Project title:	Sustainable soil management for stand longevity and yield optimization in asparagus
Project number:	FV 450b
Project leader:	Dr Rob Simmons, Cranfield University
Report:	Final Report, July 2022
Key staff:	Dr Lucie Maskova and Dr Lynda Deeks
Location of project:	Gatsford, Ross-on-Wye
Date project commenced:	01/07/2021
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The results and conclusions in this report are based on an investigation conducted over a three-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

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

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GROWER SUMMARY

Headlines

- The results of this study confirm the previous findings of the FV450 and FV450a projects that asparagus yield, profitability, alleviation of soil compaction, increased infiltration and improved soil health can be achieved by moving away from conventional practice and adopting one of several alternative Best Management Practice (BMP) options.
- PAS 100 Compost applied annually to asparagus interrows in combination with shallow soil disturbance (SSD) without annual re-ridging continues to result in significant (>20%) yield uplift, reduced in soil compaction, improved infiltration rates and improved profitability as compared to conventional practice.
- Zero-tillage also referred to as ‘ridging for the life of the crop’ continues to result in significant (>20%) yield uplift, improved yield and profitability, reduced soil compaction and improved soil health as compared with conventional practice.
- Companion cropping with rye (*Secale cereale*) with annual re-ridging, can result in >20% yield uplift as compared to conventional practice. However, non-ridging carries a risk of a 20% yield penalty compared with conventional practice suggesting that growers need to be confident that they can re-ridge if rye is grown as a companion crop for run-off and erosion control.

Background

Conventional operations associated with UK asparagus production, i.e., tillage operations, such as ridging and sub-soiling, spray operations, harvesting (foot-trafficked and/or hand harvested using picking rigs) can result in progressive and severe compaction of all inter-bed wheelings. In addition, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and productivity and increases the susceptibility to crown and root rots caused by *Phytophthora* and *Fusarium* species.

Further, compaction of wheelings leads to a significant reduction in infiltration resulting in an increased risk of surface water ponding and on sloping land, run-off generation and erosion. In turn, surface water ponding and/or erosion compromises field operations by restricting foot and vehicular traffic, and water ponding in furrows increases the risk of crown and root rots leading to yield decline.

The long-term field trials established under this project have evaluated a range of best management practices (BMPs) to prevent and/or mitigate compaction, improve soil structural status in asparagus wheelings and facilitate long-term profitability of asparagus production.

Summary

This report represents the continuation of research activities initiated in 2016 under FV 450, continued until the end of June 2021 under FV 450a (Figure 1) and further pursed under FV 450b.

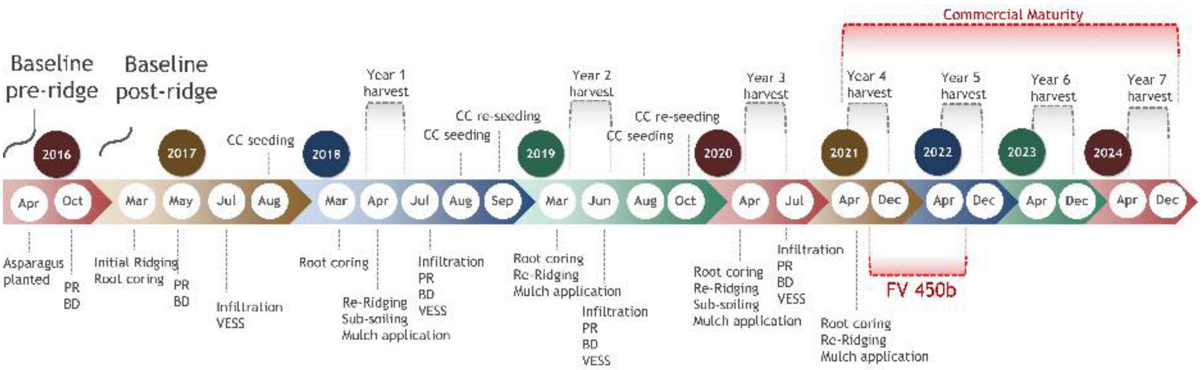

Figure 1. FV 450 / FV 450a and FV450b project timeline indicating activities undertaken to date and period of commercial maturity.

Financial Benefits

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

Cost-benefit analysis for the 2021 harvest demonstrated potential revenue increases for the Zero-tillage, Oats non-ridged (NR), PAS 100 NR, PAS 100 ridged (R), Rye R and Straw Mulch NR treatments of 64%, 61%, 96%, 63%, 52% and 52%, as compared with Conventional practice, respectively. In 2022, only Zero-tillage, PAS 100 NR and Rye R treatments were associated with significant 48%, 61% and 48% higher potential revenues as compared to the Conventional practice.

In 2021, Zero-tillage and Bare soil SSD NR of Guelph Millennium treatments were associated with significant 40% and 45% higher potential revenues as compared to the equivalent Gijnlim treatments. Similarly, in 2022, Zero-tillage, Bare soil SSD NR and Bare soil SSD R Guelph Millennium treatments were again associated with significantly higher potential revenues as compared to the equivalent Gijnlim treatments.

Action Points

Action Points

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

SCIENCE SECTION

Introduction

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

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

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

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

Conventional asparagus production in the UK requires annual re-ridging to ensure that adequate soil depth above the emerging crown is maintained to ensure customer yield quality parameters are achieved. However, research undertaken over the last 20 years has demonstrated that root damage associated with annual re-ridging has a major impact on stand longevity and productivity (Drost and Wilcox-Lee, 2000; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991) and increases the susceptibility to crown and root rot caused by *Phytophthora megasperma* (Falloon and Grogan, 1991) (now known as *P. asparagi*) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2015, 2001), which leads to yield decline and direct economic losses to the grower.

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

Materials and methods

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

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

Table 1. Experiment 1: Treatment descriptions

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

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

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

Table 2. Experiment 2: Treatment descriptions

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

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

Mulch treatments

Under FV450 and FV450a, in 2018, 2019 and 2020 mulch treatments were applied (by Cobrey Farms team) on 20th April, 19th March and 25th March, respectively. Under FV450b, mulch treatments were applied in March/April 2021 and 2022 (by Cobrey Farms team). PAS 100 compost or straw was applied to three wheelings per treatment (central wheeling and guard rows) at rates of 25 t ha^{-1} and at 6 t ha^{-1} (Niziolomski et al., 2020).

Shallow soil disturbance (SSD) treatments

Under FV450 and FV450a shallow soil disturbance (SSD) was applied in April 2018 and in March and June 2020 (SSD was not applied in 2019). Under FV450b, SSD was applied in June 2021 and 2022. In all years, SSD was applied using a winged tine (Niziolomski et al., 2016) operating to 0.25-0.30 m depth to all mulch treatments (PAS 100 compost and Straw mulch) and to applicable bare soil treatments (Tables 1 and 2). In both years, occasional asparagus root damage was observed behind the tine.

Companion Crop treatments

The 2018-20 results from the FV 450a trials indicate that the mustard companion crop treatment has no significant impact on soil structural status or asparagus yield as compared with the bare soil conventional or zero-till treatments. As a consequence, in 2020 mustard was replaced with oats (*Avena sativa*) (following agreement from the Project Advisory Group, July 2020).

Companion crops were applied to central wheelings only. Rye (*Secale cereale* L. var. Protector) and oats (*Avena sativa L.*) were broadcast to three wheelings (central wheeling and guard rows) in August 2020 and 2021 when asparagus was at full fern stage at rates of 120 kg ha^{-1} for both rye and oats to reflect commercial practice.

Annual re-ridging treatments

Under FV450 and FV450a in 2018, 2019 and 2020, re-ridging treatments were applied on the 18th April, 15th of March and 24th of March, respectively. Under FV450b, re-ridging treatments were applied in March 2021 and 2022.The tractor used for annual ridging (R) and to apply SSD was a 155 HP with 82.74 kPa on the front tyres and 82.74 kPa on the rear tyres. The assumed area of disturbance of the ridger and soil disturbance pattern of the subsoiler (Niziolomski et al., 2016) are shown in Figure 2. As ridging was applied for the first time in April 2018, data from 2019 shows impacts of the first annual ridging event while the 2021 and 2022 data reflects impacts of three and four ridging events which took place in consecutive years.

Impact of BMPs on soil penetration resistance

Penetration resistance measurements, which were used as an indicator of soil compaction (Bengough et al., 2006), were conducted within the Experiment 1 plots planted with Gijnlim. PR was determined using a digital Eijkelkamp Penetrologger with a 1.0 cm^2 base area and 60° apex angle cone. PR was measured to 0.6 m depth (where possible) at a recording interval of 0.01 m. Each plot was sampled at six locations along the length of the plot (5, 10, 15, 20, 25 and 30 m). In addition to interrow centre measurements (12 per treatment), PR transects were taken tangentially from the asparagus CZL at 0.3 m intervals to the centre of asparagus interrow (0.9 m from CZL). For each experimental treatment, four PR transects were measured.

Soil moisture content (MC) during trafficking and tillage events were not determined. The commercial grower followed Good Agricultural and Environmental Conditions (GAEC) recommendations (GAEC, 2021) which advises that field operations are undertaken when soil MC is below field capacity in order to minimise compaction risk. As such, all trafficking and tillage events associated with the experimental treatments were undertaken at least 2-3 days after rainfall events. In addition, when applied all trafficking and tillage events associated with the experimental treatments were performed on the same day within a 2 h period. As such soil MC was considered to be uniform across treatments when trafficking and tillage events were applied.

The 2021 and 2022 PR measurements reflect a legacy effect of the inter annual machinery passes associated with ridging and tillage operations as well as foot trafficking during the 3-month annual harvest periods applied to the treatments. Consequently, data from each year were evaluated separately.

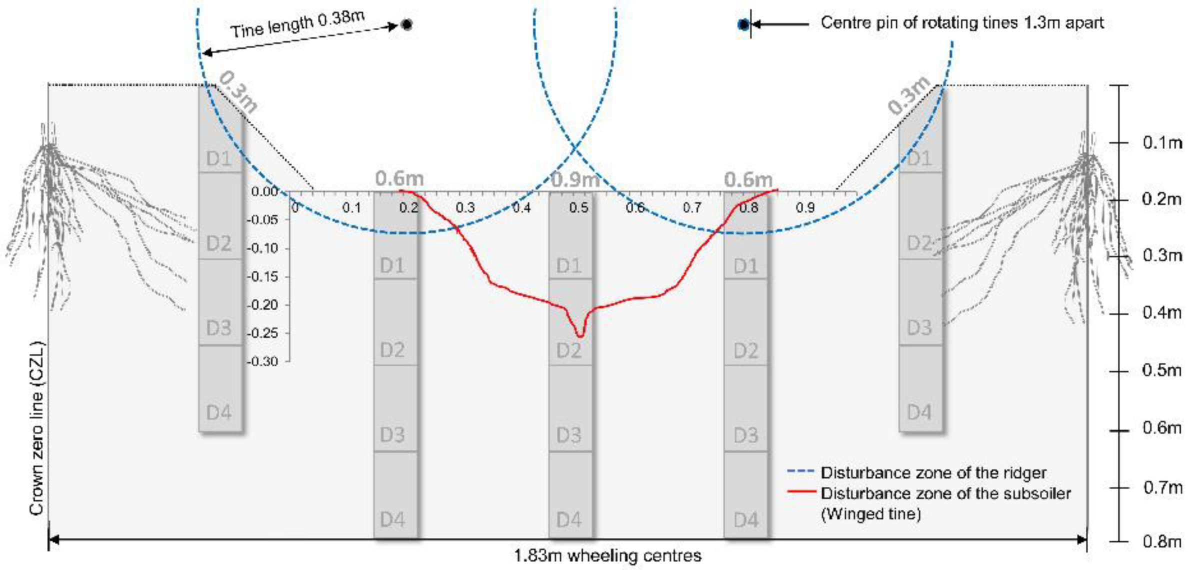

Figure 2. Visualisation of assumed ridger tine disturbance areas and subsoiler soil disturbance areas with different tine options (Niziolomski et al., 2016) alongside root coring locations.

Assessment of root architecture and root profile distribution

Root architecture was determined following the procedure of Drost and Wilson (2003). The root coring procedure adopted from Drost and Wilson (2003) is a method allowing mapping of changes in root distribution which accounts for ca. 85% of the total root mass. Annual collection of root samples can be used to effectively map differences between growing practices and their impact on asparagus root growth patterns. For each treatment, four randomly selected transects were sampled using a handheld Eijkelkamp bi-partite root auger (internal diameter: 0.08 m, internal core depth: 0.15 m, volume: 754 cm^3). Root cores were taken at 0.3 m distance intervals starting with the crown zero line (CZL) and subsequently in line with the asparagus crown at distances of 0.3 m, 0.6 m and 0.9 m (centre of asparagus interrow) to a maximum depth of 0.6 m. The total number of root samples collected per treatment each year was 64 (4 locations x 4 distances from the crown x 4 depths).

Root samples taken at different distances from the CZL and depths were assigned a code consisting of two values based on their location coordinates (Figure 3). The first number indicates the distance of the sample from the CZL, e.g., 0.3 m, 0.6 m or 0.9 m. For fields sampled from the wider grower landbank, this spacing varied as a function of wheeling centres (Figures 4 and 5). The second number then indicates the depth from which the root core has been extracted. Depth 0-0.15 m as D1, depth 0.15-0.30 m as D2, depth 0.30-0.45 m as D3 and depth 0.45-0.60 m as D4. Subsequently, 12 unique location codes will be used to identify a specific sample location in the soil profile. Those codes are 0mD1, 0mD2, 0mD3, 0mD4, 0.3mD1, 0.3mD2, 0.3mD3, 0.3mD4, 0.6mD1, 0.6mD2, 0.6mD3, 0.6mD4, 0.9mD1, 0.9mD2, 0.9mD3 and 0.9mD4. Crown root data (0mD2) was not included in statistical analyses due to large variability in values obtained from the location. At the time of root sampling, it is impossible to identify the exact crown location. Consequently, some CZL samples contain the whole crown while others do not. This variability was also reflected in the visualisation heat maps shown as Figure 11 – Figure 15.

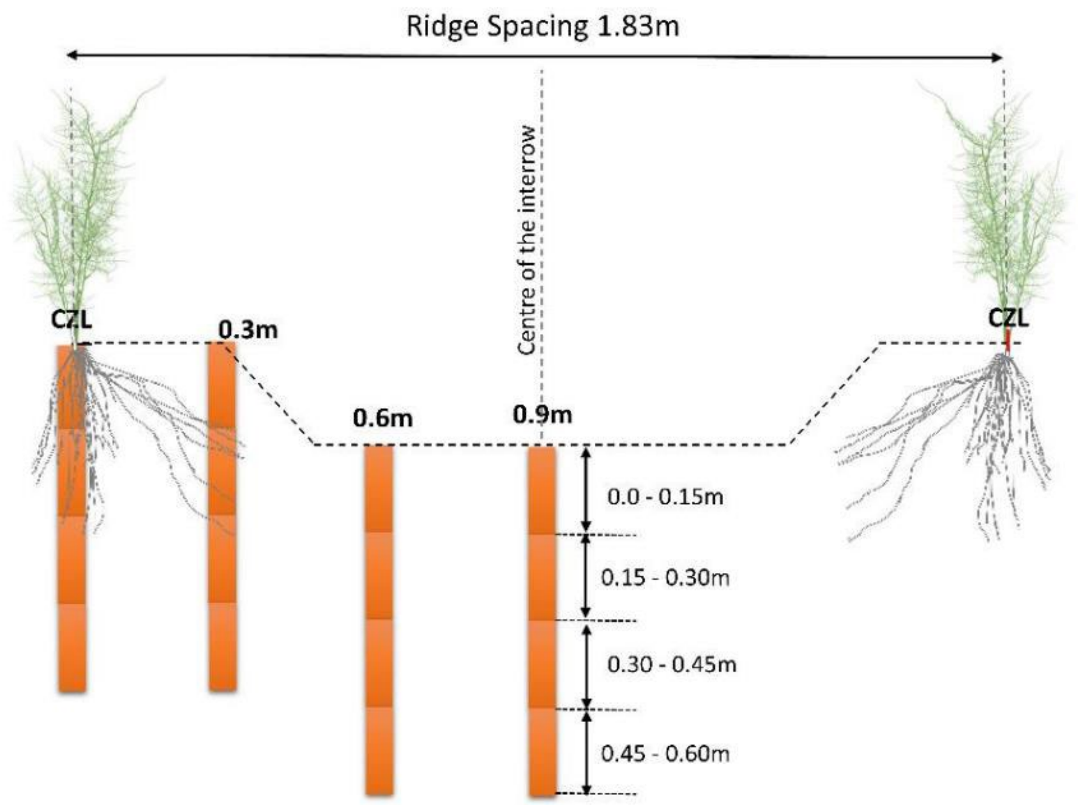

Figure 3. Root coring protocol adopted at the FV 450/FV 450a trial site.

Determination of root mass density

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

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

Root biomass as a percentage of the total root biomass (TRB%) was used to express proportionate root distribution for each coring location, where RMD_{Cl} represents the sum of RMD for each sample class (i.e. sample location or PR class) and RMD_t represents the total sum of all RMD in the sample, as equation:

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

Root Mass Density interpolation maps

To map the spatial distribution of roots, root mass density (RMD) or root biomass as a percentage of total root biomass (TRB%) can be used. All root core samples were given x, y coordinates according to the position from the row (x-value) and soil depth (y-value) they were sampled at and given a corresponding z-value for RMD or TRB. These x, y, z values were then used to construct contour interpolated root mass density maps in in Esri ArcMap™ (GIS software) version using the inverse distance weighing (IDW) geo-statistical interpolation method, predicting values at unmeasured locations (Figure 4).

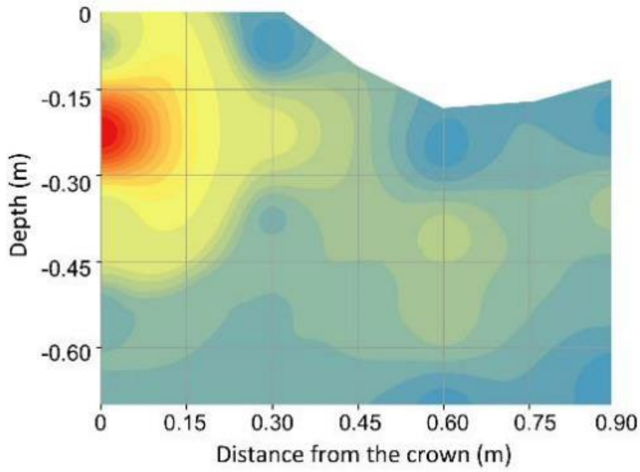

Figure 4. Root mass density (RMD) map generated using the inverse distance weighing (IDW) interpolation method in ARC-GIS.

Crop performance indicators

In 2021, asparagus spears were harvested from all experimental plots between the 24th April to 27th June (65 days) from 48 cuts. In 2022, asparagus spears were harvested from all experimental plots between the 26th April to 19st June (55 days) from 32 cuts. Spear count and additional spear quality indicators (spear diameter, open tips and curving) were determined on seven cuts, which were randomly distributed throughout the harvest period. Harvested spears were divided into three commercial size grades by spear thickness (<10 mm, 10-22 mm and >22mm). Spears with flowering heads/open tips and curvature were also weighed and counted. Total yields were reported as mean total mass of all harvested spears (t ha^{-1}).

Determination of root soluble carbohydrate (CHO) values

Method to obtain CHO values followed the methodology outlined in FV 271 Appendix 2 (AHDB, 2007). Asparagus storage roots for the determination of pre-harvest root soluble carbohydrate content (CHO) were obtained in March 2022 at 0.15-0.30 m depth from the crown zero line (CZL) following the root coring procedure of Drost and Wilson (2003). Roots of similar diameters were separated from soil, washed, and frozen at -20^{o}C prior to CHO analysis. Determination of CHO followed the method outlined by Wilson et al. (2002). Roots were cut into smaller pieces and crushed in a garlic press. Obtained root sap was then used to determine Brix% values using a refractometer (Atago PR-32α) with a range of 0 to 32% Sugar (Brix%). Brix values were converted to equivalent root CHO content using the linear regression equation of Wilson et al. (2008):

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

Cover crop selection and seeding rates

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

In addition, rye is a host of arbuscular mycorrhizal fungi (AMF), known to increase mycorrhizal fungus colonisation of the subsequent crop (Kabir and Koide, 2002) and promote yields. AMF form a symbiotic relationship with the roots of most agricultural crops and aid acquisition of soil phosphorus as well as promoting soil aggregation, and carbon sequestration. In addition, AMF have been shown to increase plant resistance to biotic and abiotic stresses (Smith and Read, 2008). Asparagus is strongly mycorrhizal, with root colonization reaching up to 70% (Matsubara et al., 2001). Many species of the AMF glomus are associated with reduced crown and root rot damage from Fusarium infection and improved root health of asparagus (Matsubara et al., 2001).

Oats (*Avena sativa* L.) were selected as an alternative companion crop to Rye in order to provide over-winter runoff/erosion protection. The aim of utilising contrasting companion crops in the FV 450/450a/450b asparagus trials was to evaluate the potential for the synergistic enhancement of multiple soil functions such as weed suppression, improving soil structure, promoting AMF, mitigating crown and root rots associated with Fusarium and for runoff and erosion mitigation.

Results

The results presented in this section are from field work and data analyses completed since submission of the FV 450a Final Report. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without shallow soil disturbance (SSD) applied to the interrows (Bare soil, No-SSD, R). Zero tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD of interrows.

Effect of BMPs on soil physical properties

Penetration resistance (PR)

In 2021 and 2022, PR was measured in the whole soil profile, from the CZL to the centre of the interrow (Figure 5 – Figure 8). Each diagram represents PR as measured tangentially from the asparagus CZL at 30 cm intervals to the centre of asparagus interrow (90 cm from the CZL). Figure 9 – Figure 10 represent PR values measured in the centre of the interrows. Penetrative resistance values for 2021 were measured under drier soil conditions than 2022.

2021 PR values measured in the top 15 cm of the Zero-tillage (Bare soil No-SSD NR) treatment were in the lower range of 0.0-2.0 MPa (Figure 5a). Mean values measured in the interrow centres reached the highest PR value (*circa* 3 MPa) at 30 cm depth and decreased with depth to 1.7-2.5 MPa (Figure 5a, Figure 9a).

Maximum interrow PR values as high as 3.7 MPa were observed in the Conventional practice (Figure 5b). The location 30 cm from the CZL, from 35-60 cm depth of all bare soil treatments was associated with PR values ranging between 3.0-4.3 MPa. Significantly lower PR values in the centre of the interrow (90 cm from the CZL) were observed in both ridged (R) and non-ridged (NR) bare soil SSD treatments to approximately 25 cm depth which is the operating depth of the winged tine (Figure 5c and Figure 5d, Figure 9a).

All mulch treatments demonstrated a zone of significant PR reduction at the centre of the interrow (90 cm from the CZL) which is a direct result of SSD (Figure 6a - Figure 6d, Figure 9c). Penetrative resistance values of both PAS R/NR were very high (3.7 MPa and higher) in a zone 0-60 cm distance from the CZL at depths 35-60 cm. Straw mulch R treatment however had maximum PR values of only up to 3.3 MPa (Figure 6a). In comparison to treatments subject to SSD, all companion crops showed a zone of increased PR in the interrows, values of which were similar to PR of the Conventional practice (Figure 6e - Figure 6h, Figure 9b). For the non-ridged (NR) Rye treatment, PR reached values of >5.0 MPa (Figure 6h).

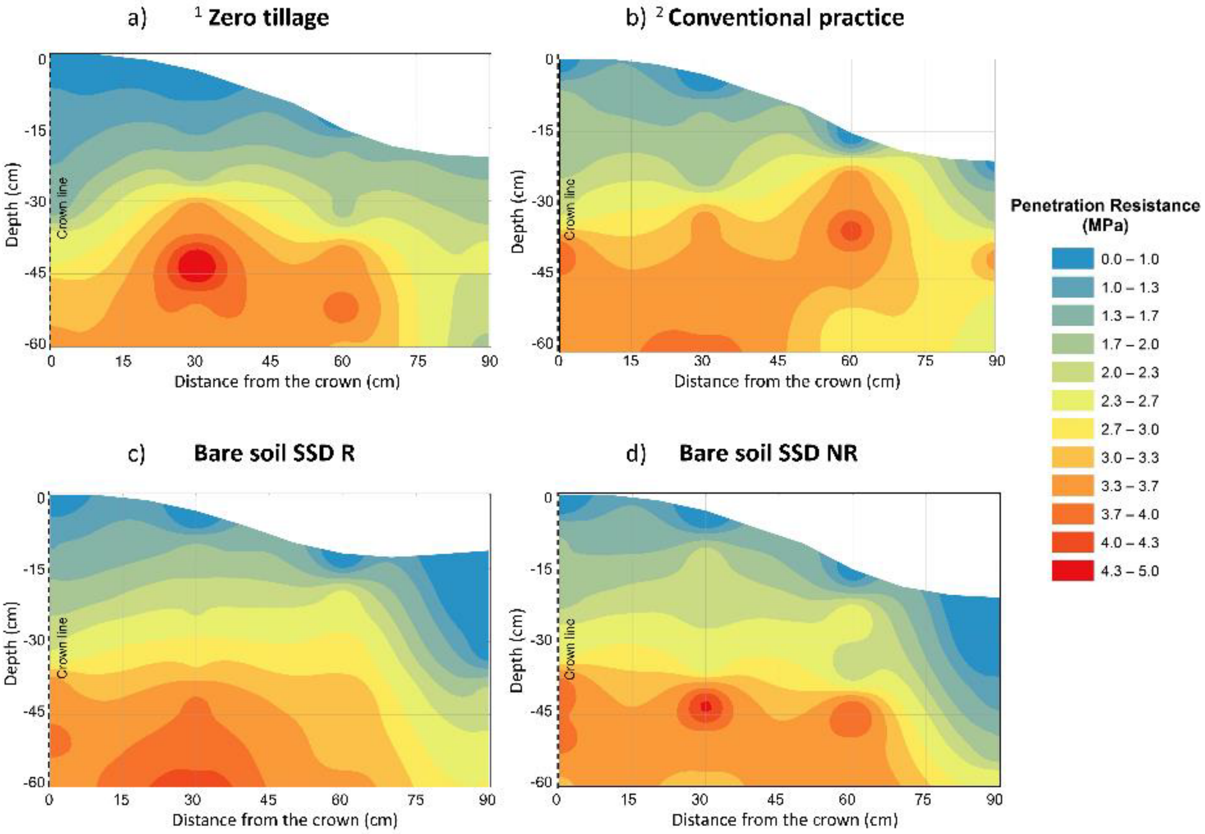

Figure 5. 2021 bare soil treatment contour diagrams based on Penetration Resistance (MPa) transects (n=4) determined tangential to the crown zero line (CZL) using the inverse distance weighing (IDW) interpolation method. [1]Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows. [2]Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows.

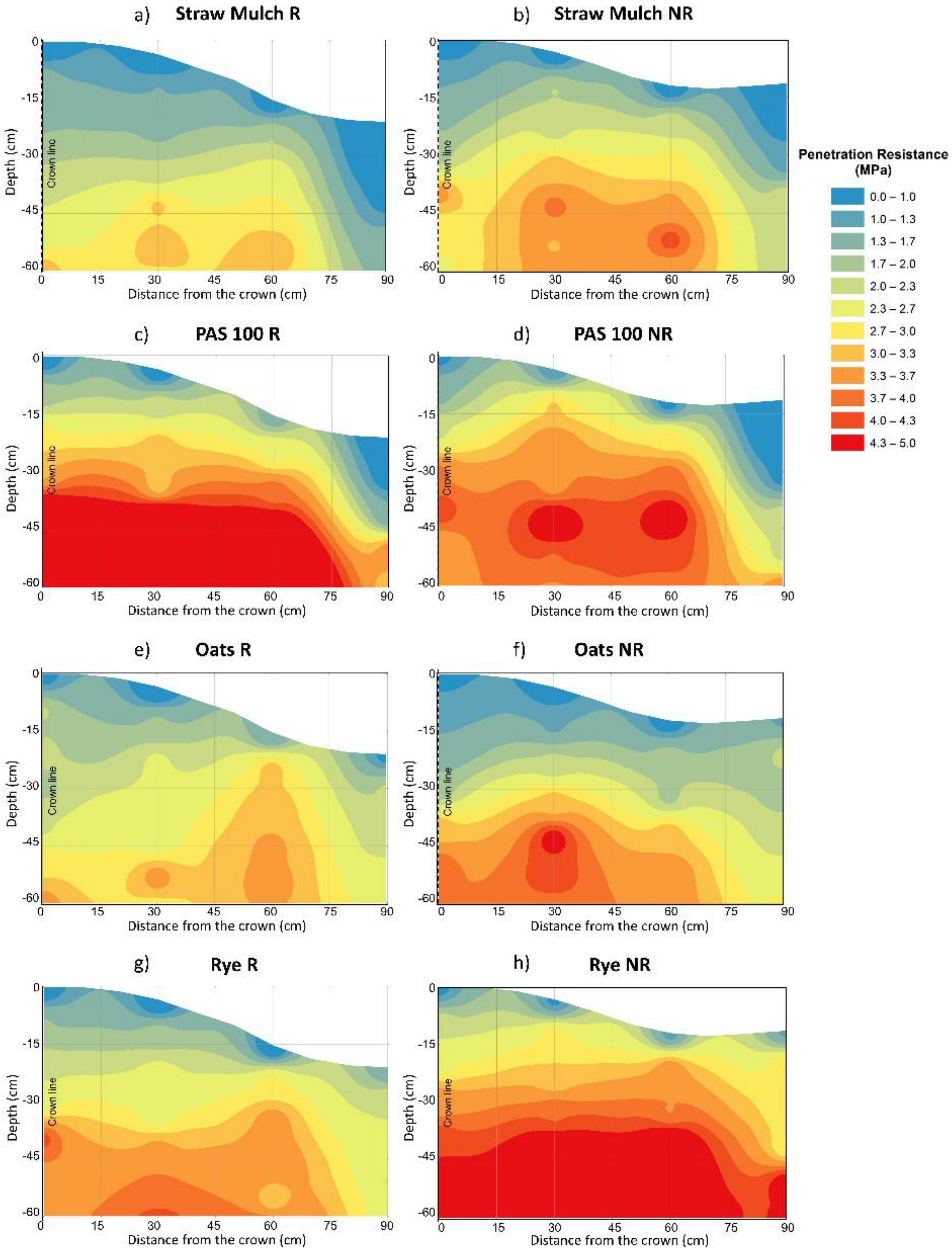

Figure 6. 2021 mulch and companion crop treatments contour diagrams based on Penetration Resistance (MPa) determined at set positions from the crown zero line (n=4) using the inverse distance weighing (IDW) interpolation method.

In 2022 PR was measured following a continuous rain period which contributed to lower PR values as compared to 2021. Mean interrow PR values of the Zero-tillage were 2.3-2.7 MPa at a depth of 35-50 cm as compared to 1.0 – 1.7 MPa 5-20 cm depth (Figure 7a, Figure 10a). Interrow PR values of the Conventional practice reached a maximum value of approximately 3.0 MPa (Figure 7b, Figure 10a). PR values of all mulch treatments except PAS 100 NR ranged from 0-3.0 MPa throughout the whole measured profile (Figure 8a – Figure 8d). PAS 100 NR had higher values of up to 4.3 MPa in depths below 45 cm (Figure 8d, Figure 10c) which is indicative of drier soil conditions. In the 0-15 cm depth of the interrows, Straw mulch R/NR PR values were significantly lower as compared to the Conventional practice (Figure 10c). All companion crops except for Rye NR had PR in the range 0-3.7 MPa (Figure 8e – Figure 8h). Rye NR had higher PR values of up to 5.0 MPa in depths below 45 cm (Figure 8h, Figure 10b).

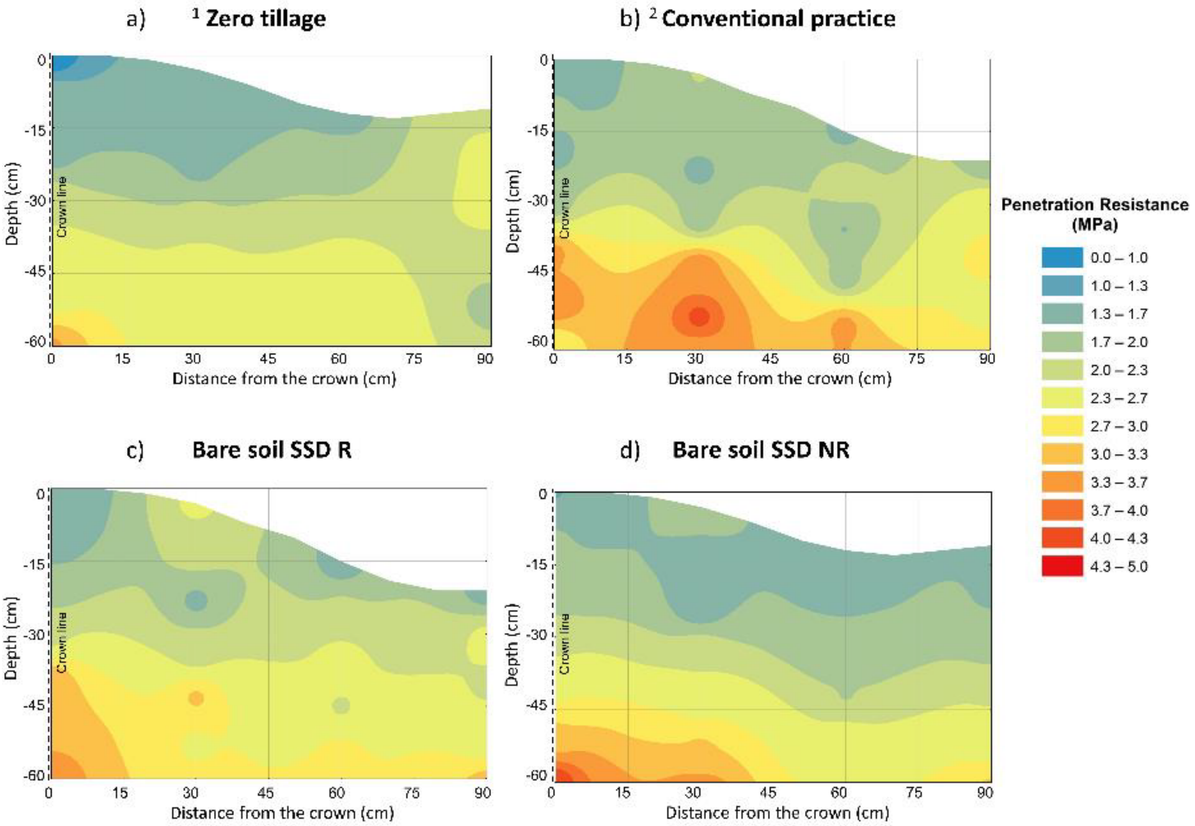

Figure 7. 2022 bare soil treatments contour diagrams based on Penetration Resistance (MPa) transects (n=4) determined tangential to the crown zero line (CZL) using the IDW interpolation method. [1]Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows. [2]Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows.

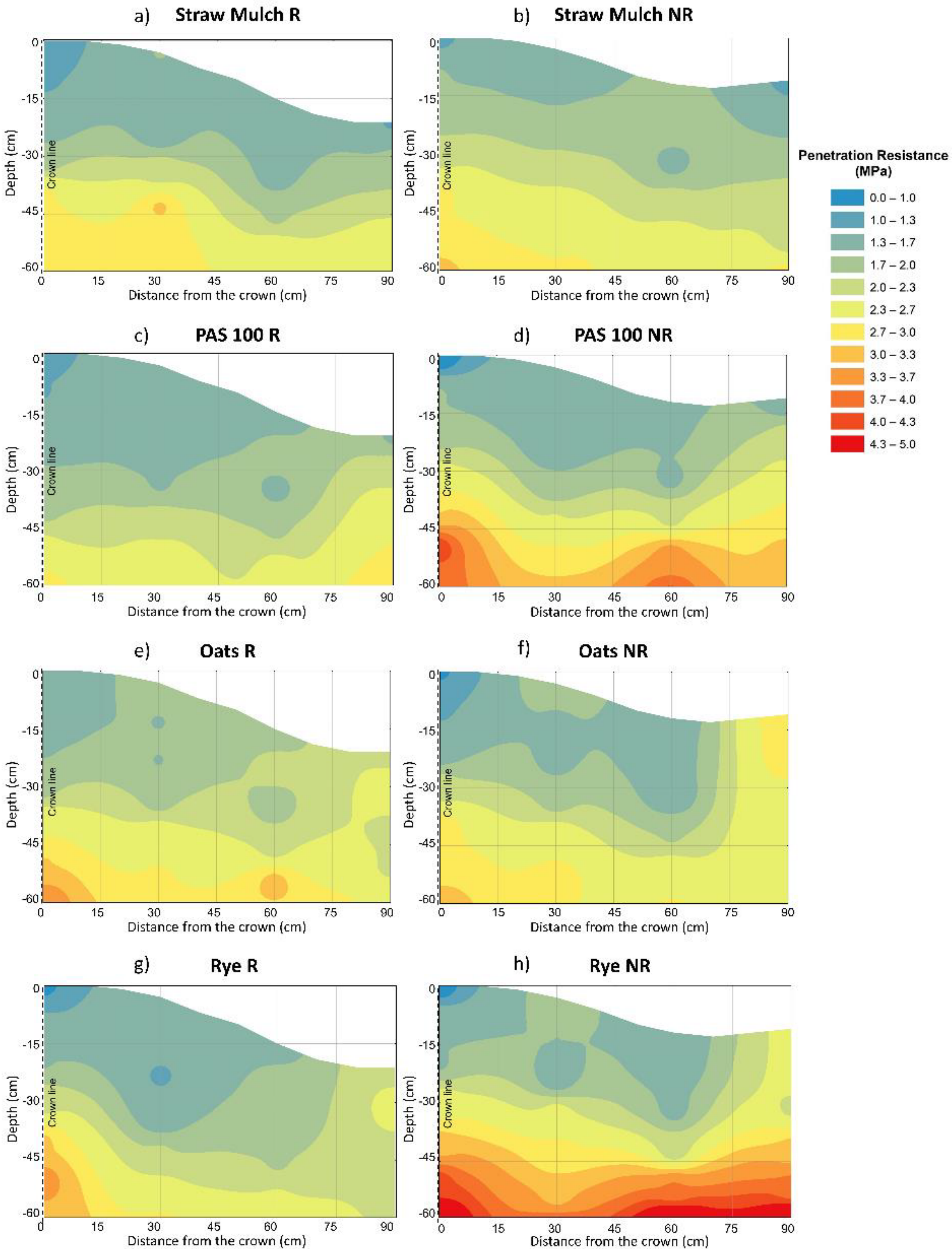

Figure 8. 2022 mulch and companion crop treatments contour diagrams based on Penetration Resistance (MPa) determined at set positions from the crown zero line (n=4) using the inverse IDW interpolation method.

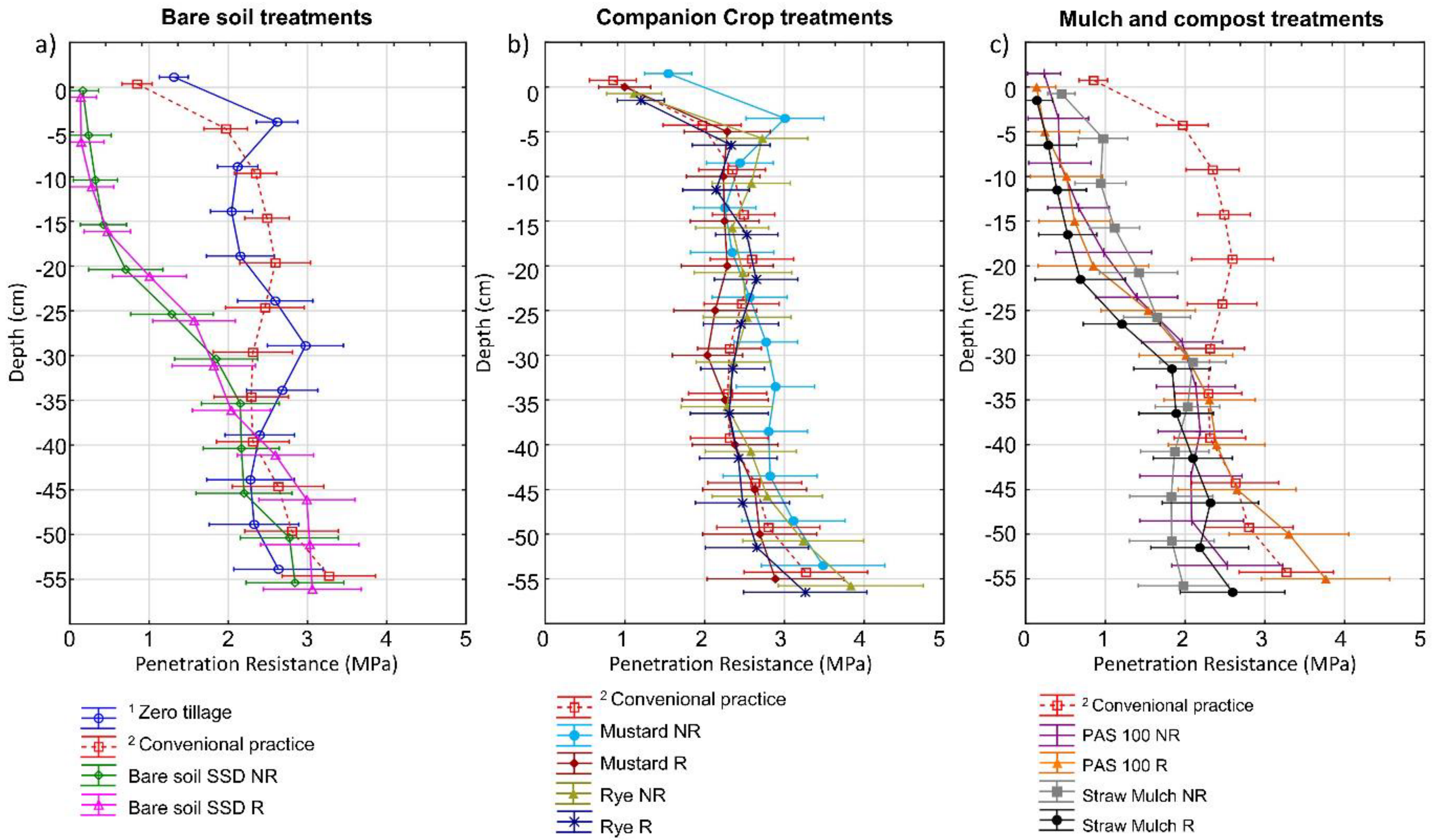

Figure 9. 2021 interrow Penetration Resistance (MPa) of all treatments as compared to the Conventional practice.

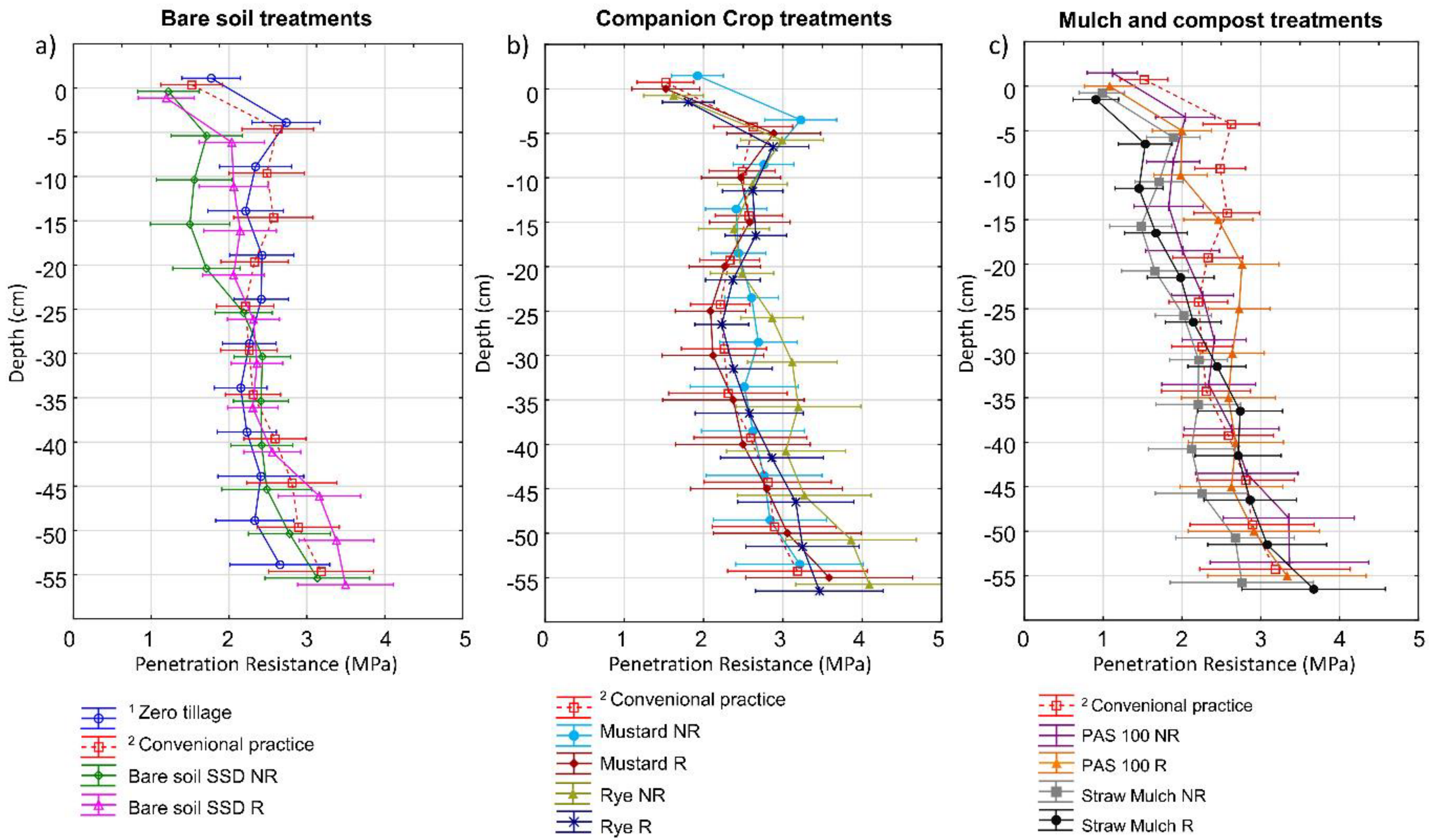

Figure 10. 2022 interrow Penetration Resistance (MPa) of all treatments as compared to the Conventional practice.

Root mass density (RMD)

The size of the asparagus root system (‘Root Engine’) and its distribution affects the ability of plants to access and acquire soil resources which determines crop health and productivity (Bengough, 2012; Lynch, 1995). Restrictions and disruptions to the underground root system can lead to plant stress and early crop decline (Bengough, 2012). Root cores extracted in March 2021 were obtained from 7-year old plants, 2022 root data represents results from 8-year old plants. Table 3 represents the year-to-year comparison of total RMD values in all ridged non-SSD treatments in 2022 as compared to the equivalent treatments in 2021. In 2021, the Zero-tillage, Oats R, Rye R, PAS 100 NR and Straw mulch NR treatments were associated with significantly higher total RMD as compared with the Conventional practice (Table 3). Similarly, in 2022 the Zero-tillage, Oats NR, Rye NR, PAS 100 NR and Straw mulch NR treatments were associated with significantly higher total RMD as compared with the Conventional practice (Table 3). Only Oats R and Rye R treatments were associated with significant reductions in total profile RMD of 45% and 63% in 2022 as compared to 2021.

The 2021 and 2022 ‘Root Engine’ of the BMP treatments are visualised in the root distribution heat maps (Figure 11 – Figure 13) in Appendix 1.

Guelph Millennium Zero-tillage, Conventional practice and Bare soil SSD R had significantly higher RMD as compared to equivalent Gijnlim treatments in 2021 (Table 4). In 2021 RMD associated with Guelph Millennium Zero tillage, Conventional practice and Bare Soil SSD R treatments were significantly higher than in equivalent Gijnlim treatments (Table 4). Figure 14 visualises the varietal differences in RMD between Gijnlim and Guelph Millennium in 2021 where roots of Guelph Millennium are significantly more expansive throughout the profile as compared to Gijnlim.

In contrast in 2022, with the exception of the Zero Tillage treatment, RMD associated with all other Guelph Millennium treatments were significantly higher than the equivalent Gijnlim treatments (Table 4). Figure 15, Guelph Millennium RMD was significantly higher only on the Bare soil SSD NR treatment. Similarly, roots of Guelph Millennium are significantly more expansive throughout the profile as compared to Gijnlim (Figure 15).

Table 3. Changes in mean (n=16) total profile root mass density (RMD) (kg m^{3}) of treatments in 2021 and 2022.

Treatment	2021	2022
[1]Zero-tillage	14.2 ^{b}	14.1 ^{cd}
[2]Conventional practice	6.74 ^{a}	4.39 ^{a}
Bare soil SSD NR	9.61 ^{ab}	4.69 ^{ab}
Bare soil SSD R	8.82 ^{ab}	8.25 ^{abc}
Oats NR	13.4 ^{ab}	11.2 ^{bcd}
Oats R	15.7 ^{b}	*8.65 ^{abc}
PAS 100 NR	15.5 ^{b}	12.0 ^{cd}
PAS 100 R	11.7 ^{ab}	10.5 ^{abcd}
Rye NR	8.52 ^{ab}	12.5 ^{d}
Rye R	23.3 ^{c}	*8.75 ^{abc}
Straw Mulch NR	15.4 ^{b}	11.2 ^{cd}
Straw Mulch R	11.4 ^{ab}	8.25 ^{abc}

Table 4. Changes in mean total profile root mass density (RMD) (kg m^{3}) of Gijnlim and Guelph Millennium treatments in 2021 and 2022.

Variety	Treatment	2021	2022
Gijnlim	[1]Zero-tillage	14.2 ^{ab}	14.1 ^{cd}
	[2]Conventional practice	6.74 ^{a}	4.39 ^{a}
	Bare soil SSD NR	9.61 ^{a}	4.69 ^{ab}
	Bare soil SSD R	8.82 ^{a}	8.25 ^{ab}
Guelph Millennium	[1]Zero-tillage	25.2 ^{c}	17.7 ^{d}
	[2]Conventional practice	18.1 ^{bc}	12.1 ^{bcd}
	Bare soil SSD NR	14.9 ^{ab}	14.2 ^{cd}
	Bare soil SSD R	20.5 ^{bc}	15.2 ^{cd}

Within each column, values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R. Conventional practice is defined as asparagus grown with bare soil interrows that is ridged on an annual basis without SSD applied to the interrows. Zero-tillage is defined as asparagus grown with bare soil interrows without any annual re-ridging applied after April 2017 or SSD applied to interrows.

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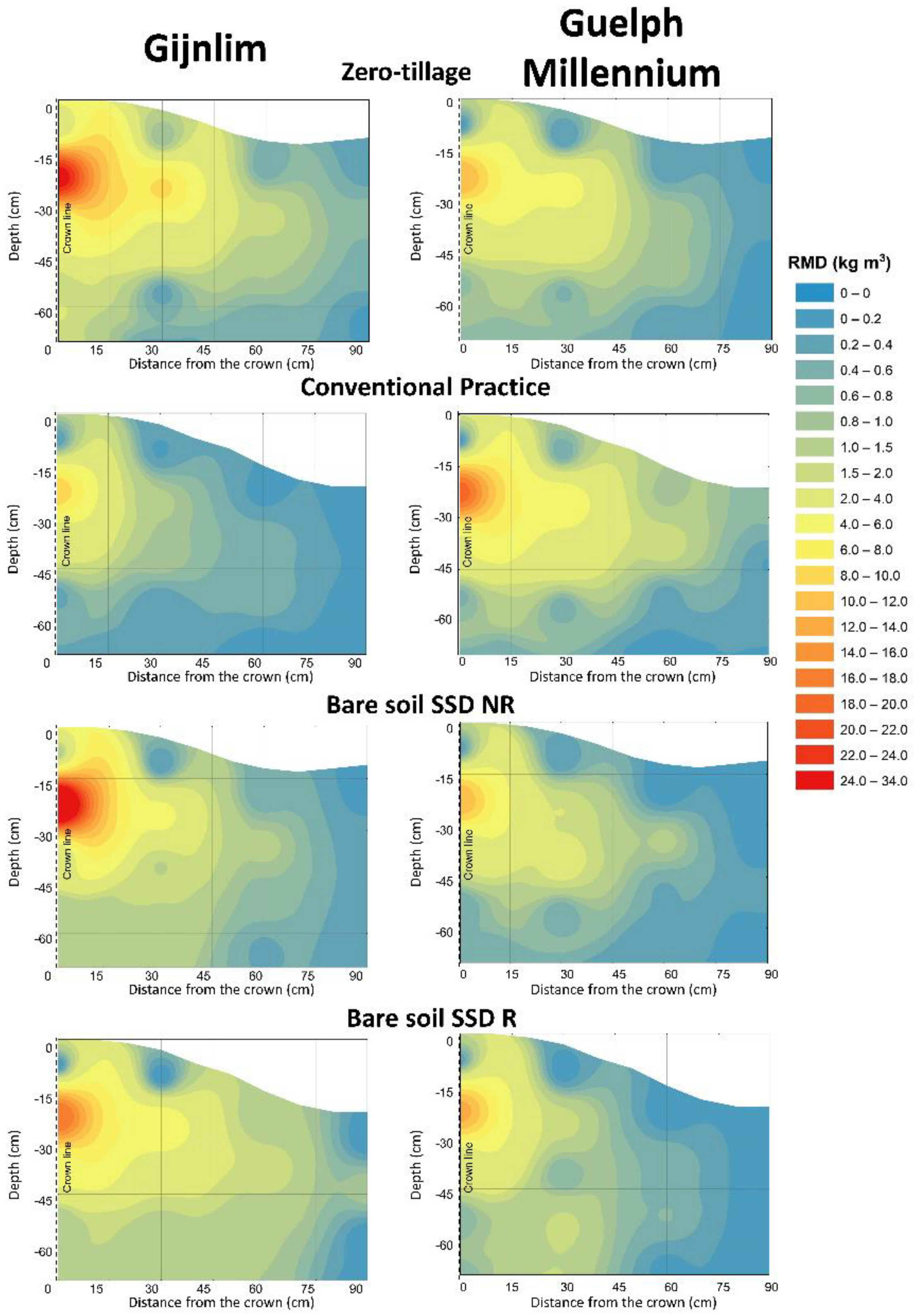


Figure 14. Root distribution hear maps representing 2021 root distribution of the Zero-tillage (Bare soil No-SSD NR), Conventional practice (Bare soil No-SSD R), Bare soil SSD NR and Bare soil SSD R of Gijnlim and Guelph Millennium.

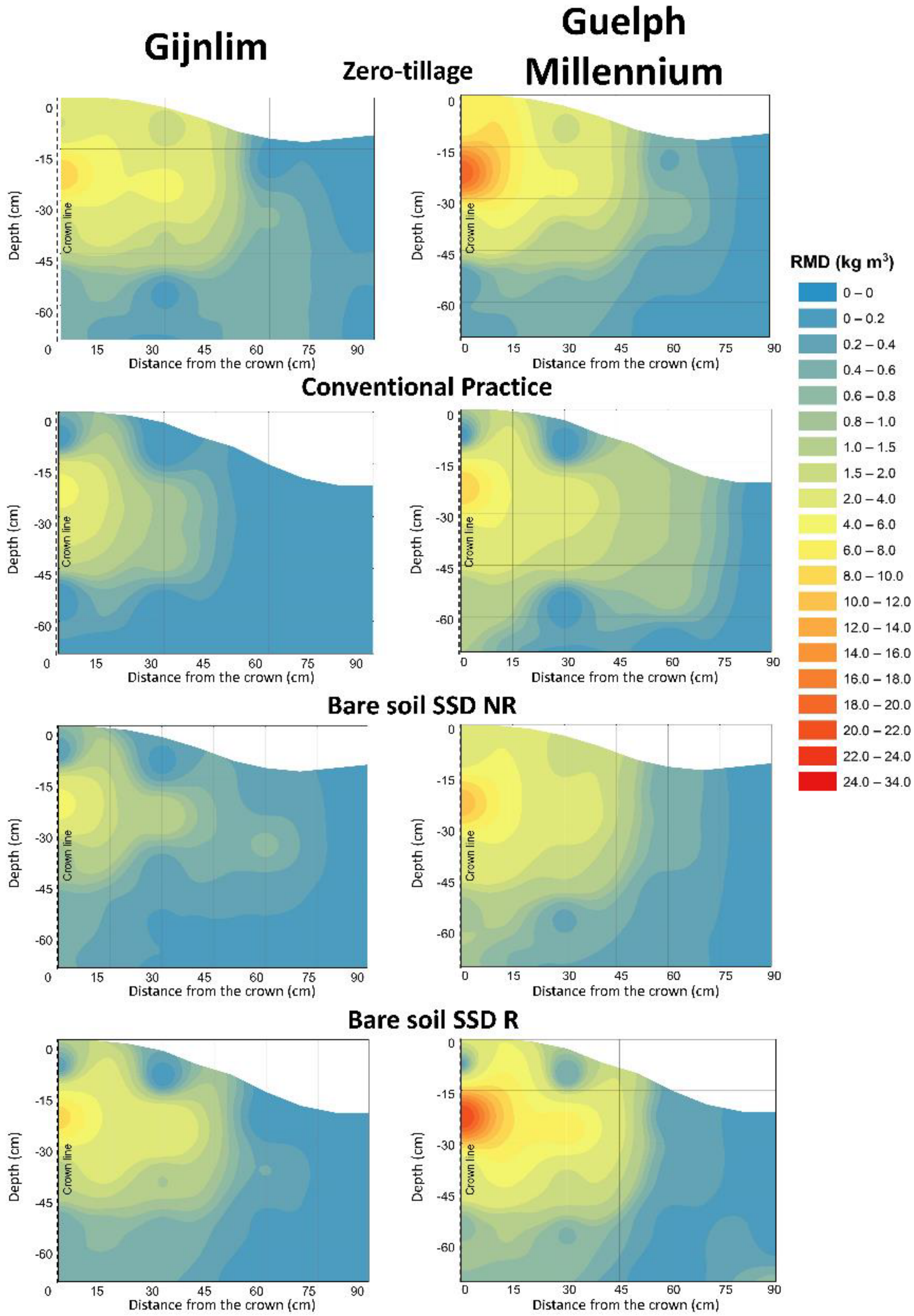


Figure 15. Root distribution hear maps representing 2022 root distribution of the Zero-tillage (Bare soil No-SSD NR), Conventional practice (Bare soil No-SSD R), Bare soil SSD NR and Bare soil SSD R of Gijnlim and Guelph Millennium.

Impact of BMPs on asparagus yield.

In 2021, Zero-tillage, Oats NR, PAS 100 R and NR with SSD, Rye R and Straw Mulch NR with SSD were associated with 36%, 33%, 46%, 35%, 31% and 32% significantly higher yields than the Conventional practice, respectively (Table 5). In contrast, in 2022, only the Zero-tillage, PAS 100 NR with SSD, Rye R treatments and Straw Mulch NR with SSD treatments were associated with 32%, 39% and 32% significantly higher yields than the Conventional practice, respectively (Table 5).

The Zero tillage treatment has over 5 harvests (2018-2022) been associated with between 14-46% significantly higher yields as compared with the Conventional practice with the greatest comparable yield uplift of 36 and 32% occurring in 2021 and 2022 (Figure 16).

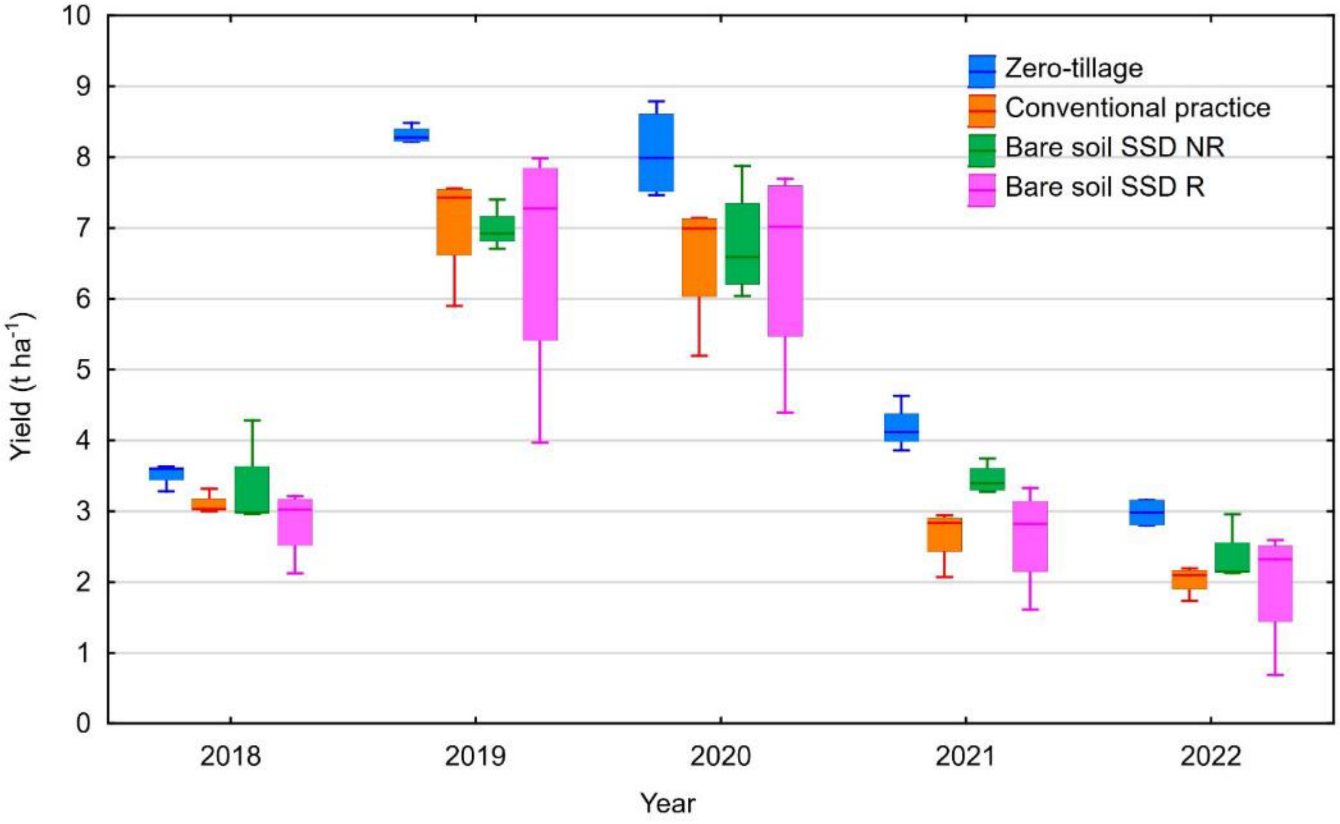
Similarly, the PAS 100 NR treatment over the 5 harvests taken to date is associated with 20%, 34%, 46% and 39% yield uplift as compared with Conventional practice in 2018, 2020, 2021 and 2022, respectively (Figure 17).

In addition, over 5 harvests the Rye R treatment is associated with 28%, 26%, 28%, 16% and 17% significantly higher yields as compared with Conventional Practice in 2018, 2019, 2020, 2021 and 2022, respectively (Figure 18).

It is note that yield decrease observed across all treatments between 2020 and 2021 has continued for the 2021 to 2022 harvests (Figure 15 – 18). Between 2021 and 2022, across all BMP treatments, there was a significant yield decrease of approximately 29%. Specific treatments which were associated with significantly lower yields in 2022 as compared with 2021 were Zero-tillage (29%), Bare soil SSD NR (32%), Oats NR (31%), PAS 100 NR (32%), PAS 100 R (32%), Straw Mulch NR (30%) and Straw Mulch R (28%) (Table 5).

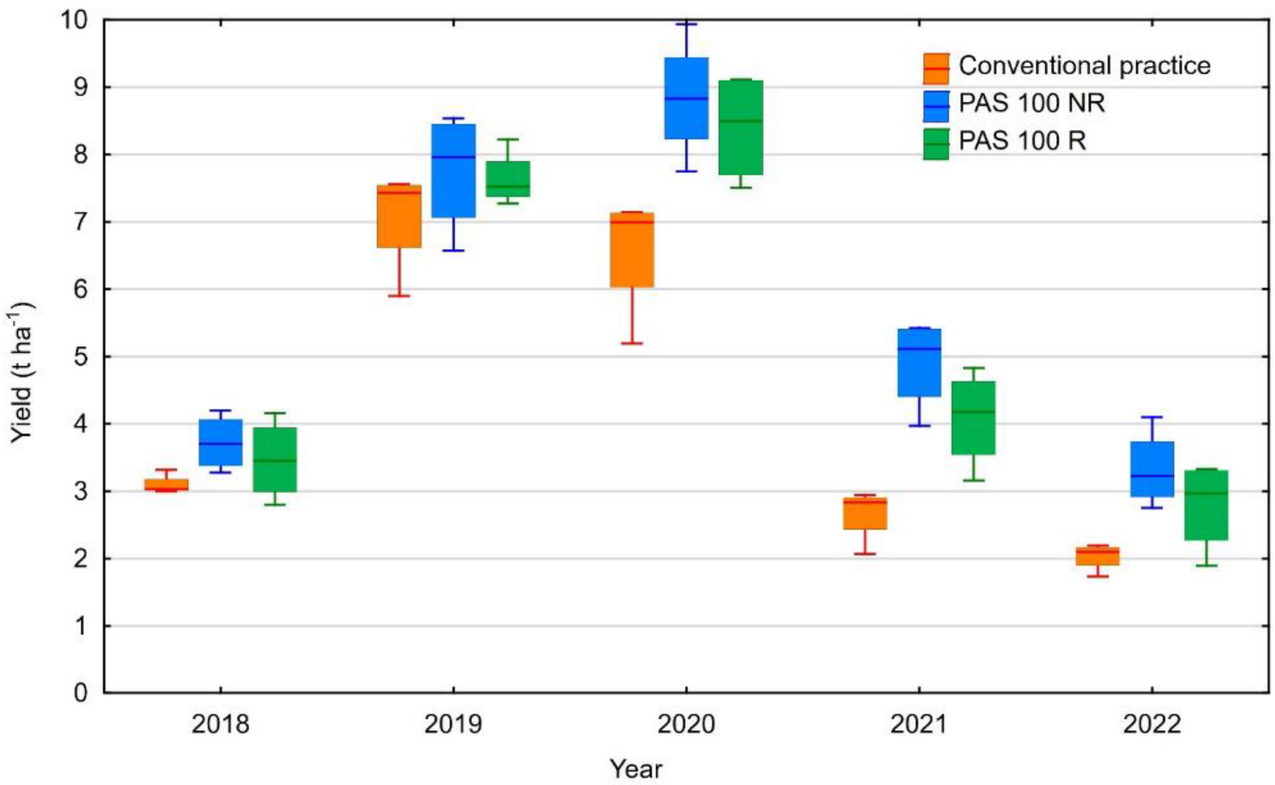
Between 2021 and 2022, there was a significant difference between Gijnlim and Guelph Millennium yields. Guelph Millennium yielded on average 28% and 47% higher as compared to Gijnlim in 2021 and 2022, respectively. Yields of Zero-tillage and Bare soil SSD NR treatments of both Gijnlim and Guelph Millennium have decreased significantly between 2021 and 2022 (Table 6). In terms of significant differences between varieties, those were also present in Zero-tillage and Bare soil SSD NR treatments in 2021. In 2022, in addition to Zero-tillage and Bare soil SSD NR, Bare soil SSD R of Guelph Millennium also yielded significantly higher as compared to the same treatment applied to Gijnlim (Table 6).

Figure 16. Total yields (t ha^{-1}) for bare soil treatments over five (2018-2022) full harvest seasons. Median (solid line), 25th and 75th percentile (box), non-outlier max and min (whisker).



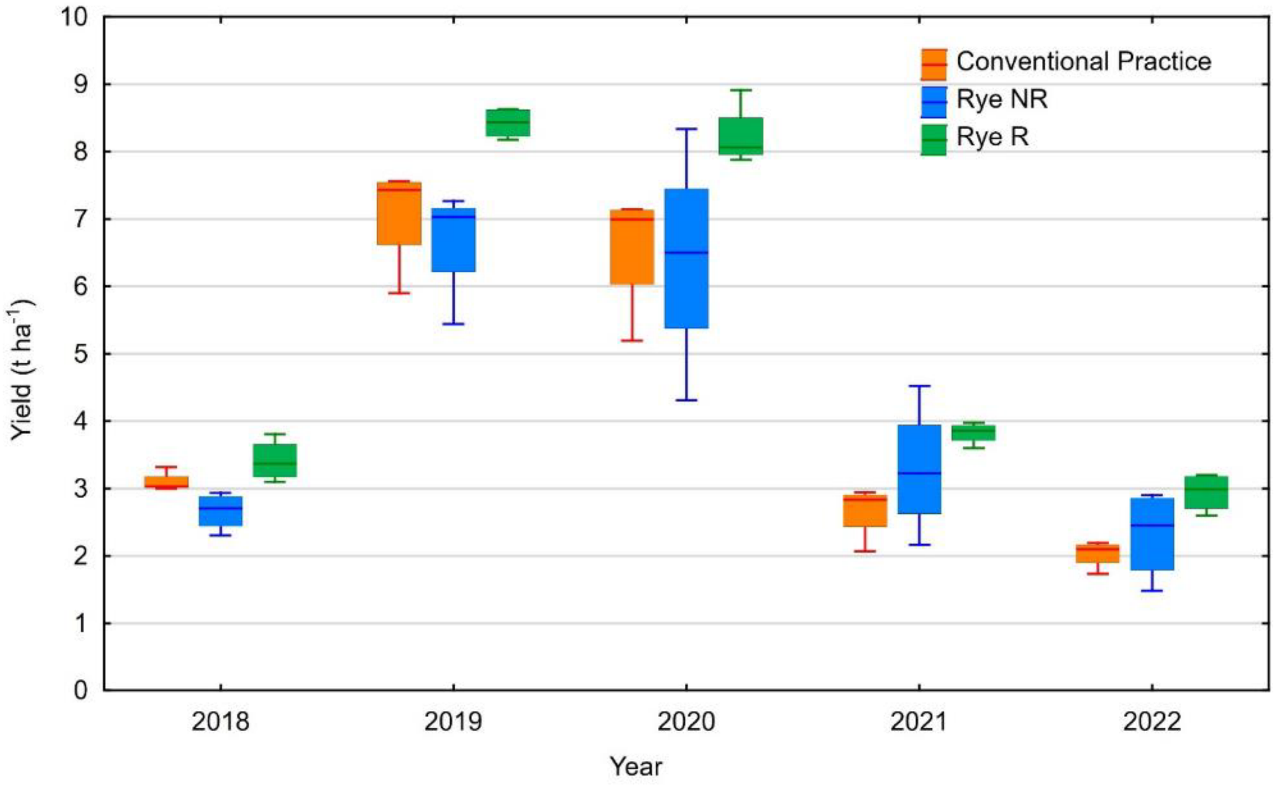
Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD. Zero-tillage = Bare soil No-SSD NR; Conventional practice = Bare soil No-SSD R.

Figure 17. Total yields (t ha^{-1}) for the PAS 100 Compost ridged and non-ridged treatments as compared to Conventional practice over five (2018-2022) full harvest seasons. Median (solid line), 25th and 75th percentile (box), non-outlier max and min (whisker).



Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD. Zero-tillage = Bare soil No-SSD NR; Conventional practice = Bare soil No-SSD R.

Figure 18. Total yields (t ha^{-1}) for the Rye Companion Crop ridged and non-ridged treatments as compared to Conventional practice over five (2018-2022) full harvest seasons. Median (solid line), 25^{th} and 75^{th} percentile (box), non-outlier max and min (whisker).



Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD. Zero-tillage = Bare soil No-SSD NR; Conventional practice = Bare soil No-SSD R.

Table 5. Total yields (t ha^{-1}) of all treatments in 2021 and 2022.

Treatment	2021	2022
[1]Zero-tillage	4.18 [cd]	*2.98 [bc]
[2]Conventional practice	2.67 [a]	2.03 [a]
Bare soil SSD NR	3.45 [abc]	*2.34 [ab]
Bare soil SSD R	2.64 [a]	1.98 [a]
Oats NR	3.96 [bcd]	*2.73 [abc]
Oats R	2.90 [ab]	2.28 [ab]
PAS 100 NR	4.90 [d]	*3.32 [c]
PAS 100 R	4.08 [cd]	*2.79 [abc]
Rye NR	3.28 [abc]	2.32 [abc]
Rye R	3.82 [bc]	2.94 [bc]
Straw Mulch NR	3.89 [bcd]	*2.71 [abc]
Straw Mulch R	3.50 [abc]	*2.52 [abc]

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Table 6. Total yields (t ha^{-1}) of Gijnlim and Guelph Millennium treatments in 2021 and 2022.

Variety	Treatment	2021	2022
Gijnlim	[1]Zero-tillage	4.18 [cd]	*2.98 [bcd]
	[2]Conventional practice	2.67 [ab]	2.03 [a]
	Bare soil SSD NR	3.45 [bc]	*2.34 [ab]
	Bare soil SSD R	2.64 [a]	1.98 [a]
Guelph Millennium	[1]Zero-tillage	5.54 [e]	*3.95 [e]
	[2]Conventional practice	2.95 [ab]	2.61 [abc]
	Bare soil SSD NR	4.84 [de]	*3.85 [de]
	Bare soil SSD R	3.18 [ab]	3.32 [cde]

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Impact of BMPs on asparagus storage root soluble carbohydrates (CHO).

Asparagus (*Asparagus officinalis* L.) is a perennial crop with a complex yield physiology strongly influenced by weather conditions during harvest and by crop management decisions (Shelton and Lacy, 1980; Wilson et al., 2008). Asparagus yield and plant growth is also highly dependent on the availability of soluble carbohydrates (CHO) in the storage root system (Wilson et al., 2008). Ultimately, root CHO levels are considered to be the key factor determining asparagus yield performance which was officially recognised by the *AspireNZ* decision support system of Wilson et al. (2002b).

There is significant variation in asparagus storage root CHO levels between plants depending on the size of the root system (Wilson et al., 2008), i.e. target pre-harvest CHO content of small root systems are expected to reach at least 550 mg g^{-1} while in large root systems, the target value is only 450 mg g^{-1} . Furthermore, CHO stored in asparagus roots is subject to seasonal fluctuations throughout the annual growth cycle (Shelton and Lacy, 1980; Wilson et al., 2008, 2002a).

Sufficient CHO levels are necessary for spear production during the harvest season as well as for optimum fern establishment after harvest which is essential for CHO replenishment (Wilson et al., 2002b). Consequently, the ability of asparagus plants to accumulate and translocate adequate CHO is crucial for both high spear yields and stand longevity.

The storage root CHO analysis indicates that in 2021, no significant differences in root CHO content were observed between any treatments with values ranging from 350-496 mg g^{-1}. However, and crucially 10 treatments (Table 7 and Figure 19) were associated with root CHO values less than the target range of 450-550 mg g^{-1} (Wilson et al., 2008). In 2022, all treatments (Table 7 and Figure 19) were associated with root CHO values less than the target range of 450-550 mg g^{-1} (Wilson et al., 2008)

In 2021, across all Experiment 2 treatments, significant varietal differences in root CHO values were observed between the Gijnlim and equivalent Guelph Millennium treatments (Table 8). Guelph Millennium treatments were associated with root CHO values > 450 mg g^{-1} with values ranging from 571-632 mg g^{-1}. In contrast, Gijnlim treatments were with the exception of the Zero tillage treatment associated with CHO values <450 mg g^{-1} with values ranging from 391-442 mg g^{-1}. In 2021, the Gijnlim Zero tillage treatment was associated with a mean root CHO content of 496 mg g^{-1} (Table 8).

Table 7. Mean root soluble carbohydrates (CHO) (mg g^{-1}) of all treatments in 2021 and 2022.

Treatment	2021	2022
[1]Zero-tillage	496 ^{a}	374 ^{bc}
[2]Conventional practice	431 ^{a}	312 ^{ab}
Bare soil SSD NR	429 ^{a}	*223 ^{a}
Bare soil SSD R	429 ^{a}	327 ^{abc}
Oats NR	437 ^{a}	333 ^{abc}
Oats R	492 ^{a}	*300 ^{ab}
PAS 100 NR	356 ^{a}	355 ^{bc}
PAS 100 R	350 ^{a}	384 ^{bc}
Rye NR	383 ^{a}	347 ^{abc}
Rye R	406 ^{a}	278 ^{ab}
Straw Mulch NR	421 ^{a}	443 ^{c}
Straw Mulch R	421 ^{a}	339 ^{abc}

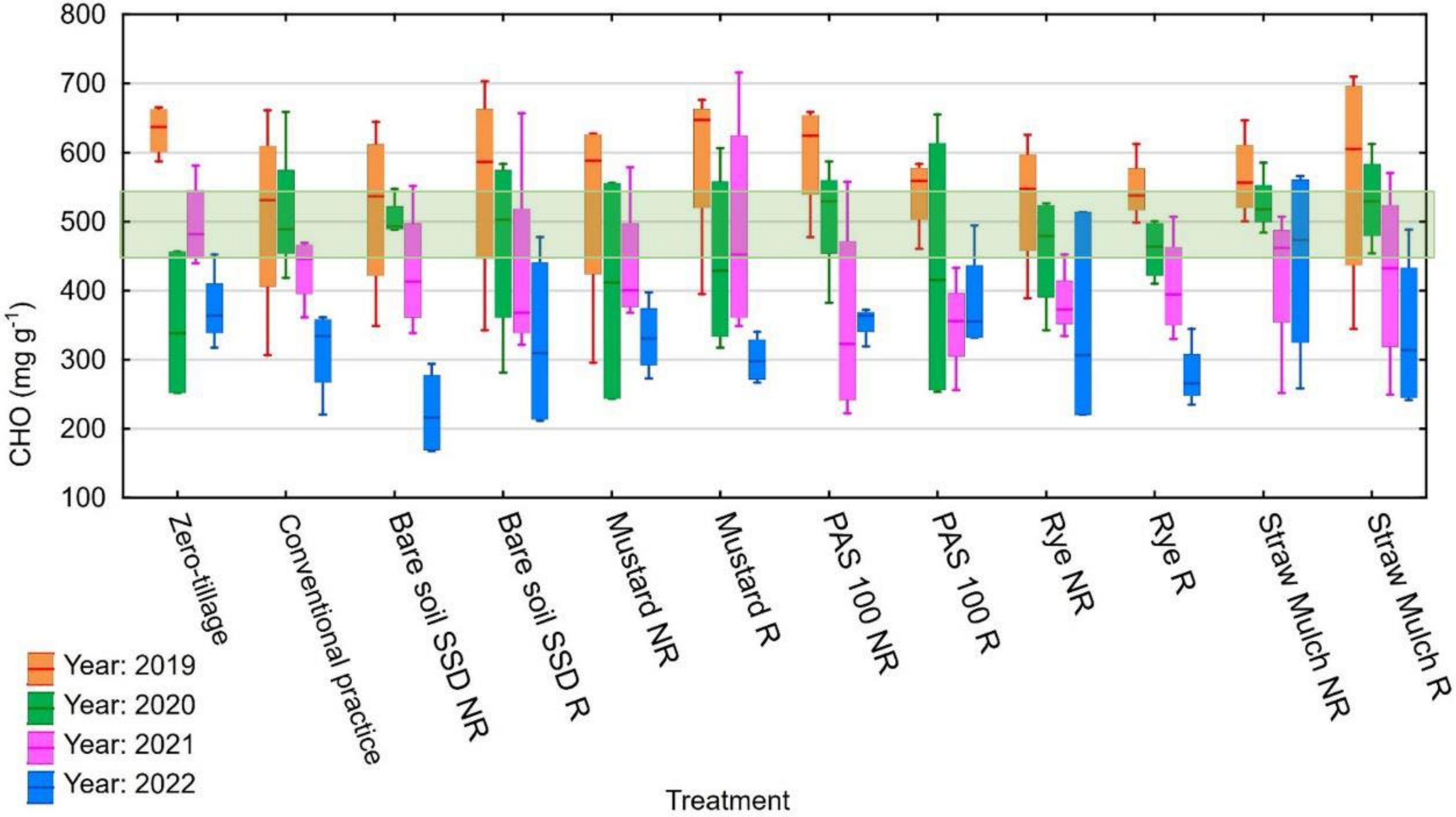
Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Table 8. Mean root soluble carbohydrates (CHO) (mg g^{-1}) of Gijnlim and Guelph Millennium treatments in 2021 and 2022.

Variety	Treatment	2021	2022
Gijnlim	[1]Zero-tillage	496 ^{ab}	374 ^{abc}
	[2]Conventional practice	431 ^{a}	312 ^{ab}
	Bare soil SSD NR	429 ^{a}	*223 ^{a}
	Bare soil SSD R	429 ^{a}	327 ^{abc}
Guelph Millennium	[1]Zero-tillage	632 ^{c}	521 ^{c}
	[2]Conventional practice	616 ^{bc}	*391 ^{abc}
	Bare soil SSD NR	571 ^{bc}	422 ^{abc}
	Bare soil SSD R	582 ^{bc}	442 ^{bc}

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Figure 19. Mean (n=46) 2019-2022 storage root CHO values (mg g^{-1}). Median (solid line), 25th and 75th percentile (box), non-outlier max and min (whisker).



In contrast, in 2022, varietal differences in root CHO values between equivalent treatments were not significant (Table 8). However, it is of note that with the exception of the Guelph Millennium Zero tillage treatment, all treatments across both varieties were associated with root CHO values of < 450 mg g^{-1} with mean values ranging from 223-442 mg g^{-1} (Table 8). The long-term trend if for a systematic year on year decline in root CHO content across all treatments (Figure 19).

Relationship between root CHO, yields and RMD

Extensive research has claimed that asparagus productivity is primarily determined by the root CHO content (Paschold et al., 2008; Shelton and Lacy, 1980; Wilson et al., 2008). Nevertheless, following a simple correlation analysis of yields and root CHO of all treatments, no relationship between these two variables were found corroborating findings reported by Drost (2012) who found that the size of the root system needs to be accounted for when estimating CHO storage. Thus, total CHO was calculated using the method proposed by Drost (2012), which accounts for the dry root mass density (RMD) to obtain an estimate of the total field CHO stores:

$$\text{Total CHO (kg ha}^{-1}\text{)} = \text{Mean CHO content (mg g}^{-1}\text{)} \times \text{RMD (kg m}^{3}\text{)}$$

Following the procedure suggested by Drost (2012), 2022 yield and total CHO values formed a positive significant relationship which is visualised in Figure 20. This relationship only became significant following the 5th harvest season and will need to be monitored.

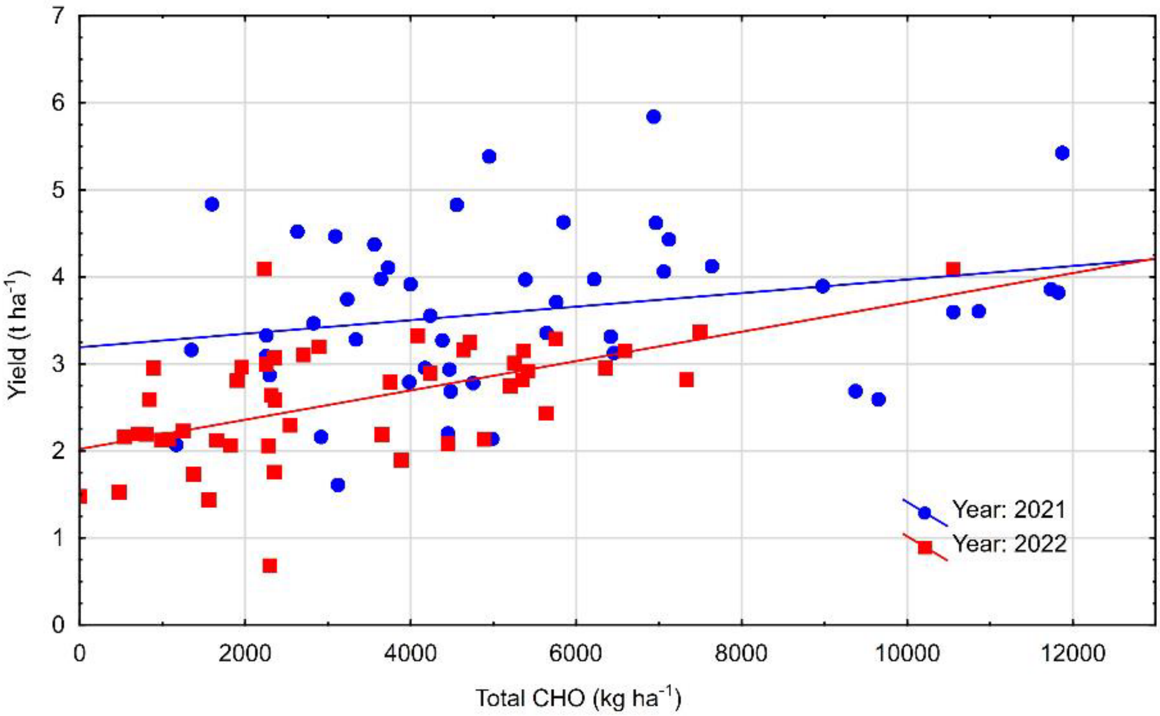


Figure 20. Relationship between yield (t ha^{-1}) and total CHO (kg ha^{-1}) in 2021 and 2022. 2021: r = 0.24, p = NS/non-significant; 2022: r = 0.56, $p < 0.0001$.

Impact of BMPs on asparagus yield quality attributes.

In general, spear quality is determined by spear diameter, spear weight, and by spear defects as affected by physiological disorders such as open tips, curving, wilting or tip rot and pest/disease damage.

In 2021 (Table 9), across all treatments, on average 35% of harvested spears had open tips, 12% were curved, 0.2% were classed as large spears (>22mm), 54% were classed as medium spears (10-22mm) and 46% were classed as thin spears (<10mm).

Specifically, the Rye NR treatment is associated with a significantly higher percentage of spears classified as thin (<10mm) that the Rye R treatment with values of 61.4 and 42.0 %.

In addition, the Rye NR treatment was associated with a significantly higher % of thin spears as compared with the Zero tillage, Oat NR/R, Straw mulch with SSD NR/R, PAS 100 compost with SSD NR/R treatments (Table 9). Only the Zero tillage and PAS 100 compost with SSD NR treatments were associated with a lower % of thin spears as compared with Conventional practice with values of 38.7, 37.0 and 53.5%, respectively.

In 2022, across all treatments, on average 15% of harvested spears had open tips, 20% were curved, 0.5% were classed as large spears (>22mm), 74% were classed as medium spears (10-22mm) and 26% were classed as thin spears (<10mm).

In 2022 (Table 10), the occurrence of open tip spears decreased significantly (from 35% to 15%) whereas curving spears incidence increased significantly as compared to 2021 (from 12% to 20%). Production of thin spears (<10mm) has significantly decreased in 2022 (from 46% to 26%) and was compensated by significantly higher proportion of medium spears (10-22mm) as compared to 2021 (from 54% to 74%).

Table 9. Impact of BMPs on spear diameter, spear defects and percentage marketable yield summed over the whole 2021 harvest season.

Treatment	Percentage (%) of potential marketable yield				
	<10mm (Thin)	10-22mm (Medium)	>22mm (Thick)	Open tip	Curving
Zero-tillage	38.7 ^{a}	61.3 ^{d}	0.00 ^{a}	35.3 ^{a}	11.2 ^{ab}
Conventional practice	53.5 ^{bcd}	46.5 ^{abc}	0.00 ^{a}	42.9 ^{a}	11.7 ^{b}
Bare soil SSD NR	56.5 ^{cd}	42.8 ^{ab}	0.65 ^{a}	37.0 ^{a}	11.1 ^{ab}
Bare soil SSD R	52.0 ^{bcd}	48.0 ^{abc}	0.00 ^{a}	46.1 ^{a}	14.1 ^{b}
Oats NR	41.8 ^{ab}	57.6 ^{cd}	0.60 ^{a}	28.6 ^{a}	5.41 ^{a}
Oats R	46.9 ^{abc}	52.8 ^{bcd}	0.32 ^{a}	35.1 ^{a}	11.9 ^{b}
PAS 100 NR	37.1 ^{a}	62.9 ^{d}	0.00 ^{a}	30.9 ^{a}	14.7 ^{b}
PAS 100 R	44.0 ^{ab}	56.0 ^{cd}	0.00 ^{a}	30.5 ^{a}	11.7 ^{b}
Rye NR	61.4 ^{d}	38.3 ^{a}	0.25 ^{a}	38.4 ^{a}	10.1 ^{ab}
Rye R	42.0 ^{ab}	57.8 ^{cd}	0.25 ^{a}	28.9 ^{a}	10.4 ^{ab}
Straw Mulch NR	46.4 ^{abc}	53.6 ^{bcd}	0.00 ^{a}	35.6 ^{a}	15.8 ^{b}
Straw Mulch R	35.7 ^{a}	64.3 ^{d}	0.00 ^{a}	36.0 ^{a}	11.7 ^{b}

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

Table 10. Impact of BMPs on spear diameter, spear defects and percentage marketable yield summed over the whole 2022 harvest season.

Treatment	Percentage (%) of potential marketable yield				
	<10mm (Thin)	10-22mm (Medium)	>22mm (Thick)	Open tip	Curving
Zero-tillage	20.8 ^{ab}	79.0 ^{de}	0.18 ^{a}	12.1 ^{ab}	22.4 ^{a}
Conventional practice	26.4 ^{abcd}	72.8 ^{bcd}	0.82 ^{ab}	13.9 ^{ab}	17.8 ^{a}
Bare soil SSD NR	28.4 ^{cd}	71.4 ^{bc}	0.27 ^{ab}	15.7 ^{b}	20.6 ^{a}
Bare soil SSD R	30.4 ^{de}	68.0 ^{ab}	1.61 ^{b}	16.3 ^{b}	22.8 ^{a}
Oats NR	23.9 ^{abc}	75.9 ^{cde}	0.26 ^{ab}	13.4 ^{ab}	20.4 ^{a}
Oats R	25.8 ^{abcd}	73.2 ^{bcde}	1.02 ^{ab}	15.3 ^{b}	16.5 ^{a}
PAS 100 NR	22.8 ^{abc}	76.8 ^{cde}	0.43 ^{ab}	17.3 ^{b}	21.7 ^{a}
PAS 100 R	24.4 ^{abcd}	75.5 ^{cde}	0.11 ^{a}	16.0 ^{b}	18.6 ^{a}
Rye NR	35.0 ^{e}	64.6 ^{a}	0.40 ^{ab}	16.2 ^{b}	18.4 ^{a}
Rye R	20.3 ^{a}	79.4 ^{e}	0.25 ^{ab}	9.84 ^{a}	18.6 ^{a}
Straw Mulch NR	26.8 ^{bcd}	72.9 ^{bcd}	0.38 ^{ab}	16.9 ^{b}	21.5 ^{a}
Straw Mulch R	25.7 ^{abcd}	74.2 ^{bcde}	0.11 ^{a}	16.4 ^{b}	19.8 ^{a}

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

In 2021, there were no differences between open tip spear production between BMP treatments (Table 9). Production of curving spears was however significantly lower on Oats NR (5%) as compared to the Conventional practice (12%), Bare soil SSD R (14%), Oats R (12%), PAS 100 NR (15%), PAS 100 R (12%), Straw mulch NR (16%) and Straw mulch R (12%). In 2022, there were no differences between treatments in production of curved spears (Table 10). There were however differences in open tip incidence, Rye R produced significantly lower proportions of open tip spears as compared to Bare soil SSD NR, Bare soil SSD R, Oats R, PAS 100 NR, PAS 100 R, Rye NR, Straw mulch NR and Straw mulch R.

Production of thin spears (<10mm) in 2021 was significantly higher for the Conventional practice as compared to Zero-tillage, PAS 100 NR and Straw mulch R (Table 9). In 2022 however, with the exception of the Rye NR treatment, no significant difference in the % of thin (<10 mm diameter) spears was observed between the BMP treatments and Conventional practice (Table 10). Rye R had significantly lower proportions of thin spears as compared to Bare soil SSD NR, Bare soil SSD R, Rye NR and Straw mulch NR.

Impact of BMPs on potential revenues

Spear value is determined by spear grade specifications and on the stage of the harvesting season. In the UK, there is no legally binding standard for asparagus spear classification. Spear class specifications are however set by individual retailers usually following the British Asparagus Growers Association (AGA) standards for spear quality specification. Spear quality is divided in two classes, high quality 'Class I' and lower quality 'Class II'.

In this study, a simplified yield value estimation was adopted which disregarded differences in spear diameter and focused on overall spear quality which significantly affects overall profits. Misshapen and deformed spears (flowering or curved heads) were classified as 'Class II' and priced at £1.50 per kg [Personal communication John Chinn, Cobrey Farms]. All spears without noticeable defects, regardless of diameter, were valued as 'Class I' spears and priced at £3.00 per kg [Personal communication John Chinn, Cobrey Farms]. Both Class I and Class II fell within the marketable yield category and were used to estimate potential revenues.

In line with yield and root CHO values, there was also an overall significant decrease in potential revenues from 2021 to 2022 (Table 11) for the Oats NR, PAS 100 NR and PAS 100 R treatments.

In 2021, Zero-tillage, Oats NR, PAS 100 NR, PAS 100 R, Rye R and Straw Mulch NR were associated with significantly higher potential revenues as compared to the Conventional practice by 64%, 61%, 96%, 63%, 52% and 52%, respectively. Further, PAS 100 Compost NR was associated with potential revenues that were significantly higher than the Bare Soil SSD NR/R, Oats R, Rye NR, and Straw Mulch NR and Conventional practice (Table 11). In 2021, Zero tillage, Oats NR, PAS 100 Compost NR/R, Rye R and Straw Mulch NR were associated with potential revenues significantly higher than the Conventional practice (Table 11).

In 2022, only Zero-tillage, PAS 100 NR and Rye R were associated with significantly higher potential revenues as compared to the Conventional practice by 48%, 61% and 48%, respectively.

Table 11. Estimated potential revenues (£ ha^{-1}) of BMP treatments in 2021 and 2022.

Treatment	2021	2022
[1]Zero-tillage	£10,931 ^{cd}	£8,479 ^{bc}
[2]Conventional practice	£6,653 ^{a}	£5,730 ^{a}
Bare soil SSD NR	£9,133 ^{abc}	£6,550 ^{ab}
Bare soil SSD R	£6,659 ^{a}	£5,577 ^{a}
Oats NR	£10,743 ^{cd}	*£7,700 ^{abc}
Oats R	£7,504 ^{ab}	£6,404 ^{ab}
PAS 100 NR	£13,044 ^{d}	*£9,245 ^{c}
PAS 100 R	£10,862 ^{cd}	*£7,851 ^{abc}
Rye NR	£8,607 ^{abc}	£6,454 ^{ab}
Rye R	£10,131 ^{bcd}	£8,477 ^{bc}
Straw Mulch NR	£10,115 ^{bcd}	£7,536 ^{abc}
Straw Mulch R	£8,849 ^{abc}	£7,059 ^{abc}

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Within the varietal trial (Experiment 2), Zero-tillage potential revenues of both Gijnlim and Guelph Millennium decreased significantly in 2022 as compared to 2021. In addition, Bare soil SSD NR of Gijnlim had significantly lower revenues in 2022 as compared to 2021.

In 2021, Zero-tillage and Bare soil SSD NR of Guelph Millennium was associated with significant 40% and 45% higher potential revenues as compared to the equivalent Gijnlim treatments with values of £15,293 and £10,931 and £13,262 and £9,133, respectively (Table 12). In 2022, Zero-tillage, Bare soil SSD NR and Bare soil SSD R Guelph Millennium treatments were again associated with significantly higher potential revenues as compared to the equivalent Gijnlim treatments with values of £11,091 and £8,479, £11,091 and £6550 and £5,577 and £9,684, respectively (Table 12).

Furthermore, Zero-tillage treatment was associated with significantly higher potential revenues on both varieties and in both years as compared to the Conventional practice. Bare soil SSD NR was also linked to significantly higher revenues compared to the Conventional practice on both varieties in 2021 however in 2022, Bare soil SSD NR of Gijnlim was no longer different from the Conventional practice (Table 12).

Table 12. Potential revenues (£ ha^{-1}) of Gijnlim and Guelph Millennium treatments in 2021 and 2022.

Variety	Treatment	2021	2022
Gijnlim	[1]Zero-tillage	£10,931 ^{c}	*£8,479 ^{bc}
	[2]Conventional practice	£6,653 ^{a}	£5,730 ^{a}
	Bare soil SSD NR	£9,133 ^{bc}	*£6,550 ^{ab}
	Bare soil SSD R	£6,659 ^{a}	£5,577 ^{a}
Guelph Millennium	[1]Zero-tillage	£15,293 ^{d}	*£11,365 ^{d}
	[2]Conventional practice	£7,823 ^{ab}	£7,617 ^{abc}
	Bare soil SSD NR	£13,262 ^{d}	£11,091 ^{d}
	Bare soil SSD R	£8,542 ^{ab}	£9,684 ^{cd}

Values followed by the same letter(s) are not significantly different following Factorial ANOVA and *post-hoc* Fisher LSD. *Significantly different in 2022 as compared to 2021. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

Conclusions

- The results of this study confirm that asparagus yield, profitability, alleviation of soil compaction, increased infiltration and improved soil health can be achieved by moving away from Conventional practice and adopting one of several alternative Best Management Practice (BMP) options.
- Shallow soil disturbance (SSD) is effective in reducing compaction levels of interrow wheelings to a depth of 0.25m for all bare soil and mulch BMP treatments.
- Shallow soil disturbance in the interrow wheelings continues to have no negative impact on root mass density or yield.
- In 2021 and 2022 Guelph Millennium continues to exhibit a larger root system, significantly higher CHO values and higher yields as compared with the equivalent Gijnlim treatments.
- Root soluble carbohydrate (CHO) values alone do not correlate to total asparagus yields. In order to form a relationship between root CHO and yields, individual CHO values need to be multiplied by the size of the root system. The resulting value is more representative of the real amount of ‘fuel’ within the ‘root engine’.
- PAS 100 Compost applied annually to asparagus interrows in combination with shallow soil disturbance (SSD) without annual re-ridging continues to result in significant (>20%) yield uplift, reduced in soil compaction, improved infiltration rates and improved profitability as compared to conventional practice.
- Zero-tillage also referred to as ‘ridging for the life of the crop’ continues to result in significant (>20%) yield uplift, improved yield and profitability, reduced soil compaction and improved soil health as compared with conventional practice.
- Companion cropping with rye (*Secale cereale*) with annual re-ridging, can result in >20% yield uplift as compared to conventional practice. However, non-ridging carries a risk of a 20% yield penalty compared with conventional practice suggesting that growers need to be confident that they can re-ridge if rye is grown as a companion crop for run-off and erosion control.

Knowledge and Technology Transfer

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

Engagement Activities

- 12th August 2021 PAG meeting
- 1st December 2021 PAG meeting
- 26th May 2022 PAG meeting

Knowledge Exchange

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


- ASPARAGUS -

EXPLORING THE POTENTIAL OF COMPANION CROPS FOR ASPARAGUS

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

15th International Asparagus Symposium
IAS2022
CÓRDOBA (SPAIN)
June 12th-15th, 2022

- Mašková, L., Simmons, R.W., Deeks, L.K., De Baets, S., Drost D.T. (2022) Long-Term Application of Best Management Practices Affects Yields and Root Carbohydrate Content in Asparagus (Asparagus officinalis) (UK). International Asparagus Symposium 12th -15th June 2022, Cordoba, Spain.

- 6th July 2022 – The Asparagus Growers Association Biennial Conference in Coningsby, Lincolnshire
    - AHDB FV450b: Sustainable soil management for stand longevity and yield optimisation: Update and key messages
    - Asparagus field demonstration and discussions around FV450b Best Management Practices

- Mašková, L., Simmons, R.W., Deeks, L.K., De Baets, S. (2022) Alleviating Deep-Seated Compaction in Asparagus (Asparagus officinalis) Interrows (UK). World Congress of Soil Science 31st July – 5th August 2022, Glasgow, Scotland

Glossary

BMPs	Best Management Practices
PAG	Principal Asparagus Growers
PR	Penetrative resistance
RMD	Root Mass Density
%TRB	Percentage Total Root Biomass
CZL	Crown zero line
IDW	Inverse distance weighing
R	Re-ridging
NR	Non-ridging
SSD	Shallow Soil Disturbance
No-SSD	Without Shallow Soil Disturbance
CC	Companion Crops
CHO	Soluble Root Carbohydrate
ELMS	Environmental Land Management scheme

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Appendix 1

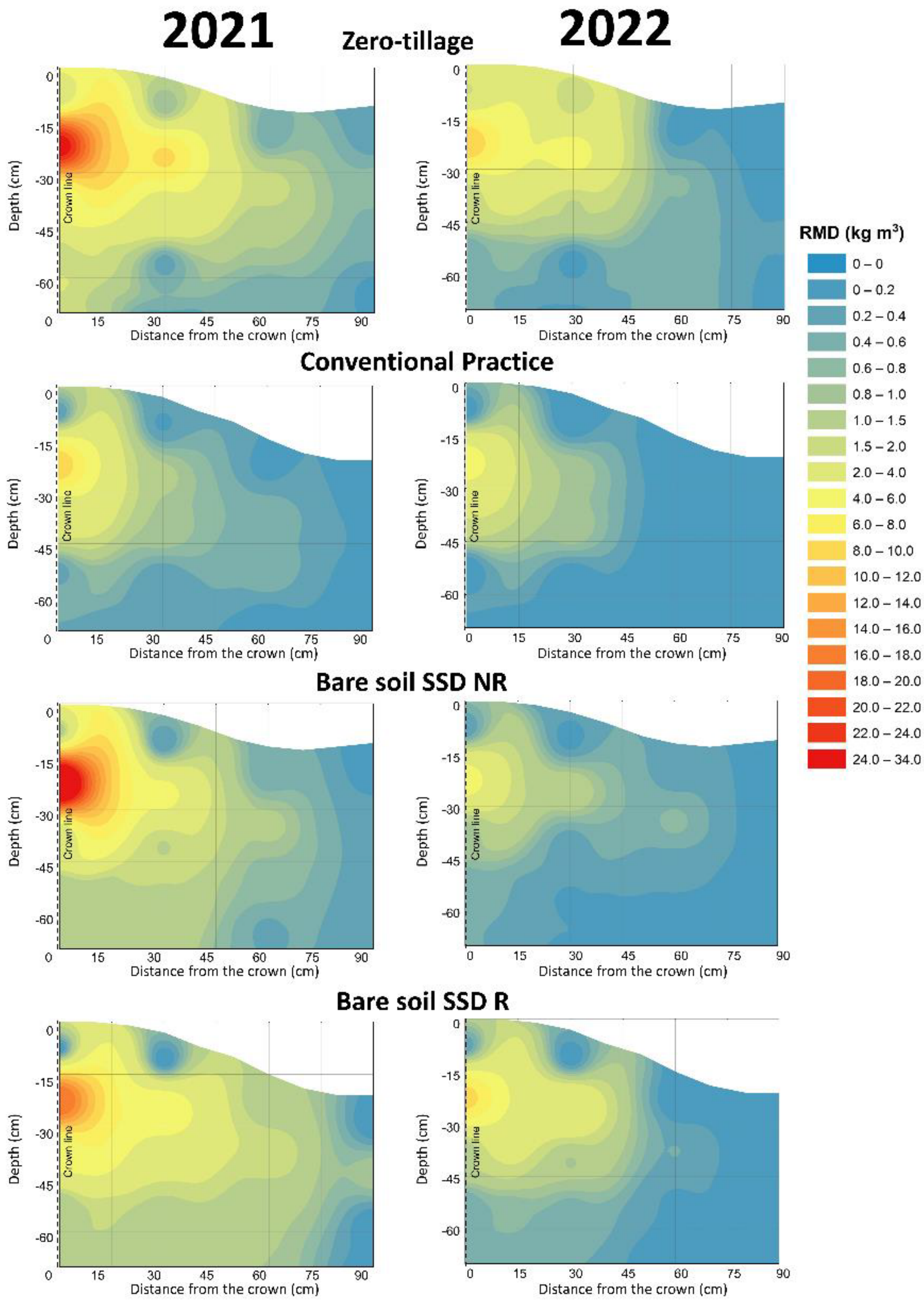

Figure 11. Root distribution heat maps representing root distribution of the Zero-tillage (Bare soil No-SSD NR), Conventional practice (Bare soil No-SSD R), Bare soil SSD NR and Bare soil SSD R in 2021 and 2022.

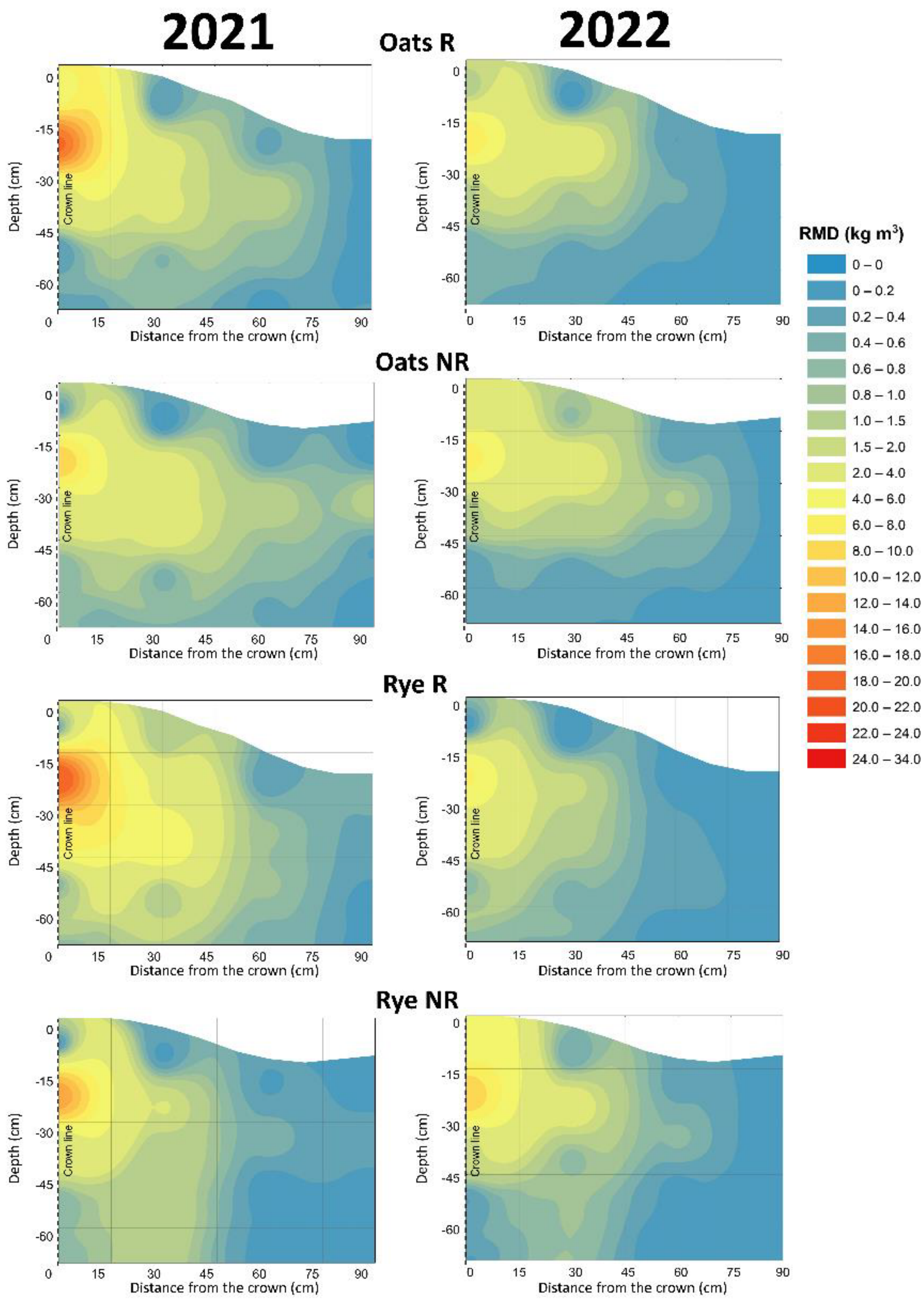

Figure 12. Root distribution heat maps representing root distribution of the Oats R, Oats NR, Rye R and Rye NR treatments in 2021 and 2022.

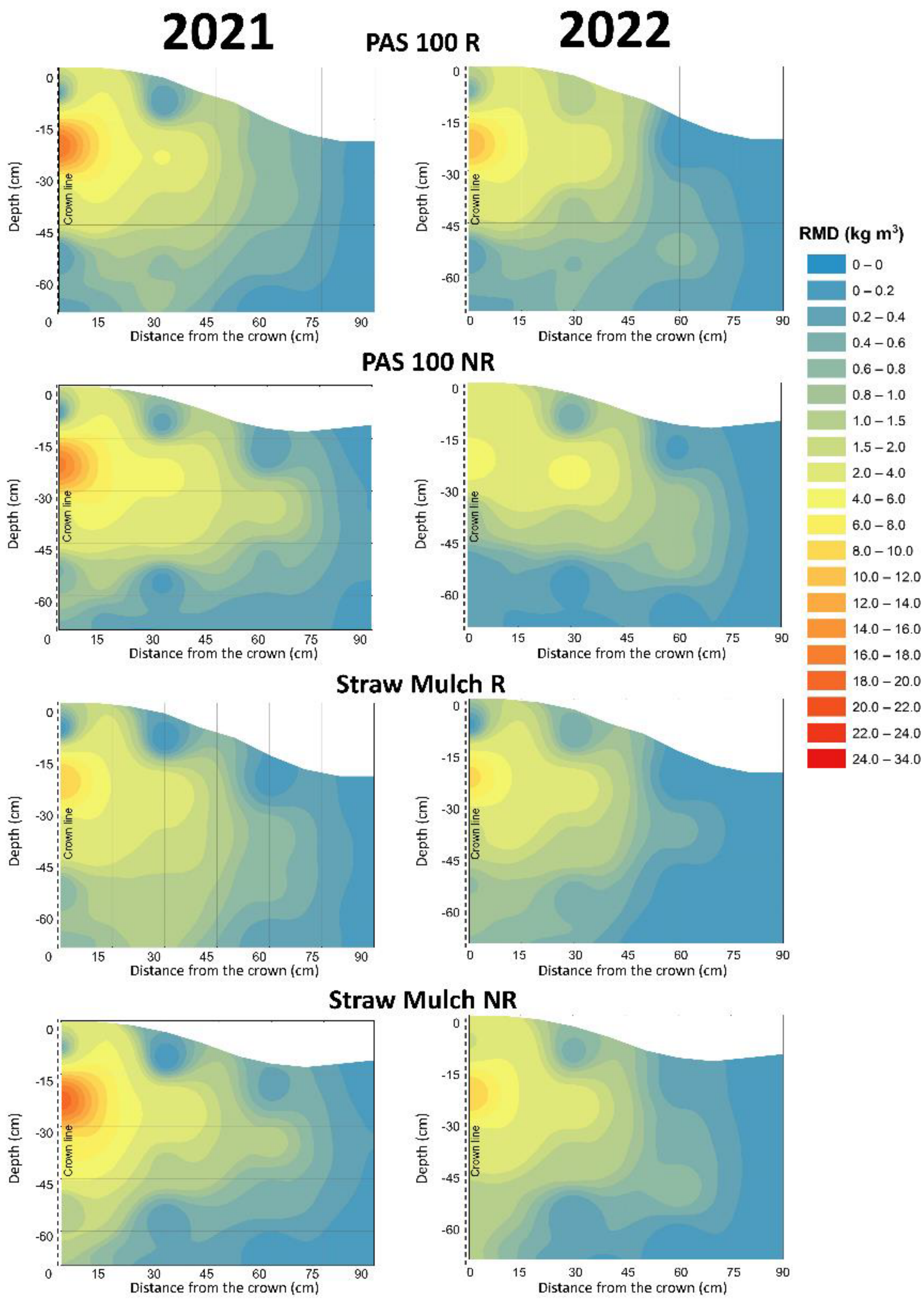

Figure 13. Root distribution heat maps representing root distribution of the PAS 100 R, PAS 100 NR, Straw mulch R and Straw mulch NR treatments in 2021 and 2022.