium. This can be visualised in the Arc-GIS derived root maps (Figure 8). However, although there is a robust trend, statistical results (ANCOVA analysis) show that there are no significant differences (p=0.870) in RMB between varieties for the Year 2 data. Only the distance from the crown zero line significantly (p < 0.0001) affects RMD values.

Figure 7. Root mass density (kg m^{-3}) profiles after 1 and 2 years of plant growth for Gijnlim and Guelph Millennium at the crown zero line (Year 1 7a and Year 2 7b) 0.3m (Year 1 7c and Year 2 7d), 0.6m (Year 1 7e and Year 2 7f) and 0.9m (Year 1 7g and Year 2 7h).




Year 1 Root Mass Density (kg m-3) at 0.6 m from crown
e
Year1 Root Mass Density (kg m-3) at 0.9 m from crown
g
Year 2 Root Mass Density (kg m-3) at 0.6 m from crown
f
Year 2 Root Mass Density (kg m-3) at 0.9 m from crown
h
d (cm)
Gijnlim Bare
Guelph Bare

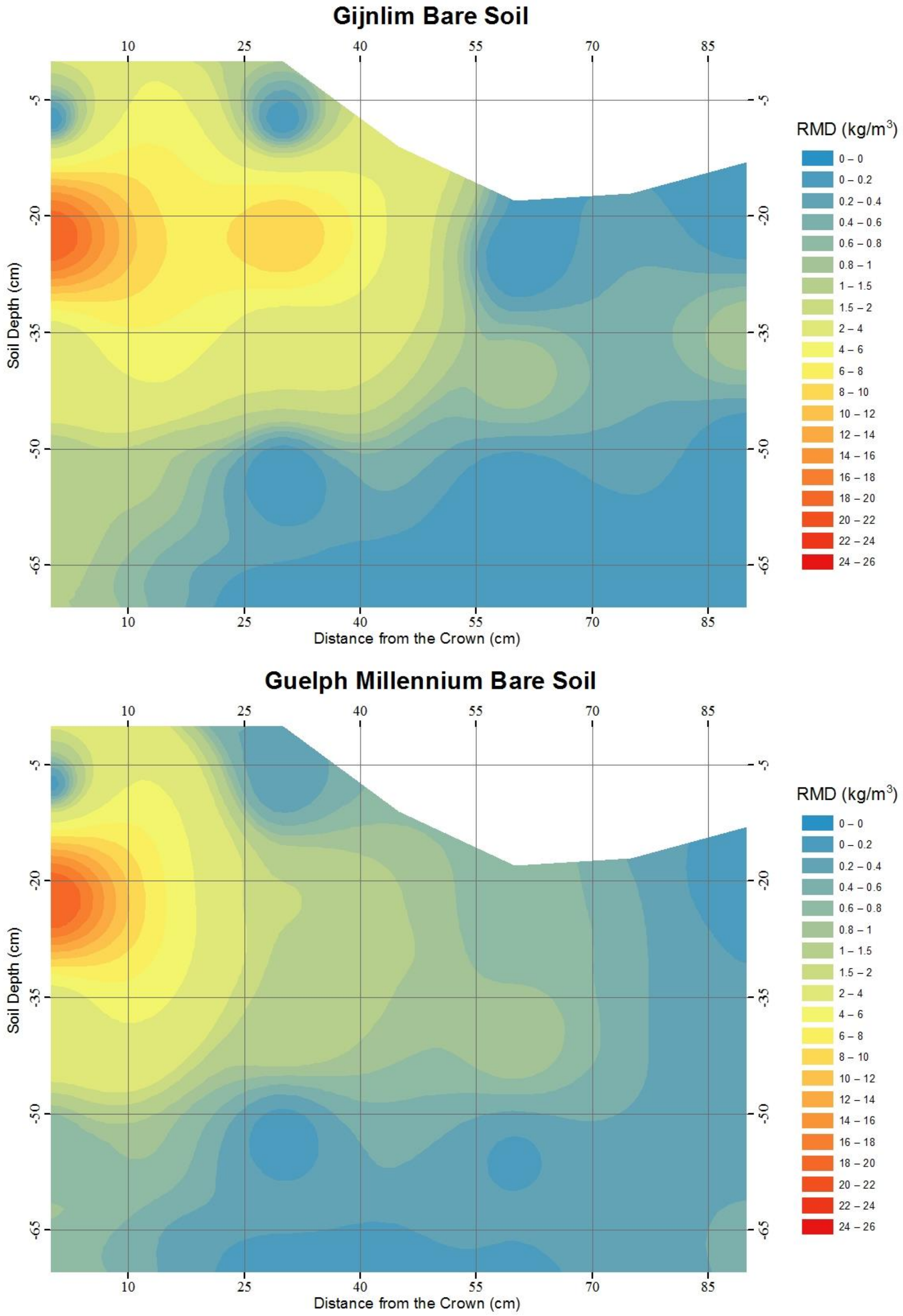
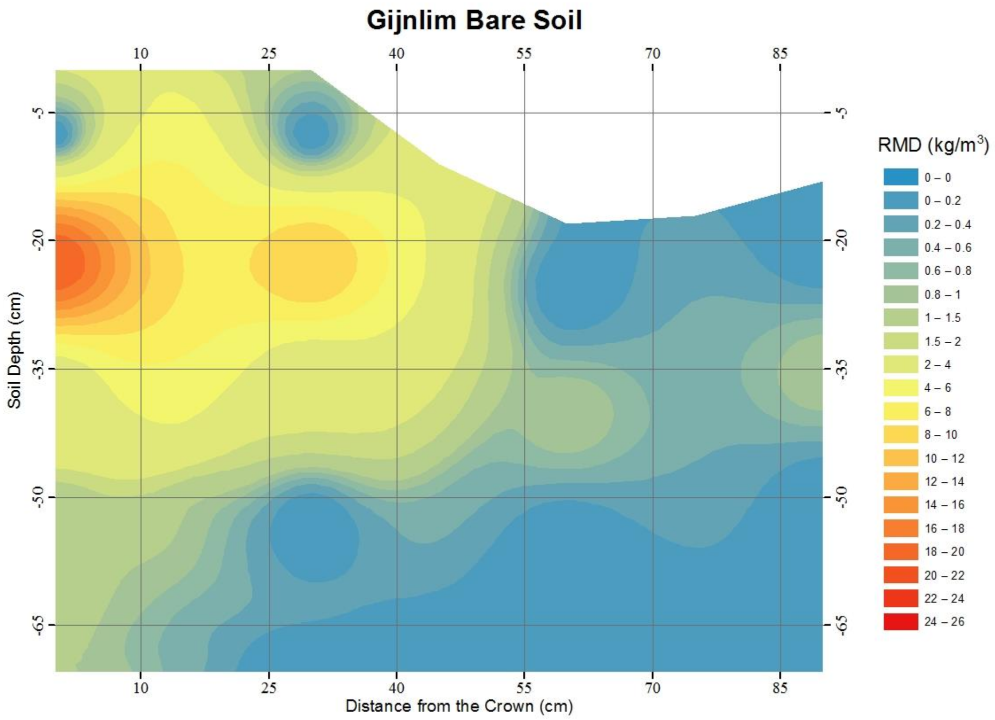
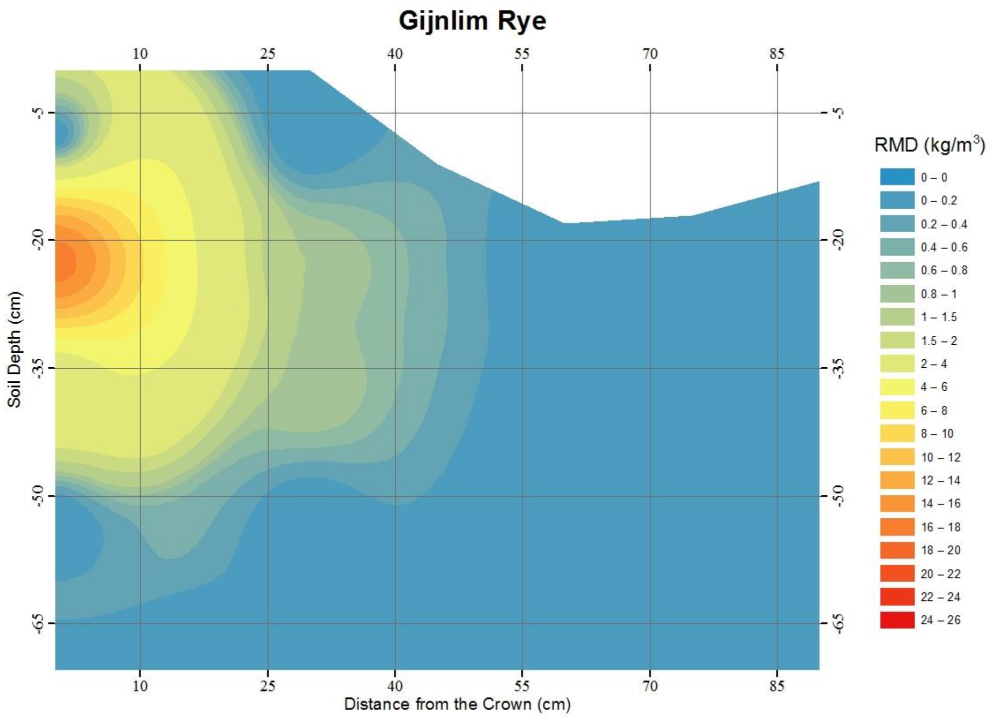


Figure 8. Year 2 root maps visualizing the spatial distribution of RMD (kg m^{-3}) for Gijnlim and Guelph Millennium as a function of soil depth and distance from the crown zero line.

Effect of companion crop on asparagus root development.

Year 2 asparagus root coring also included sampling 6 asparagus plants randomly selected from Gijnlim with rye companion crop and Gijnlim with mustard companion crop treatments. Interpolated root maps were created using Arc-GIS software using Inverse Distance Weighting as the interpolation method.





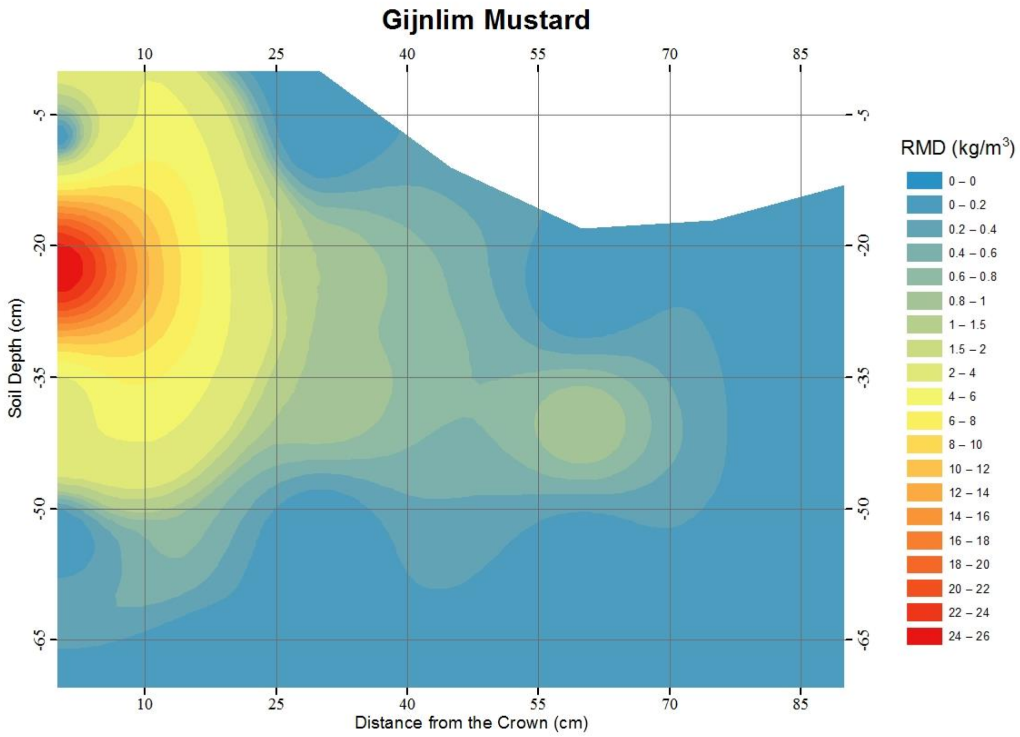
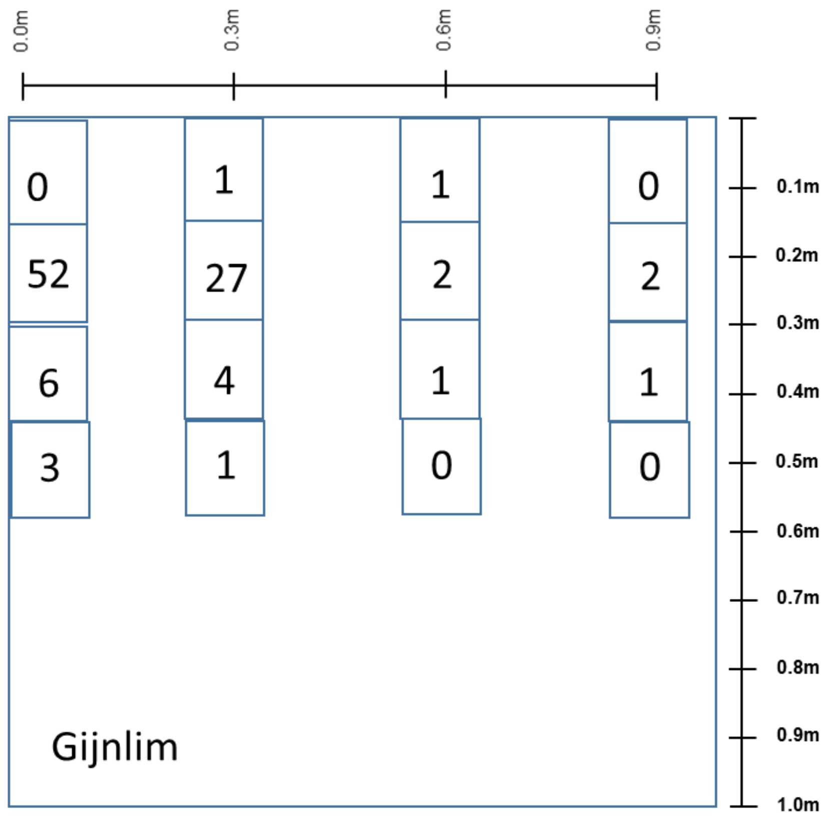


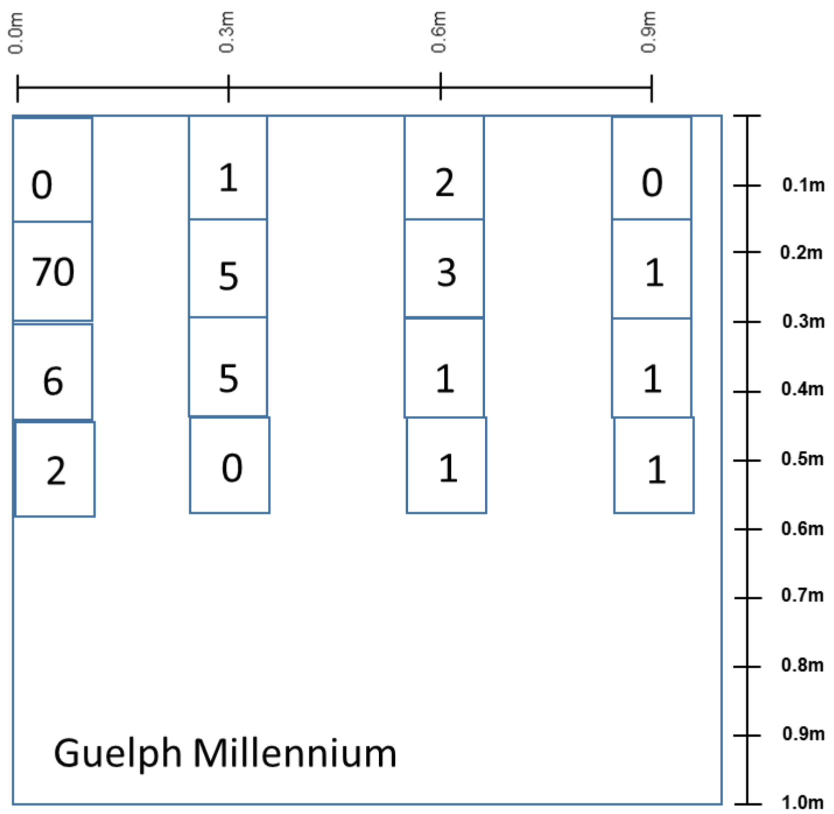
Figure 9. Year 2 root maps visualizing the spatial distribution of RMD (kg m^{-3}) for Gijnlim (Bare Soil) as a function of soil depth and distance from the crown zero line with or without a rye or mustard companion crop.

Year 2 root maps comparing the spatial distribution of the root mass for Gijnlim crops grown with and without companion crops in the wheelings (Figure 9), show that the presence of the companion crop seems to restrict the asparagus storage roots to the ridge zone (crown zero line). This is particularly apparent 0.3m from the zero crown line at 0.15 – 0.3m depth. With companion crops growing in the wheeling the wheeling zone shows low densities of asparagus roots. Figure 10a-d also indicates that on average the Gijnlim Bare Soil treatments have greater proportion of their total root mass at 0.6 m and 0.9m from the crown zero line as compared to the companion crop treatments.

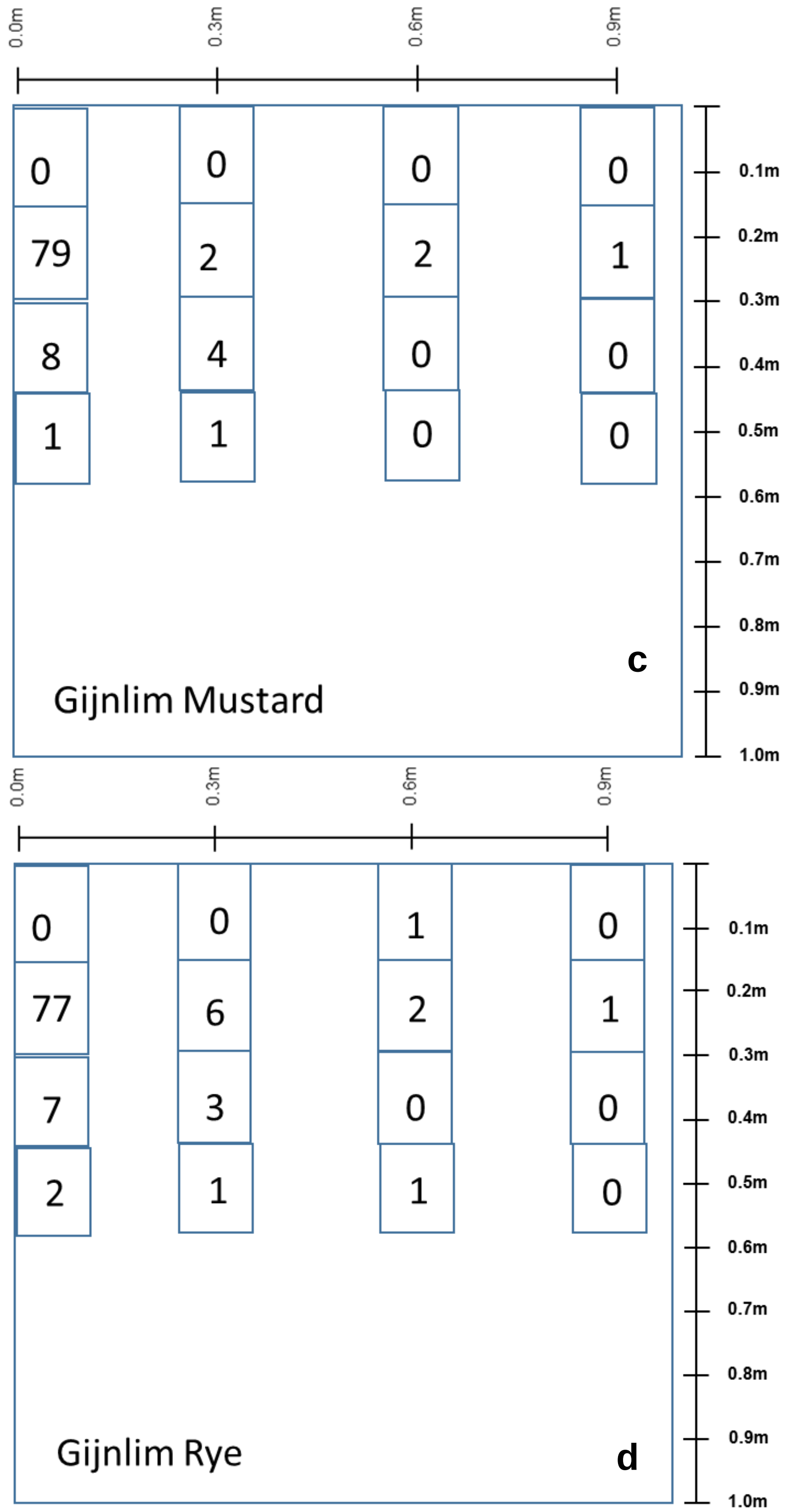
a


0.0m
0.3m
0.6m
0.9m
0
52
6
3
1
27
4
1
1
2
1
0
0
2
1
0
Gijnlim
0.1m
0.2m
0.3m
0.4m
0.5m
0.6m
0.7m
0.8m
0.9m
1.0m

b


0.0m
0.3m
0.6m
0.9m
0
70
6
2
1
5
5
0
2
3
1
1
0
1
1
1
Guelph Millennium
0.1m
0.2m
0.3m
0.4m
0.5m
0.6m
0.7m
0.8m
0.9m
1.0m

C



d

Figure 10 a-d: Profile distribution of mean total plant root mass (%) for Gijnlim and Guelph Millennium varieties associated with Bare Soil treatments (a) and (b) and Gijnlim mustard (c) and rye (d) companion crop treatments.

Figure 10 suggests that Gijnlim with bare soil has a lower proportion of its total root mass at the crown zero line at 0.15-0.3 m depth compared to Gijnlim with mustard or rye companion crops (68, 79 and 77%, respectively). Although the average percentages of total plant root mass under the ridge are higher for Gijnlim with companion crops as compared to Gijnlim Bare Soil treatments, statistical results (Univariate Analysis of Comparison) show that there are no significant differences in the spatial distribution of the storage roots ($p=0.685$) as a function of the type of companion crop. Only distance and depth ($p < 0.0001$) significantly affect root mass density values.

It is also appears to be a trend for companion crops to reduce the % of total plant root mass 0.6 and 0.9m from the crown zero line within whole profile (all depths combined). At the 0.6m distance from the crown zero line Gijnlim non-companion crop (Bare Soil), Gijnlim mustard and Gijnlim rye are associated with total plant root mass values of 5%, 3% and 4%. Further, at 0.9m distance from the crown zero line (centre of wheeling) Gijnlim non-companion crop (Bare Soil), Gijnlim mustard and Gijnlim rye are associated with total plant root mass values of 5%, 1% and 1%, respectively. This trend will continue to be monitored under FV 450a.

2018 Asparagus Yield

In 2018 a short 4-week (April 24th to May 21st) harvest from 19-cuts was taken from the experimental plots by George Nairn (Cobrey Farms). For Experiment 1 (Gijnlim), Mean ($n=19$) spear count, Total Harvest (kg per plot^{-1}) and Estimated Yield (kg ha^{-1}) were recorded. For the varietal component of the FV 450 trial (Experiment 2), average spear weight, Total Harvest and Estimated Yield were recorded for both Gijnlim and Guelph Millennium.

Experiment 1 Yield Results:

With the exception of the rye No-SSD ridged as compared with the non-ridged treatment, ridging did not result in any significant difference ($p <0.1$) in yield (Table 3) for the BMPs evaluated in this trial.

However, it is of note that rye No-SSD ridged and non-ridged Total Harvest and Estimated Yield values are 43.0 and 33.5 (kg per plot^{-1}) and 2984 and 2327 (kg ha^{-1}), respectively. This equates to a 22% reduction in yield for the non-ridged as compared with ridged rye No-SSD treatments (Figure 11).

Table 3. Experiment 1: Differences in 2018 asparagus yield (Gijnlim) attributes between treatments.

Variety	Cover Type	Shallow Soil Disturbance	Re-ridging	Mean (n=19) spear count	Total Harvest (kg per plot^{-1})	Estimated Yield (kg ha^{-1})
Gijnlim	Mustard-CC	No-SSD	R	63.6^{abc}	41.32^{abc}	2869.6^{abc}
	Mustard-CC	No-SSD	Non-R	68.6^{abcd}	39.33^{acd}	2731.2^{acd}
	Rye-CC	No-SSD	R	68.7^{acd}	42.97^{ab}	2984.2^{ab}
	Rye-CC	No-SSD	Non-R	64.3^{abc}	33.52^{d}	2327.4^{d}
	PAS 100 Compost	SSD	R	66.8^{abcd}	43.67^{ab}	3032.5^{ab}
	PAS 100 Compost	SSD	Non-R	75.1^{d}	46.87^{b}	3254.6^{b}
	Straw Mulch	SSD	R	71.6^{ad}	44.85^{ab}	3114.6^{ab}
	Straw Mulch	SSD	Non-R	65.8^{abcd}	41.37^{abc}	2873.1^{abc}
	Bare soil	SSD	R	58.1^{b}	35.83^{cd}	2488.0^{cd}
	Bare soil	SSD	Non-R	62.1^{abc}	41.61^{abc}	2889.8^{abc}
	Bare soil	No-SSD	R	60.6^{bc}	38.98^{acd}	2707.1^{acd}
	Bare soil	No-SSD	Non-R	71.8^{ad}	44.46^{ab}	3087.3^{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 0.90 confidence interval. Annual re-ridging (R) or Zero non-ridging (Non-R).

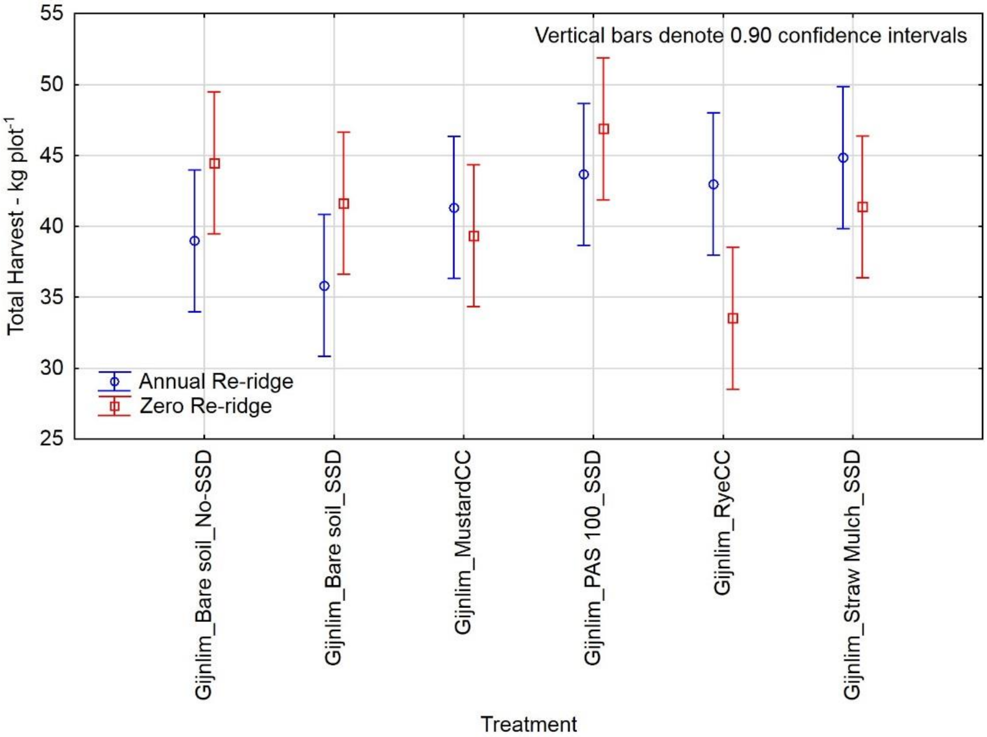


Figure 11. Differences in Total Harvest (kg plot^{-1}) between treatments as influenced by annual re-ridging and non-ridging.

Further, and critically, the rye No-SSD non-ridged Estimated Yield (kg ha^{-1}) is significantly, 18.9%, 23.3%, 28.5%, 25.3%, 19.0%, 19.5% and 24.7% lower than the mustard No-SSD ridged, PAS 100 Compost_SSD and Straw Mulch_SSD ridged and non-ridged, Bare soil_SSD non-ridged and Bare soil_No-SSD non-ridged treatments, respectively (Table Y). This reduction in yield associated with the non-ridged rye No-SSD treatment is contrary to findings of North America asparagus growers (Personal Communication: Prof. Dan Drost) and may in part be due to the continued release of allelopathic exudates (Kruse et al. 2000) from non-ridged rye roots in wheelings not destroyed by the action of re-ridging. This will require further investigation. PAS 100 Compost_SSD non-ridged Total Harvest (kg per plot^{-1}) and Estimated Yield (kg ha^{-1}) values of 46.9 kg per plot^{-1} and 3255 kg ha^{-1} are significantly (p <0.1) higher as compared with the mustard No-SSD non-ridged, rye No-SSD non-ridged, Bare soil_SSD ridged and Bare soil_No-SSD ridged treatments respectively (Table 3).

Experiment 2 Yield Results

The results indicate that Guelph Millennium is associated yield as compared with Gijnlim. The Guelph Millennium, Bare soil No-SSD ridged, Bare soil No-SSD non-ridged, Bare soil-SSD ridged, Bare soil SSD non-ridged treatments are associated with 16%, 31%, 23% and 27.3% lower Total Harvest and Estimated Yield (kg ha^{-1}) as compared with the equivalent Gijnlim treatments (Table 4).

Table 4. Experiment 2: Varietal differences in 2018 asparagus yield attributes between treatments.

Variety	Cover Type	Shallow Soil Disturbance	Re-ridging	Mean Spear Weight (g)	Total Harvest (kg per plot^{-1})	Estimated Yield (kg ha^{-1})
Gijnlim	Bare soil	SSD	R	24.5^{a}	35.8^{cd}	2488^{cd}
	Bare soil	SSD	Non-R	24.3^{a}	41.6^{b}	2890^{b}
	Bare soil	No-SSD	R	25.3^{a}	39.0^{bd}	2707^{bd}
	Bare soil	No-SSD	Non-R	25.7^{a}	44.4^{b}	3087^{b}
Guelph Millennium	Bare soil	SSD	R	18.5^{b}	30.2^{a}	2099^{a}
	Bare soil	SSD	Non-R	20.0^{b}	28.7^{a}	1995^{a}
	Bare soil	No-SSD	R	20.7^{b}	30.2^{a}	2095^{a}
	Bare soil	No-SSD	Non-R	21.2^{b}	32.3^{ac}	2246^{ac}

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 Zero non-ridging (Non-R).

Discussion

Year 2: Implications for damaging roots during tillage operations

<u>Potential root damage associated with ridging operations:</u>

When the dimensions of the bed-form are superimposed on the Year 2 varietal root distribution this indicates that for Gijnlim there is a risk of damaging <2% of total plant root biomass if the rotating tines of the bed-former till soil to 0.15 m depth within 0.3m and 0.6 of the crown zero line (Figure 12). For Gijnlim if ridging tines disturb soil at 0.15 – 0.30m depth 0.3 and 0.6m from the crown zero line there is a risk of damaging *circa* 6% and 2-5% of total plant root biomass respectively (Figure 12).

For Guelph Millennium there is a risk of damaging <2% and 2.2% of total plant root biomass if the rotating tines of the bed-former till soil to <0.15m depth within 0.3m and 0.6m of the crown zero line (Figure 12).

If ridging tines disturb soil at 0.15 – 0.30m depth 0.3 and 0.6m from the crown zero line there is a risk of damaging *circa* 5% and 2-5% of total plant root biomass respectively (Figure 12). This risk of root damage corroborates the research of Drost & Wilcox-Lee (2000), Putnam (1972), Reijmerink (1973) and Wilcox-Lee & Drost 1991). For both varieties <2.0% of total plant root biomass occurs 0.9m from the crown zero line for all depths sampled. This suggests that minimal (<2.0%) damage to roots will occur through the rotating action of the tines associated with bed-formers operating in the centre of the wheeling on 1.83m centres to depths of up to 0.3m.

<u>Potential root damage associated with sub-soiling operations:</u>

Results indicate that for Gijnlim, sub-soiling operations in the wheelings (0.6-0.9m away from the crown) to 0.175 with the full range of tine configuration options can be undertaken with the potential to damage <2.0% of total plant root biomass (Figures 13 and 14). In contrast, the root profile distribution of Guelph Millennium suggests that a modified para-plough (Niziolomski et al. 2016) should not be utilised at 0.175m depth as this could potentially damage 2-5% of roots at 0-0.15m depth 0.6m from the crown zero line (Figure 13). At a sub-soiling depth of 0.3m, neither the modified para-plough or the winged tine should be utilised as the below ground disturbance patterns intersect the 0.15-0.30m depth 0.6m from the crown zero line suggesting damage to 2-5% of total plant root biomass for both varieties (Figure 14).

As stated earlier, Year 2 root maps comparing the spatial distribution of the root mass for Gijnlim crops grown with and without companion crops in the wheelings (Figure 15), show that the presence of the companion crop appears to restrict the asparagus storage roots to the ridge zone (crown zero line). This is particularly apparent 0.3m from the zero crown line at 0.15 – 0.3m depth, but even more so at 0.6m and 0.9m away from the crown where the proportional root mass is < 2% at all soil depths for the companion plots

For Gijnlim, this has potential implications in terms of reducing potential root damage associated with subsoiling to both 0.175 and 0.3m depth as root development in the 0-0.15m depth 0.6m from the crown zero line is reduced (Figure 15 and 16). This implies that sub-soiling operations to 0.175 or 0.3m depth with the full range of tine configuration options can be undertaken with the potential to damage <2.0% of total plant root biomass (Figure 15 and 16).

However, it is strongly recommended that growers undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations. Training in root sampling will be provided to growers under FV 450a.

Figure 12. Year 2: Potential root damage associated with annual re-ridging operations.

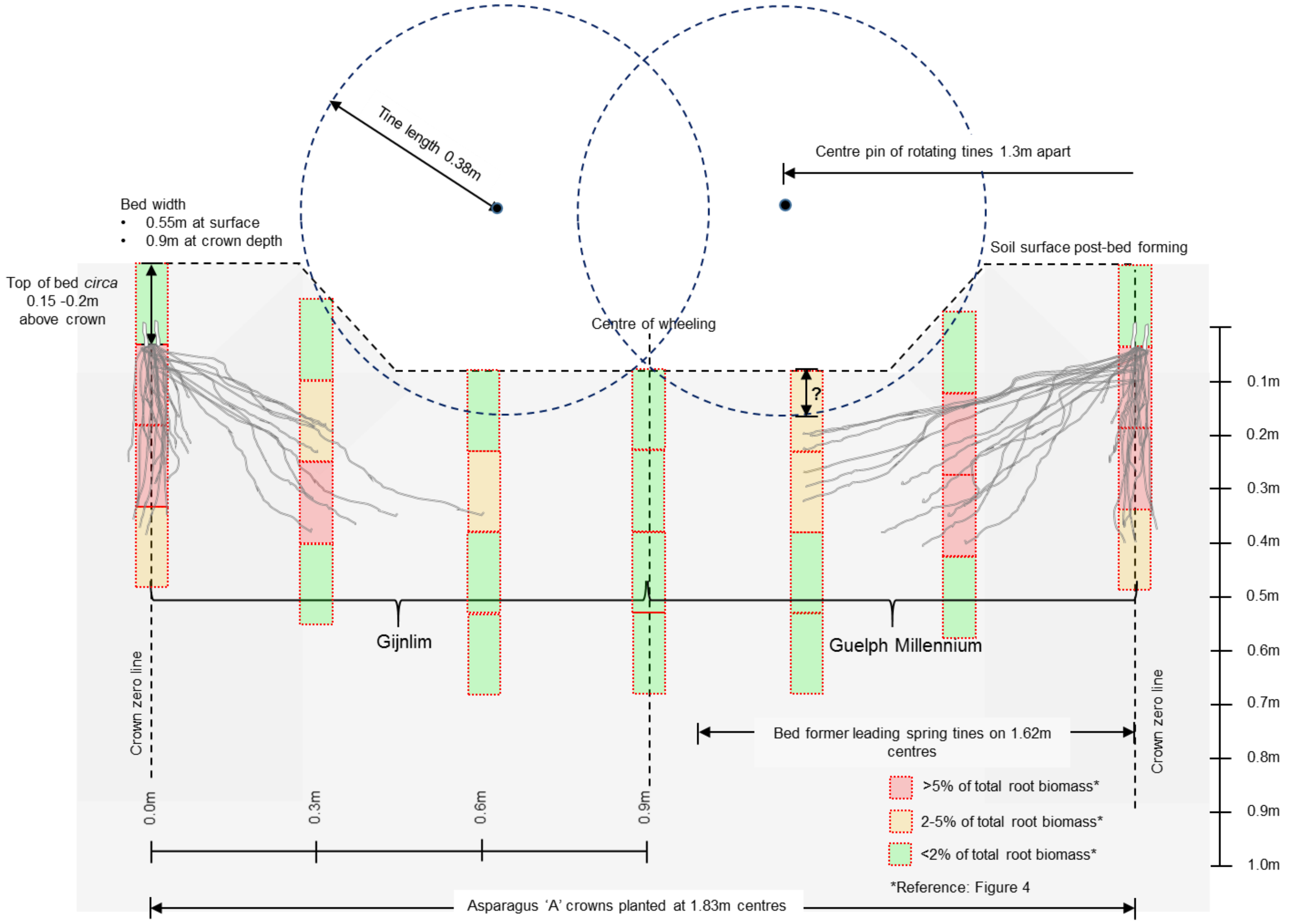
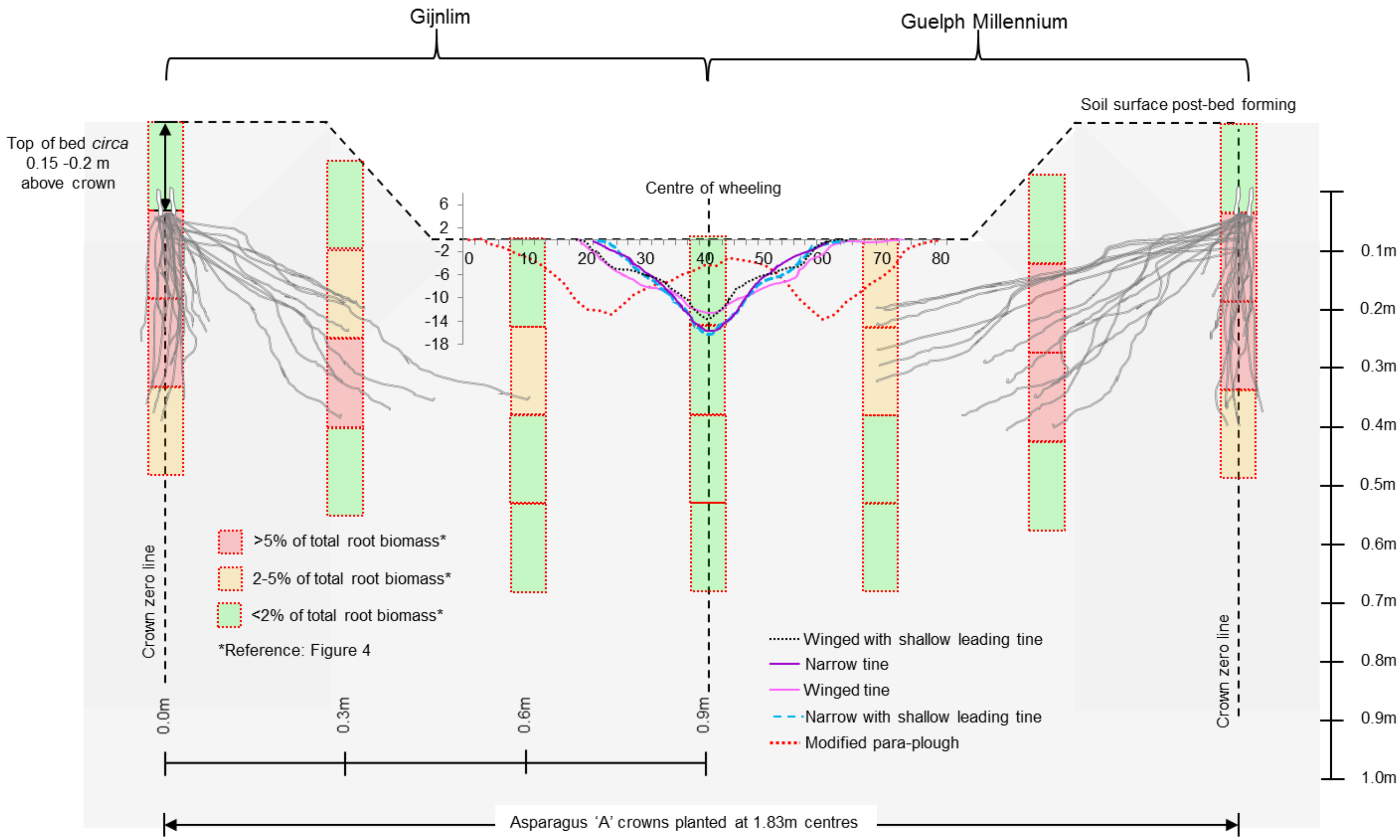


Figure 13. Year 2: Potential root damage associated with below ground soil disturbance profiles associated with a range of tines types and geometries operating at 0.175m working depth: Gijnlim and Guelph Millennium Bare Soil treatments.

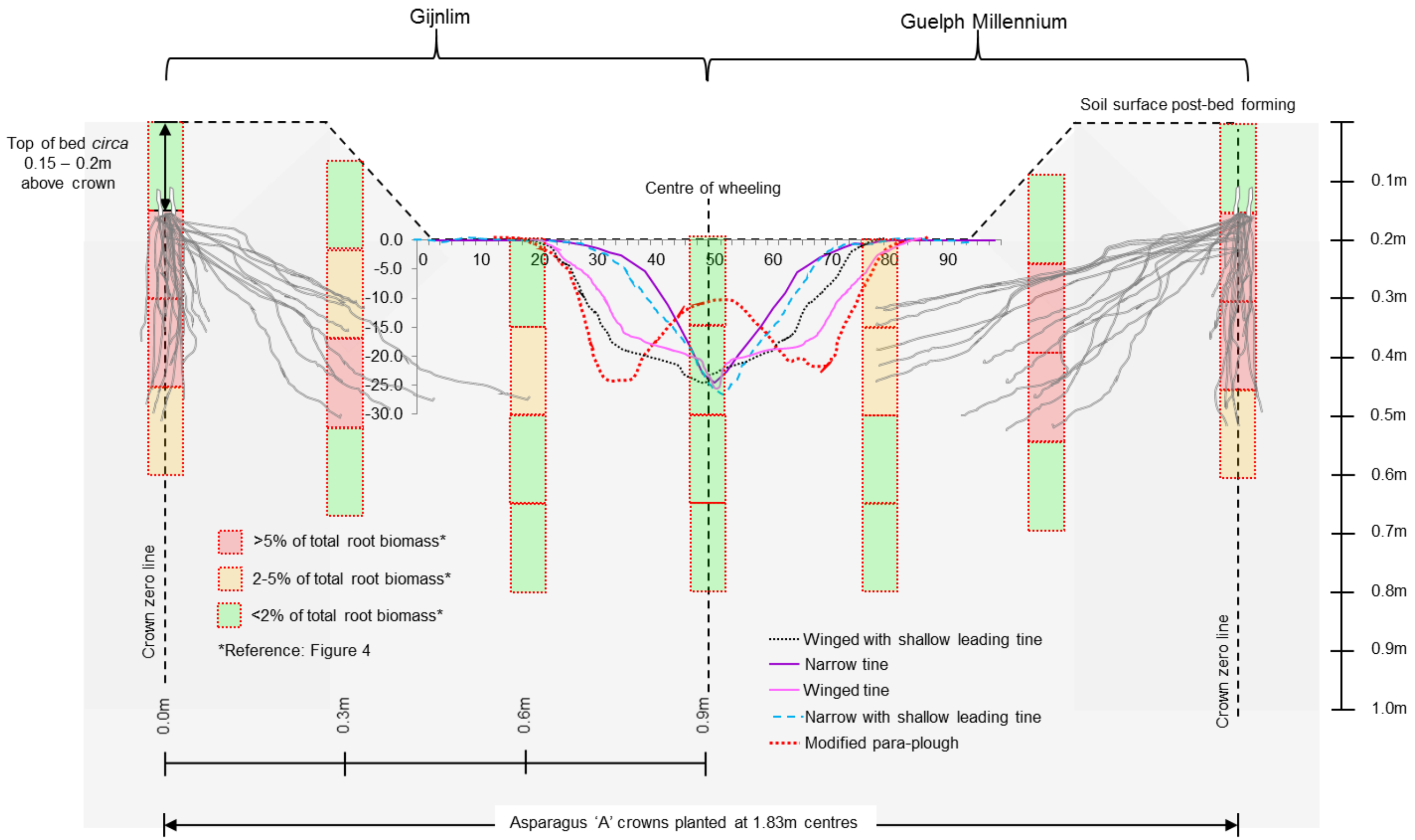


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

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

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For Year 2 profile root distribution values refer to relevant Figures and Tables in main body of report..

Figure 14. Year 2: Potential root damage associated with below ground soil disturbance profiles associated with a range of tines types and geometries operating at 0.3m working depth: Gijnlim and Guelph Millennium Bare Soil treatments.

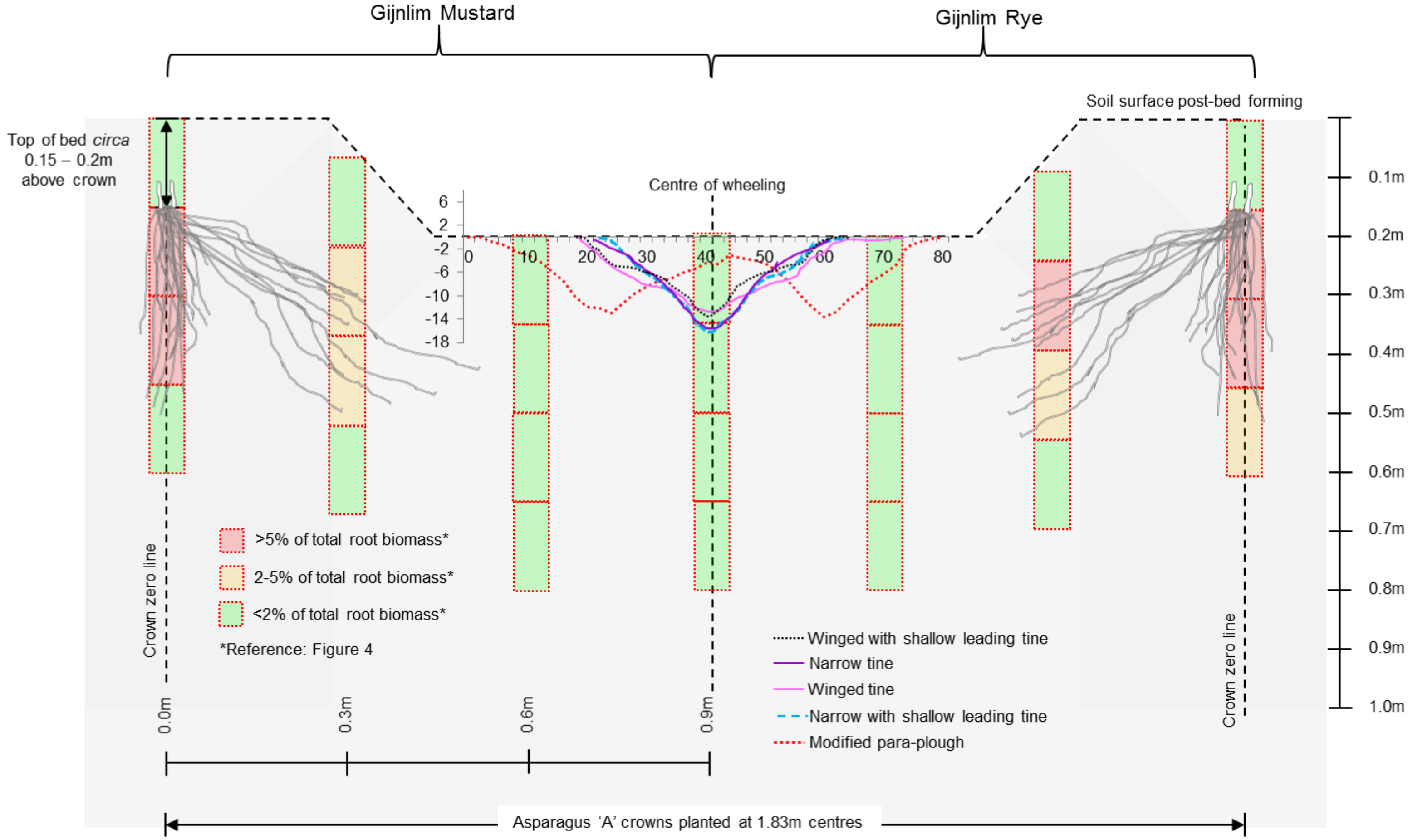


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

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

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For Year 2 profile root distribution values refer to relevant Figures and Tables in main body of report..

Figure 15. Year 2: Potential root damage associated with below ground soil disturbance profiles for a range of tines types and geometries operating at 0.175m working depth: Gijnlim mustard and rye companion crop treatments.

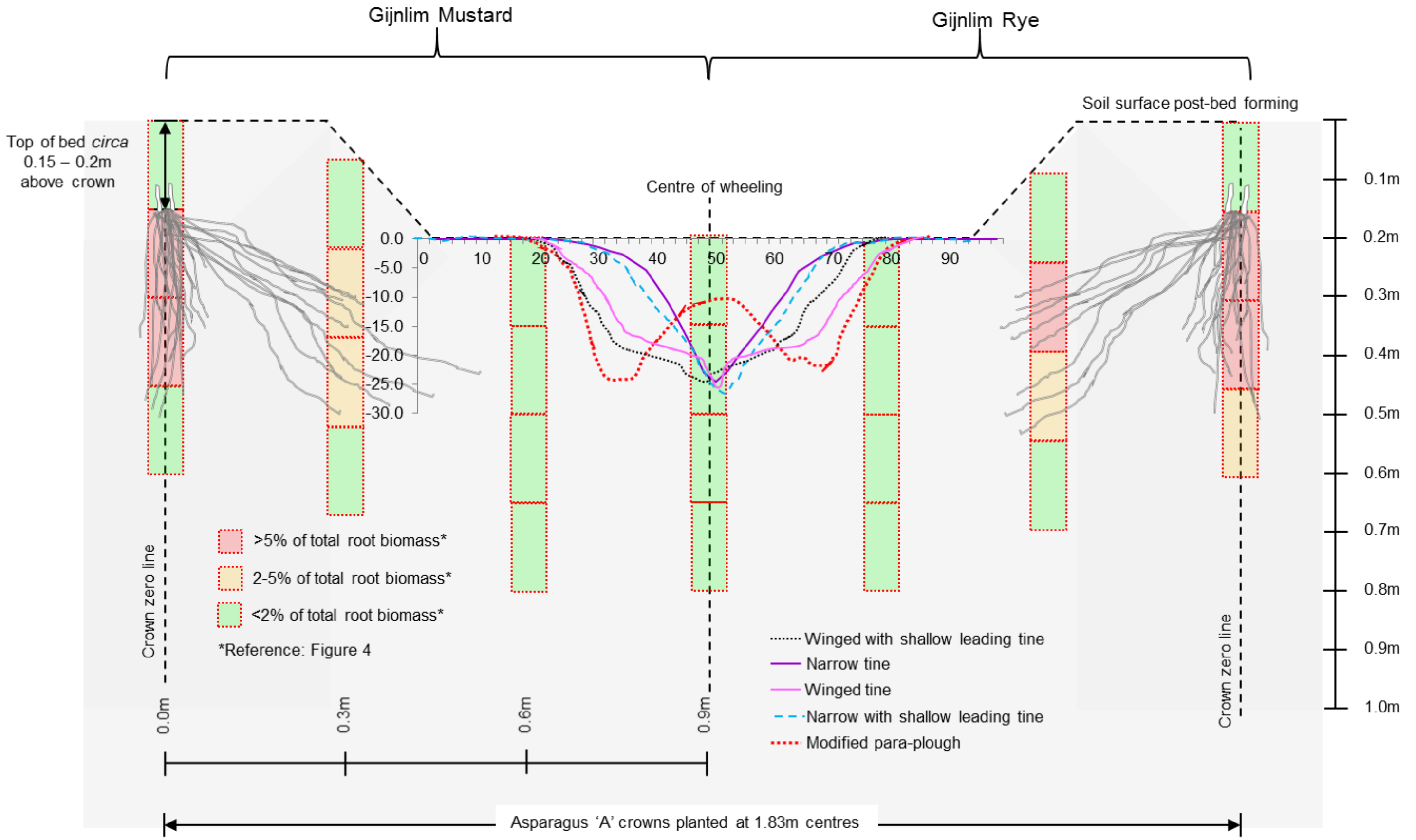


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

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

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For Year 2 profile root distribution values refer to relevant Figures and Tables in main body of report..

Figure 16. Year 2: Potential root damage associated with below ground soil disturbance profiles for a range of tines types and geometries operating at 0.3m working depth: Gijnlim mustard and rye companion crop treatments.



*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 disturbance (cm)

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For Year 2 profile root distribution values refer to relevant Figures and Tables in main body of report..

Evaluation of asparagus root architecture associated with the wider UK asparagus grower land bank: Preliminary survey

During May-Sept 2017 an MSc thesis was undertaken to investigate of asparagus root architecture associated with the wider UK asparagus grower land bank. The aim of this project was to assess the lateral and vertical distribution of the storage roots for two asparagus varieties, Gijnlim and Guelph Millennium across age of stand.

This research investigated the effect the spatial distribution of asparagus storage roots in function of stand age and the relationship between the spatial distribution of asparagus roots and relevant soil properties. Fields of 1, 4, 6 and 9 years of stand age were selected. One-year old stands were represented by the FV 450 trial site data. Root cores were taken for a total of 10 plants per field following the FV 450 root coring protocol. Root maps were created, visualizing the spatial distribution of the storage roots. A selection of these maps is shown in Figure 17 and 18.

The results indicated that while variety is not a prevailing factor in root mass distribution, stand age had a significant effect on the spatial distribution of asparagus storage roots. Over time, roots mainly expand (Figure 18) under the ridge (0-30cm away from the crown) and further into deeper soil layers within this zone.

Root growth is inhibited under the wheeling due to compaction and probably also due to tillage operations. Correlation analysis showed that there was a significant ($p<0.05$) negative but weak correlation between root mass distribution and soil penetrative resistance (PR) data integrated for the same soil depth intervals and positions; r^2=-0.183.

This was a pioneer study, only based on 5 fields. More work is needed to provide a more robust picture of root mass density distribution for different asparagus varieties, stand ages, management practices and soil types. This will be a core objective in FV 450a.

Figure 17. Root maps visualizing the spatial distribution of Guelph Millennium storage roots as a function of soil depth and distance from the centre line of the ridge for fields with a different age of stand.

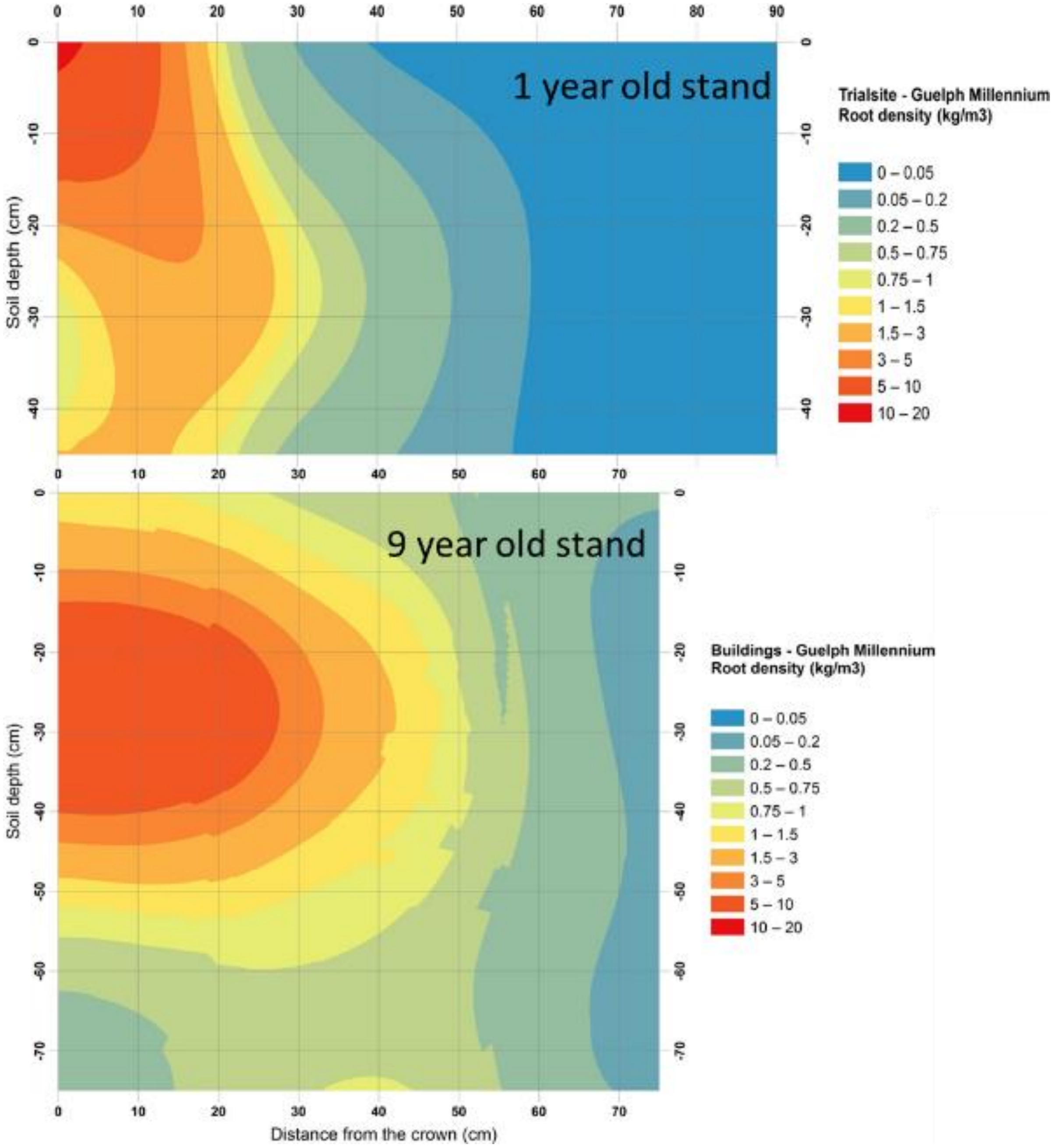
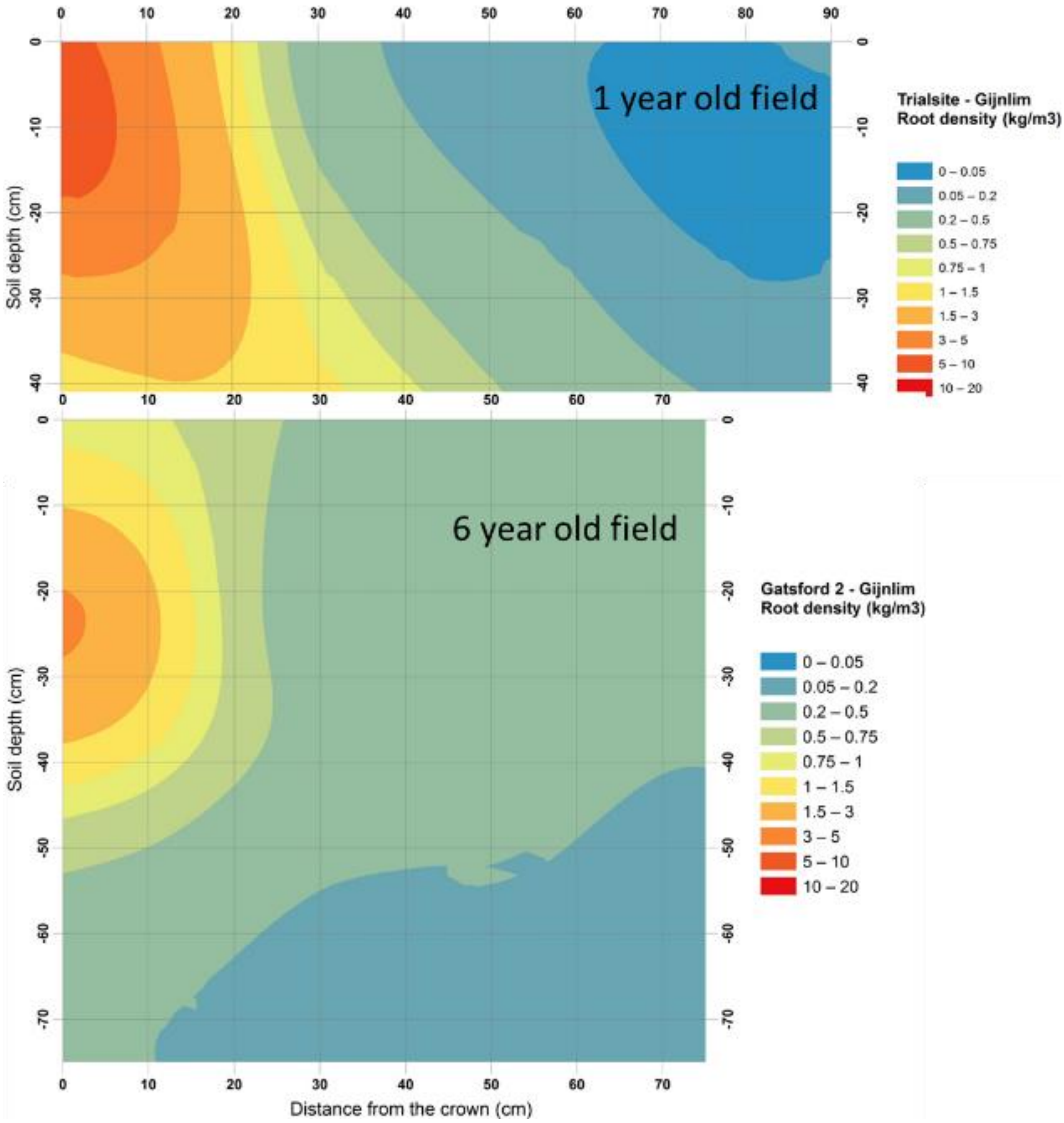


Figure 18. Root maps visualizing the spatial distribution of Gijnlim storage roots as a function of soil depth and distance from the centre line of the ridge for fields with a different age of stand.



Grower Questionnaire

As agreed by the PAG (15th December 2017) in February 2018, an online questionnaire (Qualtrics software) with supporting information was distributed to AGA members by Jayne Dyas at 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 (FV271 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^{-1}) 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. Row spacings were dominated by 1.8-1.83m centres representing 50% of fields with 34% of fields on 1.5-1.54m centres and 15% outside of this range (including 1.2, 1.6, 1.75 and 2.0m centres).

With regards planting method, 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 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 be investigated under FV 450a to identify fields (based on the criteria listed below) that will be incorporated in the wider asparagus root architecture survey conducted during 2018-2020.

Conclusions

The baseline root coring results suggest that the current coring protocol will as expected form a robust basis to quantify the effect of BMPs on asparagus root architecture and varietal differences in root profile distribution. This will be continued under FV 450a.

Year 1:

- Root mass density values were found to be generally higher for Gijnlim as compared to Guelph Millennium for most soil depths and sample locations. However, after 1-year of growth no significant differences were detected,
- For both varieties, 1 year after planting and prior to ridging, circa 65% of the total measured plant root mass is found at the crown zero line, near the surface at 0.0 - 0.15 m depth.
- Very few roots had explored the soil at 0.3m, 0.6m and 0.9m away from the crown zero line. Further away from the crown zero line, roots tend to be mostly in the 0.15 – 0.30m and 0.3 - 0.45m soil layers and avoid the topsoil (0.0-0.15m). For both varieties, there were no roots detected (RMD values <0.1 kg m^{-3}) in any of the root cores (0.0 – 0.45m depth) taken 0.9m away from the crown zero line.

Year 2:

- The year 2 root mass densities were significantly higher as compared to the year 1 root mass densities. For both Gijnlim and Guelph Millennium, the average RMD at the crown zero line for the 0.15 – 0.3m depth increased from 8-12 kg m^{-3} in Year 1 up to ca. 20 kg m^{-3} in Year 2. No significant differences in the spatial distribution of RMD were observed between varieties.
- However, the results of year 2 continue to indicate that although not significant, Gijnlim roots tend to expand more into the wheeling (0.9m away from the crown) as compared to Guelph Millennium, whereas more Guelph Millennium roots tend to be closer to the surface 0.6m away from the crown. This trend will be monitored under FV540a.

Potential impact of tillage (sub-soiling) and ridging operations on root damage

The current trials form an evidence base for a paradigm shift in the way asparagus is cultivated in the UK particularly the need for and intensity of re-ridging operations.

Year 1:

- When the dimensions of the re-ridged bed-form are superimposed on the baseline varietal root distribution, the results indicates that;
- For both Guelph Millennium and Gijnlim there is a risk of damaging 7-9% of total root biomass if the rotating tines of the bed-former used were to till soil to 0.15 -0.3m depth within 0.3m of the crown zero line.
- In addition, for Guelph Millennium there is a risk of damaging 2% of total plant root biomass if the rotating tines of the bed-former till soil to 0.0 - 0.15m depth within 0.3m of the crown zero line.
- The year-one field trial results indicate that for both Gijnlim and Guelph Millennium varieties sub-soiling operations [as a mitigation measure to improve infiltration for the control runoff and erosion] could be undertaken at operating depths of 0.175 – 0.3m, when crowns are planted on 1.83m centres.

Year 2:

- When the dimensions of the bed-form are superimposed on the year 2 varietal root distribution this indicates that for Gijnlim there is a risk of damaging <2% of total plant root biomass if the rotating tines of the bed-former till soil to 0.15 m depth within 0.3m and 0.6 of the crown zero line.
- For Gijnlim if ridging tines disturb soil at 0.15 – 0.30m depth 0.3 and 0.6m from the crown zero line there is a risk of damaging circa 6% and 2-5% of total plant root biomass respectively.
- For Guelph Millennium there is a risk of damaging <2% and 2.2% of total plant root biomass if the rotating tines of the bed-former till soil to <0.15m depth within 0.3m and 0.6m of the crown zero line. If ridging tines disturb soil at 0.15 – 0.30m depth 0.3 and 0.6m from the crown zero line there is a risk of damaging circa 5% and 2-5% of total plant root biomass respectively.

- For Gijnlim, sub-soiling operations to 0.175m depth with a full range of tine configuration options (Niziolomski et al. 2016) can continue to be undertaken with potential to damage <2.0% of total plant root biomass.
- The root profile distribution of Guelph Millennium suggests that a modified para-plough (Niziolomski et al. 2016) should not be utilised at 0.175m depth as this has the potential to damage 2-5% of roots at 0-0.15m depth 0.6m from the crown zero line.
- For both Gijnlim and Guelph Millennium at a sub-soiling depth of 0.3m, neither the modified para-plough or a winged tine of dimensions/configuration investigated by Niziolomski et al. (2016) should be utilised as the below ground disturbance patterns intersect roots within the 0.15-0.30m depth 0.6m from the crown zero line suggesting damage to 2-5% of total plant root biomass.

Effect of companion crop on asparagus root development:

For Gijnlim, the presence of either rye (*Cereale secale* L var. Protector) or White mustard (*Sinapis alba* L. var. Severka) grown in the wheelings at seeding rates of 150 kg ha^{-1} and 19 kg ha^{-1}, respectively, appear to restrict the asparagus storage roots to the ridge zone (crown zero line). This is particularly apparent 0.3m from the zero crown line at 0.15 – 0.3m depth.

For Gijnlim, this has implications in terms of reducing potential root damage associated with subsoiling at both 0.175 and 0.3m depth as root development in the 0-0.15m depth 0.6m from the crown zero line is reduced. This implies that sub-soiling operations to 0.3m depth with a full range of tine configuration options (Niziolomski et al. 2016) can be undertaken with the potential to damage <2.0% of total plant root biomass.

However, it continues to be strongly recommended that growers undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations. Training in root coring will be provided to interested growers under FV 450a.

<u>Effect of treatments on asparagus yield:</u>

- Year 2 yield data indicates that for both 2-year old Gijnlim and Guelph Millennium 2-year old plants, re-ridging does not result in a negative effect on yield.
- It is of note that the rye No-SSD non-ridged is associated with between 18.9 – 28.5%, significantly lower Total Yield (kg per plot^{-1}) as compared with the mustard No-SSD ridged, PAS 100 Compost_SSD and Straw Mulch_SSD ridged and non-ridged, Bare soil_SSD non-ridged and Bare soil_No-SSD non-ridged treatments, respectively. This reduction in yield associated with the non-ridged rye No-SSD treatment is contrary to findings of North America asparagus growers and requires further investigation under FV 450a.
- Varietal yield results indicate that Guelph Millennium is associated with between 16 – 31% significantly lower yield as compared with the equivalent Gijnlim treatments.

Knowledge and Technology Transfer

The following knowledge and technology transfer activities have been undertaken to date.

1. Project Advisory Group (PAG) Meetings were held every 6-months (6th December 2016; 17th May 2017; 15th December 2017; 15th February 2018) in order to update and received feedback from PAG members as well as AHDB representatives.
2. The aims and objectives of the project along with the proposed treatments and initial baseline soil analysis results were presented to AGA members present (30 members) including members of the AGA Technical Committee at the AGA Technical Meeting at Cranfield (27th January, 2017).
3. Year 1 results were presented at the Biennial Asparagus Conference 2017 (>120 participants) on Tuesday 18th July 2017. 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.

The Year 1 Grower Summary and Biennial Asparagus Conference presentation was distributed to AGA members via Jayne Dyas at British Growers.

4. 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

5. De Baets S and Simmons R. W. (2017) Cover crop roots to bio-engineer soil. Session 5: Soil Health 1: Biological interactions, 5a: Ecosystem engineers. 6th International Symposium on Soil Organic Matter. 3–7 Sept. 2017, Rothamsted Research, Harpenden, UK.

6. Niziolomski, J. C., Simmons, R.W. and De Baets, S. (2017) Sustainable soil management for stand longevity and yield optimization. XIV International Asparagus Symposium, 3-6 Sept. 2017, Potsdam University, Germany.

7. Draft Asparagus Roots Fact Sheet submitted to Grace Choto on 30th April 2018.

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
RD	Root Mass Density
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

References

1. Ball, B.C., Batey, T., Munkholm, L.J., Guimaraes, R.M.L., Boizard, H., McKenzie, D.C., Peigne, J., Tormena, C.A. and Hargreaves, P. (2015). The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. Soil and Tillage Research 148, 85-96.
2. Bjorkman, T., Lowry, C., Shail, J.W., Brainard, D.C., Anderson, D.S., Masiunas, J.B. (2015) Mustard cover crops for biomass production and weed suppression in the great lakes region. Agronomy Journal Vol 107: pp. 1235-1249.
3. Chen, G., & Weil, R. R. (2011). Root growth and yield of maize as affected by soil compaction and cover crops. Soil and Tillage Research, 117, 17-27.
4. Clark, L. J., Whalley, W. R., & Barraclough, P. B. (2003). How do roots penetrate strong soil? Plant and Soil, 255(1), 93-104.
5. Cresswell, H. P., & Kirkegaard, J. A. (1995). Subsoil amelioration by plant roots - the process and the evidence. Australian Journal of Soil Research, 33(2), 221-239.
6. De Baets, S., Poesen, J., Knapen, A. and Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surface Processes and Landforms 32, 1323-1345.
7. Drost, D. and Wilcox-Lee, D. (2000) Tillage alters root distribution in a mature asparagus planting. Scientia Horticulturae, 83(3–4), pp. 187–204.
8. Drost, D. and Wilson, D. (2003). Monitoring root length density and root biomass in asparagus (*Asparagus officinalis*). New Zealand J Crop and Horticultural Science 31:125-137.
9. Elmer, W.H. (2001). Fusarium diseases of asparagus. In: Summerell, B.A., Leslie, J.F., Bacjhouse, D., Bryden, W.L., Burgess, L.W., (editors), Fusarium, APS Press pg. 248-262.
10. Elmer, W.H., (2015). Management of Fusarium crown and root rot in asparagus, Crop Protection, 73, pp. 2-6.
11. Falloon, P.G. and Grogan, R.G. (1991) Effect of root temperature, plant age, frequency and duration of flooding and inoculum placement and concentration on susceptibility of asparagus to Phytopthora rot. New Zealand J Crop and Horticultural Science 19:305-312.
12. Finney, H.J. (1984). The effect of crop covers on rainfall characteristics and splash detachment. Journal of Agricultural Engineering Research, 29, 337-343.
13. Grzesiak, S., Grzesiak, M.T., Hura, T., Marcińska, I., Rzepka, A. (2013). Changes in root system structure, leaf water potential and gas exchange of maize and triticale seedlings affected by soil compaction. Environmental and Experimental Botany, 88, 2-10.

14. Guimarães, R.M.L., Ball, B.C. and Tormena, C.A. (2011). Improvements in the visual evaluation of soil structure. Soil Use and Management, 27, 395-403.
15. Holland, J.M. (2004). The environmental consequences of adopting conservation tillage in Europe: Reviewing the evidence. Agriculture, Ecosystems and Environment, 103, pp. 1-25.
16. Jones, C. A. (1983) Effect of Soil Texture on Critical Bulk Densities for Root Growth, Soil Science Society of America Journal, 47, pp. 1208–1211.
17. Kabir, Z., and Koide, R.T. (2002) Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. Plant Soil 238: 205-215.
18. Kirkegaard, J., Christen, O., Krupinsky, J., & Layzell, D. (2008). Break crop benefits in temperate wheat production. Field Crops Research, 107(3), 185-195.Kruse M., Strandberg M., Strandberg B. (2000). Ecological effects of allelopathic plants. A review. Department of Terrestrial Ecology, Silkeborg, Denmark.
19. Matsubara, Y., Ohba, N., Fukui, H., 2001. Effect of arbuscular mycorrhizal fungus infection on the incidence of Fusarium root rot in asparagus seedlings. J. Jpn. Soc. Hort. Sci. 70, 202-206.
20. Matsubara, Y., Okada, T., Liu, J., 2014. Suppression of Fusarium crown rot and increase in several free amino acids in mycorrhizal asparagus. Amer. J. Plant Sci. 2014, 235-240.
21. Mennan H., Ngouajio M. (2012). Effect of brassica cover crops and hazelnut husk mulch on weed control in hazelnut orchards, Hort. Technology 22: 99 -105.
22. Miransari, M. (2014). Plant growth promoting Rhizobacteria. Journal of Plant Nutrition, 37, 2227-2235.
23. Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J. (2010). The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment-A review. Soil and Tillage Research, 108, 1-15.
24. Njeru, E.M., Avio, L., Sbrana, C., Turrini, A., Bocci, G., Barberi, P., Giovannetti, M. (2014). First evidence for a major cover crop effect on arbuscular mycorrhizal fungi and organic maize growth. Agron. Sustain. Dev. 34: 841-848.
25. Niziolomski, J.C (2011). Critical evaluation of the role of sub-soiling and mulching in the control of runoff and erosion from asparagus furrows. MSc Thesis, Cranfield University.
26. Niziolomski, J.C. (2015). Optimising soil disturbance and mulch attenuation for erosion and runoff control in asparagus crops. PhD Thesis, Cranfield University.
27. 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.
28. Putnam, A.R. (1972). Efficacy of zero-tillage cultural system for asparagus produced from seeds and crowns. Journal of American Society for Horticultural Science 97:621-624.

29. Reberg-Horton S.C., Burton J.D., Daneower D.A., Ma G., Monks D.W., Murphy J.P., Ranells, N.N, Williamson J.D., Creamer N.G. (2005). Changes over time in the allelochemical content of tencultivars of rye (Secale cereale L.). Journal of Chemical Ecology 31:179-193.
30. Reijerink, A. (1973) Microstructure, soil strength and root development of asparagus on loamy sands in the Netherlands, Netherlands Journal of Agricultural Science, 21, pp. 24–43.
31. Schulz M., Marocco A., Tabaglio V., Macias F.A., Molinillo J.M. (2013). Benzoxazinoids in rye allelopathy from discovery to application in sustainable weed control and organic farming. Journal of Chemical Ecology 39: 154-174.
32. Seymour, M., Kirkegaard, J. A., Peoples, M. B., White, P. F., and French, R. J. (2012). Break-crop benefits to wheat in Western Australia - insights from over three decades of research. Crop and Pasture Science, 63(1), 1-16.
33. Shepherd, G. (2000). Visual Soil Assessment. Volume 1 Field guide for cropping and pastoral grazing on flat to rolling country. Horizons.mw & Landcare Research, Palmerston North.
34. Shelton D.R., Lacy M.L. (1980). Effect of harvest duration on yield and depletion of storage carbohydrates in asparagus roots. J. Am. Soc. Hort. Sci. 105: 332-335.
35. Smolinska, U., Morra, M.J., Knudsen, G.R., James, R.L. (2003) Isothiocyanates produced by Brassicaceae species as inhibitors of Fusarium oxysporum. Plant Disease 87: pp. 407-12.
36. Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F. and Roger-Estrade, J. (2012). No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Research, 118, 66-87.
37. Soil Survey Staff. 2014. Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51, Version 2.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.
38. Tracey, S.R., Black, C.R., Roberts, J.A., Sturrock, C., Mairhofer, S., Craigon, J. and Mooney, S.J. (2012). Quantifying the impact of soil compaction on root system architecture in tomato (Solanum lycopersicum) by X-ray micro-computed tomogropahy. Annals of Botany, 110: 511-519.
39. Weston L.A. (1996). Utilization of allelopathy for weed management in agroecosystems. Agronomy Journal 88: 860-866.
40. Whalley, W.R., Clark, L.J., Gowing, D.G.J., Cope, R.E., Lodge, R.J. & Leeds-Harrison, P.B. (2006). Does soil strength play a role in wheat yield losses caused by soil drying? Plant & Soil, 280: 279-290.

41. White, R. G., and Kirkegaard, J. A. (2010). The distribution and abundance of wheat roots in a dense, structured subsoil - implications for water uptake. Plant, Cell and Environment, 33(2), 133-148.
42. Wilcox-Lee, D. and Drost, D. T. (1991) Tillage Reduces Yield and Crown, Fern, and Bud Growth in a Mature Asparagus Planting. Journal of the American Society of Horticulture, 116(6), pp. 937–941.
43. Wilson, D.R., S.M. Sinton, R.C. Butler, D.T. Drost, P.J. Paschold, G. van Kruistum, J.T.K. Poll, C. Garcin, R. Pertierra, I. Vidal, and K.R. Green. (2008). Carbohydrates and Yield Physiology of Asparagus – A Global Overview. Acta Hort. 776:411-426.

