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Impacts of long-term application of best management practices on yields and root carbohydrate content in asparagus (*Asparagus officinalis*) (UK)

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ABSTRACT

Yield physiology of asparagus (*Asparagus officinalis* L.) is strongly influenced by biotic factors such as crown and root rot caused by *Fusarium spp.* and by abiotic conditions such as precipitation or temperatures, duration of each harvest, and field management practices. Asparagus yields are linked to the availability of soluble carbohydrates (CHO) in the storage root system which is considered a key factor in asparagus productivity. The aim of this study was to quantify the impacts of the long-term application of a range of potential Best Management Practices (BMPs) on yield and storage root carbohydrate content in green asparagus in a long-term field trial. The trial was established in 2016 with the asparagus 'Gijnlim' variety. Commercial yields were collected in 2018, 2019 and 2020. Root carbohydrate content was determined in 2019 and 2020. BMPs included (1) companion crops - Rye (*Secale cereale L.*), Mustard (*Sinapis alba L.*), (2) interrow surface mulch applications of either straw mulch or PAS 100 compost (Publicly available specification) in combination with shallow soil disturbance (SSD), (3) the conventional practice and modifications of the conventional tillage practice by applying SSD or not applying SSD and (4) a zero-tillage option. Annual re-ridging (R) and not ridging (NR) were applied to BMP options 1–3. SSD had no significant impact on asparagus yields while annual re-ridging negatively affected total yields of treatments with bare soil interrows, which were managed without SSD. Conventional practice was associated with a 22% yield reduction and ~€4250 ha^{-1} annual loss in potential revenue as compared to the Zero-tillage treatment. Companion cropping with mustard did not have a significant impact on asparagus yields. Rye without annual re-ridging was however associated with yield reductions of > 20% as compared to the Conventional practice. PAS 100 Compost applied in asparagus interrows (at 25 t ha^{-1} per year) in combination with SSD without annual re-ridging resulted in improvements to yields of 20%, 10% and 34% in 2018, 2019 and 2020, respectively, as compared to the Conventional practice. No correlation was observed between storage root soluble carbohydrate content and asparagus yields. The results of this study confirmed that asparagus yield, and thus total farm income can be significantly improved through implementation of several of the BMPs investigated.

1. Introduction

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). Asparagus yield and plant growth is 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 a key factor determining asparagus yield performance which was officially recognised by the *AspireNZ* decision support system of Wilson et al. (2002), which provided growers with an interpretation guide of root CHO content to facilitate better crop management decisions. There is significant variation in asparagus storage root CHO levels between plants depending on the size of the root system (Wilson et al., 2008). Target pre-harvest CHO content of small root systems should reach 550 mg g^{-1} while for large root systems the target content value is 450 mg g^{-1}.

Abbreviations: BMP, best management practice; SSD, shallow soil disturbance; No-SSD, no shallow soil disturbance; R, re-ridging; NR, non-ridging; PAS, publicly available specification; CZL, crown zero line.

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Furthermore, CHO stored in asparagus roots is subject to fluctuations throughout the annual growth cycle (Bhowmik et al., 2001) and is strongly affected by air and soil temperatures (Alam et al., 1998). 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., 2002). Consequently, the ability of asparagus plants to accumulate and translocate adequate CHO is crucial for high spear yields in both the current and subsequent harvests.

Previous research has demonstrated that root damage associated with tillage operations can have a major negative impact on asparagus stand longevity and productivity (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). In contrast, it has been demonstrated that Zero-tillage is associated with significant increases in marketable yield of asparagus spears compared to tilled asparagus (Wilcox-Lee and Drost, 1991). Tillage operations such as sub-soiling of interrow wheelings for runoff and erosion control (Niziolomski et al., 2020) are thought to pose a high risk of damage to asparagus root systems if roots grow into tillage disturbance zones (Niziolomski et al., 2016). While tillage can reduce the size of the root CHO storage, it can also create wound pathways for pathogens such as *Phytophthora asparagi* (Falloon and Grogan, 1991) and *Fusarium oxysporum f. sp. Asparagi* (Elmer, 2015). In intensive commercial systems the expected economic production of asparagus should range between 10 and 20 years. However, chronic disease incidence and 'asparagus decline' can limit the commercial production period to only 5–10 years (Elmer et al., 1996) and result in significant economic losses to the grower. Between 2010 and 2019, the asparagus cultivation area in the UK increased by 40% and the value of home marketed production increased by 27% (Defra, 2020) marking a significant expansion in UK asparagus production. In the UK, economic losses due to 'asparagus decline' were estimated to be > €18 million over a 10 year cultivation cycle (AHDB, 2017).

Re-ridging of green asparagus is the conventional practice adopted by British asparagus growers which is applied in order to promote the growth of spears meeting customer specifications, to raise asparagus beds for efficient manual harvest, and as a means of conveying excess rainfall off field. Subsoiling is also commonly used to alleviate interrow compaction as a result of intensive machinery and foot trafficking (Niziolomski et al., 2020, 2016). Consequently, conventional operations associated with tillage, harvest and agronomy of asparagus in the UK pose a risk to crop productivity and stand longevity. Companion cropping with rye is commonly practiced by North American asparagus growers for weed suppression and to provide soil protection from rainfall erosion (Brainard, 2012). Rye also promotes arbuscular mycorrhizal fungi (White and Weil, 2010), which is known to be in mutualistic symbiosis with asparagus (Pedersen et al., 1991). Rye has also 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 bio-drilling (Cresswell and Kirkegaard, 1995; Hudek et al., 2021) effect due to its tap-root system and for its bio-fumigation potential, which has been shown to reduce *Fusarium* levels (Cresswell and Kirkegaard, 1995; Sarwar et al., 1998).

While best management practices (BMPs) are widely used to reduce negative environmental impacts of agriculture in several crops such as winter cereals, potatoes and vines (Deasy et al., 2009; Gordon et al., 2011; Judit et al., 2011), there is a paucity of practical and effective BMPs for asparagus cropping systems. Furthermore, the impacts of potential BMPs on spear weight, spear quality, total yield and profitability have not been quantified. Long-term implications of annual re-ridging and subsoiling on asparagus yields and root CHO levels in UK asparagus also remain unknown. As management decisions in asparagus can have a significant impact on plant growth, root CHO content and yields (Wilson et al., 2002), alternative management practices need to be subject to thorough assessment prior to wider commercial application. The aim of this study was to critically evaluate the impacts of a range of potential BMPs on asparagus yields, yield quality, root CHO content and potential revenues, as compared with UK conventional practice.

2. Materials and methods

The field trial was undertaken 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 (represents 70% of UK field grown asparagus) were planted on 20–21st of April 2016 on the flat at an anticipated depth of 0.14 m, and 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.

2.1. Experimental design

The trial investigated a range of potential BMPs (Table 1); BMPs included (1) companion crops - Rye (Secale cereale *L.*), Mustard (*Sinapis alba L.*), (2) interrow surface mulch applications (straw mulch and PAS 100 compost (Publicly available specification for Composted Materials (WRAP, 2011)) in combination with shallow soil disturbance (SSD)), (3) the conventional practice and modifications of the conventional tillage practice by applying SSD or not applying SSD), and (4) a zero-tillage option. Annual re-ridging (R) and not ridging (NR) were applied to BMP options 1–3.

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. PAS 100 compost has a specified minimum quality to guarantee it safety however its content changes with each supplier and each batch. 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 6155 R 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, March 2020 and in June 2020 using a winged tine operating to 0.25–0.3 m depth to all mulch treatments 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 April 2020. Companion crops were broadcast for the first time on the 10th August 2017 at rates of 150 kg ha^{-1} and 19 kg ha^{-1} for Rye and Mustard, respectively. In the first year, the emergence

Table 1
Summary of the experimental treatments.

Treatment	Cover	Annual re-ridging (R)	Sub-soiling (SSD)
Conventional Practice	Bare soil	Ridged	No SSD
Zero Tillage	Bare soil	Non-ridged	No SSD
Bare soil SSD R	Bare soil	Ridged	SSD
Bare soil SSD NR	Bare soil	Non-ridged	SSD
Mustard R	Mustard	Ridged	No SSD
Mustard NR	Mustard	Non-ridged	No SSD
Rye R	Rye	Ridged	No SSD
Rye NR	Rye	Non-ridged	No SSD
Straw mulch SSD R	Straw mulch	Ridged	SSD
Straw mulch SSD NR	Straw mulch	Non-ridged	SSD
PAS 100 SSD R	Compost	Ridged	SSD
PAS 100 SSD NR	Compost	Non-ridged	SSD

NR = no annual re-ridging; R = annual re-ridging; SSD = shallow soil disturbance.

rate of the companion crops achieved sufficient ground cover of 70–75% (Morgan, 2005). However, for August 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 sown again in September 2018 and October 2019. Mulch treatments 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.

2.2. Sampling methodology

In 2018, 2019 and 2020, asparagus spears were harvested from all experimental plots. In 2018, spears were harvested between the 24th April to 21st May (28 days; 19 cuts). In 2019, the harvest season extended from 20th April to 17th June (59 days; 53 cuts) and in 2020, from 12th April to 22nd June (72 days; 65 cuts). The reduced number of cuts in 2018 reflects conventional practice for a 3 yr old asparagus stand. Spear count for 2018, 2019 and 2020 were determined from 7, 9 and 8 cuts, which were randomly distributed throughout the harvest period. Daily average individual spear weight per plot was determined by dividing the weight of all harvested spears by the total number of harvested spears on the same day for each treatment ($n = 4$ per treatment), as Eq. (1):

$$\mathbf{Averagespearweight(g)} = \frac{\mathbf{Total\ spear\ weight(g)}}{\mathbf{Total\ spear\ count}} \tag{1}$$

Additional spear quality indicators were measured in 2020. Spear diameter, head flowering and head curving were recorded on 8 cuts throughout the harvest period, in order to determine the impact of the BMPs on spear quality and potential revenue. Based on Bussell et al. (2000), a simplified (non-daily) recording method can be used to obtain marketable yield values with 90% accuracy. All harvested spears were of marketable quality. Spears were divided into three commercial size grades by spear thickness (<10 mm, 10–22 mm and >22 mm). Spears with flowering heads and curvature were also weighed and counted and were graded as a lower quality ‘Class II’ spears. Marketable yields were calculated as a sum of both Class I and Class II spears. Proportions (%) of high quality ‘Class I′ spears were obtained by subtracting Class II spears from the total mass of spears collected. In 2020, potential revenues were calculated by extrapolating spear quality data over the full harvest period to estimate the yield value, as (2):

$$\begin{aligned}\mathbf{Revenue}(€) = {} & [((\mathbf{totalspearweight} - (\mathbf{ClassII}(\%) \times \mathbf{totalspearweight}))\\ & \times \mathbf{ClassI}(€)] + [(\mathbf{ClassII}(\%) \times \mathbf{totalspearweight})\\ & \times \mathbf{ClassIIvalue}(€)]\end{aligned} \tag{2}$$

Asparagus storage roots for the determination of pre-harvest root soluble carbohydrate content (CHO) were obtained pre-harvest in March 2019 and in March 2020 when CHO content should be the peak, at 0.15–0.30 m depth from the crown zero line (CZL) following the root coring procedure of Drost and Wilson (2003). CHO values for 2018 were not collected as not all treatments had been applied at the time of root sampling. Root samples were collected using a handheld Eijkelkamp bi-partite root auger (internal diameter: 0.08 m, internal core depth: 0.15 m, volume: 754 cm^3). Roots of similar diameters were separated from soil, washed, and frozen at − 20°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 0–32% Sugar (Brix%). Brix values were converted to equivalent root CHO content using the linear regression equation of Wilson et al. (2008), as Eq. (3):

$$\mathbf{CHO\ (mg\ g^{-1}) = 21.1 \times Brix\% + 42.9} \tag{3}$$

2.3. Statistical analysis

Statistical analysis was undertaken using the TIBCO Statistica 13.3.0 analytics software. Significant differences in asparagus yield and spear weight were determined by analysis of variance (ANOVA) repeated measures and by *post-hoc* Fisher LSD analysis at 95% conf. level. Root CHO levels were analysed by one-way ANOVA and by *post-hoc* Fisher LSD analysis at 95% conf. level. Pearson correlation coefficients were calculated to determine the relationships between yield variables and root CHO.

3. 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, 2007) of Eardiston series soil association (Cranfield University, 2020; Hollis and Hodgson, 1974) with 77% sand, 11% silt and 12% clay composition. Soil parameters showed a 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).

3.1. Impact of BMPs on asparagus yield and spear weight

Due to the year-on-year variability in yields caused by changes in annual weather patterns, data from each year was analysed separately. In 2018, there were few significant differences in total seasonal yield (sum of all cuts) between treatments (Fig. 1). None of the BMP treatments were associated with total yield significantly different from the Conventional practice. However, the Bare soil SSD R treatment yield was significantly (19%) lower compared to Zero-tillage treatment. Rye NR treatment yields were 25%, 28%, 23%, 22% and 25% lower as compared to the Zero-tillage, PAS 100 NR, PAS 100 R, Rye R and Straw mulch R treatments, respectively. In contrast to re-ridging, SSD was not associated with any significant yield penalty.

The low yields observed for 2018 are due to the shorter harvest season (28 days and 19 cuts) as compared with the 2019 (59 days and 53 cuts) and 2020 (72 days and 65 cuts) seasons. The lower number of cuts in 2018 follows conventional practice for the first year of commercial harvest. The 2019 total yield data showed that the yields for the Zero-tillage and Rye R treatments were significantly higher as compared to the Conventional practice, Bare soil SSD NR, Bare soil SSD R, Rye NR and Straw Mulch NR (Fig. 1). Furthermore, re-ridging in the absence of SSD was found to have a negative impact on yield with Conventional practice associated with a 15% yield reduction as compared to Zero-tillage. Similar to 2018 the Rye NR treatment was associated with a 21% reduction in yield as compared to the Rye R treatment. Shallow soil disturbance for runoff and erosion control, was again not associated with any significant yield penalty.

Contrary to 2019, the 2020 yield results showed that Zero-tillage was not significantly different from the Conventional practice at 95% confidence interval (Fig. 1). At 90% confidence interval however, the 18% yield reduction associated with Conventional practice as compared to the Zero-tillage was significant. In contrast, both the PAS 100 R and NR treatments were in 2020 associated with 28–34%, 24–30%, 29–35% and 31–38% higher yields as compared to the Conventional practice, Bare soil SSD NR, Bare soil SSD R and Rye NR treatments, respectively. Except for Rye R and NR treatments, ridging had no significant effect on asparagus yields. It is of note that the 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. Yields from the Conventional practice were 12%, 15% and 18% lower as compared to the Zero-tillage treatment in 2018, 2019 and in 2020, respectively.

In addition to yield variation between various BMPs, significant differences were also observed in mean spear weight. As shown in Table 2, the mean weight of spears harvested from the Rye NR treatment

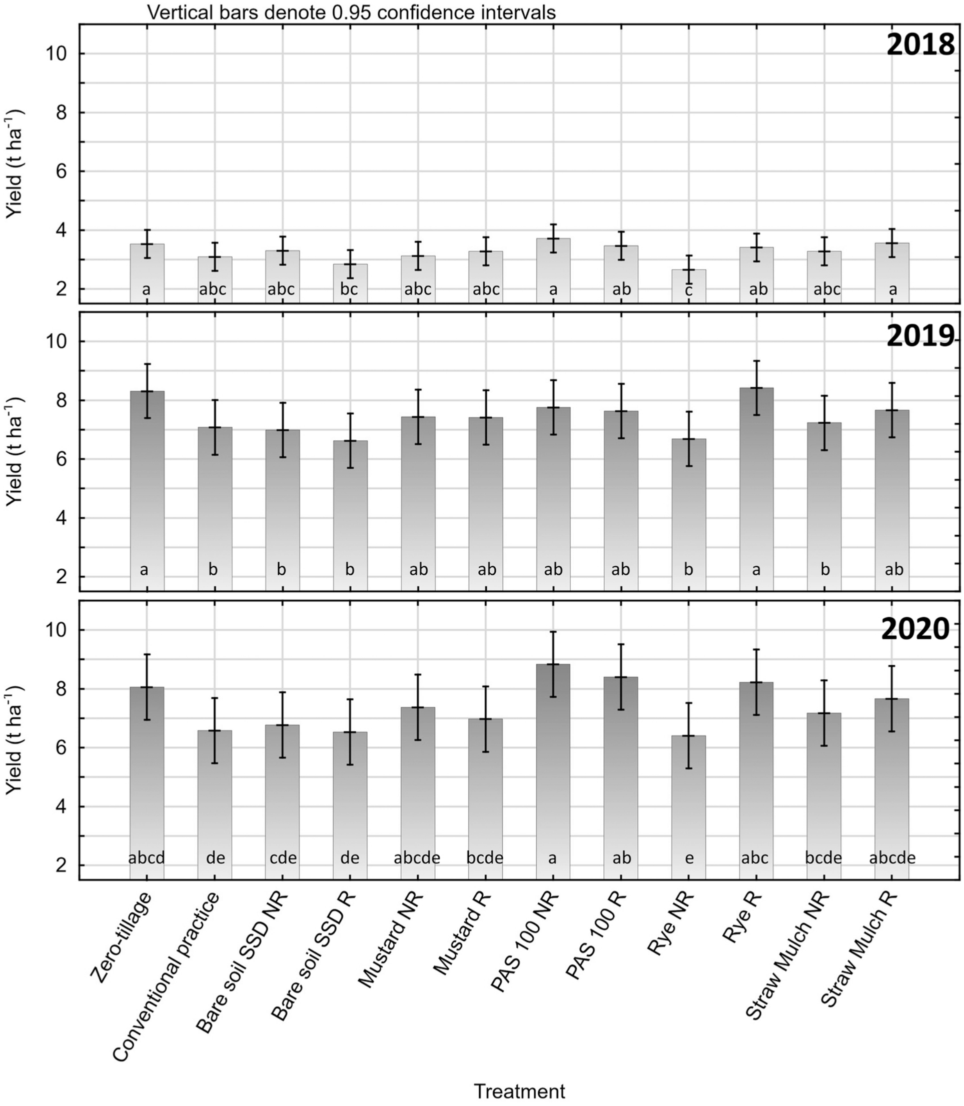

Fig. 1. Cumulative yields (t ha $^{-1}$) over three (2018–2020) full harvest seasons. 2018 harvest lasted 28 days (19 cuts); 2019 harvest lasted 59 days (53 cuts); 2020 harvest lasted 72 days (65 cuts). Bars followed by the same letter(s) are not significantly different following repeated measures ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval.
Modified from Mašková et al. (2021).

was significantly lower compared to multiple other treatments. Rye NR spears were significantly lighter as compared to spears from the PAS 100 NR, Rye R and Straw Mulch R/NR treatments by 14–17%, 13–19% and by 14–23% in 2018, 2019 and in 2020, respectively. Spears harvested from the Rye R treatment were on the other hand significantly heavier (16–23%) compared to spears harvested from the Rye NR treatment. Although mean spear weight was similar between the Zero-tillage and the Conventional practice in 2018 and in 2019, in 2020, Zero-tillage spears were 14% heavier compared to spears from the Conventional practice.

Correlation analysis indicated that spear size was significantly positively correlated with yields (Fig. 2). Between 2018 and 2020, the strength of the relationship, as indicated by the correlation coefficient r increased from r = 0.58 to r = 0.67. This finding suggests that production of large spears is the primary reason for higher recorded total yields. Furthermore, since 2018, mean spear size has decreased every year by a 22%.

3.2. *Impact of BMPs on asparagus storage root CHO content*

Across all treatments, 2019 and 2020 mean pre-harvest storage root CHO values ranged from 508 to 632 mg g^{-1} and 377 – 525 mg g^{-1}, respectively (Table 3). The difference between the mean 2019 and 2020 CHO values was significant. The 2019 mean CHO values of all BMP treatments were within the target range for pre-harvest root CHO content of 450–550 mg g^{-1} outlined by Wilson et al. (2008). In contrast, the 2020 mean CHO values of the Zero-tillage, Bare soil SSD NR, Mustard NR, PAS 100 R and Rye R treatments were associated with CHO values below this target range (Wilson et al., 2008) indicating inadequate CHO levels for optimum harvest. Nonetheless, these same treatments were not linked to reductions in yield. PAS 100 R and Rye R with lower CHO levels had yields significantly higher as compared to the Conventional practice which had adequate CHO levels of 506 mg g^{-1} (Table 3). No significant differences in root CHO values were observed between treatments in 2019. In 2020 however, the Zero-tillage treatment had significantly lower root CHO content compared to the Conventional practice and Straw Mulch R (Table 3). Across all treatments, mean storage root CHO content significantly decreased by 18% in 2020 as

Table 2
Differences in mean spear weight (g) between treatments for the 2018, 2019 and 2020 harvests.

Treatment	Average spear weight (g) ±SE					
	2018		2019		2020	
Zero-tillage	24.3 ^{ab}	±0.47	20.7 ^{a}	±0.70	16.5 ^{ab}	±0.50
Conventional practice	24.5 ^{ab}	±1.39	19.4 ^{a}	±1.28	14.2 ^{cde}	±0.60
Bare soil SSD NR	26.5 ^{a}	±0.98	18.6 ^{ab}	±1.09	14.6 ^{bcde}	±0.28
Bare soil SSD R	25.3 ^{ab}	±1.27	18.8 ^{ab}	±0.69	13.6 ^{de}	±0.80
Mustard NR	24.4 ^{ab}	±1.31	19.9 ^{a}	±0.63	15.3 ^{abcd}	±0.51
Mustard R	26.2 ^{a}	±1.55	19.0 ^{a}	±0.34	14.6 ^{bcde}	±0.25
PAS 100 NR	25.9 ^{a}	±1.10	19.4 ^{a}	±1.38	17.0 ^{a}	±0.86
PAS 100 R	25.3 ^{ab}	±0.71	18.8 ^{ab}	±0.40	15.1 ^{abcde}	±0.60
Rye NR	22.3 ^{b}	±0.90	16.9 ^{b}	±0.66	13.1 ^{e}	±0.68
Rye R	26.6 ^{a}	±2.51	20.7 ^{a}	±0.16	17.0 ^{a}	±0.81
Straw Mulch NR	26.7 ^{a}	±1.35	19.4 ^{a}	±0.68	15.2 ^{abcd}	±0.95
Straw Mulch R	26.2 ^{a}	±0.87	19.4 ^{a}	±1.01	16.0 ^{abc}	±0.97

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.

compared to 2019.

3.3. Impact of BMPs on spear quality, total yield and potential revenues in 2020

In general, spear quality is determined by spear diameter, spear weight, and by spear defects associated with physiological disorders such as head flowering, curvature, wilting or tip rot. Spear value is then determined by spear grade specifications. In the UK, there is no legally binding standard for asparagus spear classification. Those are 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'. Thin (<10 mm diameter) spears of good quality can be sold at a premium as fine or extra fine asparagus, this however barely covers the extra costs of harvesting, grading and packing. Thus, growers generally aim for the production of medium (10–22 mm diameter) or thick (>22 mm diameter) spears which are easier and less costly to harvest and pack.

In this study, a simplified yield value estimation was adopted which disregarded differences in spear diameter and focused on the overall spear quality which significantly affects total profits. Misshapen and deformed spears (open tips or curved heads) were classified as 'Class II' and priced at €1.77 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 €3.54 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, as shown in Table 4.

Across all treatments, the abundance of spear defects (head flowering and curving) fluctuated through the season. In the first week, approximately 21% of harvested spears were affected by head curving while in the last week, the proportion of spears affected decreased to only 5%. The percentage of spears with flowering heads however increased towards the end of the season, from 11% at the beginning of the harvest to

Table 3
Mean 2020 and 2019 storage root CHO values (mg g^{-1}). Roots were obtained from the 0.15-0.30 m depth at the crown zero line.

Treatment	CHO (mg g^{-1}) ±SE			
	2019		2020	
Zero-tillage	632^{a}	±18.6	*377 ^{b}	±89.4
Conventional practice	508^{a}	±74.4	506 ^{a}	±59.3
Bare soil SSD NR	517^{a}	±63.8	*418 ^{ab}	±63.4
Bare soil SSD R	555^{a}	±77.4	481 ^{ab}	±47.4
Mustard NR	525^{a}	±78.3	*426 ^{ab}	±79.4
Mustard R	592^{a}	±65.8	491 ^{ab}	±94.7
PAS 100 NR	596^{a}	±41.6	502 ^{ab}	±27.2
PAS 100 R	540^{a}	±27.7	*435 ^{ab}	±87.8
Rye NR	513^{a}	±50.3	484 ^{ab}	±27.7
Rye R	547^{a}	±23.9	*419 ^{ab}	±90.2
Straw Mulch NR	565^{a}	±31.0	477 ^{ab}	±62.5
Straw Mulch R	566^{a}	±84.0	525 ^{a}	±25.0

Within each column, values followed by the same letter(s) are not significantly different following One-Way ANOVA and *post-hoc* Fisher LSD analysis at 0.95 confidence interval. *Mean CHO values below the target range (450-550 mg g^{-1}) outlined by Wilson et al. (2008).

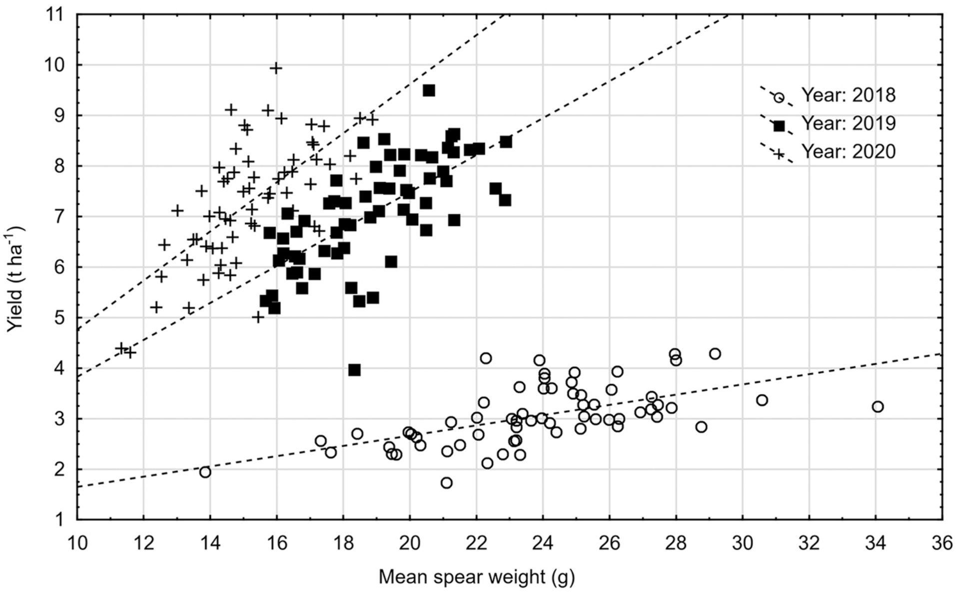

Fig. 2. Relationship between total asparagus yields (t ha^{-1}) and average spear weight (g) (n = 48). 2018: $r^2 = 0.34$, $r = 0.58$, * **$p < 0.001$; 2019: $r^2 = 0.44$, $r = 0.67$, * **$p < 0.001$; 2020: $r^2 = 0.45$, $r = 0.67$, * **$p < 0.001$.

Table 4

Impact of BMPs on spear diameter, spear defects and on potential revenues over the whole 2020 harvest season.

Treatment	Percentage (%) of marketable yield					Potential revenue (thousand € ha^{-1})
	Class I			Class II		
	< 10 mm (Thin)	10–22 mm (Medium)	> 22 mm (Thick)	Flowering	Curving	
Zero-tillage	17.1^{de}	82.8^{ab}	0.16^{ab}	23.2^{ab}	11.1^{a}	€ 24.1^{abc}
Conventional practice	24.5^{abc}	75.5^{cde}	0.00^{b}	26.1^{ab}	9.03^{abc}	€ 19.8^{cd}
Bare soil SSD NR	20.5^{bcde}	79.4^{abcd}	0.23^{ab}	27.8^{ab}	9.61^{ab}	€ 19.9^{cd}
Bare soil SSD R	25.7^{ab}	74.0^{de}	0.57^{a}	26.1^{ab}	6.22^{c}	€ 20.2^{cd}
Mustard NR	18.7^{cde}	81.2^{abc}	0.26^{ab}	23.5^{ab}	10.1^{ab}	€ 22.3^{abcd}
Mustard R	22.9^{abcd}	77.1^{bcde}	0.00^{b}	26.3^{ab}	8.07^{bc}	€ 20.9^{bcd}
PAS 100 NR	15.1^{e}	84.9^{a}	0.10^{ab}	25.1^{ab}	11.1^{a}	€ 25.7^{a}
PAS 100 R	19.4^{bcde}	80.4^{abcd}	0.34^{ab}	25.0^{ab}	8.48^{abc}	€ 25.1^{ab}
Rye NR	27.9^{a}	72.0^{e}	0.09^{ab}	30.3^{a}	7.59^{bc}	€ 19.4^{d}
Rye R	15.6^{e}	84.1^{a}	0.54^{a}	21.3^{b}	9.06^{ab}	€ 25.5^{ab}
Straw Mulch NR	16.0^{e}	84.0^{a}	0.00^{b}	21.4^{b}	9.57^{ab}	€ 21.7^{abcd}
Straw Mulch R	17.7^{de}	82.1^{abc}	0.53^{a}	20.8^{b}	8.46^{abc}	€ 23.4^{abcd}

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.

approximately 30% in the last week of harvest. While curving affected on average only 9% of harvested spears, flowering affected approximately 25% of all harvested spears.

Across all treatments, thick spears ($>$22 mm diameter) were rare and accounted for on average, 0.2% of spears, produced solely during the early season and in the first half of the main season. Medium spears (10–22 mm diameter) were most abundant and accounted for between 72.0% and 84.9% of all spears (Table 4). Rye NR was associated with a significantly lower percentage of medium spears (72%) as compared to multiple other treatments (Table 4). Zero-tillage, PAS 100 NR, Rye R, Straw Mulch NR were associated with significantly higher % of medium spears as compared to the Conventional practice. The Rye NR treatment also significantly higher numbers (28%) of thin spears ($<$10 mm) as compared to multiple other treatments. High overall production of thin spears was also associated with the Bare soil SSD R (26%), Conventional practice (25%) and Mustard R (23%). In contrast, PAS 100 NR, Rye R and Straw Mulch NR treatments produced only 15–16% of thin spears. In the Zero-tillage, thin spears accounted for 17% of harvested spears as compared to the Conventional practice where 25% of total spear production were classified as thin. Zero-tillage, PAS 100 NR, Rye R, Straw Mulch NR and Straw Mulch R produces significantly lower % of thin spears as compared to the Conventional practice.

Re-ridging was associated with significantly ($p < 0.05$) higher percentage of thin spears (22%) as compared to non-ridging (17%) across all treatments. Non-ridging was also associated with a significantly higher percentage of medium spears (82%) as compared to re-ridging (78%). Re-ridging was however also associated with significantly less spear curving defects (8%) as compared to non-ridging (10%). While ridging had a significant negative impact on spear quality in all treatments (except rye), SSD had no significant impact on any of the spear quality indicators. Spear flowering (%) was significantly positively correlated ($r^2 = 0.369$, $p < 0.005$) with higher production of thin spears indicating higher susceptibility of thin spears to this defect. In general, there were no significant differences in spear defects between BMP treatments and the Conventional practice (Table 4).

Potential revenue varied amongst treatments. The lowest potential revenues of between €19,000 – €20,000 ha^{-1} were associated with the Conventional practice, Bare soil SSD NR and Rye NR treatments (Table 4). Although the 21% increase in potential revenue associated with the Zero-tillage (€24,000 ha^{-1}) as compared to the Conventional practice (€19,800 ha^{-1}) was not statistically significant at 95% confidence interval, at 90% confidence, the difference between these two treatments was significant. Significantly higher potential revenues of €25,700, €25,100 and €25,500 ha^{-1} were associated with the PAS 100 NR, PAS 100 R and Rye R treatments as compared to the Conventional practice, Bare soil SSD NR, Bare soil SSD R and Rye NR (Table 4). Critically, potential revenues associated with the PAS 100 treatments showed a 21–23% gain in potential value of the harvest as compared to the Conventional practice.

4. Discussion

Yields recorded during three consecutive harvest seasons showed that average total yields were 3.3 t ha^{-1} in 2018, 7.4 t ha^{-1} in 2019 and 7.4 t ha^{-1} in 2020. The low total yield in 2018 was due to a shortened harvest period which is a normal practice for the first harvest of green asparagus. The remaining 2019 and 2020 yields were slightly higher as compared to values of 5.1–5.3 t ha^{-1} reported by Paschold et al. (2001) and very similar to a 7.06 t ha^{-1} average for the third harvest season recorded by Rodkiewicz (2011).

Research conducted over the past 50 years has shown that tillage operations can have a major negative impact on asparagus root growth and yields through damage to the root system which reduces the size of the root engine (Drost and Wilcox-Lee, 2000; Drost and Wilson, 2003; Putnam, 1972; Reijmerink, 1973; Wilcox-Lee and Drost, 1991). In contrast, this study indicates that when asparagus is grown on 1.83 m centres SSD applied using a winged tine operating to 0.25–0.3 m depth had no significant impact on asparagus yields or CHO content in storage roots across both mulch and bare soil treatments. Conversely, in line with the prevailing paradigm, annual re-ridging negatively affected yields of non-SSD Bare soil treatments.

Yields of the Conventional practice were lower as compared to the Zero-tillage (by approximately 12–18%) which can be attributed to the effect of re-ridging of the Conventional practice. These rates were comparable to findings of Wilcox-Lee and Drost (1991) who observed tilled asparagus (cultivar '*Centennial*') marketable yields decreased over a 4 year period from 12% to 51% as compared to a no-till treatment. Mean spear weight in 2018 and 2019 did not differ significantly between the Zero tillage and Conventional practice. In 2020 however, the mean spear weight from the Conventional practice treatment was significantly lower (14%) as compared to Zero-tillage. Spear weight is an important factor determining yield profits. As the asparagus spears are sold by weight, growers generally prefer spears of 10–22 mm diameter for reduced grading and packing costs as compared to $<$ 10 mm diameter spears. Larger diameter spears can also be linked to plant vigour (Dufault and Ward, 2005). Spear size directly impacts the potential profit margin for Zero-tillage with the cost of production also lower due to the absence of costs associated with tillage. In 2020, Conventional practice produced an abundance of thin ($<$10 mm diameter) spears which formed approximately 25% of the total spear production. In comparison, Zero-tillage was associated with 17% thin spears. This resulted in a €4250 ha^{-1} increase in potential revenues from asparagus alone as compared with the Conventional practice.

Results from the companion crop treatments were mixed. Yield and mean spear weight from both Mustard R and Mustard NR were not significantly different from the Conventional practice during the study period (2018–2020). These results correspond with the findings of Ngouajio et al. (2014) who found that a mixture of Brassicas (radish (*Raphanus sativus* L.) and brown mustard (*Brassica juncea* L.) applied as a companion crop had no impact on asparagus yields.

While re-ridging had no significant impact on asparagus yield of treatments seeded with mustard, it significantly impacted yields, spear weights, spear quality and potential revenues of the rye companion crop treatments. In all years, annual re-ridging in the rye companion crop treatments resulted in significant increases in asparagus yields as compared to the non-ridged (NR) rye treatment. This was in large part due to the significantly 19% lower spear weight associated with the Rye NR (17.1 g) as compared to Rye R (21.1 g) treatment. As a result, Rye NR was linked to a significantly higher production of thin and Class II spears which led to a €6100 ha^{-1} decrease in potential revenues as compared to Rye R.

Rye was sown for the first time in August 2017 and sprayed off in February 2018. In the Rye R treatment, following re-ridging in April 2018, rye roots and plant residues were lifted from the interrows and incorporated into the soil above asparagus crown. In the Rye NR treatment however, these residues remained in the interrows undisturbed, potentially increasing the duration during which the rye root biomass could release allelochemicals including benzoxazinone, phenolic acids, beta-hydroxybutyric acid and hydroxamic acids (Macías et al., 2014; Schulz et al., 2013). Allelochemicals have a potential to reduce plant vigour and although there are no reports of plant competition between asparagus and other crops, significant yield reductions of Rye NR treatments may suggest the presence of allelopathy.

These results contradict observations of North American growers who successfully grow asparagus on flat beds without tillage and with rye as a companion crop. Companion crops are sown when fern is fully developed thus rye had no impact on fern development. Rye could compete with mature asparagus fern for water or nutrients thus affect yields and CHO assimilation (Brainard, 2012; Brainard et al., 2012). This impact would however be expected to be similar for both Rye R and Rye NR treatments. Root CHO values of Rye treatments were also not significantly different compared to the Conventional practice although it can be argued that total root CHO content would change based on the size of the 'root engine'. Nevertheless, in 2019 and in 2020, Rye R treatments were associated with significantly higher mean yields, mean spear weights and potential revenues as compared to the Conventional practice. The period between ridging and crop response was also extremely short as significant yield reduction from Rye NR was already observed in 2018 which was only nine months post the 2017 companion crop treatment application. The time period between ridging and the start of the harvest always ranged between 7 and 50 days. Brainard et al. (2012) however observed that cereal rye broadcast at 188 kg ha^{-1} and rotavated immediately after harvest in late June had no effect on asparagus yields. It is important to note that from a management perspective, if rye is grown as a companion crop and soil conditions prohibit re-ridging in the spring prior to harvest, the growers risk a significant yield penalty of *circa* 20% as compared with the Conventional practice.

Annual re-ridging had no impact on asparagus yields under interrow applications of PAS 100 compost and Straw Mulch. Thus, potential yields loss associated with annual re-ridging and SSD may have been offset by the benefits of Straw Mulch and PAS 100 compost application. Although yields from Straw Mulch treatment were not significantly higher as compared to the Conventional practice, the PAS 100 compost treatments were in 2020 associated with a significant yield uplift as compared to the Conventional practice. A similar finding was observed by Ngouajio et al. (2014) who found that dairy compost significantly improved asparagus yield and numbers of spears as compared to the control with no soil amendment. PAS 100 yield uplift may be in part due to the additional macro/micronutrient load and/or a stimulation of soil microbiology associated with compost addition. Straw mulch and compost were applied each year less than a month prior to the onset of harvest. Composts have been repeatedly linked to increased soil temperatures (Deguchi et al., 2009; Naeini and Cook, 2000) while straw mulch is often associated with lower, and less fluctuating soil temperatures as compared to bare soils (Gaur and Mukherjee, 1980; Yordanova, 2017). The increase of soil temperature under composts could therefore play a role in enhanced yields as spear production in asparagus is known to be strongly depend on soil temperature (Bouwkamp and McCully, 1975; Culpepper and Moon, 1939; Gąsecka et al., 2013). Ultimately, further research needs to be undertaken in order to gain a better understanding of mechanisms behind yield uplift associated with the interrow application of PAS 100 compost.

This study demonstrates that mean asparagus yields are strongly related to spear weight as treatments associated with higher yields also produced a high percentage of medium Class I 10–22 mm diameter spears while poorly yielding treatments produced a high percentage of thinner < 10 mm diameter lighter spears. In asparagus, both yield volume and quality decline after multiple years of consecutive production. Based on Elmer et al. (1996), plants usually do not show any changes before their third production year suggesting that from 2020 onwards, measurable differences between treatments should be even more pronounced. Asparagus decline symptoms include growth of thinner spears of lower quality and eventually lead to death of the crown (Elmer et al., 1996; Schofield, 1991). Noperi-Mosqueda et al. (2020) observed that spears from fields with asparagus decline weighed 22% less than spears from fields without decline. Spear weight and quality is however one of the key factors determining price. Consequently, asparagus decline leads to decreased marketable spear quality, plant productivity and plant density, ultimately causing unsustainable economic losses (Elmer, 2018; Noperi-Mosqueda et al., 2020).

Apart from the asparagus decline, other factors such as root CHO content, water stress, air and soil temperature can have a strong impact on the sizes of spears, and hence on commercial spear value (Bouwkamp and McCully, 1975; Haynes, 1987; Paschold et al., 2002). Multiple studies have found that summer irrigation or precipitation significantly increase asparagus yields and spear sizes in the following year (Hartmann, 1981; Sterrett et al., 2019). Drost (1999) reported that in a four-year experiment, marketable yields of irrigated asparagus were on average 21–26% higher as compared to non-irrigated treatments. As larger diameter spears are priced higher due to lower costs associated with harvesting and packing (Dufault and Ward, 2005; Paschold et al., 2002; Watanabe et al., 2018), growers generally aim for higher production of larger diameter spears. Results from the current field trial showed that spear weight and quality can be significantly improved by adoption of the Zero-tillage, PAS 100 and Straw Mulch NR with SSD and Rye R BMP treatments. Although other studies (Wilcox-Lee and Drost, 1991) reported a decrease in marketable yields following tillage, in 2020, tillage (either ridging or SSD) of asparagus with bare interrows had a significant impact on total marketable value of the harvest and revealed losses in potential revenue as compared to Zero-tillage. Positive relationship between head flowering and production of thin spears suggests that high numbers of thin spears further decrease overall yield quality and total revenues. Production of spears with flowering heads increases in hot periods, usually late in the season (AHDB, 2014) which corresponds with the observations of this study where head flowering increased towards the end of the harvest and accounted for 30% of all harvested spears compared to 9% at the beginning of the harvest. In contrast, across all treatments, spear curving was dominant at the start of the harvest (21%) and decreased to 5% in the last week of harvest. Literature suggests that curving of spears occurs during periods of rapid growth when water losses from tips of spears surpass speed of moisture supply and can even occur in adequate soil moisture conditions (AHDB, 2014). Critically, spears with defects are classified as Class II which has a major impact on spear value.

5. Conclusions

The main outcome from this research is that green asparagus spear quality, yields and therefore potential revenues can be significantly increased through the adoption of several of the BMPs investigated. Annual tillage has been reported previously to have a negative impact on green asparagus yields. However, the results of study the impact of tillage on yield can have both positive or negative impacts on yield depending on the BMP applied. The significantly lower yields in the Conventional practice and BMP treatments with bare soil interrows without SSD confirm the previously reported impact of annual tillage on yield. However, and critically, in this study SSD applied to interrow wheelings in bare soil and mulch-based BMPs resulted had no significant impact on green asparagus yields. Annual re-ridging of asparagus planted with an interrow rye companion crop was associated with significantly higher yields as compared to the Conventional practice. Conversely, non-ridging of rye carries the risk of a~ 20% yield penalty. Growers need to be confident that they can re-ridge in spring prior to harvesting if rye is grown as a companion crop for overwinter runoff and erosion control. The application of PAS 100 compost in asparagus interrows in combination with SSD resulted in significant and consistent yield improvements which were not significantly affected by annual re-ridging. Due to the significantly lower yield associated with Conventional practice as compared with the BMPs investigated in this study, it is strongly recommended that British green asparagus growers transition towards adopted of the BMPs. Although significant and financially meaningful benefits of adopting the BMPs were observed after 3 years of commercial harvests, observations need to continue in order to assess the long-term impact of BMPs on soil health and the effect that this has preventing or delaying the onset and rate of asparagus decline.

CRediT authorship contribution statement

Lucie Maskova: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Robert W. Simmons:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Lynda K. Deeks:** Conceptualization, Investigation, Writing – review & editing, Supervision. **Sarah De Bates:** Methodology, Investigation, Writing – review & editing, Supervision. **Daniel T. Drost:** Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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