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

AUTHENTICATION

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

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GROWER SUMMARY

Headline

Year one root profile distributions for asparagus varieties Gijnlim and Guelph Millennium can be used to identify and minimise risk of root damage associated with re-ridging and subsoiling operations. Success could have significant implications for stand longevity and productivity through decreasing susceptibility to crown and root rot.

Background

Field operations associated with UK asparagus production [tillage and spray operations, installation of plastic cloches, 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 can decrease the susceptibility to crown and root rot 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.

In addition, 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, whilst ponding in furrows increases the risk of crown and root rot leading to yield decline. The long-term field trials established under this project will critically evaluate a range of Best Management Practices (BMPs) to prevent and/or mitigate compaction, improve soil structural status in asparagus wheelings and facilitate long-term profitability of asparagus production. The experimental trials will compare shallow soil disturbance (SSD) and mulch attenuation options, cover/companion cropping, and non-till options against a conventional practice control.

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 cultivars Gijnlim and Guelph Millennium were planted on 20-21st of April 2016 on the flat at an anticipated depth of 0.14m with 0.16m spacing between the crowns on 1.83m wide bed centres.

Experiment 1 (48 experimental plots) is restricted to Gijnlim which represents 70% of UK field grown asparagus. Shallow soil disturbance (SSD) will be applied using a winged tine to 0.175m depth (Niziolomski et al., 2016). 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.

The companion crops to be included in the trials will be broadcast in July/August 2017 and are likely to be frost tolerant varieties of oil radish (or mustard), and rye. Final selection will be made at the Project Advisory Group (PAG) Meeting on 17th May 2017. Experiment 2, will elucidate varietal differences in root development/architecture and root profile distribution as affected by subsoiling treatments [as a mitigation measure to improve infiltration for the control of runoff and erosion] and annual re-ridging vs zero tillage. Experiment 2 is adjacent to Experiment 1 and is a cost effective way (16 additional experimental plots) of incorporating two experimental programmes within a single field trial.

Baseline soil sampling was undertaken during 17th – 21st October and 1st – 3rd November 2016. The results indicate that there is no significant difference is the parameters tested between experimental plots. This is critical as it means that any differences observed can in future, be attributed to the BMP treatments applied. It is of note that the high Penetrative Resistance (PR>3 MPa) measurements in the upper sub-soil could impact asparagus root development. Further, the observed high Bulk Density (BD) measurements (>1.45 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). 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.

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

Root mass density values are generally higher for Gijnlim as compared to Guelph Millennium for most soil depths and sample locations. However, after one-year of growth no significant differences were as yet detected. For both varieties, one year after planting 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 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 – 0.30m and 0.3 - 0.45m soil layers and avoid the topsoil (0.0 - 0.15m). For both varieties, there were no roots detected (Root mass density (RD) 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.

It is expected that the current long-term trials 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. Minimizing root damage contributes to stand longevity and productivity and decreases the susceptibility to crown and root rot. 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 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 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. However, it is strongly advised that growers undertake exploratory root profile distribution surveys prior to commencing sub-soiling operations. Root coring protocols will be demonstrated and discussed at the Annual Asparagus Conference 2017 which will be held on Tuesday 18 July 2017. Results from year one of this long-term trial will also be presented.

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).

- Project outputs will provide a useful tool for dissemination, discussion and knowledge exchange with AGA members as well as the wider horticultural community that will help stimulate interest and develop awareness and industry expertise in sustainable soil management practices.
- 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 2,396t, are valued at £8.4 million. Annual asparagus imports to the UK in 2014 amounted to 14,200t, 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 £16 million in lost revenue per annum. A 10% reduction in yield losses due to asparagus decline would amount to a saving of >£1.6 million 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 first year of this proposed long-term replicated field trial. As such it is not feasible to make robust action points. However, it is strongly recommended that growers undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations. Root coring protocols will be demonstrated and discussed at the Annual Asparagus Conference 2017 held on Tuesday 18th July 2017.

SCIENCE SECTION

Introduction

Field operations associated with UK asparagus production [tillage and spray operations, installation of plastic cloches, 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 attained. However, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and productivity (Drost & Wilcox-Lee 2000; Putnam 1972; Reijmerink 1973; Wilcox-Lee & Drost 1991) and increases the susceptibility to crown and root rot caused by *Phytophthora megasperma* (Falloon & Grogan 1991) and *Fusarium oxysporum* f. sp. *asparagi* (Elmer, 2001) 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. This is particularly pertinent in the light of the ‘extreme’ rainfall events that have become the norm over the last few years. 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 the context of this project 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 three-dimensional asparagus root architecture and root profile distribution is currently under-researched and will be assessed under Work package 1 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). 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 0.14 m, 0.3 m and 0.45 m, 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 0.14 m with a 0.16 m spacing between crowns on 1.83m wide bed centres.

In both experiments, trial plots were 35 m long and comprised 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 and 2017 (Appendix 1).

Note: 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, the Zero tillage (ZT) treatment will be implemented from spring 2018.

Experiment 1 cannot be established as a full factorial design as the number of factorial combinations and subsequent experimental replicates would be prohibitive. Consequently, a General Linear Model based on a nested design was adopted. Experiment 1 is restricted to Gijnlim variety which represents 70% of UK field grown asparagus. Shallow soil disturbance (SSD) will be applied using a winged tine to 175mm depth (Niziolomski et al., 2016). SSD 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.

Companion crops to be included in the trials are likely to be oil radish, and rye. Final selection will be made at the PAG Meeting on 17th May 2017). Seed will be supplied by Frontier (Pers. Comm. Paul Brown). A total of 48 experimental replicates will be investigated under the main experiment (Table 1). All treatments are replicated in quadruplicate.

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	ZT
Gijnlim	Companion Crop – Oil radish	R
Gijnlim	Companion Crop – Oil radish	ZT
Gijnlim	PAS 100_SSD	R
Gijnlim	PAS 100_SSD	ZT
Gijnlim	Straw Mulch_SSD	R
Gijnlim	Straw Mulch_SSD	ZT
Gijnlim	Bare soil_SSD	R
Gijnlim	Bare soil_SSD	ZT
Gijnlim	Bare soil_No-SSD	R
Gijnlim	Bare soil_No-SSD	ZT

Annual re-ridging (R) or Zero tillage (ZT). Treatments highlighted in green will be included in Experiment 2. These treatments were confirmed during the PAG Meeting on 6th December 2016.

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 ANOVA) design and will elucidate varietal differences in root development/architecture and root profile distribution as affected by SSD treatments (175mm depth) and annual re-ridging vs zero tillage (Table 2). Experiment 2 will be 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	ZT
Gijnlim	Bare soil_No-SSD	R
Gijnlim	Bare soil_No-SSD	ZT
Millennium	Bare soil_SSD	R
Millennium	Bare soil_SSD	ZT
Millennium	Bare soil_No-SSD	R
Millennium	Bare soil_No-SSD	ZT

Annual re-ridging (R) or Zero tillage (ZT). Treatments highlighted 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. This will be replaced by replicated measures of infiltration. ** Asparagus yield and spear size to be evaluated from 2018 harvest onwards.*

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 except that 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 3-D distribution of roots within wheelings as effected 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 0.01 m 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 (0.05 m depth x 0.05 m internal diameter) were taken at two depths mid-topsoil (0.20 - 0.25 m) and upper sub-soil (0.45 - 0.50 m). 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 – 0.2 m) 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)). Soil pH was determined on a 1:5 (w/w) soil:deionised water suspension with a Mettler Toledo MA 235 pH analyser (BS ISO 10390:2005; BS 7755 Section 3.4:1995). Soil organic matter was determined following loss on ignition (BS EN 13039:2000) using a Carbolite AAFF 1100 Muffle Furnace set at 450°C temperature overnight (16 hours) with TOC determined following BS 7755 section 3.8:1995 (ISO 10694:1995) and analysed using a Vario EL III CHNOS Elemental Analyser system, Germany. Total-N was also determined on the Vario EL III CHNOS Elemental Analyser, Germany following British Standard BS EN 13654-2:2001. Olsen-P was determined in a sodium hydrogen carbonate solution using a Nicolet Evolution 100 atomic absorption spectrophotometer (AAS) at 880nm absorbance following BS 7755 Section 3.6:1995 (ISO 11263: 1994). Particle size distribution (PSD) was determined using the sieving and sedimentation method (ISO 11277:1998) for sand (0.063mm – 2 mm), silt 0.002 mm – 0.063 mm) and clay (<0.002) following the particle size classification of the Soil Survey of England and Wales (Gee and Bauder, 1986).

Structural assessments will be carried out on the topsoil (typically to 25 cm depth) using the BioAgriNomics Visual Soil Assessment (VSA - Shepherd, 2000) and Visual Evaluation of Soil Structure (VESS - Guimarães *et al*., 2011) methods, and on the deeper subsoil (at 40-60 cm depth) using the subsoil VESS method. These structural assessments will be undertaken post-harvest re-ridging and implementation of the SSD and mulch treatments (circa May 2017) when wheelings would have experienced maximum levels of annual compaction (via foot and vehicular traffic).

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 rot.

Root architecture is determined following the procedure of Drost and Wilson (2003). Replicated root cores (0.06 m internal diameter) were taken from the crown centre line (from hence forth defined as the crown zero line) at 0.3 m intervals to the centre of the wheeling in Experiment 1 (Objective 2 - BMP’s) and Experiment 2 (Objective 4 - Varietal Differences). Soil cores were collected using an Eijhelkamp bi-partite hand held root auger at 0.15 m intervals to a maximum depth of 0.45 m (Figure 1). Roots were washed and will be scanned (using WhinRhizo software) to give root length density, specific root length and root diameter for fleshy storage roots.

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

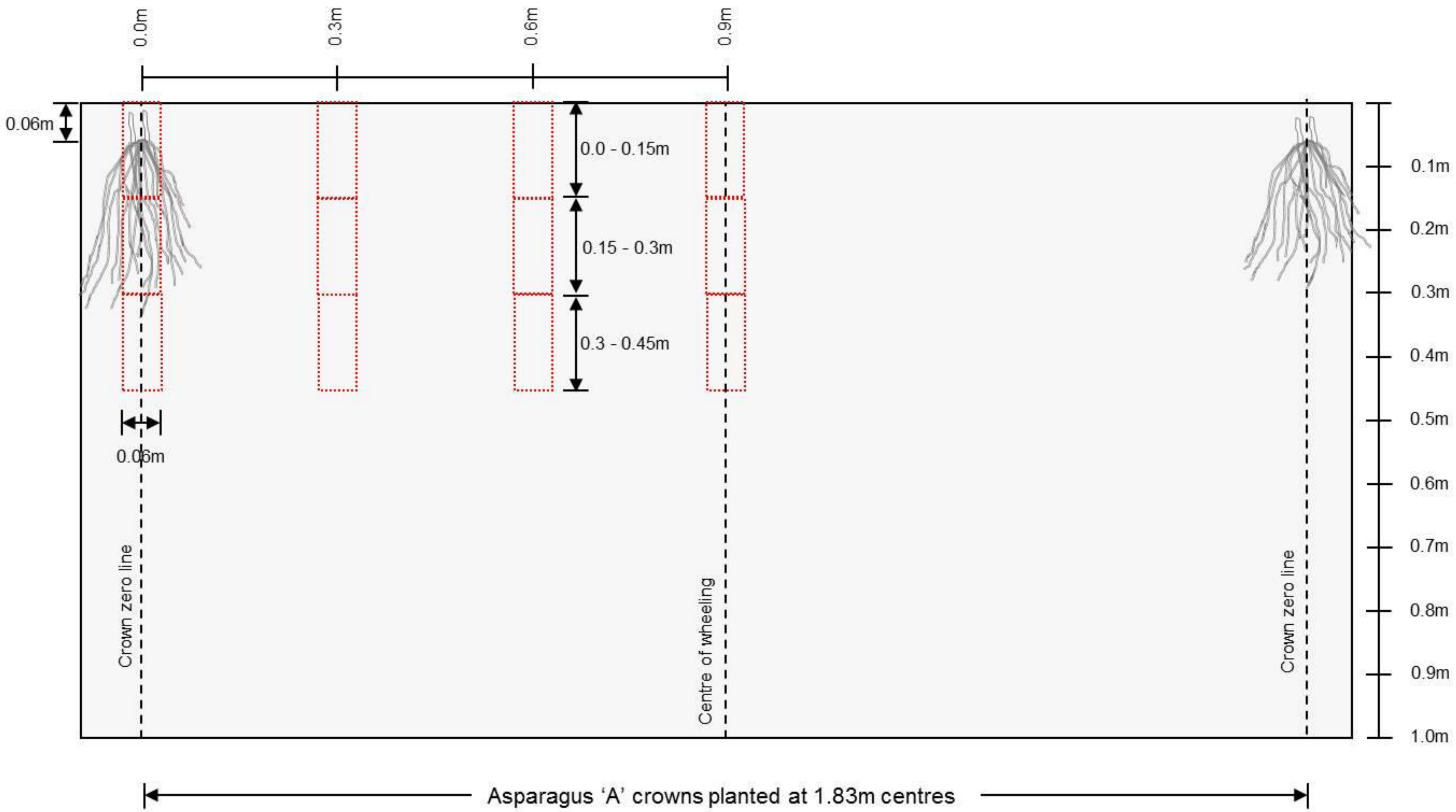


Figure 1. Root coring protocol adopted in this study.

During project planning, it was envisaged that both feeder and storage roots would be differentiated. However, post-consultation with Prof. Dan Drost (Advisor to the project and Visiting Fellow at Cranfield from March – November 2017) and initial in-field root washing it was considered appropriate that root coring on both varieties would only focus on investigating storage root distributions and characteristics [root length density, specific root length and root diameter, root mass density (DW)]. Feeder roots are hard to distinguish from weed and grass roots, are readily damaged during root washing, are highly seasonal and have a short life span. Depending on the time of sampling you may find fewer or more feeder roots. From an economic and stand longevity perspective it is critical to assess the effect of BMPs on the distribution and volume of the main storage root system.

Baseline root coring (prior to re-ridging and treatment implementation) was carried out during the 7-9th of March 2017. In total 16 plants were sampled per variety from eight randomly selected plots. 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 1). Root cores were extracted with an Eijkelkamp bi-partite hand held root auger (internal diameter: 0.06 m, volume: 754 cm^3) at the following soil depths: 0.00 - 0.15 m, 0.15 - 0.30 m and 0.30 - 0.45 m. Asparagus storage roots were separated from the soil by dry selection. Fresh roots were then washed in the laboratory and spread out on white paper with scale bar and photographed for further root length analysis. Fresh roots where then oven dried at 48°C for 24hr and stored in paper bags 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). In order to assess the risk of roots being cut during tillage operations, spatial root distribution will be visualised using a traffic light colouring scheme (see Figures 5-8). 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 both varieties, at each coring position, the mean (n=16) value of the percentage (%) of total root mass was used (Figure 4).

Cover crop selection and seeding rates

The aim of utilising companion crops in asparagus production is to synergistically enhance multiple soil functions such as runoff and erosion mitigation, weed suppression, improving soil structure and increasing available N/P for sustainable crop productivity.

The main reason 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 cereale* L.) produces a number of allelochemicals including the phenolic acids beta-phenyl-lactic acid (PLA) and betahydroxybutyric acid (BHA) and the hydroxamic acids benzoxazinone and benzoxazolinone (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).

The second cover crop species is selected from the Brassicaceae family - (oil radish (*Raphanus sativus L*.) or white mustard (*Sinapis alba L*.). Glucosinolates are released into the environment and decomposed into several biologically active compounds, such as isothiocyanates. These can suppress the growth and development of plants (Mennan and Ngouajio, 2012). Glucosinolates and other volatile sulphur compounds that are released from Brassicas are also toxic to many soil borne pests and can be used to biofumigate soils and help combat pests.

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). In contrast, rye a widely adopted cover/companion crop, 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 damage from *Fusarium* infection and improved root health of asparagus (Matsubara *et al.*, 2001, 2014).

Soil management practices such as cover crops and companion cropping are also increasingly used to improve soil structure and manage the runoff and erosion problems, but there is a lack of data to demonstrate their efficacy. Few recommendations exist on cover crop or companion crop seeding rates. Growers often try at low-medium seeding rate and if germination is poor, reseed, which is not cost effective. Seeding rate (broadcast) of rye currently practiced by Cobrey Farms is 125 kg ha^{-1}. Two fields at Gatsford were visited during the PAG Meeting on December 6th 2016, of which one received 140 kg ha^{-1} and the other 90 kg ha^{-1}. No obvious differences in rye establishment or surface cover were observed. Cotswold Seeds recommend 187.5 kg ha^{-1} for a rye-vetch mix.

To identify an appropriate seeding rate an MSc student thesis will be undertaken at Cranfield (May – August 2017) to critically evaluate the seeding rates of three cover crops (two monocrops Rye and Oil radish/Mustard and one mixture). Performance will be based on germination rate, stem density and ground cover and resilience to erosion stresses. After 3 weeks, 4 weeks and 6 weeks of growth in the glasshouse, erosion tests will be performed to test treatment performance. Erosion rates of the cover crops trays will be compared to bare soil. The aim is to formulate recommendations that can feed into the field trials on seeding rates and best companion crop species for the mitigation runoff and erosion. Tests will be performed in the Soil Erosion Facility at Cranfield, but plants will be grown in the same soil as the experimental trail site and will be subjected to simulated rainstorm events indicative to Ross-on-Wye. It is envisaged that treatments replicating 1, 5 and 30 year return period storm events will be applied. A second MSc this will investigate root profiles for the same asparagus varieties as function of stand age under conventional practice. This work aims to critically evaluate how root distribution develops with stand age. This will allow the conventional treatments applied during the long-term field trial to be contextualised against a wider baseline which will form a 'projected' root profile distribution for a given stand age.

Results

Baseline soil sampling

No significant differences were observed ($p \leq 0.05$) between plot baseline soil parameters [following one-way ANOVA and *post hoc* Fisher LSD analysis] (Table 3). Particle size distribution analysis revealed the site soil texture as a sandy loam.

Table 3: Mean results of baseline soil parameters.

Baseline parameter	**Mean**	**Standard deviation**
Sand (%)*	76.94	+/- 5.72
Silt (%)*	11.26	+/- 6.54
Clay (%)*	11.80	+/- 1.75
Loss on ignition (%)†	2.78	+/- 0.24
pH†	6.34	+/- 0.2
Total N (%)	0.12	+/- 0.01
Olsen-P (mg kg^{-1})	9.18	+/- 1.87
Total C (%)	1.25	+/- 0.11

*Taken from a randomised 20 % of the 64 sampled plots.
†Sampled from the upper topsoil at 0-15 cm.

Baseline PR measurements to 0.5 m revealed increasing resistance from the mid top-soil to the upper sub-soil (Figure 2). 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 (Figure 3), 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.

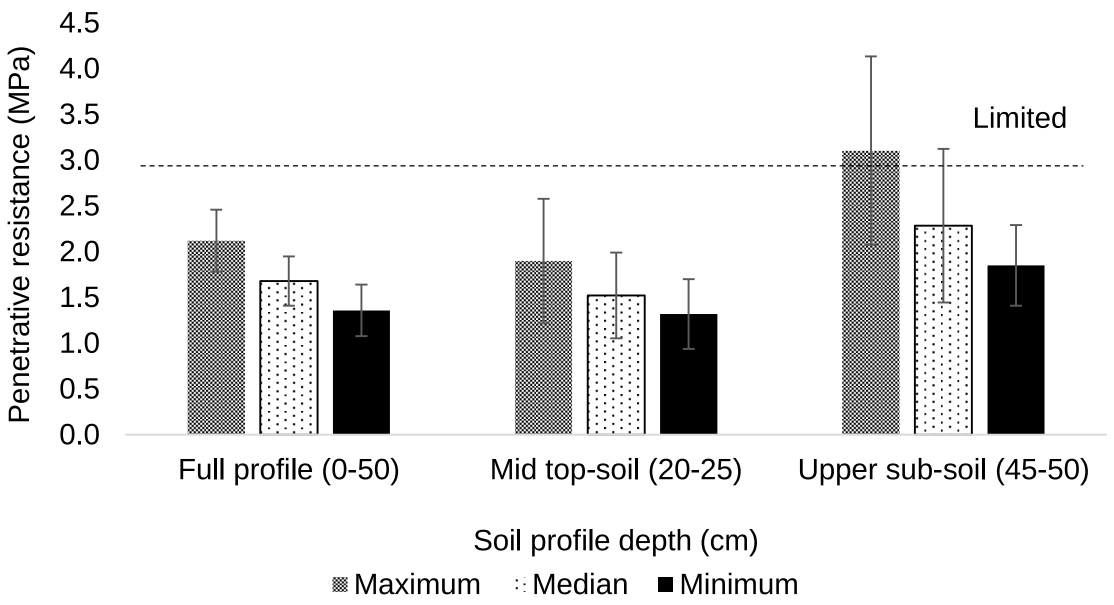


Figure 2. Mean maximum, median and minimum penetrative resistance (PR) measurements (MPa) across the full soil profile, mid top-soil and upper sub-soil. Error bars show standard deviation +/-1. The dashed line indicates the PR at which root growth becomes limited. Moisture content at the point of measurement was 17.9 % +/- 4.3 % (Mid top-soil) and 11.3 % +/- 2.3 %

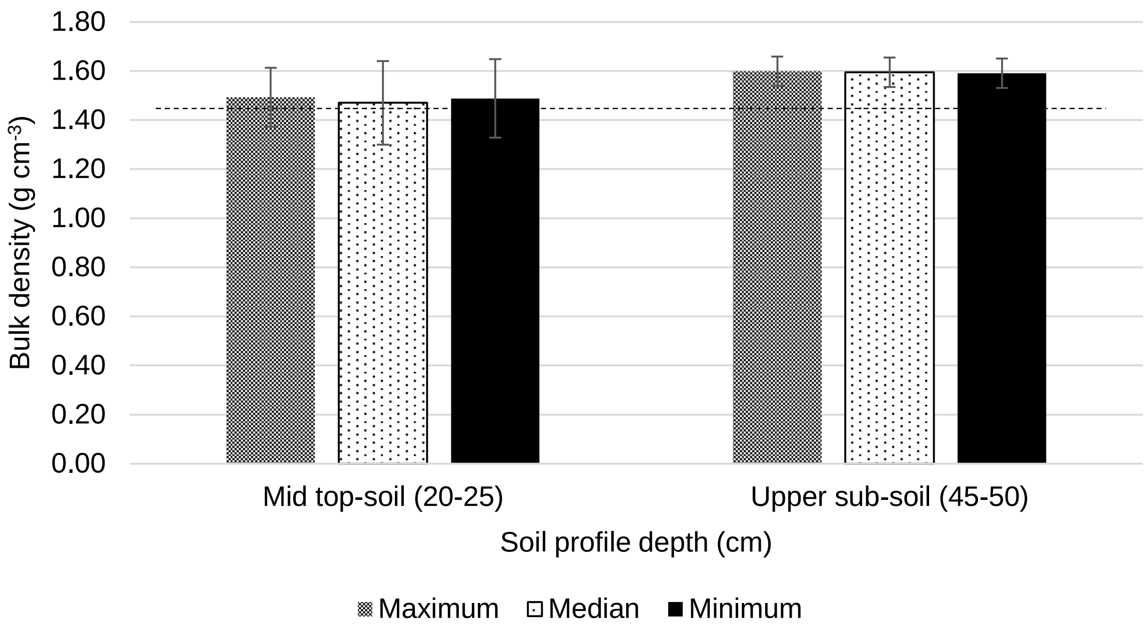


Figure 3. Mean maximum, median, minimum bulk density (BD) values for the top 5 cm of the mid top-soil and upper sub-soil in the wheelings. The dashed line indicates a BD (1.45 g cm^{-3}) based on soil type beyond which fewer roots are likely to be found (Jones, 1983).

Baseline root coring

Root distribution profiles per variety are presented in Figure 4 for Gijnlim and Guelph Millennium. Average root mass density (RD, kg m^{-3}) values and standard errors are also presented in Table 4 per variety, soil depth and distance from the crown zero line. Root mass density values are generally higher for Gijnlim as compared to Guelph Millennium for most soil depths and sample locations. However, no significant differences were detected, so it is concluded that roots of both varieties are exploring the soil profile in a similar way. Figure 4 shows that 1 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 0.3 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). There were no roots detected (RD values <0.1 kg m^{-3}) in any of the root cores taken 0.9m away from the crown zero line (Table 4 and Figure 4).

Table 4: Average Root Mass Density (RD, kg m^{-3}) and standard error (SE) values per variety, soil depth and distance from the crown zero line (0.0 cm).

Variety	Distance from crown zero line (m)	Root coring depth (m)	RD (kg m^{-3})	SE
Gijnlim	0.0	0.00 – 0.15	11.92	1.58
Gijnlim	0.0	0.15 – 0.30	2.44	0.48
Gijnlim	0.0	0.30 – 0.45	0.79	0.45
Gijnlim	0.3	0.00 – 0.15	0.15	0.06
Gijnlim	0.3	0.15 – 0.30	1.57	0.40
Gijnlim	0.3	0.30 – 0.45	0.67	0.34
Gijnlim	0.6	0.00 – 0.15	0.01	0.01
Gijnlim	0.6	0.15 – 0.30	0.12	0.07
Gijnlim	0.6	0.30 – 0.45	0.31	0.20
Gijnlim	0.9	0.00 – 0.15	0.0	0.0
Gijnlim	0.9	0.15 – 0.30	0.0	0.0
Gijnlim	0.9	0.30 – 0.45	0.10	0.07
Guelph Millennium	0.0	0.00 – 0.15	8.5	1.13
Guelph Millennium	0.0	0.15 – 0.30	1.8	0.24
Guelph Millennium	0.0	0.30 – 0.45	0.85	0.18
Guelph Millennium	0.3	0.00 – 0.15	0.32	0.11
Guelph Millennium	0.3	0.15 – 0.30	0.88	0.18
Guelph Millennium	0.3	0.30 – 0.45	0.63	0.16
Guelph Millennium	0.6	0.00 – 0.15	0.01	0.00
Guelph Millennium	0.6	0.15 – 0.30	0.04	0.02
Guelph Millennium	0.6	0.30 – 0.45	0.03	0.02
Guelph Millennium	0.9	0.00 – 0.15	0.01	0.01
Guelph Millennium	0.9	0.15 – 0.30	0.00	0.00
Guelph Millennium	0.9	0.30 – 0.45	0.00	0.00

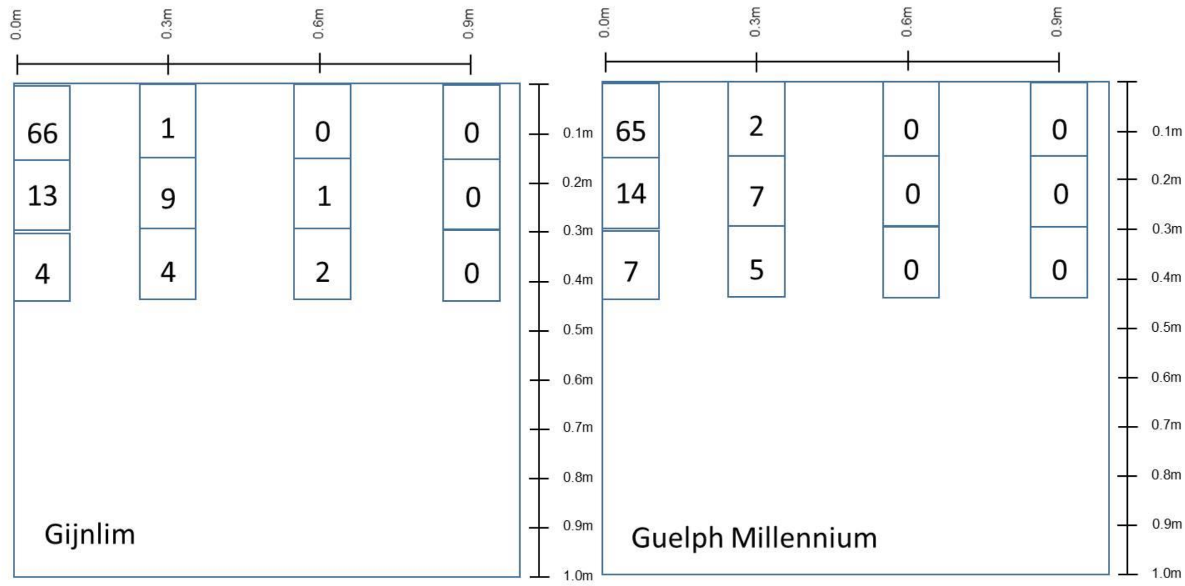


Figure 4: Profile distribution of mean total plant root mass (%) for Gijnlim and Guelph Millennium varieties.

Discussion

The baseline soil analyses indicate that there is no significant difference is the parameters tested between experimental plots. This is critical as it means that any differences observed can in future, be attributed to the BMP treatments applied. It is of note that the high PR (>3 MPa) measurements in the upper sub-soil could impact asparagus root development. Further, the observed high BD measurements (>1.45 c 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, 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.

Root distribution and implications for damaging roots during tillage operations

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. Figures 4 and 5 indicate that there are trends in varietal differences in profile root distribution. The general trend is for Gijnlim roots to have extended further from the crown particularly at 0.3 - 0.45 m depth 0.6 m from the crown zero line. However, after one year of storage root growth the predominance of roots are still immediately under the crown where the risk of being damaged by tillage operations is nil.

Specifically, for both Gijnlim and Guelph Millennium 65-66% of the total plant root biomass is within 0.0 – 0.15 m depth at the crown zero line. This decreases rapidly for both varieties to 13-14% of total plant root biomass at 0.15–0.30 m depth (Table 4 and Figures 4 and 5). At 0.3 m from the crown zero line for both varieties, root biomass is concentrated at 0.15–0.3 m and 0.3–0.45 m depths with % total plant root biomass values of 7-9 and 4-5% respectively. For Guelph Millennium circa 2% of total plant root biomass is at 0.0–0.15 m depth 0.3m from the crown zero line. Further for Guelph Millennium, at 0.6 and 0.9 m from the crown zero line no storage roots were recorded. In contrast, for Gijnlim, 2% of total plant root biomass is at 0.3 – 0.45 m depth 0.6 m from the crown zero line.

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 allii* (sexual stage of *Stemphylium vesicarium*). Consequently, on 22nd April 2017 the experimental trials were re-ridged. A target ridge depth of 0.2 m soil above the soil was required in order to facilitate the zero tillage treatments associated with this long-term experimental trial. The bed-former achieved bed dimensions of 0.55 m at the bed-surface and 0.9 m at the base. Rotating 0.38 m tines were on 1.3m centres (above the crown zero line) with leading spring tines at 1.62 m centres (Appendix 2).

The dimensions of the bed-form have been superimposed on the baseline varietal root distribution (Figure 6). This 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 till soil to 0.15-0.3 m depth 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 to 0.0-0.15 m depth within 0.3 m of the crown zero line (Figure 6). This corroborates the research of Drost & Wilcox-Lee (2000), Putnam (1972), Reijmerink (1973) and Wilcox-Lee & Drost 1991) who over the last 20 years have demonstrated annual re-ridging has a major impact on stand longevity through root damage which increases the susceptibility to crown and root rot caused by *Phytophthora megasperma* (Falloon & Grogan 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2001).

The current trials will form the 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.

A detailed penetrometer and BD survey will be undertaken in May 2017 to determine the exact dimensions of the tillage zone associated with the bed-former used in this study. 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 (Table 5) 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.

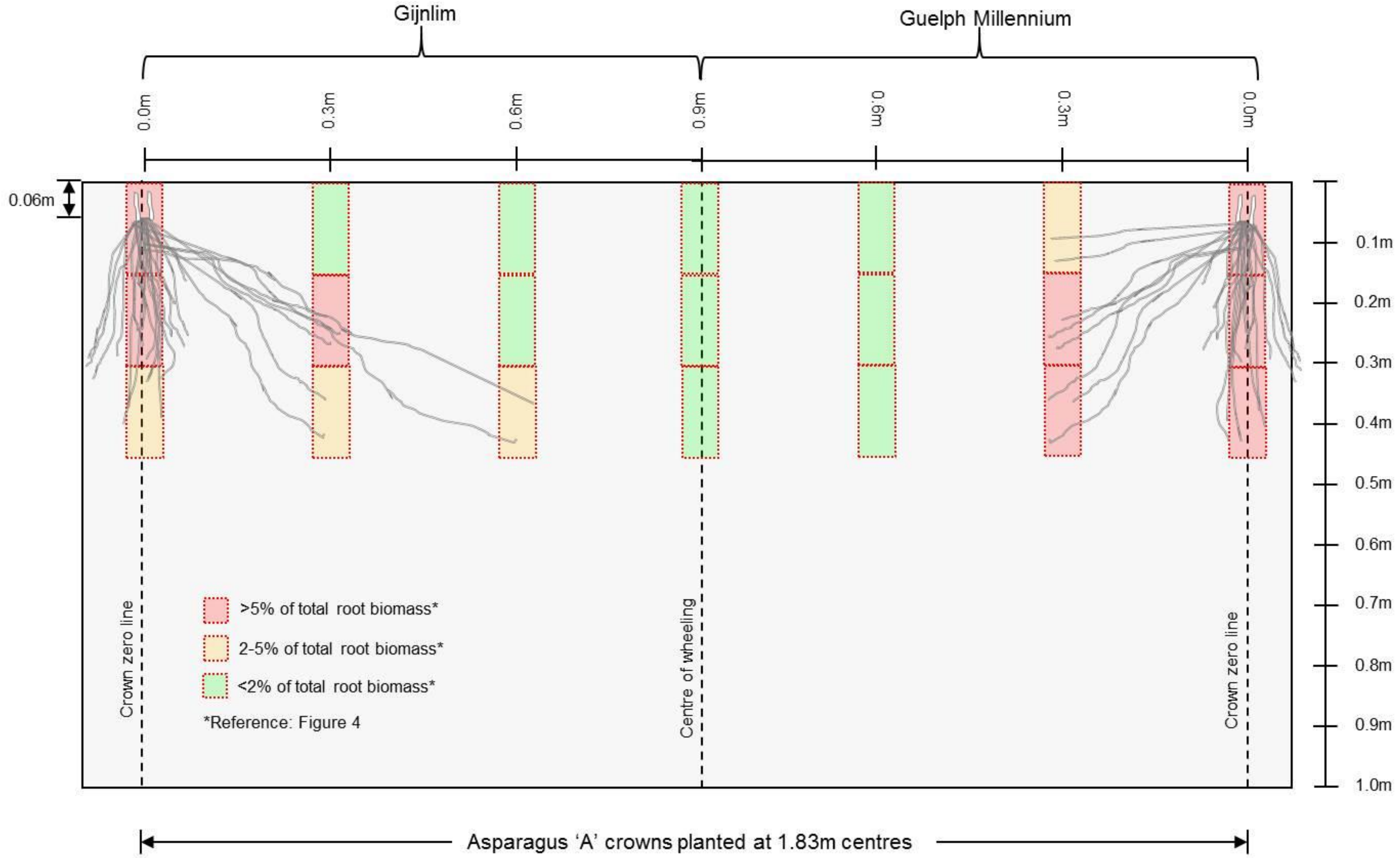
Table 5. Effect of tine type and operating depth on below ground disturbance and specific draught.

Cultivation depth (m)	Tine	Below Ground Disturbance (m^2)	Specific draught (kN m^2)
0.175 m	NT	2.68a	0.49ab
	WT	3.41b	0.75c
	MPP	5.07c	0.41a
	NSLT	2.92a	0.58b
	WSLT	2.82a	0.98d
0.25 m	NT	3.78b	3.88a
	WT	6.28a	3.60a
	MPP	6.67a	3.31ab
	NSLT	5.43c	2.71b
	WSLT	6.53a	3.93a
0.30 m	NT	4.62b	4.95a
	WT	8.38a	3.83a
	MPP	8.02a	4.78a
	NSLT	5.66b	3.50a
	WSLT	8.47a	3.82a

Values followed by the same letter are not significantly different following One-way ANOVA and post-hoc fisher LSD analysis. Source: Niziolomski et al., 2016.

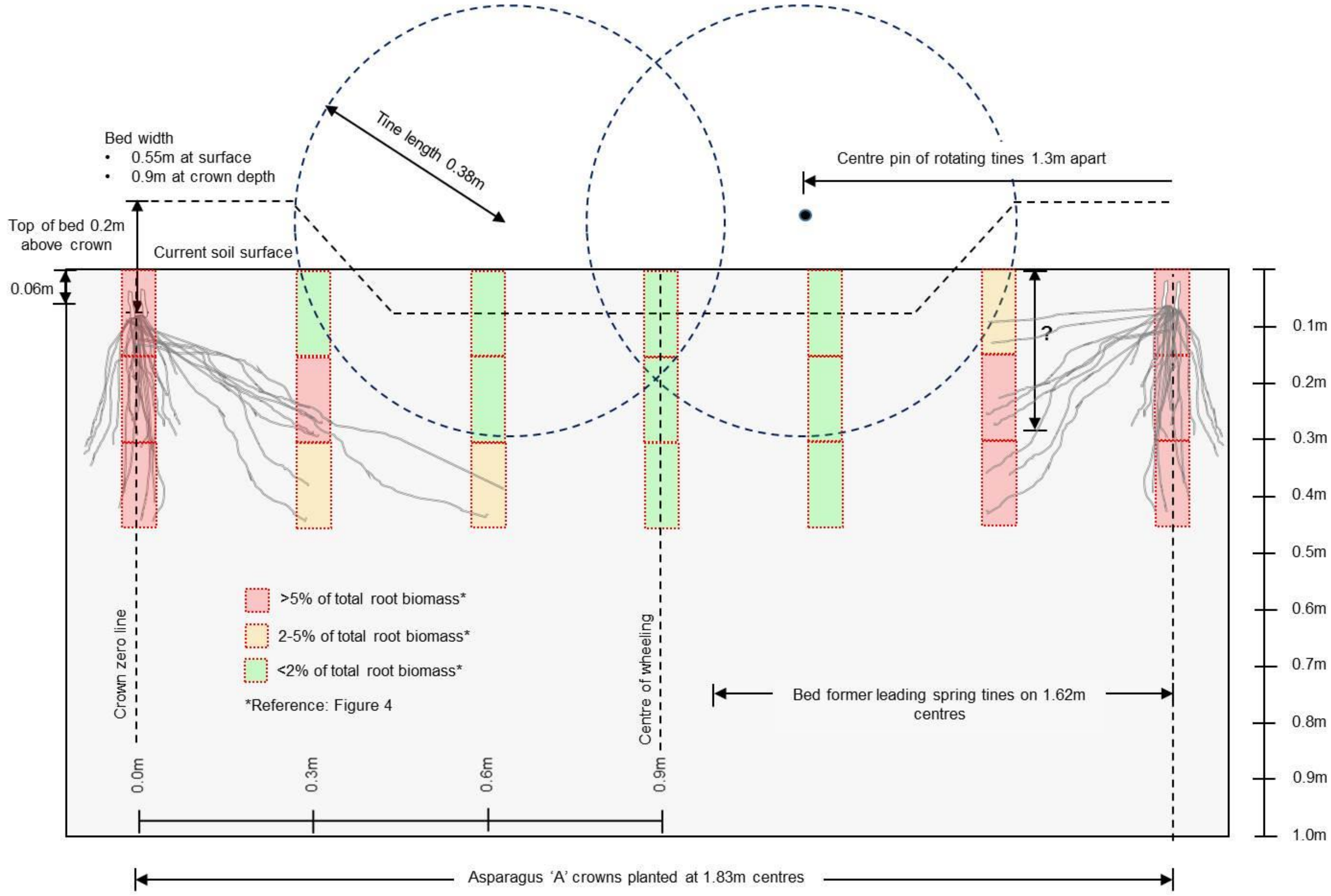
The below ground disturbance profiles of the tines investigated by Niziolomski et al. (2016) at 0.175m and 0.3m operating depths have been superimposed on the root profile distributions (Figures 7 and 8). The results indicate that for both Gijnlim and Guelph Millennium varieties at both operating depths, with crowns planted on 1.83m centres SSD operations could be undertaken to alleviate compaction without the risk of damaging asparagus roots.

Figure 5. Visualization of root profile distributions based on critical thresholds of the percentage (%) of total plant root biomass associated with each root coring depth or distance from the crown zero line.



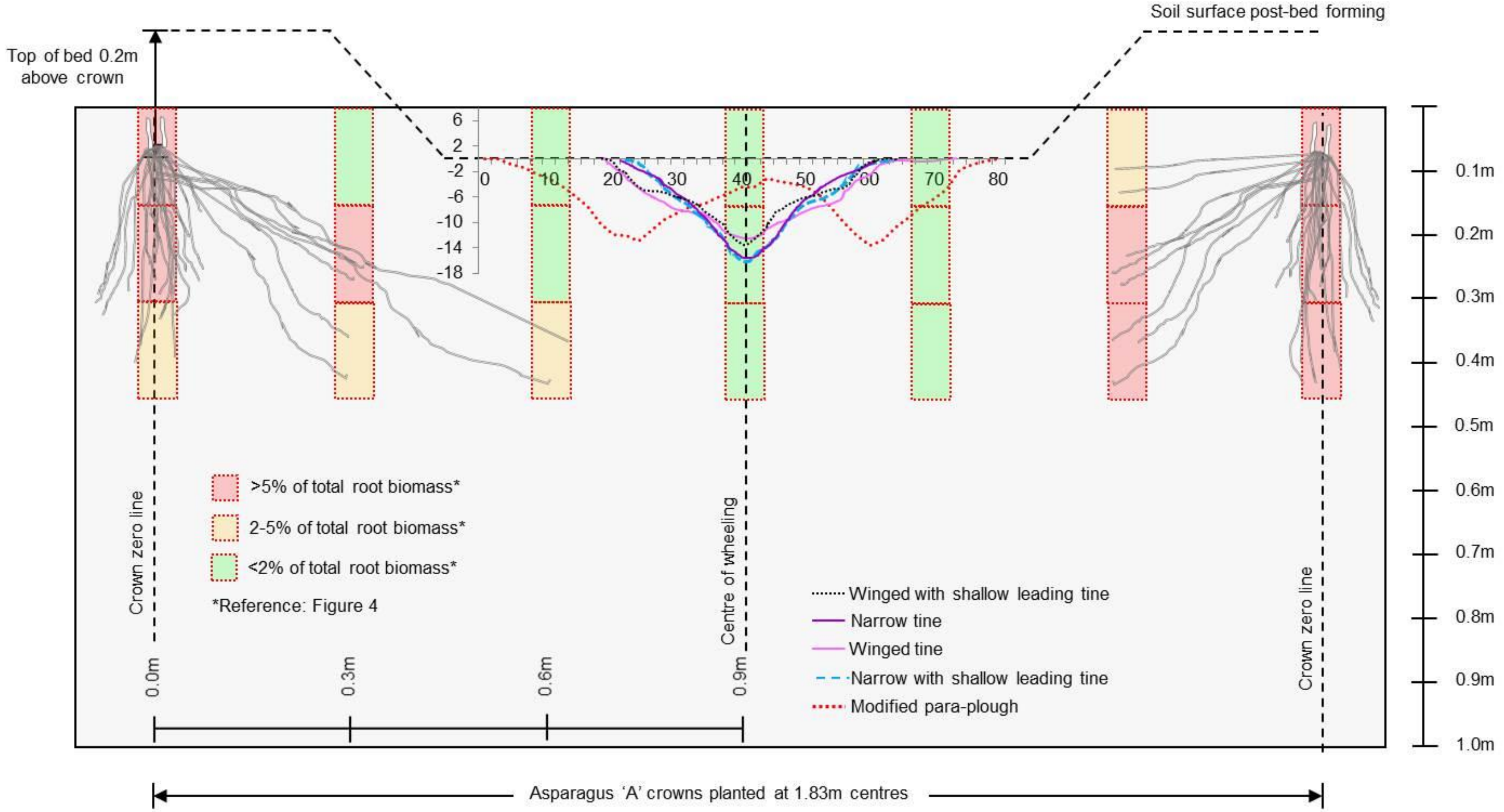
Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For profile root distribution values refer to Table 4 and Figure 4

Figure 6. Potential root damage associated with annual re-ridging operations.



Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For profile root distribution values refer to Table 4 and Figure 4

Figure 7. 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.

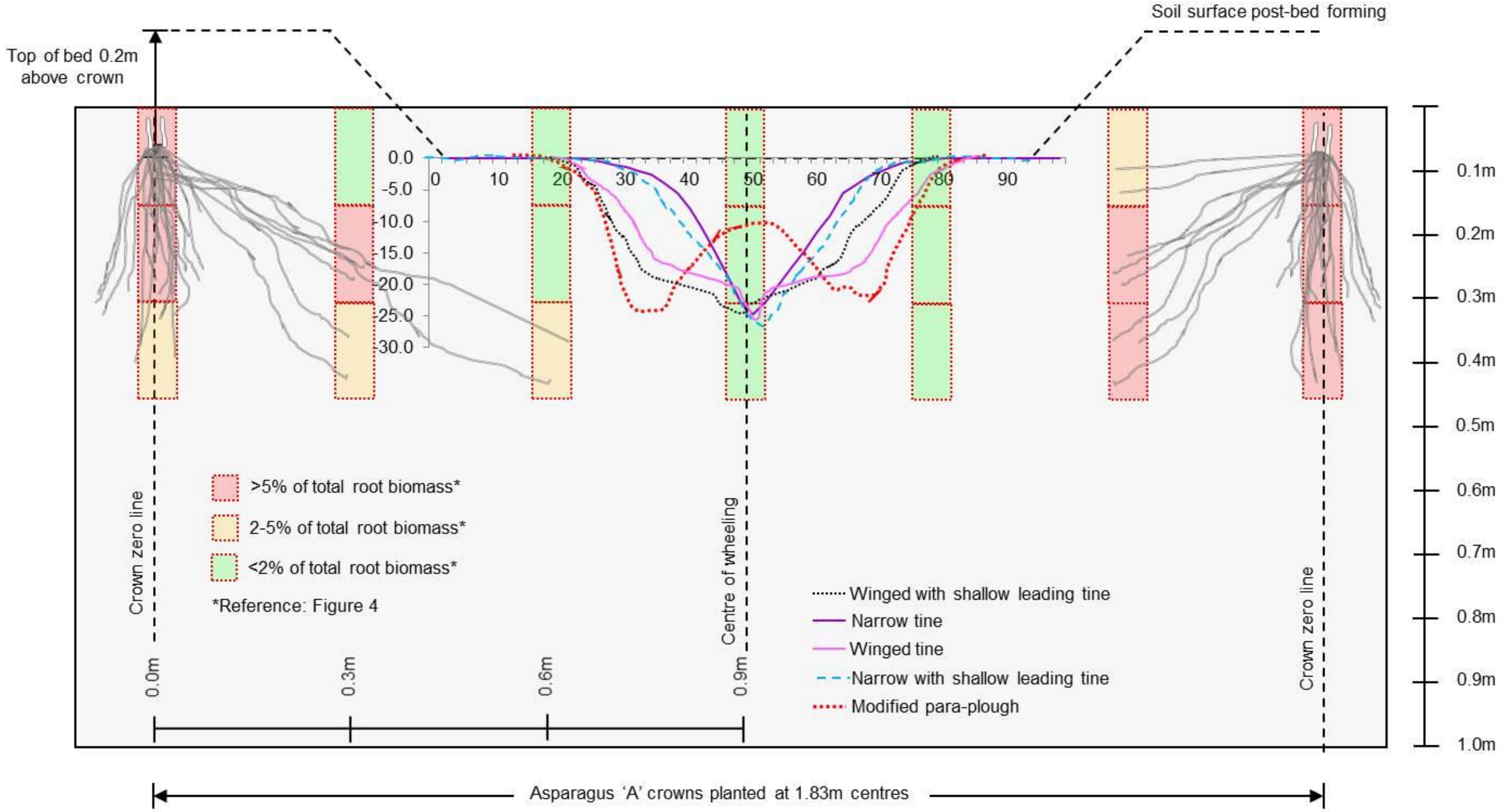


*Source: Niziolomski et al. (2016) Tine options for alleviating compaction in wheelings. Soil and Tillage Research, Vol. 161, pp47-52.

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

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For profile root distribution values refer to Table 4 and Figure 4

Figure 8. 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.



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

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

Note: Asparagus root distribution presented pictorially here are for visualization purposes only. For profile root distribution values refer to Table 4 and Figure 4

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.

- Root mass density values are 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 as yet detected,
- For both varieties, 1 year after planting 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 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 (0.0-0.15m). For both varieties, there were no roots detected (RD values <0.1 kg m^{-3}) in any of the root cores (0.0-0.45 m depth) taken 0.9 m away from the crown zero line.

The current trials 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 re-ridging operations.

- 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 0.15-0.3 m depth 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 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 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.

However, it is strongly recommended that growers undertake exploratory root profile distribution surveys prior to commencing re-ridging and/or sub-soiling operations.

Knowledge and Technology Transfer

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

1) The PAG Meeting (6th December 2016) was attended by AGA members Phil Langley, John Chinn and Claire Donkin. Stephen McGuffie was unable to attend but the presentation and actions from the meeting were circulated to all PAG Members for their feedback and comments. Cranfield team members Dr. Joanna Niziolomski, Dr Sarah De Baets and Dr Rob Simmons were also present. AHDB project manager Dr Jim Dimmock and Harley Stoddart also attended.

Agreed outcomes from that meeting were as follows.

- Treatments to remain as outline in the proposal document.
- PAS 100 compost to be applied by hand at prescribed rates [to be determined following determination of T-N in selected compost] off the back of trailer to replicate trafficking associated with future mechanical application of compost to wheelings
- Straw to be applied via a straw blower at prescribed rates following the procedure adopted for the Niziolomski 2014 Field Trials. Ensure same tractor is used in both operations, if applicable, such that trafficking (tyre configuration/mass of tractor) of wheelings is replicated.
- Companion crops to be broadcast in July/August 2017.
- It was agreed that rye would be one of the companion crops with either oil radish or mustard as the second companion crop. Frost tolerant varieties to be utilised.
- It was proposed that further research needs to be undertaken to determine optimum seeding rate. Potential MSc thesis project at Cranfield May-July 2017 to investigate seeding rates, emergence, establishment and % grown cover.
- The means of removing companion crop in spring of 2018 needs to be finalised/discussed at next PAG meeting (17th May 2017).
- It was agreed that due to the topography of the field site, rainfall/runoff will not be measured. This will be replaced by replicated measures of infiltration.
- Asparagus yield and spear size to be evaluated from 2018 harvest onwards.
- Revision of *Activities and Milestones* schedule: It was agreed that the *Establishment of Replicated Field Trials* in the *Activities and Milestones* schedule be extended to August/Sept 2017 so as to include the broadcasting and establishment of the proposed companion crops.

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. The results outlined in this Annual Report will be presented at the Annual Asparagus Conference 2017 held on Tuesday 18th July 2017.

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

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Appendices

Appendix 1: Spray and fertiliser applications associated with experimental field trial.

Appendix 2: Bed-former dimensions

Appendix 3: Baseline root coring data

Appendix 4: Baseline soil analyses data

