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Best Management Practices to Alleviate Deep-Seated Compaction in Asparagus (*Asparagus officinalis*) Interrows (UK)

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ABSTRACT

Field operations associated with UK asparagus production (re-ridging and intensive foot and vehicular trafficking of the wheelings) can result in severe deep-seated compaction in interrows, impacting on crop health and productivity. In this project, we investigate the long-term efficacy of a range of Best Management Practices (BMPs) targeted at preventing or remediating soil compaction in asparagus (*Asparagus officinalis* L.) interrows as compared to Conventional practice. BMPs included (1) companion crops - Rye (*Sereale cecale* L.), Mustard (*Sinapis alba* L.), (2) interrow surface mulch applications (straw mulch and PAS 100 compost in combination with shallow soil disturbance (SSD)), (3) modifications of the conventional tillage practice (re-ridging (R) or not ridging (NR) and applying SSD or not applying SSD) and (4) a zero-tillage option. In general, companion cropping had no effect on soil compaction or water infiltration rates as compared to the Conventional practice. Application and incorporation of straw mulch or PAS 100 compost however significantly reduced soil compaction of the interrows to >0.45 m beyond the working depth of the subsoiler (0.25 m). Composts and mulches in combination with SSD significantly reduce deep-seated compaction of the interrows within 3 years of annual application. Further, Conventional practice equivalent treatment (Bare soil No-SSD R) was associated with significantly higher PR values as compared to the zero-tillage (Bare soil No-SSD NR). These findings show that the extremely high levels of deep-seated compaction in interrows, associated with re-ridging, foot and vehicular traffic can be alleviated using surface mulches in combination with SSD.

1. Introduction

Achieving sustainable agriculture is a global challenge and excessive pressure continues to be applied to soil systems by a lack of viable alternatives to conventional soil management practices. This has led to soil degradation in the form of soil compaction, soil erosion, carbon-loss and loss of soil biodiversity (Bronick and Lal, 2005). Soil compaction in particular can severely restrict root development (Clark et al., 2003; Whalley et al., 2007) and compromise the ability of crop plants to access water and nutrients (White and Kirkegaard, 2010). Soil compaction can also increase susceptibility to disease and pest damage with direct impacts on yield, yield quality and production costs.

In the UK, the asparagus planted area increased from 1710 ha in 2010 to approximately 2392 ha in 2019 equating to a 40% increase in cropped area (Defra, 2020). However, over a typical 10-year commercial production cycle 'asparagus decline' caused by crown and root rot (CRR) and associated progressive loss of stand results in ca. £1.6 M in lost revenue per annum. It is postulated that soil compaction of interrows contributes to 'asparagus decline' (AHDB, 2017). In 2019, global asparagus production was estimated to be >9.4 Million t with 88.8, 2.88 and 3.88% of production in China, Mexico and Peru, respectively. This was associated with an estimated global production area of >1.6 Million ha of which 90.5% was in mainland China (FAO, 2021). In over 90% of this global land bank asparagus is ridged. Regular interrow trafficking associated with asparagus and other row crop production systems in particular promote deep-seated compaction which is one of the most challenging problems growers can encounter (Alakukku et al., 2003; Chamen et al., 2003; Håkansson, 1994; Niziolomski et al., 2020). Deep-seated compaction is considered extremely difficult and costly to remediate, with the damage often being permanent (Håkansson, 1994).

Field operations associated with ridged asparagus production systems [tillage operations such as ridging, spray operations, harvesting

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(foot-trafficking and/or hand harvesting using picking rigs)] can result in progressive and severe compaction of all interrows. In the UK, the majority of tillage operations in asparagus are undertaken in March-April, when soil is at or close to field capacity (Niziolomski et al., 2016). Such operations are undertaken to promote the growth of spears which meet customer specifications, for *Stemphyllium* control, to raise asparagus beds for efficient manual harvest and as a means of conveying excess rainfall offsite. 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 crop productivity (Reijmerink, 1973; Wilcox-Lee and Drost, 1991). Re-ridging also increases the susceptibility to CRR caused by *Phytophthora megasperma* (Falloon and Grogan, 1991) (now known as P. asparagi) and *Fusarium oxysporum f. sp. asparagi* (Elmer, 2015) which leads to yield decline and direct economic losses to the grower. In contrast, zero-tillage options have been shown to significantly increase the marketable weight of asparagus spears as compared to tilled asparagus (Wilcox-Lee and Drost, 1991) due to higher soluble carbohydrate (CHO) levels in storage roots of non-tilled treatments. Tillage operations such as sub-soiling of interrows for runoff and erosion control (Niziolomski et al., 2020) pose a high risk of damage to asparagus root systems which can cause reductions to CHO storage capacity.

Asparagus is a perennial crop with expected economic production between 10-20 years (Elmer et al., 1996). With such a long lifespan, it is expected that decisions made in one year determine the next years' crop performance. A single year of mismanagement may also result in years of stunted growth and associated yield losses (Wilson et al., 2002). Annual re-ridging of asparagus continues to be adopted by the majority of British growers, however, long-term effect of this practice and trafficking operations associated with harvest and agronomy on soil compaction in asparagus is unknown.

Best Management Practices (BMPs) have been used to prevent and/or ameliorate soil compaction in several crops such as winter cereals, potatoes and vines (Deasy et al., 2009; Gordon et al., 2011; Judit et al., 2011). However, there is a paucity of research focusing on how to effectively manage interrow compaction in asparagus. The objective of this research is to critically evaluate the efficacy of a range of BMPs to mitigate deep seated compaction in asparagus interrows as compared to Conventional practice. Impacts of interrow compaction on marketable asparagus yield are also quantified.

1.1. Materials and Methods

The trial took place as part of the AHDB Horticulture FV 450/450a long-term asparagus field trial, in collaboration with Cobrey Farms. The long-term field trial (4.5 ha) is located at Gatsford Farm, Ross-on-Wye, Herefordshire. Asparagus 'A' crowns of Gijnlim variety (which represents 70% of UK field grown asparagus) were planted on 20–21st of April 2016 on a flat surface at an anticipated depth of 0.14 m, at 0.16 m spacing between crowns. Beds were on 1.83 m wide centres. In spring 2017, all plots were re-ridged as a consequence of the shallowness of the crown (circa 0.06 m) instead of the intended 0.14 m. Conventional agrochemical treatments have been applied to all trial plots from 2016 to 2020.

1.2. Experimental Design

The trial investigated the efficacy of a range of potential BMPs (Table 1); (1) companion crops - Rye (*Sereale cecale* L var. Protector.) and Mustard (*Sinapis alba* L. var. Severka), (2) interrow surface mulch (Straw and PAS 100 compost) applications in combination with shallow soil disturbance (SSD), (3) modifications of the conventional tillage practice by not re-ridging (NR) and applying SSD and (4) a zero-tillage option. Rye is commonly used by North American asparagus growers as a strong weed suppressor which also provides soil protection through interception of rainfall kinetic energy. Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which are known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991). Furthermore, rye has been reported to have the ability to reduce the severity of *Fusarium* crown and root rot in asparagus (Matsubara et al., 2001). Mustard is known for its extensive tap-rooting system associated with bio-drilling and for its bio-fumigation potential, which has been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998). Two mulch products, straw mulch and PAS 100 certified quality compost (WRAP, 2011) were investigated. Both mulch options used in the experiment were subject to SSD so as to replicate the bio-drilling (Cresswell and Kirkegaard, 1995) and canopy effects associated with companion crops to test the ability of mulches to simulate companion crops. The experiment comprised 48 randomly distributed, 35 m long treatment plots. Each plot consists of 2 asparagus rows, central interrow and 2 guard interrows (separating the treatments). All treatments were replicated in quadruplicate. As appropriate, treatment plots were separated by tramlines to facilitate sprayer operations.

The tractor used for ridging and SSD operations was John Deere 6155R of 155 HP with Michelin 650/65 R38 rear tyres and Michelin 540/65 R28 front tyres. Tyre pressure was 82.74 kPa on the front tyres and 82.74 kPa on the rear tyres. SSD was applied in April 2018 and in March and June 2020 (Fig. 1) using a winged tine operating to 0.25-0.3 m depth to all mulch treatments (PAS 100 Compost or Straw) and to selected bare soil treatments (Table 1). Re-ridging was undertaken using a tractor mounted 1.83 m double disk ridger in March 2017, April 2018, March 2019 and March 2020. Companion crops were broadcast for the first time on the 10th August 2017 when the asparagus was at full fern stage at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard, respectively.

In the first year, the emergence rate of the companion crops achieved sufficient ground cover of 70-75% (Morgan, 2005). However, in 2018 and 2019, due to predation, seeding rates were increased to 200 kg ha^{-1} and 25 kg ha^{-1} for rye and mustard, respectively and repeated in September 2018 and October 2019. Mulches were applied annually in April 2016, April 2018, March 2019 and March 2020 at rates of 25 t ha^{-1} and 6 t ha^{-1} for PAS 100 and straw mulch, respectively. Hereafter, the Bare soil No-SSD NR and Bare soil No-SSD R treatments will be also referred to as a 'zero-tillage' and 'Conventional practice', respectively (Table 1).

Table 1
Summary of the experimental Best Management Practice treatments applied to asparagus interrows.

Treatment	Interrow Cover	Annual re-ridging (R)	Sub-soiling (SSD)
[2]Bare soil No-SSD R	Bare soil	R	No SSD
[1]Bare soil No-SSD NR	Bare soil	NR	No SSD
Bare soil SSD R	Bare soil	R	SSD
Bare soil SSD NR	Bare soil	NR	SSD
Mustard R	Mustard	R	No SSD
Mustard NR	Mustard	NR	No SSD
Rye R	Rye	R	SSD
Rye NR	Rye	NR	SSD
Straw mulch SSD R	Straw mulch	R	No SSD
Straw mulch SSD NR	Straw mulch	NR	No SSD
PAS 100 SSD R	Compost	R	SSD
PAS 100 SSD NR	Compost	NR	SSD

NR = No annual re-ridging and R = annual re-ridging; SSD = shallow soil disturbance.
[1] Zero-tillage.
[2] Conventional practice.

1.3. Sampling methodology

Penetrative Resistance (PR) was used as an indicatory of soil compaction (Bengough et al., 2006). PR measurements were taken twice during the trial establishment period. Legacy compaction was measured,

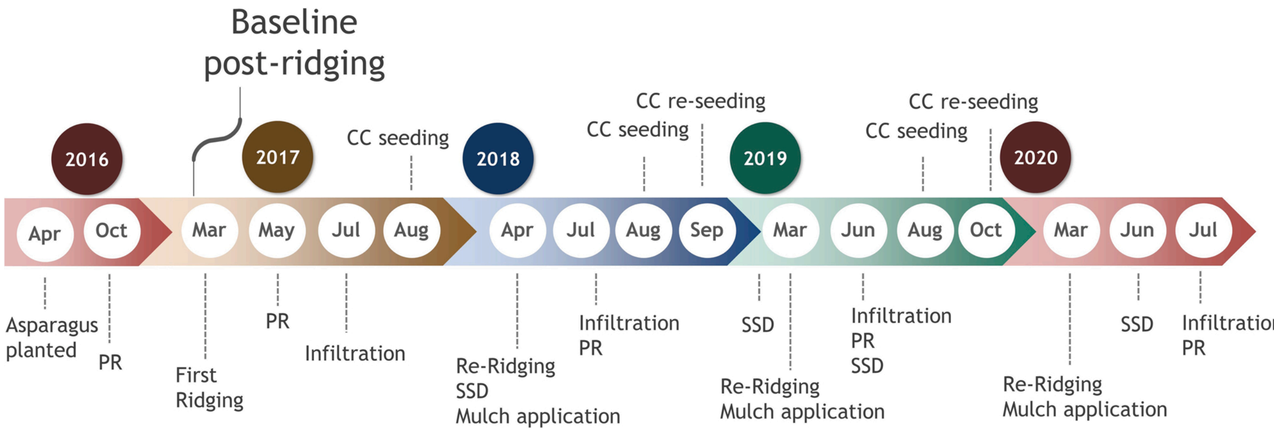

Fig. 1. Timeline of the AHDB FV450/FV450a projects indicating when treatments were applied, and metrics measured. PR = penetration resistance, SSD = shallow soil disturbance, CC = companion crop.

in October 2016 (n = 6), 6 months after asparagus was planted on a flat bed. Baseline PR compaction measurements were taken in May 2017 (n = 60) tangentially from the asparagus crown line (CL) (at 0.10, 0.15, 0.20, 0.25, 0.30, 0.45, 0.60 and 0.90 m distances from the crown) after the first ridging operation. Both legacy and baseline compaction levels are critical as they enable differences in PR to be linked to the BMP treatments applied. PR and infiltration rates were subsequently measured in July 2017, June 2018, June 2019, and July 2020 (n = 12 per treatment per year).

All measurements were conducted in the compacted central asparagus interrow. Measurements were obtained from two randomly selected plots per treatment. 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 6 locations along the length of the plot (5, 10, 15, 20, 25 and 30 m). In addition, in 2020, PR transects were taken tangentially from the asparagus CL at 0.3 m intervals to the centre of asparagus interrow (0.9 m from CL). For each experimental plot, four PR transects were measured. Cumulative rainfall for a 2-day period immediately prior to the start of PR measurements was 22.2 mm in 2018, 700 mm in 2019 and 11.8 mm in 2020. Soil samples of known volume (69 cm^3), collected at 10-15 cm depth, were obtained within the same timeframe as PR measurements. These soil samples were dried at 105 °C for 24 hrs and volumetric soil moisture content (SMC) was determined.

SMC 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 SMC is below field capacity in order to minimise compaction risk. As such in 2018, 2019 and 2020 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 (Table 1) were performed on the same day within a 2 hr period. As such SMC was considered to be uniform across treatments when trafficking and tillage events were applied.

Penetrative Resistance soil moisture normalisation models such as PENETR model by Canarache (1990) or covariance analysis for correcting cone index to soil moisture content by Christensen et al. (1989) were not applied to facilitate direct comparison between the 2018, 2019 and 2020 PR datasets. This was due to the complexity of data required by these models, which were not able to be recorded in the context of the experimental program. However, the annual PR measurements represent a quantification of the efficacy of the BMPs to mitigate against repeated intra and inter annual tillage and/or trafficking operations irrespective of the prevailing and contrasting climatic conditions during 2018-2020. The 2018, 2019 and 2020 PR measurements reflect a legacy effect of the intra and 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, as PR data from each year had to be evaluated separately.

Infiltration rate was measured in triplicate per plot concurrently with PR in July 2017, June 2018, June 2019, and July 2020. All measurements were conducted in the compacted central asparagus interrow. Infiltration was measured following a modified USDA single ring infiltrometer method, using a 0.12 m internal diameter PVC ring with falling head (Esparcia, 2014). Infiltration rate classes were adapted from the USDA Soil Quality Test Kit Guide (USDA, 1999).

Yields from all experimental plots were collected in 2018, 2019 and 2020. In 2018, harvest took place over a 28 day period between the 24th April to 21st May from 19 cuts. In 2019, the harvest extended to 53 cuts between the 20th April to 17th June and in 2020 from a total of 65 cuts between the 12th April to 22nd June.

1.4. *Statistical Analysis*

Statistical analysis was undertaken using the TIBCO Statistica 13.3.0 analytics software. Infiltration data was checked for normality and analysed by the standard analysis of variance followed by *post-hoc* Fisher LSD analysis at 95% conf. level. For data which failed to meet requirements for normal distribution, a log-normal transformation was applied prior to analysis. Penetrative resistance in asparagus interrows was analysed using the repeated measures ANOVA. Penetrative resistance spatial distribution contour maps were generated using the inverse distance weighing interpolation method (IDW) in Esri ArcMap™ (GIS software) version 10.7. Pearson correlation coefficients were calculated to determine the relationship between the 2018, 2019 and 2020 marketable asparagus yield and mean PR of the asparagus interrow.

2. Results

Soil analyses conducted in 2016 indicated that there were no significant differences in the soil parameters tested ($p \leq 0.05$) between plots. Soils at the trial site are Cambisols (IUSS Working Group WRB, 2007) of Eardiston series association (Cranfield University, 2020) with 77% sand, 11% silt and 12% clay composition. Other soil parameters showed soil pH of 6.34 (± 0.03), soil organic matter of 2.78% (±0.03), total soil C of 1.24% (±0.01) and total mineralizable N of 0.13% (±0.001).

2.1. Infiltration rate in asparagus interrows

The 2017 baseline mean infiltration rate was 99.8 mm hr^{-1} (Moderately Rapid), with 75% of the measurements being classified as moderate (15-50 mm hr^{-1}) and moderately rapid (50-150 mm hr^{-1}) (USDA, 1999).

In 2018, SSD significantly increased infiltration rates in Bare Soil SSD NR, PAS 100 R/NR and straw mulch R/NR treatments as compared to the zero-tillage, Conventional practice, Bare soil SSD R, Mustard R/NR and Rye R/NR treatments (Table 2). Re-ridging had a significant effect on infiltration rates in Bare soil SSD treatments, with Bare soil SSD R significantly reducing infiltration rates as compared to the Bare soil SSD NR.

In 2019, SSD application was not undertaken. Consequently, no significant effect of SSD on infiltration rates was observed. Even so, the PAS 100 R/NR treatments were associated with significantly higher infiltration rates (234.2 and 217.7 mm hr^{-1}) as compared to the Conventional practice, Bare soil SSD R, Mustard R, Rye R/NR and straw mulch R treatments. Re-ridging significantly decreased infiltration rate in Mustard R compared to Mustard NR.

In 2020 (Table 2), all treatments subject to SSD were classified as "Very Rapid" (>500 mm hr^{-1}) and as expected, had significantly higher infiltration rates as compared to all other treatments. No significant differences in infiltration rates were observed between SSD treatments. Re-ridging significantly decreased infiltration rates of Mustard R as compared to the Mustard NR. Conventional practice had significantly lower infiltration as compared to Mustard NR and Rye NR.

2.2. Penetration resistance in asparagus interrows

Mean soil moisture content (SMC) during 2016 pre-ridging PR measurements was 18% (±0.54) and 16% (±0.83) during the 2017 post-ridging PR measurement. SMC in the PR sampling period of 2018 was 15% (±0.34), 16% (±0.28) in 2019 and 15% (±0.19) in 2020 as measured in the topsoil (5-10 cm depth).

Mean profile PR values were significantly higher following the 2017 re-ridging as compared to the 2016 legacy compaction with mean PR in the interrows (0.90 m distance from the crown) of 2.56 MPa and 1.80 MPa, respectively. Spatial distribution patterns of pre and post-ridging PR are shown in Fig. 2.

Table 2
Mean (n = 6) infiltration rates (mm hr^{-1}) in the asparagus interrows for all Best Management Practice treatments as compared with Conventional practice for 2018, 2019 and 2020.

Treatment	Infiltration (mm hr^{-1})		
	2018	2019	2020
[1]Zero-tillage	161 [ab]	129 [abcd]	48.8 [ab]
[2]Conventional practice	94.6 [a]	51.5 [ab]	23.2 [a]
Bare Soil SSD NR	3984 [d]	59.5 [abc]	10145 [de]
Bare Soil SSD R	299 [ab]	24.4 [ab]	11942 [de]
Mustard NR	289 [ab]	136 [bcd]	230 [c]
Mustard R	175 [ab]	16.3 [a]	43.7 [ab]
PAS 100 NR (SSD)	3764 [d]	234 [d]	13513 [d]
PAS 100 R (SSD)	5724 [d]	218 [cd]	10064 [de]
Rye NR	578 [bc]	52.1 [a]	128 [bc]
Rye R	331 [ab]	22.5 [ab]	48.0 [abc]
Straw mulch NR (SSD)	4049 [cd]	100 [abc]	10334 [de]
Straw mulch R (SSD)	4437 [cd]	92.6 [a]	23146 [e]

For each year, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence *interval* (following log-normal transformation). Annual re-ridging (R) or No-ridging (NR). Shallow soil disturbance (SSD) or No-SSD.

[1] Bare Soil No-SSD NR.

[2] Bare Soil No-SSD R. Moderately rapid (50-150 mm hr^{-1}); Rapid (150-500 mm hr^{-1}); very rapid (>500 mm hr^{-1}) (USDA, 1999). Note due to logistical challenges, in 2019, SSD was not applied.

Pre-ridging, PR values of 2.3-2.7 MPa were measured at 0.30 m depth and below (Fig. 2). Post-ridging, PR of the interrows (90 cm) increased to between 2.7-3.0 MPa. As shown in Table 3. Mean (n = 60) PR (MPa) of the 2017 post-ridging baseline (n = 60) at specific soil depths (cm) and set distances from the crown line (cm) as compared with the mean (n = 6) 2016 legacy compaction levels (n = 6). 90 cm distance from the crown line refers to the centre of the interrow3, PR values were significantly higher post-ridging (2017) as compared to pre-ridging (2016) at the 60 cm distance from the crown at 0-5, 10-15 and 20-30 cm depths and at the 90 cm distance from the crown at 5-30 cm depth, corresponding to the assumed zone of influence of the ridger.

Figs. 3–5 show the evolution of soil compaction in the interrows from 2018 to 2020. Each year, differences between treatments were more pronounced than the year before. In 2018, the Conventional practice was associated with significantly higher PR values as compared to the zero-tillage treatment at 50-55 cm depth (Fig. 3a). No major differences could be seen between the four companion crop treatments and the Conventional practice (Fig. 3b). Early signs of differences could however be observed between straw mulches and the conventional treatment (Fig. 3c). In 2019, the effect of SSD on PR in bare soil treatments could be seen, with Conventional practice having a higher PR than the bare soil SSD R to the subsoiler working depth of 0-25 cm (Fig. 4a). All companion crop treatments had elevated levels of soil compaction at 0-10 cm depth, comparable to compaction of the conventional treatment (Fig. 4b). Rye R had the lowest PR of any companion crop in the subsoil area at 40-60 cm depth. Mulches showed a significant decrease in PR as compared with the Conventional practice at the 0-25 cm depth (Fig. 4c). Straw mulch NR further showed reduction in subsoil compaction to 30-60 cm depth as compared to the Conventional practice. In 2020, clear differences were observed between the bare soil treatments (Fig. 5a). Bare soil SSD treatments had significantly lower PR levels at 0-30 cm depth. Companion crops exhibited similar PR levels to the Conventional practice equivalents while no further differences were observed between the different companion crops (Fig. 5b). Finally, there was a noticeable reduction in PR levels for all mulch-SSD treatments as compared to the Conventional practice to 0-45 cm depth (Fig. 5c and Table 4). Straw mulch NR continued to have significantly lower PR compared to the conventional throughout the whole measured depth.

Comparison of 2016 legacy compaction and 2020 PR results showed that Conventional practice had significantly higher compaction levels throughout the whole measured profile while Zero-tillage had similar compaction levels to the 2016 legacy compaction at 30-50 cm depth. Further, treatments subject to SSD saw significant decreases in PR as compared to the legacy compaction to 5-25 cm depth. Crucially, mulches though subject to SSD exhibited significant decrease in PR beyond the subsoiler working depth. Compared to the 2016 legacy compaction, PAS 100 compost saw reduction in PR from 5-40 cm depth while straw mulch NR achieved significantly lower PR values from 5-20 and 30-50 cm depths. Compared to the 2017 post-ridging baseline, in 2020, Conventional practice showed a significant increase in PR at 40-60 cm depth. All SSD treatments were associated with significantly lower PR to 0-35 cm depth although straw mulch NR significantly decreased PR values 10 cm deeper, to 0-45 cm depth.

In 2020, a negative response to re-ridging was observed in Bare soil No-SSD treatments, where the Conventional practice (Bare soil No-SSD R) had significantly higher PR at 35-60 cm depth as compared to the zero-tillage (Bare soil No-SSD NR) (Table 4). Furthermore, all SSD treatments (Bare soil SSD, PAS 100 and straw mulch) had significantly lower interrow compaction levels as compared to the Conventional practice to at least 0-45 cm depth. PR values of companion crop treatments were similar to the Conventional practice.

In 2020, PR was measured in the whole soil profile, from the crown line (CL) to the interrow (Fig. 6). Each diagram represents PR as measured tangentially from the asparagus CL at 30 cm intervals to the centre of asparagus interrow (90 cm from the CL). Very high PR values (3.3 – 5.0 MPa) were observed for the interrows of the Conventional

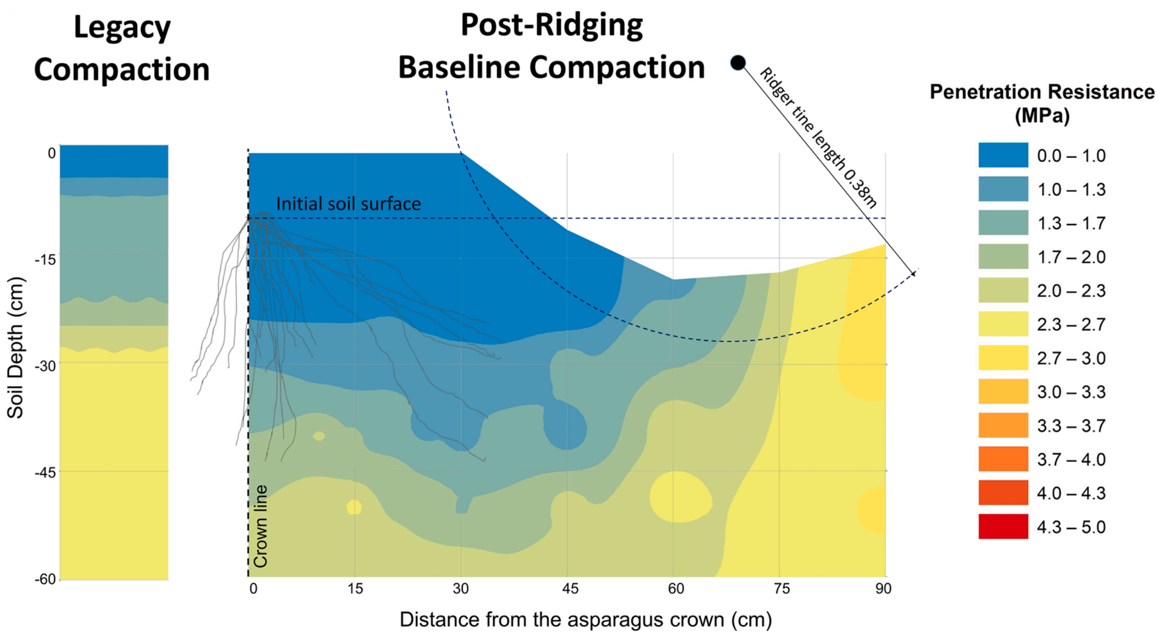

Fig. 2. Contour diagrams based on Penetration Resistance (PR) determined at set positions from the crown line using the inverse distance weighing (IDW) interpolation method. The left image is the 2016 legacy compaction (n = 6) and the right, the 2017 post-ridging baseline compaction (n = 60).

Table 3
Mean (n = 60) PR (MPa) of the 2017 post-ridging baseline at specific soil depths (cm) and set distances from the crown line (cm) as compared with the mean (n = 6) 2016 legacy compaction levels. 90 cm distance from the crown line refers to the centre of the interrow.

PR depth (cm)	2016 legacy compaction	2017 Post-ridging				
		Distance from the crown line				
		25 cm	30 cm	45 cm	60 cm	90 cm
0-5	**0.31**	0.02 ns	0.04 ns	0.03 ns	0.45 ns	1.63 +
5-10	**0.95**	0.19 -	0.25 -	0.56 -	2.11 +	3.74 +
10-15	**1.35**	0.40 -	0.45 -	1.35 ns	1.86 +	3.04 +
15-20	**1.58**	0.63 -	0.80 -	1.55 ns	1.58 ns	2.62 +
20-25	**1.54**	0.92 -	0.98 -	1.16 ns	2.02 +	2.41 +
25-30	**1.70**	1.29 -	1.22 -	1.24 -	2.41 +	2.24 +
30-35	**2.25**	1.20 -	1.18 -	2.05 ns	2.51 ns	2.73 +
35-40	**2.46**	1.13 -	1.18 -	2.40 ns	2.45 ns	2.75 +
40-45	**2.32**	1.52 -	1.49 -	2.27 ns	2.12 ns	2.50 ns
45-50	**2.32**	2.06 ns	1.88 -	2.28 ns	2.04 ns	2.43 ns
50-55	**2.39**	2.13 ns	2.34 ns	2.44 ns	2.68 ns	2.32 ns
55-60	**2.50**	2.15 ns	2.37 ns	2.56 ns	2.73 +	2.25 ns

Values followed by +, - or ns are significantly higher, lower or not significantly different as compared to the 2016 legacy compaction value (highlighted in bold) following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

practice (Bare soil No-SSD R), to within 30 cm of the CL (Fig. 6b). The zero-tillage treatment was associated with reduced PR at depth (45 – 60 cm) compared to all other bare soil treatments (Fig. 6). The significantly lower PR associated with SSD was observed on both Bare soil SSD treatments to approximately 20 cm depth (right hand upper corner of Fig. 6c and d).

All mulch treatments demonstrated a zone of PR reduction at the centre of the interrow (at 90 cm from the CL) which is a direct result of SSD (Fig. 9a–d). Further, straw mulch NR PR values in the interrow (90 cm distance from the CL) did not exceed 2.3 MPa (Fig. 7b). In comparison to treatments subject to SSD, all companion crops showed a zone of increased soil compaction in the interrows (>3.0 MPa), values of which were similar to PR of the Conventional practice in the same location (Fig. 7e–h). Mustard NR surface PR (Fig. 7f) reach values of up to 5.0 MPa, which are comparable to deep-seated (45 – 60 cm depth) compaction of the Conventional practice (Fig. 6b).

2.3. Soil compaction and asparagus yields

Yield data indicates that re-ridging of Rye R treatment was associated with 28, 26 and 28% higher yields as compared to the Rye NR in 2018, 2019 and in 2020, respectively (Table 5). For bare soil interrow treatments, re-ridging in the absence of SSD as seen in the Conventional practice treatment was associated with yield reductions of 12, 15 and 18% as compared to the Zero-tillage treatment in 2018, 2019 and in 2020, respectively (Table 5). Although in 2018 and in 2020 the differences between Zero-tillage and the Conventional practice were not significant at 95% confidence interval, decreasing the confidence level to 90% indicates that a significant difference would also be present in 2020. Consequently, re-ridging did have a significant impact on asparagus yields. In contrast, SSD applied to bare soil treatments did not affect yields in any of the three years.

For both the PAS 100 R and NR treatments there was a robust trend for 12-20%, 8-10% and 28-34% yield increases as compared to the Conventional practice in 2018, 2019 and in 2020, respectively (Table 5). Although this yield uplift was non-significant in 2018 and 2019 in. 2020 significant yield uplift was observed (Table 5). This suggests that long-term application of the PAS 100 R and NR treatments is required in order to promote increased yield as compared with Conventional practice.

Infiltration rates of the asparagus interrows and asparagus yields were not correlated in any of the three years. The analysis of relationships between mean PR of the interrows and yields however revealed a weak but significant negative correlation between these two variables in 2018 and in 2020 (Fig. 8). Furthermore, correlation coefficients for those two years were nearly identical, with a r = -0.38 in 2018 and r = -0.38 in 2020. These negative correlations suggest that increasing soil compaction of asparagus interrows can have a negative impact on asparagus yields.

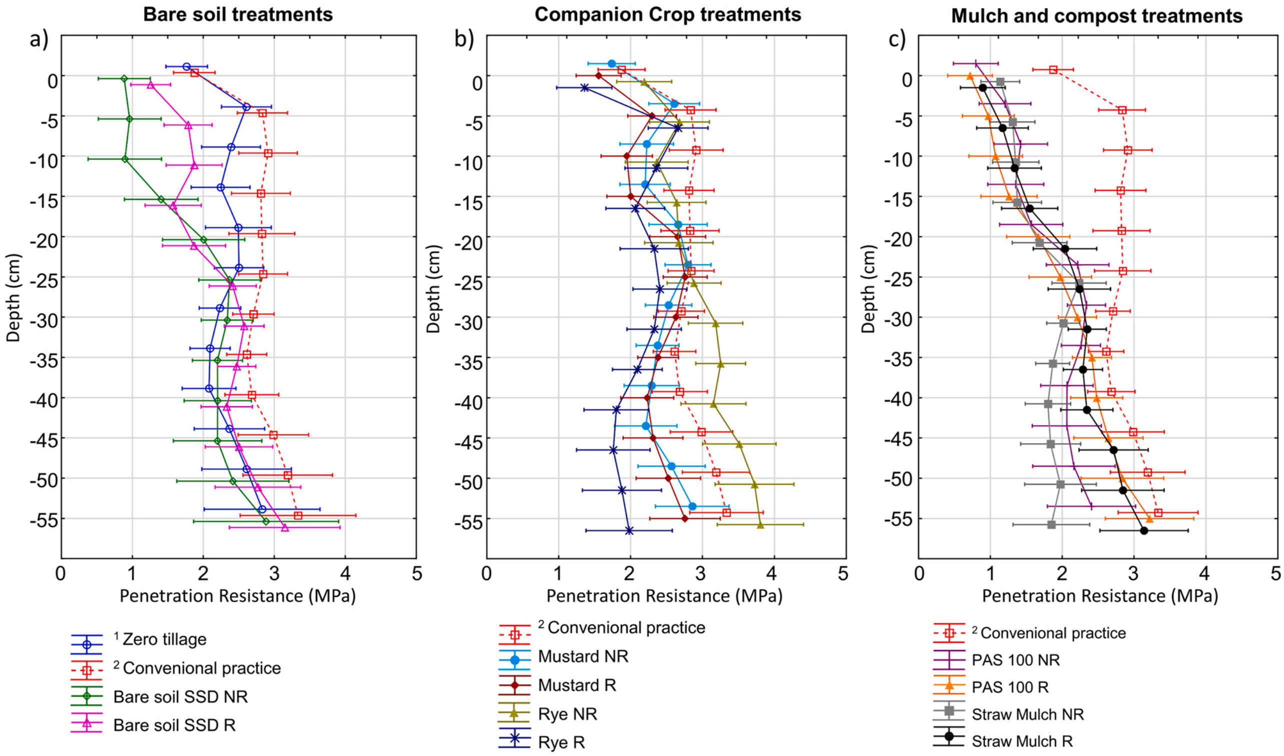

Fig. 3. Mean (n = 12) 2018 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals. Horizontal bars denote 0.95 confidence interval. [1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

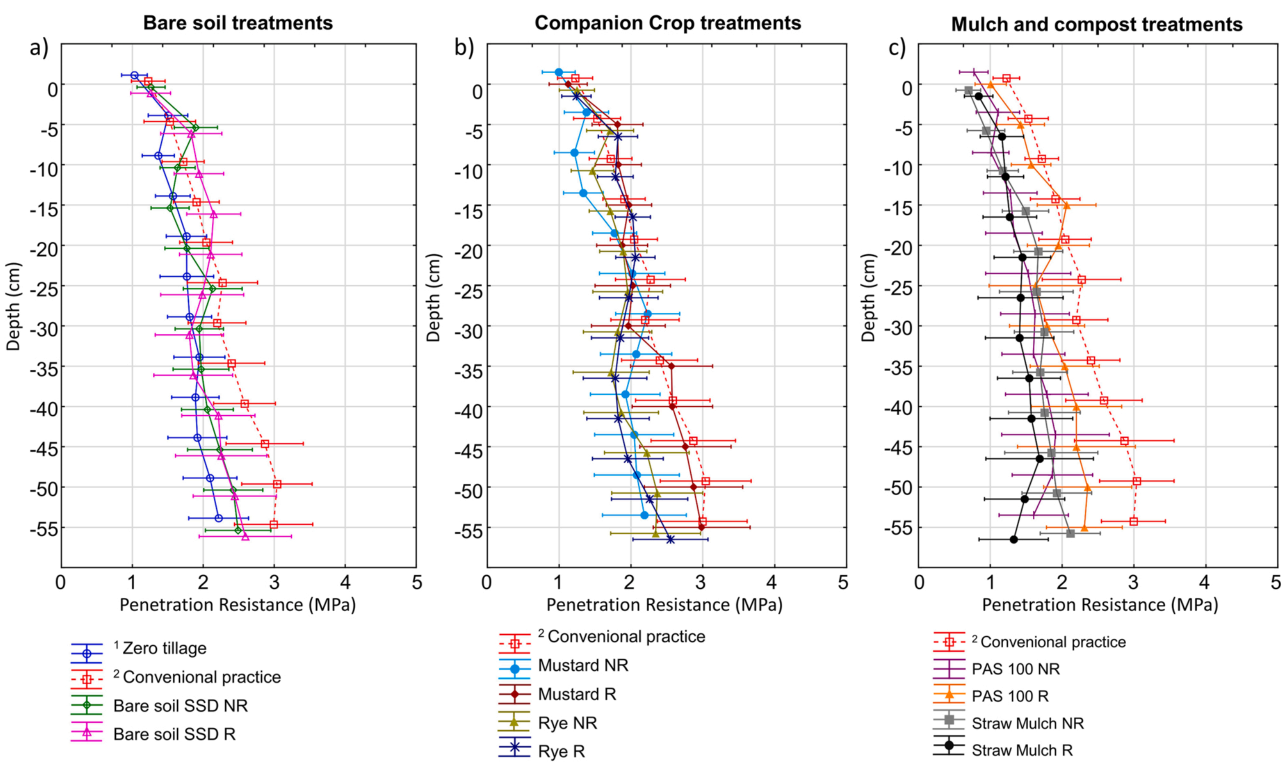

Fig. 4. Mean (n = 12) 2019 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals (n = 12). Horizontal bars denote 0.95 confidence interval. [1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

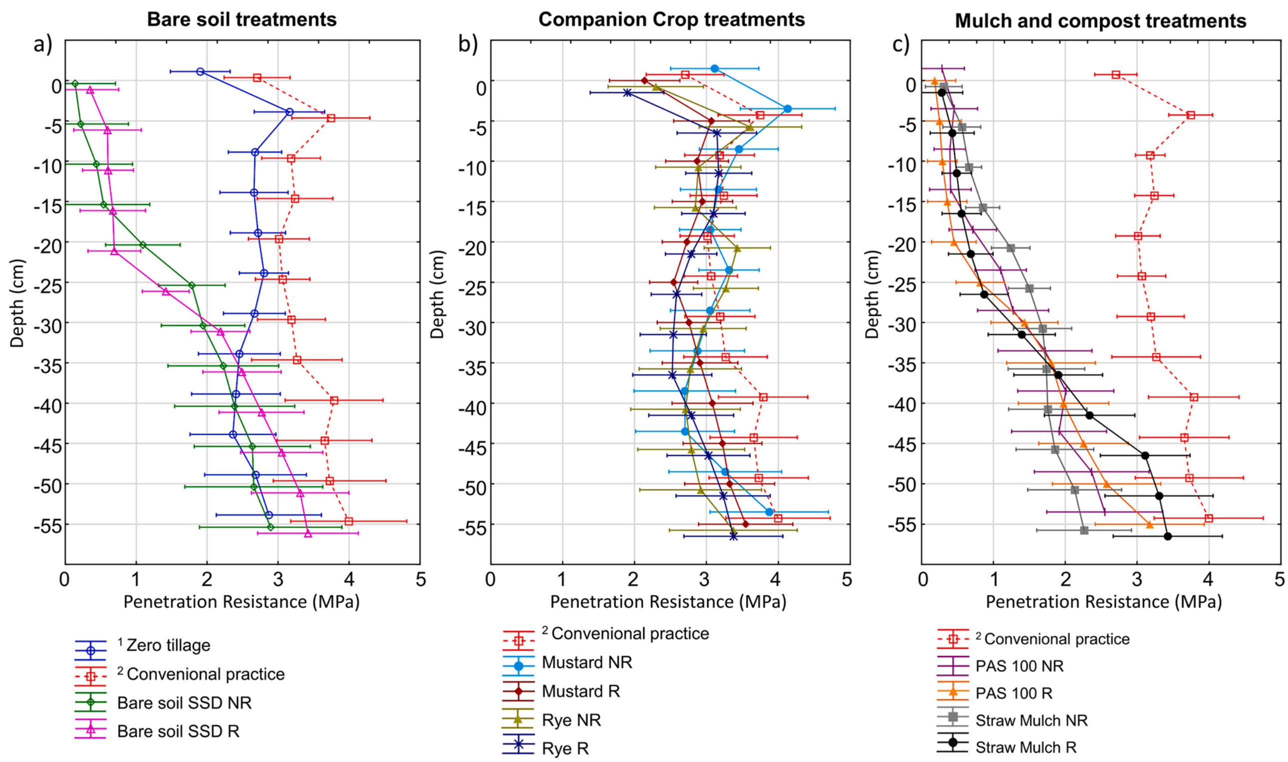

Fig. 5. Mean (n = 12) 2020 Penetration Resistance (MPa) in the centre of the asparagus interrow at 5 cm depth intervals (n = 12). Horizontal bars denote 0.95 confidence interval. [1] Bare soil No-SSD NR; [2] Bare soil No-SSD R.

Table 4
Differences in the 2020 mean (n = 12) PR (MPa) in the centre of the asparagus interrow (90 cm distance from the crown line) between treatments for 5 cm depth intervals.

PR Depth (cm)	Treatment: Bare soil no-SSD NR[1]	Bare soil no-SSD R[2]	Bare soil SSD NR	Bare soil SSD R	Mustard NR	Mustard R	PAS 100 NR	PAS 100 R	Rye NR	Rye R	Straw mulch NR	Straw mulch R
0-5	1.96 -	**2.91**	0.11 -	0.35 -	3.11 ns	2.11 -	0.18 -	0.17 -	2.29 ns	1.78 -	0.31 -	0.28 -
5-10	3.27 ns	**3.88**	0.16 -	0.60 -	4.13 ns	3.03 -	0.30 -	0.23 -	3.61 ns	3.00 -	0.56 -	0.43 -
10-15	2.72 ns	**3.27**	0.32 -	0.60 -	3.45 ns	2.83 ns	0.28 -	0.27 -	2.89 ns	2.98 ns	0.66 -	0.49 -
15-20	2.71 ns	**3.37**	0.44 -	0.67 -	3.17 ns	2.98 ns	0.26 -	0.33 -	2.85 ns	3.04 ns	0.85 -	0.56 -
20-25	2.75 ns	**3.11**	0.97 -	0.69 -	3.05 ns	2.78 ns	0.57 -	0.43 -	3.43 ns	2.65 ns	1.24 -	0.68 -
25-30	2.87 ns	**3.12**	1.67 -	1.42 -	3.31 ns	2.60 ns	1.01 -	0.80 -	3.27 ns	2.41 ns	1.50 -	0.87 -
30-35	2.75 ns	**3.27**	1.87 -	2.19 -	3.05 ns	2.82 ns	0.99 -	1.37 -	2.95 ns	2.52 ns	1.68 -	1.39 -
35-40	2.55 -	**3.31**	2.22 -	2.49 -	2.87 ns	2.98 ns	1.24 -	1.76 -	2.78 ns	2.60 ns	1.74 -	1.90 -
40-45	2.48 -	**3.88**	2.34 -	2.77 -	2.70 -	3.08 -	1.64 -	1.97 -	2.71 -	3.04 -	1.76 -	2.34 -
45-50	2.41 -	**3.72**	2.64 -	3.05 ns	2.70 -	3.18 ns	1.59 -	2.28 -	2.79 -	3.33 ns	1.86 -	3.11 ns
50-55	2.55 -	**3.80**	2.65 -	3.31 ns	3.26 ns	3.22 ns	1.65 -	2.58 -	2.92 -	3.36 ns	2.13 -	3.31 ns
55-60	2.60 -	**3.96**	2.80 -	3.42 ns	3.87 ns	3.54 ns	1.80 -	2.93 -	3.37 ns	3.39 ns	2.26 -	3.43 ns

[1] Zero-tillage.
[2] Conventional practice. Values followed by - or ns are significantly lower or not significantly different as compared to the Conventional practice (highlighted in bold) following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.

3. Discussion

3.1. Companion crops

The cultivation of companion cropping in asparagus interrows is a novel strategy which has the potential to redress compaction and increase infiltration through remediation of soil structure and bio-drilling. However, the results of the current study indicate that three cycles of companion cropping with rye or mustard did not increase infiltration rates or decrease compaction compared with the Conventional practice or any other BMP treatment investigated.

These results conflict with the observations of other researchers. Research has shown that companion cropping can be very effective in mitigating soil compaction and increasing water infiltration rates (Alvarez et al., 2017; Clark, 2012; Dabney et al., 2001; Haruna et al., 2018; Howard, 2016; Storr et al., 2019). Available evidence suggests that roots of larger diameters have greater ability to penetrate compacted soils than fibrous roots (Clark et al., 2003; Materechera et al., 1991) and mustard and other tap-rooting species have been reported to have a high bio-drilling potential (Chen and Weil, 2010; Clark et al., 2003; Ren et al., 2019). However, rye has also been associated with reduced soil compaction (Ess et al., 1998) and increased infiltration rates (Kaspar et al., 2001), despite having a fibrous root system. The absence of a measurable improvement in infiltration rates for either of the companion crop treatments in this study may be due to the timing of infiltration tests (done in June/July) and the seasonality of companion

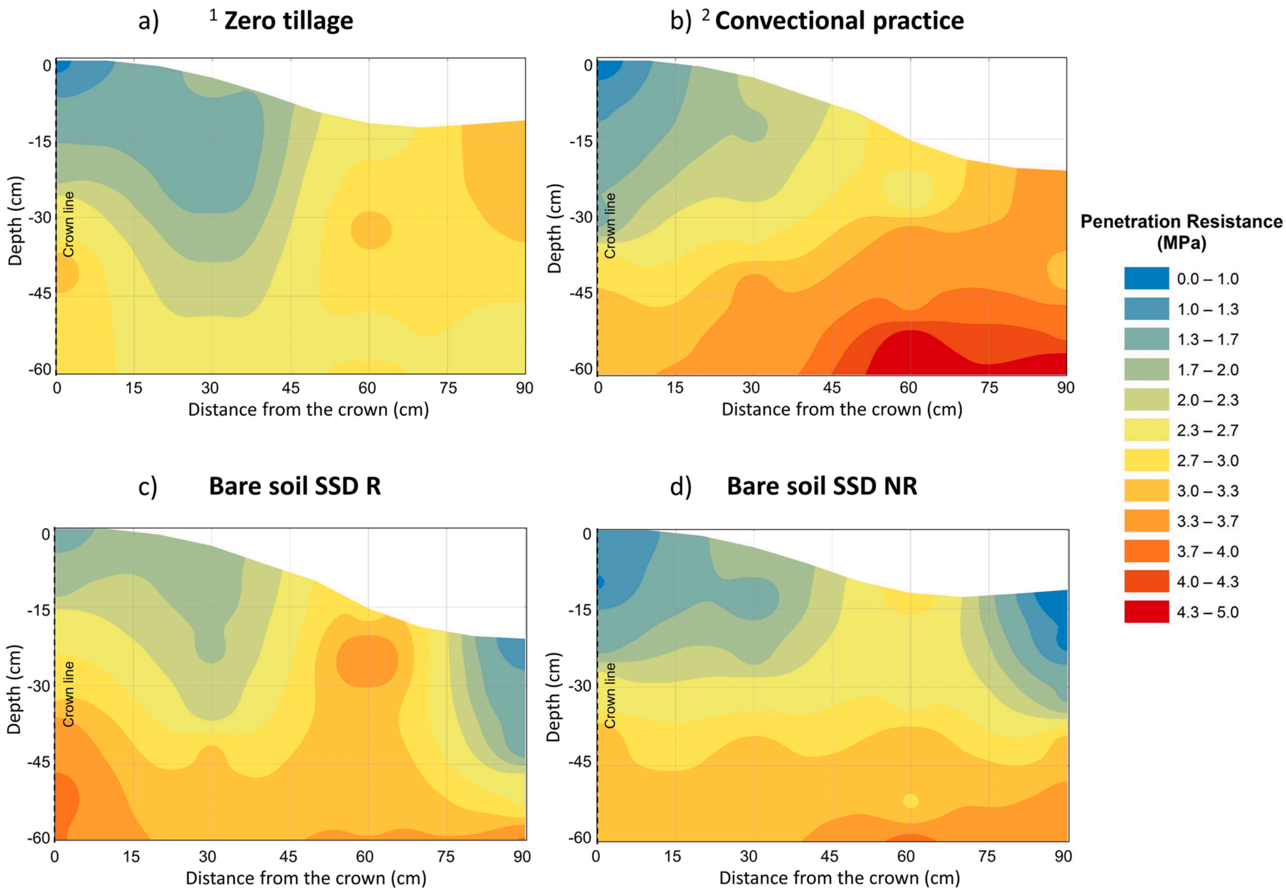

Fig. 6. 2020 bare soil treatments contour diagrams based on Penetration Resistance (MPa) transects determined tangential to the crown line (n = 4) using the inverse distance weighing (IDW) interpolation method. [1]Bare soil No-SSD NR; [2]Bare soil No-SSD R.

crops, which are broadcast in late August/early autumn and subsequently removed in March. Cresswell and Kirkegaard (1995) highlight that the effectiveness of companion crops will depend on the seasonal climate. Even though the effect of bio-drilling is supposedly effective in zero-tillage systems (Chen and Weil, 2010; Williams and Weil, 2004), overall, companion crop non-ridged (NR) treatments did not perform significantly better as compared to companion crop ridged (R) treatments. PR of all companion crops measured in the asparagus interrows (Figs. 3b, 4 b and 5 b) showed generally higher soil compaction in the 0-10 cm depth which are not significantly different from PR levels seen on the Conventional practice. Although bio-drilling effect of companion crops is believed to last even after the crop dies (Cresswell and Kirkegaard, 1995), the results of this study indicate that following an intensive harvest, companion crops were no longer effective in decreasing soil compaction or increasing water infiltration rates.

3.2. *Mulch and compost*

Composts and mulches have been reported to increase soil resilience (Thomas et al., 1996), decrease soil compaction (Arthur et al., 2011), improve water infiltration and water retention (Curtis and Claassen, 2009) and can be reportedly used as an alternative to companion crops (Brennan and Acosta-Martinez, 2017). In the current study, the 2018 and 2020 data showed significant increases in infiltration rates in all mulch and compost treatments as compared to the Conventional practice. The extremely high infiltration rates in 2018 and 2020 were likely caused by the SSD and the subsequent macro-pore formation. In 2019, the annual SSD application was omitted. Even so, a legacy effect was observed with the PAS 100 compost treatments having significantly higher infiltration rates compared to the Conventional practice. Most findings confirm that composts are associated with higher water retention and infiltration rates. Arthur et al. (2011) reported increased macro-porosity following incorporation of composts, Curtis and Claassen (2009) also found that compost-treated plots exhibited improved infiltration rates. Weindorf et al. (2006), however, attributed differences in infiltration rates to soil properties and climate, rather than to the use of compost alone.

Based on the presented PR data, straw mulch and compost were highly effective in reducing soil compaction in the interrows. Even in 2019, all compost and mulch treatments had significantly lower PR as compared to the Conventional practice to 0-20 cm depth. Furthermore, by 2020, the effect of compost and straw mulch on PR had extended to 0-40 cm depth as compared to the Conventional practice indicating that although SSD helps to loosen the soil surface and incorporate mulches, reduced soil compaction beyond the working depth of the subsoiler (winged tine operating to 0.25-0.30 m depth) can also be attributed to the compost and mulch applications. This corroborates previous research that compost application can significantly reduce soil compaction if incorporated into the soil (Muzzi et al., 1997; Olson et al., 2013; Weindorf et al., 2006). However, the longevity of the effect of compost is debated. Cogger (2005) found that the effect of compost was present even after five years. While, Arthur et al. (2011) suggest the effect of compost is not significant in the long-term. Olson et al. (2013) state that in cases where roots take advantage of the compost application, the effect can last long after decomposition of the compost itself. Several studies also found increased microbial and enzymatic activity under composts (Clark, 2012; Siczek and Frac, 2012; Tu et al., 2006) which can stimulate soil structural improvement. Due to reduced PR values beyond the depth of sub-soiling the results of this study indicate that the long-term use of mulches in combination with SSD in asparagus

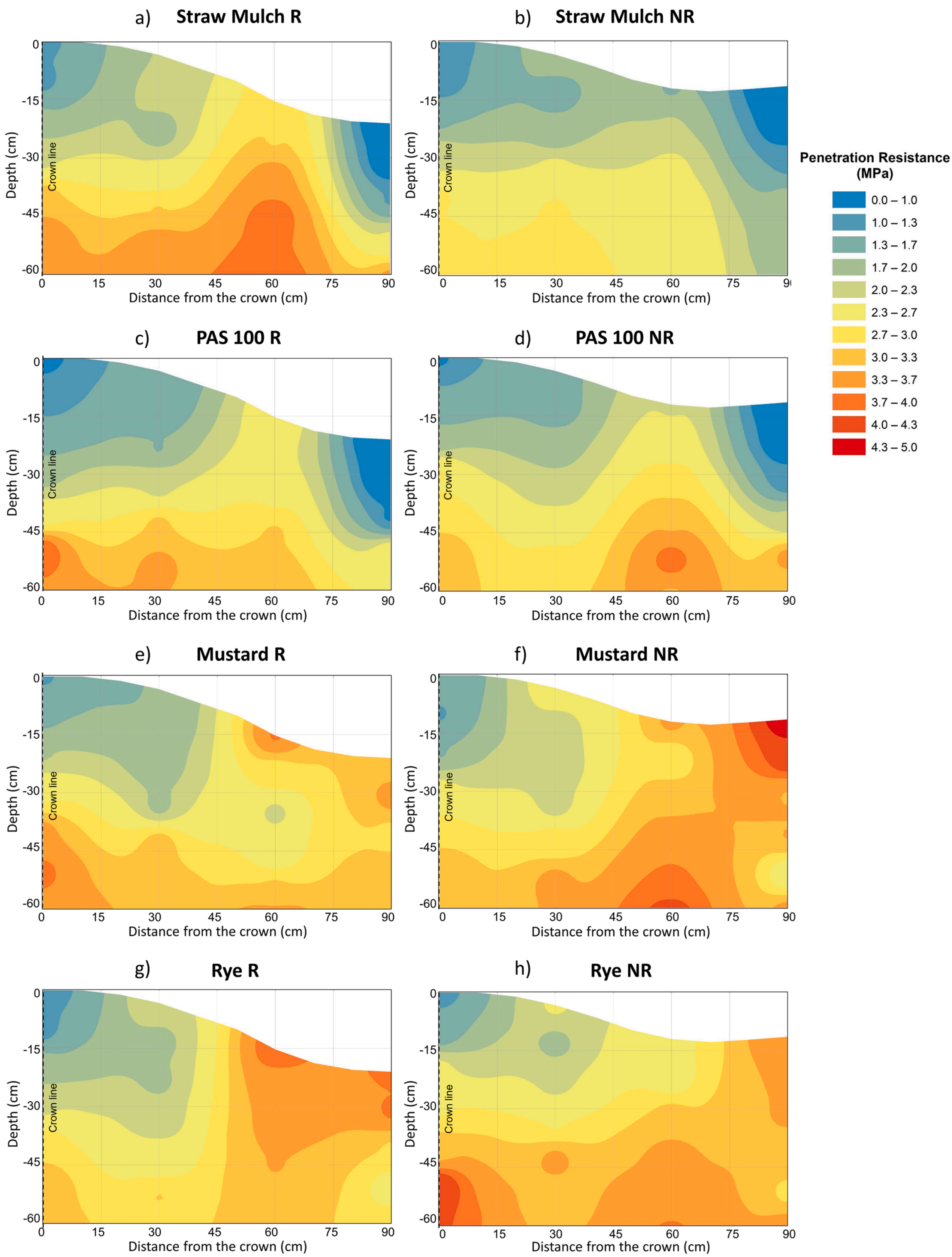

Fig. 7. 2020 mulch and companion crop treatments contour diagrams based on Penetration Resistance (MPa) determined at set positions from the crown line ($n = 4$) using the inverse distance weighing (IDW) interpolation method.

Table 5
Differences in 2018, 2019 and 2020 asparagus yield (kg ha $^{-1}$) between experimental treatments.

Treatment	Yield (kg ha^{-1})		
	2018	2019	2020
Zero-tillage	186 ^{c}	*163 ^{b}	124 ^{bcde}
Conventional practice	**163^{abc}**	**139^{a}**	**101 ^{ab}**
Bare soil SSD NR	174 ^{abc}	137 ^{a}	104 ^{abc}
Bare soil SSD R	150 ^{ab}	130 ^{a}	101 ^{ab}
Mustard NR	164 ^{abc}	146 ^{ab}	113 ^{abcde}
Mustard R	172 ^{abc}	145 ^{ab}	107 ^{abcd}
PAS 100 SSD NR	196 ^{c}	152 ^{ab}	*136 ^{e}
PAS 100 SSD R	182 ^{bc}	150 ^{ab}	*129 ^{de}
Rye NR	140 ^{a}	131 ^{a}	98.6 ^{a}
Rye R	180 ^{bc}	*165 ^{b}	*127 ^{cde}
Straw Mulch SSD NR	173 ^{abc}	137 ^{a}	110 ^{abcd}
Straw Mulch SSD R	187 ^{c}	150 ^{ab}	118 ^{abcde}

Within each column, values followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. *Treatments associated with significantly higher yield as compared with Conventional practice (highlighted in bold).

interrows can significantly reduce deep-seated compaction and, alleviate legacy soil compaction.

Although mulches in combination with SSD alleviate soil compaction in the interrows, their use in asparagus still needs to be approached with caution. Although asparagus can temporarily tolerate wet conditions, long term exposure carries the risks of increased pathogen incidence (in particular of *Stemphylium and Phytophthora*) (Saude et al., 2008). Mulches not only retain water in the deeper horizons, but also on the surface. The continuous long-term effect of higher soil moisture status on asparagus root systems and susceptibility to diseases requires further research.

3.3. *Trafficking*

Management choices in asparagus impact the number of times each interrow is trafficked and the level of compaction observed (Figs. 6 & 7). Research has shown that increasing the number of heavy machinery passes increases soil stress, often resulting in high levels of soil compaction. Pytka (2005) claims that greatest soil deformations are usually observed during the first two machinery passes. Balbuena et al. (2000) found that 10 passes significantly affected soil physical properties to 50 cm depth compared to a no-trafficked control. While Håkansson (1985) observed that four passes was sufficient to increase soil compaction to 60 cm depth. According to Duiker (2004), the first vehicular pass is responsible for up to 75% increase in compaction. Following the first ridging in 2017, mean profile PR of the interrows (90 cm distance from the crown line) on bare soil treatments increased on average by 47%. By comparison, at 60 cm distance from the crown line, the increase in PR was approximately 15%.

Since 2017, the Bare soil SSD R, PAS 100 R and straw mulch R interrows have experienced the highest numbers of heavy machinery passes (Table 6). However, following 10 tractor passes, all three treatments had significantly lower PR values compared to the Conventional practice, interrows which were trafficked seven times. The positive effect of composts and mulches combined with SSD was able to withstand a high number of tractor passes and critically, significantly reduced PR beyond the working depth of the subsoiler. Although Jourgholami et al. (2020) found that straw mulch was, unlike compost, most effective under minimal traffic intensity, in this study, no significant differences were observed between the effects of compost or straw mulch in combination with SSD and amount of traffic.

3.4. *Tillage*

Tillage is considered to be a useful approach to improve soil physical properties through promoting water infiltration and facilitating root penetration (Botta et al., 2019; Lipiec and Stępniewski, 1995; Niziolomski et al., 2016; Schneider et al., 2017). In bare soil treatments, SSD as expected, significantly improved infiltration and decreased soil PR of the interrows to the subsoiler operating depth of 25 cm depth. The very

Table 6
Number of interrow machinery passes per treatment including all passes associated with re-ridging, SSD and fern topping since the first re-ridging operation undertaken in March 2017.

Treatment	Total number of machinery passes since 2017
[1]Zero-tillage	3
[2]Conventional practice	7
Bare soil SSD NR	6
Bare soil SSD R	10
Mustard NR	3
Mustard R	7
PAS 100 NR	6
PAS 100 R	10
Rye NR	3
Rye R	7
Straw mulch NR	6
Straw mulch R	10

[1] Bare soil No-SSD NR.
[2] Bare soil No-SSD R.

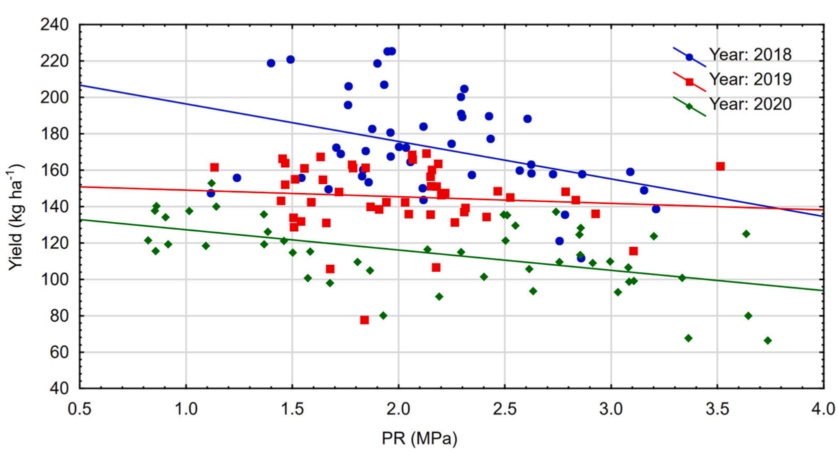

Fig. 8. Linear correlation between mean Penetration Resistance (MPa) in the centre of the asparagus interrow and asparagus yields (kg ha^{-1}). Points represent paired values obtained across all treatments. **2018**: $r^2 = 0.15$, r = -0.384, $p \leq 0.05$; **2019**: $r^2 = 0.01$, r = -0.097, p = NS; **2020**: $r^2 = 0.15$, r = -0.381, $p \leq 0.05$. NS = Non-significant at 95% confidence interval.

rapid infiltration rates observed on all plots subject to SSD in 2018 and 2020 were due to macro-pore formation. Bare soil SSD R did not have extremely high PR values (of up to 5.0 MPa) as observed in the Conventional practice, indicating that on bare soils, SSD was able to remediate compaction of the interrow.

Every field operation requiring use of heavy machinery poses a risk to the soil structure and while sub-soiling may reduce compaction levels, it does not improve soil structure (Duiker, 2004; Lipiec and Stępniewski, 1995). According to Loper et al. (2010), depending on the local climate and soils, SSD may not affect soil compaction. Cultivations under unsuitable conditions may have detrimental effects on soil structure (Håkansson, 1985). Alakukku et al. (2003) and Chamen et al. (2003) further added that in-furrow ploughing is the most serious source of deep-seated compaction. Håkansson (1985) claims that sub-soiling cannot fully alleviate deep-seated compaction and is also expensive, which was confirmed by our results in which SSD remediated soil compaction to the working depth of the subsoiler however not beyond. In 2019, contractor charges were on average £38.11 ha^{-1} for light cultivations and £59.58 ha^{-1} for sub-soiling (NAAC, 2019). This highlights the importance of carefully considering each sub-soiling operation with regards to possible risks, benefit, and economic cost.

In the past 20 years, many authors argued that zero-tillage or conservation tillage has even greater long-term benefits as compared to regular tillage (Botta et al., 2019; Dang et al., 2018; Duiker, 2004; Holland, 2004; Raper and Bergtold, 2007; Schneider et al., 2017; Wolz et al., 2018). The present study found that compaction of the zero-tillage treatment at subsoil depth (30-60 cm) in 2020 was similar to the pre-ridging legacy compaction levels measured 4 years earlier. Furthermore, there was no significant difference in the interrow compaction between the 2020 zero-tillage and 2017 post-ridging baseline suggesting that little to no additional compaction occurred between 2017 and 2020 on zero-tillage treatments. Also, as zero-tillage has many advantages over conventional tillage systems, such as reduced labour requirements, decreased surface runoff and erosion and higher biological activity granting soils greater resilience against physical pressure (Duiker, 2004; Thomas et al., 1996; Wolz et al., 2018), cultivation practices based on decreased soil disruption have a strong potential to prevent deep-seated compaction and increase soil resilience in UK asparagus systems.

3.5. *Impact of soil compaction on yields in asparagus*

Many studies have found that soil compaction results in yield reductions as observed on wheat, peanut and sunflower (Biberdzic et al., 2020; Botta et al., 2018; Hu et al., 2021; Shen et al., 2016; Whalley et al., 2006). Yield decrease has been linked to increased mechanical pressure (Alakukku and Elonen, 1994; Håkansson, 1994), reduced water availability (Whalley et al., 2006) and to reduction in root growth (Lipiec et al., 2003; Soane and van Ouwerkerk, 1995) affecting nutrient uptake (Singh et al., 2015) or a combination of all depending on weather conditions (Lipiec and Hatano, 2003). This study has demonstrated that compaction in asparagus interrows has a negative impact on asparagus yield. Inter annual variability in climate at the study site may in part explain why a relationship between soil PR and yield was found only in 2018 and in 2020.

4. Conclusions

The results of this 3-yr field trial indicate that the interrow application of PAS 100 compost and straw mulch in combination with SSD is an effective BMP to alleviate deep-seated compaction in asparagus interrows associated with inter and intra annual tillage, trafficking and harvesting operations as compared with Conventional practice. The PAS 100 compost in combination with SSD treatments are also associated with yield uplift. The high infiltration rates and surface cover associated with the mulch/SSD treatments has also been demonstrated to mitigate runoff and erosion (Niziolomski et al., 2002). In addition, the results indicate that Zero-tillage is a viable option to prevent soil compaction in asparagus interrows without negative impacts on yield. The effect of zero-tillage on soil erosion and run-off control from asparagus fields in the UK requires further research to assess the holistic benefits of this treatment.

Contrary to expectations, annual intercropping with either rye or mustard did not remediate interrow soil compaction. This may in large part be due to the seasonality of the companion crops, which are broadcast in late August/early autumn and removed the following March.

It is anticipated that the research outcomes from this study will feed directly into policy discussions associated with the future Environmental Land Management scheme (ELMS) in England, allowing asparagus growers to receive ‘financial reward in return for delivering environmental benefits’.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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