Project title:	The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems (PF-*Hort*)
Project number:	Review conducted as part of AHDB Horticulture project CP107c
Project leaders:	Dr Lizzie Sagoo & Dr Paul Newell Price, RSK ADAS Ltd.
Report:	Survey of soil structure and soil management in horticulture
Previous report:	Nil
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Location of project:	Grower sites around the country
Industry Representative:	Andy Richardson, Allium & Brassica Centre
Date project commenced:	01/04/2015

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

CONTENTS

GROWER SUMMARY

Headline

- A survey of 75 fields covering a range of crop types identified soil compaction in 70% of annual crops and 60% of perennial crops and a clear need to improve assessment and management of soil structure for greater efficiency and profitability of horticultural crop production.

Background

Soil compaction was the principal issue identified by the AHDB Horticulture panel consulted in AHDB Horticulture project CP107 '*A gap analysis of soil management research and knowledge transfer in horticulture to inform future research programmes'*. Developing and facilitating industry uptake of good crop rotation and soil management practice forms a key part of the AHDB Horticulture strategic plan. There was plenty of anecdotal evidence on frequent cultivation and late autumn and winter harvesting resulting in soil compaction, but very little data on the actual condition of soils within horticultural systems. This project provided the opportunity to carry out a structured and systematic assessment of soil physical properties under horticultural production and to capture typical soil management practices across a number of sectors.

Summary

The majority of topsoils under annual and perennial cropping were in moderate condition and improved as a result of cultivation practices. However, in some circumstances (e.g. when soil was 'wet'), cultivation either had no effect or resulted in a deterioration in soil structure. The majority of annual cropping sites (63%) had a well-developed tillage pan before cultivation and fewer than half had a pan after planting. Compacted topsoil layers and signs of subsoil compaction were also common in perennial crops, although there was no clear pattern relating the age of perennial crops and soil condition. Earthworm numbers were generally low in both annual and perennial crops, although numbers tended to be higher in fields with abundant crop residue and in apple orchards.

Bulk density (BD) values indicated that porosity was low in many annual cropping subsoils. However, the implications for system efficiency and productivity are unclear and further work is needed to determine the best management option in each situation, as the optimal response may differ according to soil type, crop type and field conditions.

Growers acknowledged that soil structural condition is an issue for crop production and used a variety of methods to improve soils, including the use of cover crops and organic amendments.

Ploughing was commonly used to address shallow compaction and subsoiling was widespread, although the latter was not always closely related to a clear need to alleviate compaction. Equally, in some situations deep cultivation was not carried out when a tillage pan was present.

Many growers visually assessed soils and adjusted subsoiling depth based on their observations. Nevertheless a significant proportion of growers were keen to learn more about visual assessment of soil structure and how to link this to management options.

The results of the soil survey will provide a useful tool for dissemination, discussion and knowledge exchange that will help stimulate interest and develop awareness and industry expertise in soil management practices.

Financial Benefits

Poor soil structure can impact on the efficiency and productivity of horticulture systems. Conversely, better structured soils increase opportunities to access land (improved timeliness); reduce irrigation and tillage costs; and can improve the evenness and overall yield of commercial crops.

Soil compaction typically reduces yield by around 20%, with gross margins in some horticulture crops reduced by 15-30% or by £600-£1,200/ha (Balshaw *et al*., 2014; Hallett *et al*., 2012; Nix, 2015). In some circumstances soil degradation in any single year can result in the complete loss of yield.

Soil compaction can also result in higher weed/disease pressure; increased fuel use (50%+; Mouazen and Palmqvist, 2015); as well as poor drainage and poor rooting, thereby increasing frequency of irrigation and overall irrigation costs. Typical overall operating costs for 25 mm of irrigation are £85-£155/ha (Nix, 2015).

Action Points

Guidance to assess the structural condition of soils is available for growers on the AHDB Greatsoils website. Growers are advised to access this guidance and use it to select management strategies that are tailored to their specific situation. A broad range of factors should be considered including farm type, soil type, crop rotation, soil condition, ease of access to capital investment and availability of machinery.

An initial appraisal of soil structural condition and how it relates to current soil management practices is important, to identify relevant, practical measures that will either maintain a good situation or improve poorly structured soil over time.

SCIENCE SECTION

Introduction

Optimum soil and nutrient management is key to enhancing the productivity, profitability and sustainability of horticultural production. Poor soil structure can be a key factor limiting crop production in cultivated systems (Hallet et al., 2012; Marks & Soane, 1987). Developing and facilitating industry uptake of good crop rotation and soil management practice is a key part of the AHDB Horticulture strategic plan.

Soil compaction was the principal issue identified by the AHDB Horticulture panel consulted in AHDB Horticulture project CP107. Intensive or frequent cultivations can be deleterious to soil structure as a result of the consequent oxidation of organic matter and weakening of soil structure. Soil compaction occurs when soil particles are compressed, reducing the spaces (pores) between them. Compacted soil contains few large pores, which are the main channels for water movement in soil, and consequently has a reduced rate of both water infiltration and drainage (DeJong-Hughes et al., 2001). There is a strong link between soil type, land use practices and soil compaction. Soils can bind more effectively to resist deformation through the release of root and fungal exudates and there is a general positive relationship between soil resilience and soil organic matter content (Barre and Hallet, 2009; Gregory et al., 2009). Compaction also reduces the air content of soils, reducing biological activity including plant growth and faunal activity and restricts root growth, water storage capacity, fertility and stability. In most cases, measures to alleviate or prevent compaction would be expected to increase crop production and enhance other soil functions, but there are clear conflicts between the need to establish and harvest crops in restricted timing windows and the need to avoid compaction. Wet seasons such as the summer/autumn of 2012 and the winters of 2012/13 and 2013/14 present significant challenges for compaction impacts on soils, as the need to maintain continuity of supply and meet demands for extended season requirements from retailers can lead to crops being harvested during unfavourable weather and soil conditions (Balshaw et al., 2013).

Objectives

To assess the structural condition of horticultural soils and establish baseline information on typical soil management practices across a range of horticultural crops (perennial, biennial and annual).

Materials and methods

The survey was stratified by crop type (perennial, biennial and annual); and for annual crops was carried out twice (pre- and post-planting/drilling) in 47 fields across 31 holdings. For the perennial crops (e.g. asparagus, apples) measurements were carried out prior to establishment at nine sites and in the growing crop at nineteen sites (**Table 1.** Soil structure survey stratification). The soil structure survey sites were distributed from Cornwall in south west England to Perthshire in eastern Scotland (Figure 1). The pre-planting field measurements were carried out between late September 2015 and March 2016 when soils were 'moist' or close to field capacity. The post- planting field measurements were mostly carried out during the late winter to early spring 2016, with the final measurements on late established winter brassicas in Cornwall carried out in autumn 2016. Pre- and post-planting measurements were taken under comparable conditions.

Table 1. Soil structure survey stratification

Crop	**Number of fields**	**Pre-planting**	**Post-planting**
Brassicas	15	15	15
Carrots/Parsnips	9	9	9
Onions	5	5	5
Leeks	5	5	5
Lettuce	10	10	10
Vining peas	3	3	3
Asparagus	6	2	4
Blackcurrants	6	2	4
Raspberries	4	1	3
Apples	6	2	4
Narcissus/cut flowers	6	2	4
Total	**75**	**56**	**66**

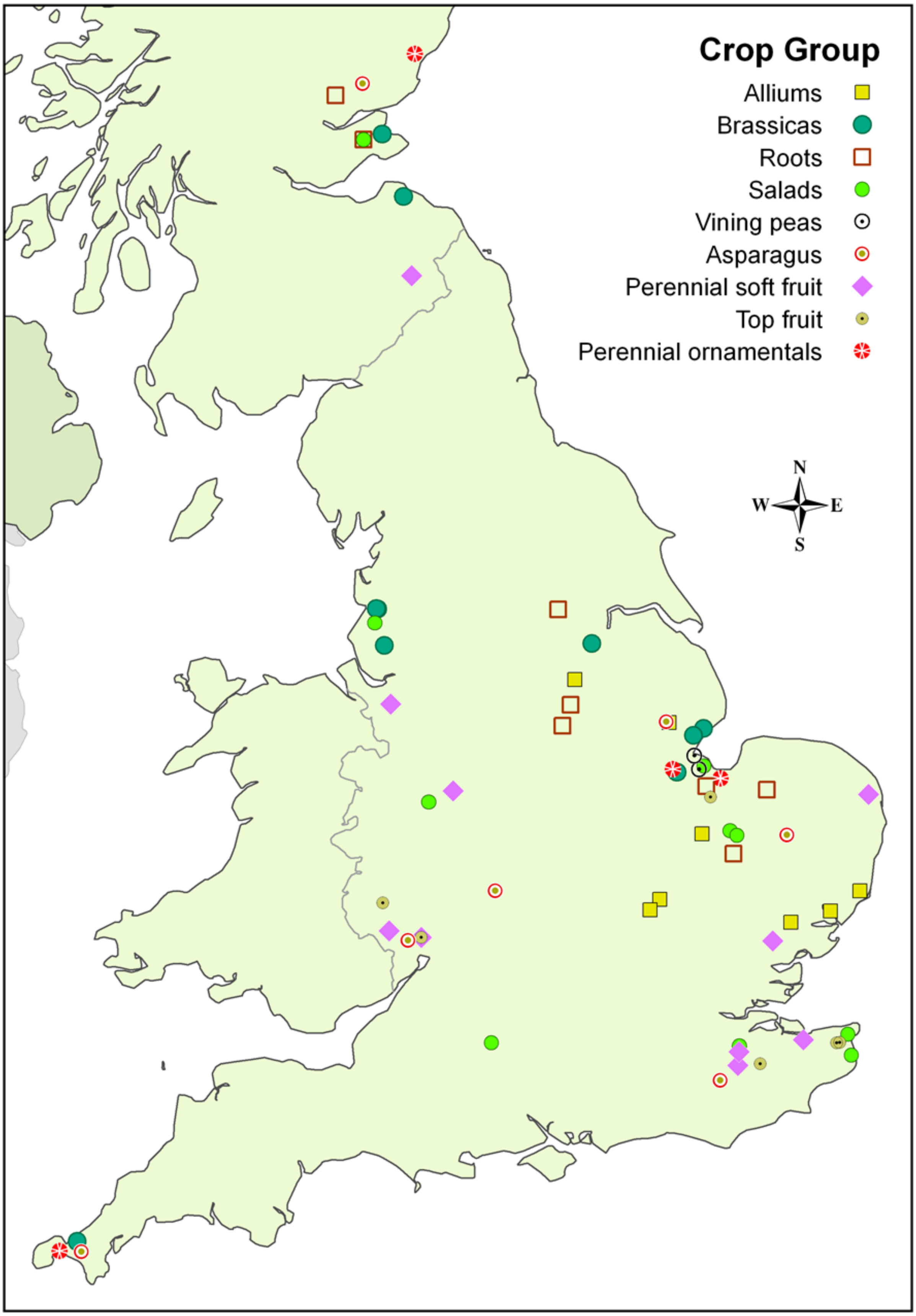


Figure 1. Location of soil structure survey sites in England and Scotland.

To characterise the topsoil at each field site, baseline topsoil samples (0-15 cm depth) were taken from each field, and analysed for:

- Soil pH (measured in water; 1:2.5)
- Particle size distribution (i.e. percentage sand, silt and clay content; laser method)
- Extractable P (sodium bicarbonate extractable), K, and Mg (ammonium nitrate extractable)
- Total N (Dumas)
- Organic matter (dichromate oxidation)
- Loss on ignition (LOI)

The soil structure survey focused on topsoil and upper subsoil condition (to a depth of 60 cm). Firstly, a cone penetrometer was used to quantify the range and depth of (maximum) penetration resistance values at twenty randomly selected points across the main body of the field (pre-planting), and, for annual crops, across the drilled/planted area (post-planting) to a depth of 50 cm. For perennial crops, post-planting penetrometer measurements and subsequent assessments were carried out in the beds for asparagus, Narcissus/cut flowers, blackcurrants and raspberries; and between the beds and alleyways in apple orchards.

Within each field and at each sampling occasion, the following measurements/assessments were carried out at the three points where the maximum, median and minimum topsoil penetrometer resistance values were measured:

- Dry bulk density (core cutter method):
    - Mid topsoil (10-15 cm depth)
    - Upper subsoil (30-35 cm depth)
    - Deeper subsoil (40-45 cm depth)
- Visual soil evaluations:
    - Visual Soil Assessment (VSA; Shepherd, 2000) – topsoil
    - Visual Evaluation of Soil Structure (VESS; Guimarães *et al*., 2011) – topsoil
    - SubVESS (Ball *et al*., 2015) – subsoil
- Cone penetrometer tests:
    - 40-60 cm depth (maximum resistance and depth of maximum resistance x 3)

Visual soil assessment (VSA)

The visual soil assessment (VSA) method was developed by Landcare New Zealand (Shepherd, 2000) and is promoted by the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) and Soil Management Initiative (SMI). At the three visual assessment locations in each field, a 20 cm block of soil was extracted and dropped a maximum of three times from a height of approximately 1m (waist height) onto a hard board; and then scored using the VSA method as summarised in Table 2. For each visual indicator, the soil sample was compared with three photographs in the VSA field guide (that correspond to poor, moderate and good conditions) to assign the Visual Score. The maximum score possible was 32.

Table 2. Landcare Visual Soil Assessment (VSA) scoring system.

Visual Indicator of Soil Quality	**Visual Score (VS)** **0 – poor condition** **1 – moderate condition** **2 - good condition**	**Weighting**	**Maximum VSA Ranking**
Soil structure and consistence		X3	6
Soil porosity		X3	6
Soil colour		X2	4
Number and colour of soil mottles (an indicator of impeded/poor drainage)		X2	4
Earthworm count		X3	6
Tillage pan		X1	2
Degree of clod development		X1	2
Degree of soil erosion	Standard score of 1	X2	2
Maximum Ranking Score (Sum of VS rankings)			32

The following VSA scoring system was used (Shepherd, 2000):

Soil Quality Assessment	**VSA Score**
Poor	< 10
Moderate	10 - 25
Good	> 25

Visual Evaluation of Soil Structure (VESS)

The VESS score is an assessment of soil structure and porosity. The topsoil is assessed by the ease of break-up of a block of soil; the size and shape of its constituent soil structural units (or aggregates); the abundance of visual pores, cracks and fissures and the distribution of roots and earthworm channels. At the three points where the maximum, median and minimum penetrometer resistance values were recorded, a 20 x 20 cm block of soil (approximately spade width and depth) was extracted, placed on a plastic sheet and pulled apart by hand for assessment. If the structure was uniform the block was assessed as a whole, but if there were two or more horizontal layers of differing structure, each layer was scored separately. The physical nature, visual appearance and smell of the soil aggregates was compared with the pictures and descriptions on the VESS field sheet. The lowest score (St1 - Friable) is given to the least compact and most porous condition, and the highest score (St5 - Very compact) to topsoil that is difficult to break up into large, plate-shaped aggregates condition with roots mainly restricted to cracks. The focus in this report is on the poorest or ‘limiting’ layer.

Other topsoil and subsoil measurements

Mid-topsoil bulk density (BD) measurements provided detailed information about the physical condition of topsoils. BD measurements at 30-35 cm depth provided an indication of the degree and extent of compaction issues in the upper subsoil, which are mainly due to the use of heavy machinery when soils are ‘wet’. Deeper subsoil measurements, including BD measurements at 40-45 cm depth, SubVESS assessments at 30-50 cm depth and penetrometer resistance measurements at 40-60 cm provided information on the extent of subsoil compaction.

The SubVESS assessment uses a similar technique to the VESS method except a knife is used to extract aggregates from subsoil layers, which are assessed for mottling, strength, porosity, roots and aggregate size and shape (Ball *et al*., 2015).

Soil BD measurements were assessed relative to the topsoil BD ‘trigger’ levels and subsoil BD ‘concern’ levels in Tables 3 and 4 (Merrington *et al*., 2006).

Table 3. Topsoil bulk density (g/cm^3) trigger values for mineral and organic soils in the UK (source: Merrington, 2006).

Organic matter content (%)*	**Bulk density (g/cm^3)**
Mineral soils	**Tilled land**
Less than 2.00	>1.60
2.00 - 2.99	>1.50
3.00 - 3.99	>1.40
4.00 - 4.99	>1.30
5.00 - 5.99	>1.25
6.00 - 7.99	>1.20
Organic mineral soils	>1.00

Table 4. Bulk density (g/cm^3) trigger values for mineral and peat subsoils in the UK (source: Merrington, 2006).

Parameter	**Bulk density (g/cm^3)**	
	Concern level	**Action level**
Clay > 50%	1.35	1.45
Clay < 50%	1.50*	1.60*
Peats	0.50	-

* For sandy textures, the levels may be up to 0.05 Mg/m^3 higher.

In addition to the compaction survey, a parallel grower survey of soil management practices was carried out at each of the holdings and 75 fields in the soil structure survey (Appendix 1). This included questions on attitudes towards soil management, visual soil evaluation and specific soil management practices carried out on farm (e.g. use of soil visual evaluation methods, cultivation sequences and frequency and depth of sub-soiling). These soil management practices were compared with the field soil structure observations to determine whether or not current soil management practices were appropriately tailored to actual observed soil structural conditions.

The soil structure and soil management practice surveys provide 'case study' evidence of soil structural conditions rather than statistical relationships between sectors or 'cause and effect' relationships between soil management practices and soil structural condition. Example grower case studies are provided in Appendix XX.

Results

The general characteristics of the sample are described before the soil measurements by crop group. Pre-planting and post-planting measurements for annual crops are presented as a single sample (n = 47) and by crop group for the annual crop types with a larger sample (e.g. brassicas and lettuce).

The smaller number of pre-planting perennial crop sites (n = 9) are presented as individual sites with results related to the soil type, previous crop and other characteristics of the site. The larger number of post-planting perennial crop sites (n = 19) are presented as individual sites and as a single sample for an approximate comparison with annual cropping sites.

Results – Annual crops

Sample characteristics – annual crops

The soil structure survey of annual crops covered farms ranging in size from 49 to 3,000 ha. As part of the survey a range of locations (*Figure 1*) and soil types were selected. At each site, field level information was collected on soil pH, P index, K index, Mg index, soil organic matter content and clay content (Figures 2 to 7).

A high percentage (70%) of fields surveyed were above the soil pH target values of 6.5 (or 7.0 for brassicas if clubroot is a problem) recommended in the *Nutrient Management Guide (RB209) - Section 6 p.5 - Vegetables and bulbs* (AHDB, 2017). Around three quarters (78%) of fields were at target P index 3 or above, 40% at or above target K index 2+ (*Figures 3 and 4*); and 86% at target Mg Index 2 or above for growing vegetables, with only two fields at Mg Index 4 or 5 (Figure 5).

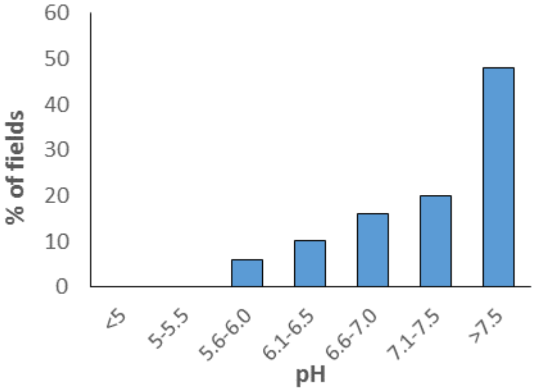


Figure 2. Frequency distribution of soil pH in annual crop fields.

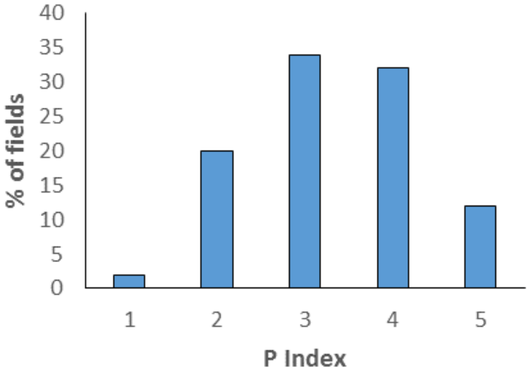


Figure 3. Frequency distribution of P indices in annual crop fields.

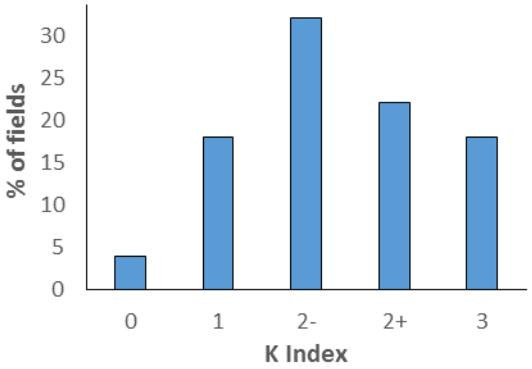


Figure 4. Frequency distribution of K indices in annual crop fields.

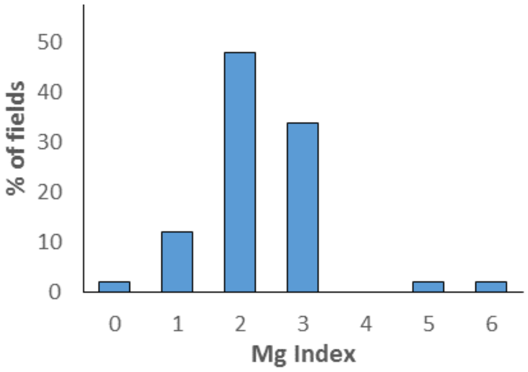


Figure 5. Frequency distribution of Mg indices in annual crop fields.

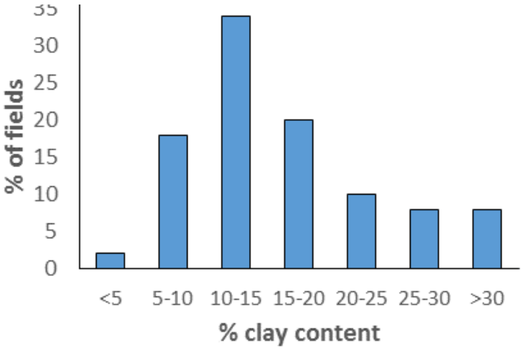


Figure 6. Frequency distribution of clay content levels in annual crop surveyed fields.

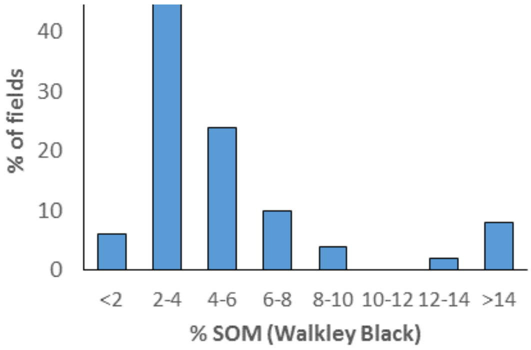


Figure 7. Frequency distribution of SOM (%) levels in annual crop surveyed fields

Topsoil clay content in around three quarters (74%) of the fields surveyed was less than 20%, indicating that the majority of the topsoils under annual cropping were ‘sandy or light silty’ (Figure 6). This corresponded with 76% of the topsoils surveyed having a soil organic matter content of 6% or less (*Figure 7*).

Bulk density – annual crops

For annual crops as a whole (n = 47) BD increased with depth as would be expected with decreasing organic matter content and increasing load above sampling depth (Figure 8). There was no indication of higher BD in the upper subsoil or 'transition' layer that can be induced through regular cultivation at the same depth (Batey, 2009). BD values were generally higher than UK Soil Quality Indicator Consortium (UKSIC; Merrington *et al*., 2006) trigger and concern values, particularly post-planting (Figure 9).

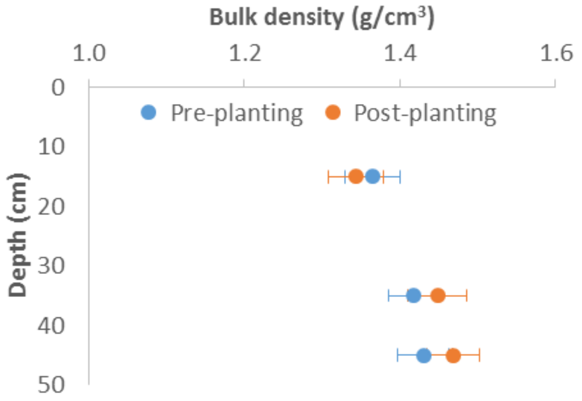


Figure 8. Mean bulk density profile in annual crops (bars represent the standard error of the mean).

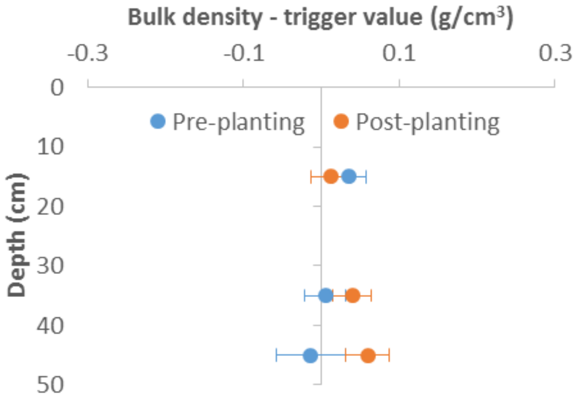


Figure 9. Mean bulk density profile in annual crops relative to BD trigger values.

For fields in brassicas, alliums and leafy salads, the mean BD profiles relative to trigger values matched the pattern for annual crops as a whole (Figures 11, 15 and 17). However, subsoil BD values in root crop fields were generally below concern levels at both pre-planting and post-planting; and for topsoil BD there appeared to be a clear difference between visits, with topsoil mean BD values well above trigger values pre-planting, but well below after planting (1.4 g/cm^3 at pre-planting *cf*. 1.3 g/cm^3 post-planting; Figure 13). This indicates effective cultivation practices for most of the carrot and parsnip fields to produce consolidated, but uncompacted seedbeds.

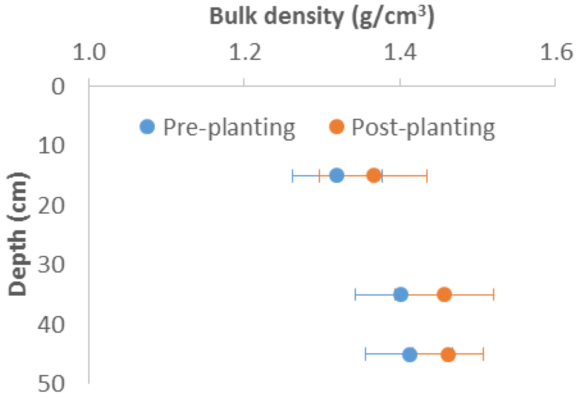


Figure 10. Mean bulk density profile for brassica fields

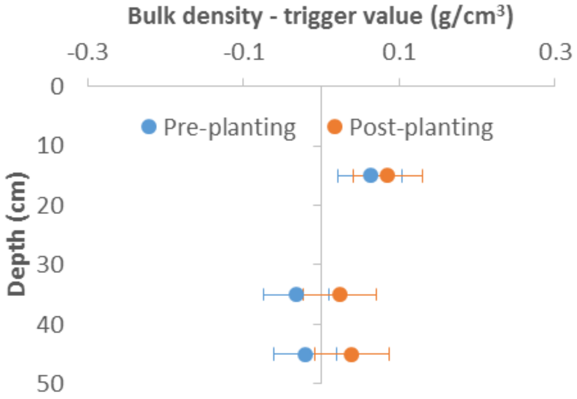


Figure 11. Mean bulk density profile for brassica fields relative to trigger values.

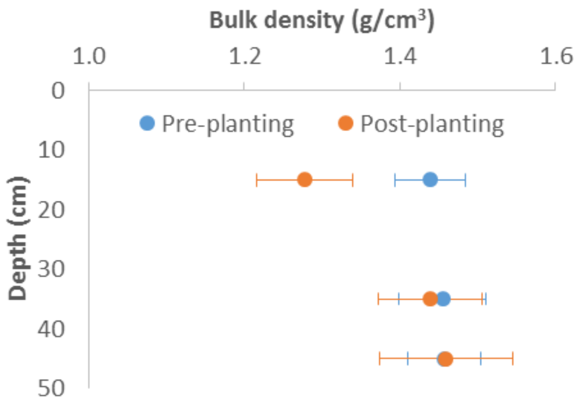


Figure 12. Mean bulk density profile for root crop fields (n = 9).

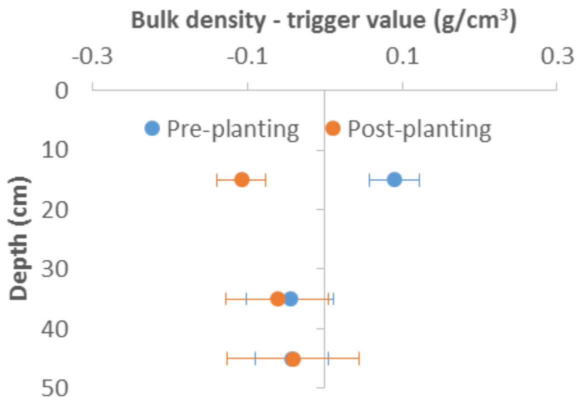


Figure 13. Mean bulk density profile for root crop fields relative to trigger values.

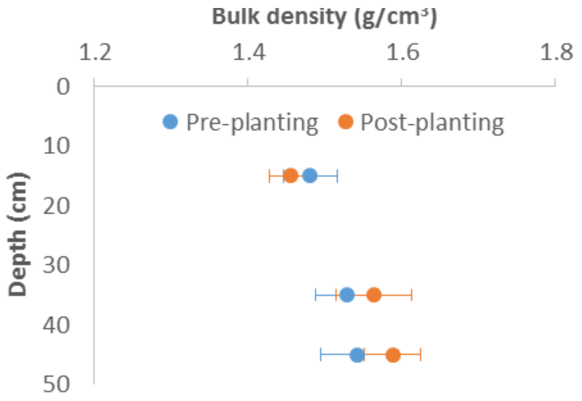


Figure 14. Mean bulk density profile for allium fields (n = 10).

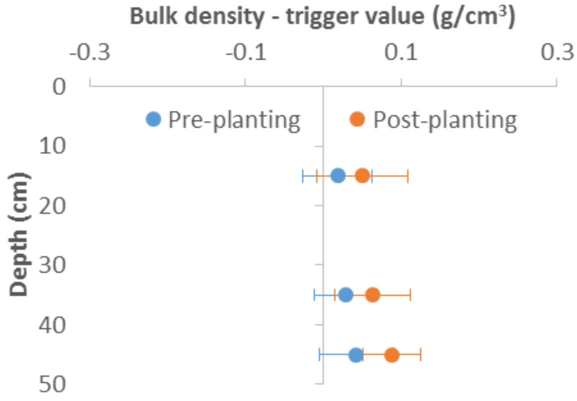


Figure 15. Mean bulk density profile for allium fields relative to trigger values.

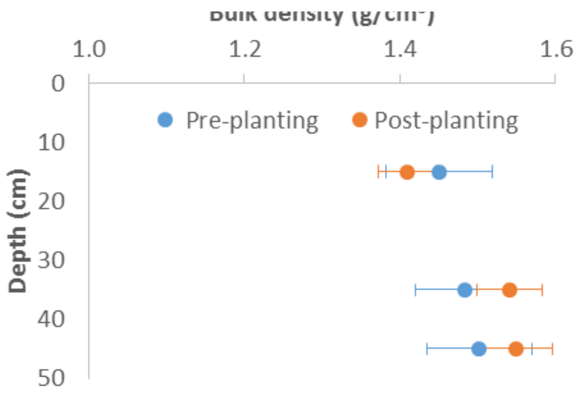


Figure 16. Mean bulk density profile for leafy salad fields (n =. 10).

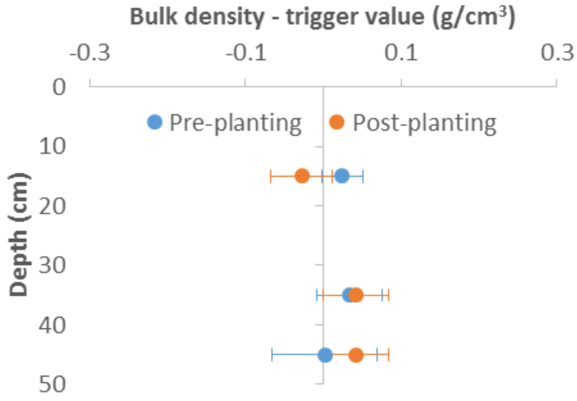


Figure 17. Mean bulk density profile for leafy salad fields relative to trigger values.

There was some contrast between crop groups, with allium sites (n = 10) above BD trigger values throughout the soil profile (Figure 15), while root crop sites (n = 9) were mainly below (Figure 13).

For the few fields in vining peas (n=3), there was a contrast in BD levels between the topsoil and subsoil, particularly post-planting (Figure 19). Topsoil BD values were clearly above trigger values post-planting, indicating a consolidated (possible slightly compacted) seedbed, whereas subsoil BD values were mainly below concern levels, indicating adequate subsoil porosity.

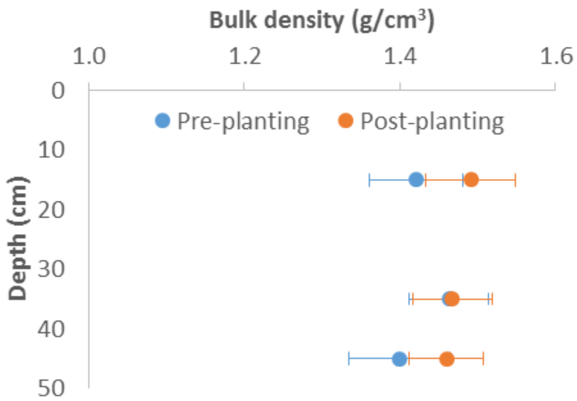


Figure 18. Mean bulk density profile for vining pea fields (n = 3).

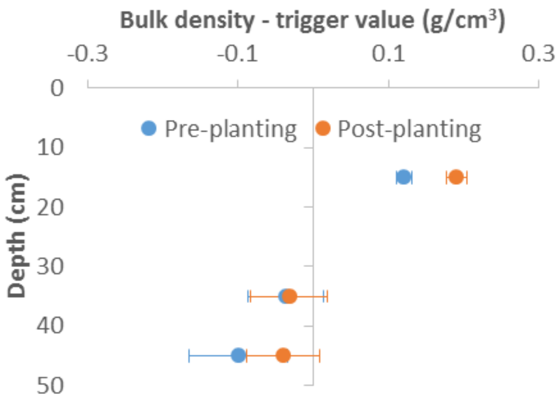


Figure 19. Mean bulk density profile for vining pea fields relative to trigger values.

Penetrometer resistance – annual crops

Penetrometer resistance (PR) measurements were mainly used to determine variability in the degree and depth of any compaction and to select locations for further assessments. Where the mean depth of maximum PR was at or close to the maximum depth measured (50 cm depth for measurements made from the surface; 60 cm depth for mid subsoil measurements) a distinct compacted layer was generally not found. For all annual crops as a group (Figure 20), the mean depth of max PR was at around 40 cm depth when measured from the ground surface ('surface' measurements) and 55 cm depth when measured in the mid subsoil (40-60 cm depth). The main exception to this was the 'surface' measurements in root crops where the mean depth of PR increased from *c*. 35 cm at pre-planting to *c*. 45 cm post-planting, indicating that pre-planting cultivations had significantly loosened the soil (Figure 22).

PR was on average firmer in the topsoil than in the subsoil at both pre-planting and post-planting visits (Figure 20). Notably, in the few vining pea fields assessed (n = 3) the reverse was true post-planting with PR in the subsoil higher than in the topsoil (Figure 25).

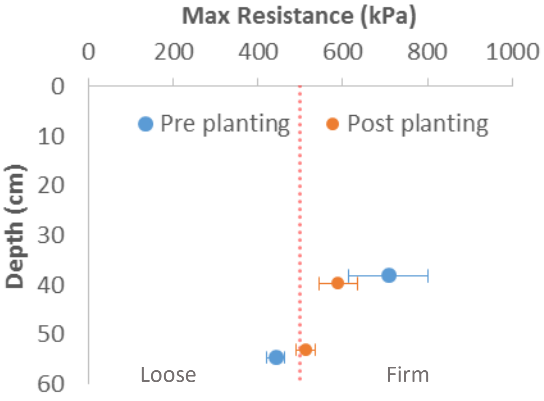


Figure 20. Penetrometer resistance profile - annual crops.

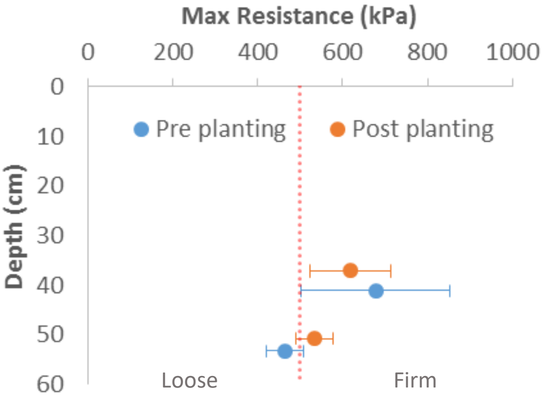


Figure 21. Penetrometer resistance profile – brassicas.

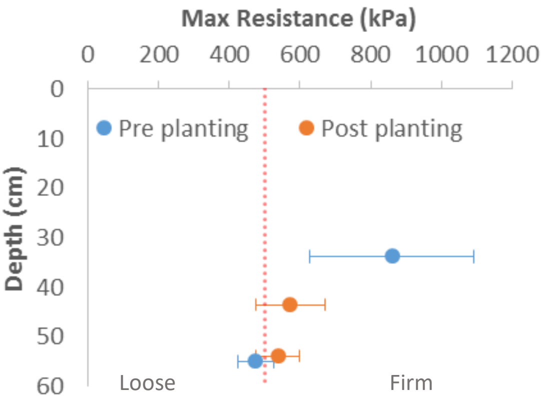


Figure 22. Penetrometer resistance profile - root crops.

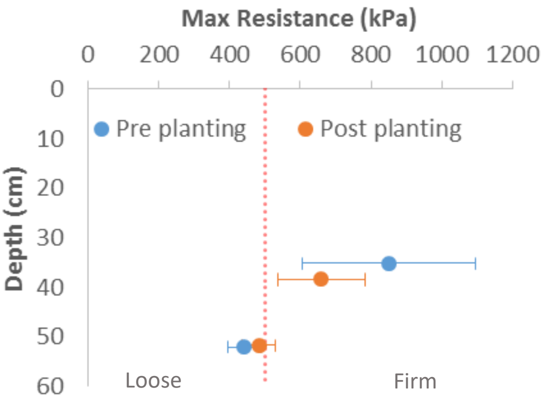


Figure 23. Penetrometer resistance profile – alliums.

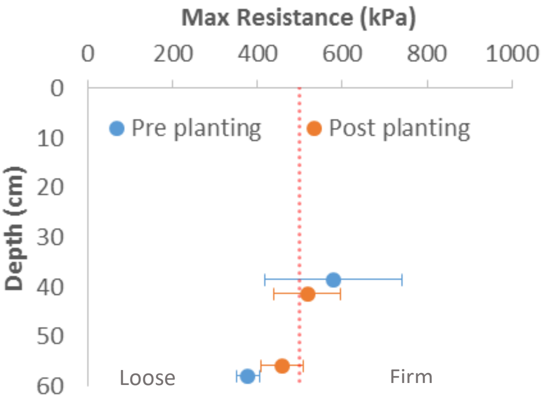


Figure 24. Penetrometer resistance profile - leafy salads.

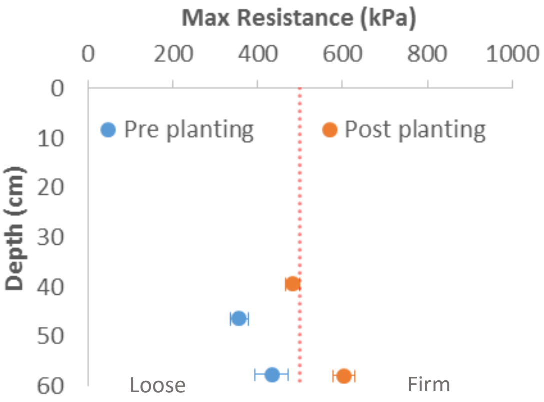


Figure 25. Penetrometer resistance profile - vining peas.

Visual Soil Assessment (VSA) – annual crops

Notably, there were no fields that scored ‘poor’ (overall VSA score < 10) either at pre-planting or post-planting (Figures 26 to 30). Therefore, although there were clear signs of compaction in many of the soils surveyed, none of the sites were severely degraded. For all annual cropping fields (n = 47), the percentage of fields in ‘moderate’ condition decreased from 56% at pre-planting to 42% post-planting, indicating an overall improvement in soil condition due to cultivation. All three vining pea sites were in ‘moderate’ condition at pre-planting and at post-planting.

Figure 26. VSA scores for all annual crops (n = 47): a) pre-planting and b) post-planting.

Figure 27. VSA scores for brassica sites (n = 15): a) pre-planting and b) post-planting

The most significant change occurred in root crop sites with 22% of sites in ‘good’ condition pre-planting and 100% post-planting (Figure 28). Allium sites were the only crop group to have fewer sites in ‘good’ condition after cultivation (60% cf. 67%). This was most likely due to cultivation in ‘wet’ field conditions at some of the sites (*Figure 29*). For the ten leafy salad crop sites there was no change following cultivation, with 50% of topsoils in ‘moderate’ condition.

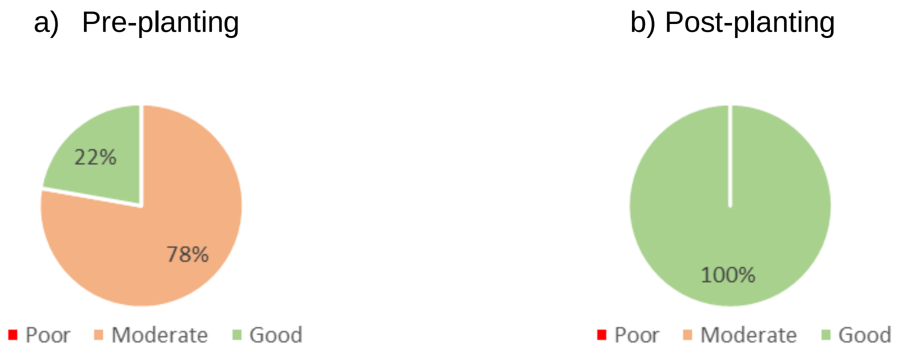


Figure 28. VSA scores for root crop sites (n = 9): a) pre-planting and b) post-planting.

Figure 29. VSA scores for allium sites (n = 10): a) pre-planting and b) post-planting.

Figure 30. VSA scores for leafy salad sites (n = 10): a) pre-planting and b) post-planting.

VSA - presence of a tillage pan

A well-developed tillage pan can have significant implications for drainage, productivity and the overall efficiency of production including water and nutrient use efficiency. As part of VSA, each annual cropping site was assessed for presence of a tillage pan. For all annual crops at pre-planting, 63% of sites had a well-developed tillage pan, with significant consolidation, no macropores and few or no cracks (Figure 31). Post-planting this had reduced to 40%, with 21% having a moderately developed pan. However, there were some significant differences between crop types in the effectiveness of cultivations.

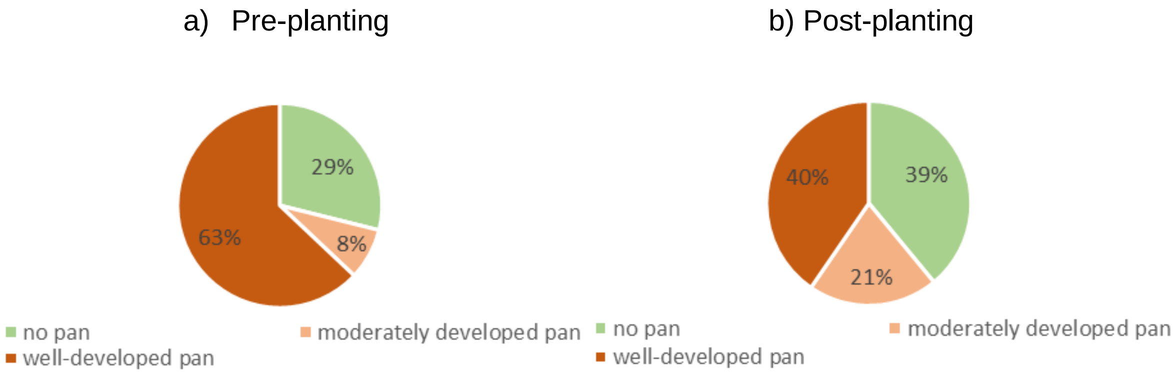
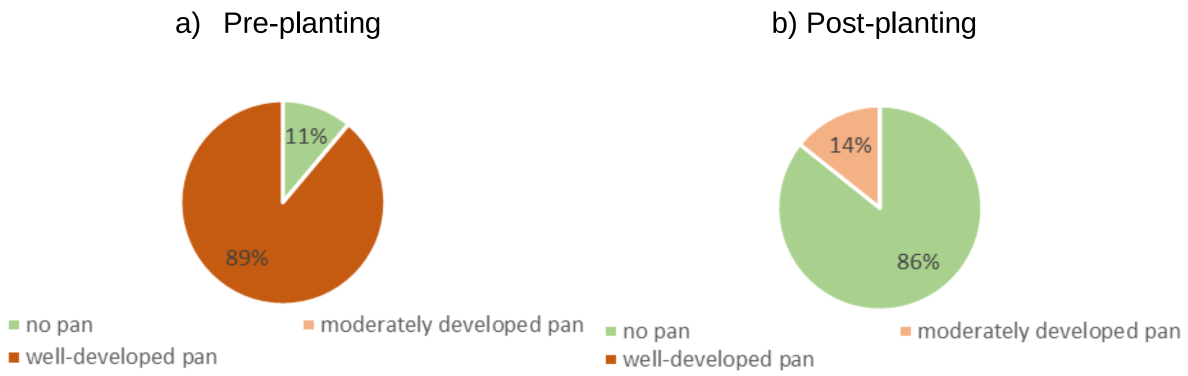


Figure 31. Presence of a tillage pan in annual cropped fields: a) pre-planting and b) post-planting.

Figure 32. Presence of a tillage pan in brassica fields: a) pre-planting and b) post-planting.

In brassica fields, cultivation had no effect on the proportion of fields with a tillage pan (Figure 32). The most dramatic change occurred on the root crop sites with 11% of sites having no pan at pre-planting and 86% post-planting (Figure 33).On the allium sites there was no change in the proportion of fields with a pan between pre-planting and post-planting. However, the percentage of fields with a well-developed pan reduced from 59% to 36% (Figure 34), indicating that cultivation had broken up well-developed pans to some degree at around a fifth of the allium sites. For leafy salad sites, the proportion of fields with a pan increased post-planting, implying that cultivation made soil conditions worse at some sites (Figure 35). All three vining pea sites had a well-developed tillage pan at pre-planting and at post-planting.


a) Pre-planting

b) Post-planting

Figure 33. Presence of a tillage pan in root crop fields: a) pre-planting and b) post-planting.

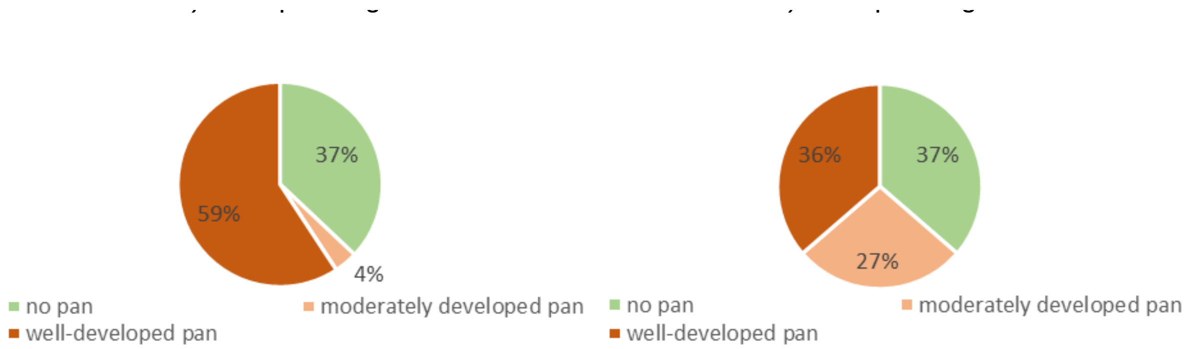
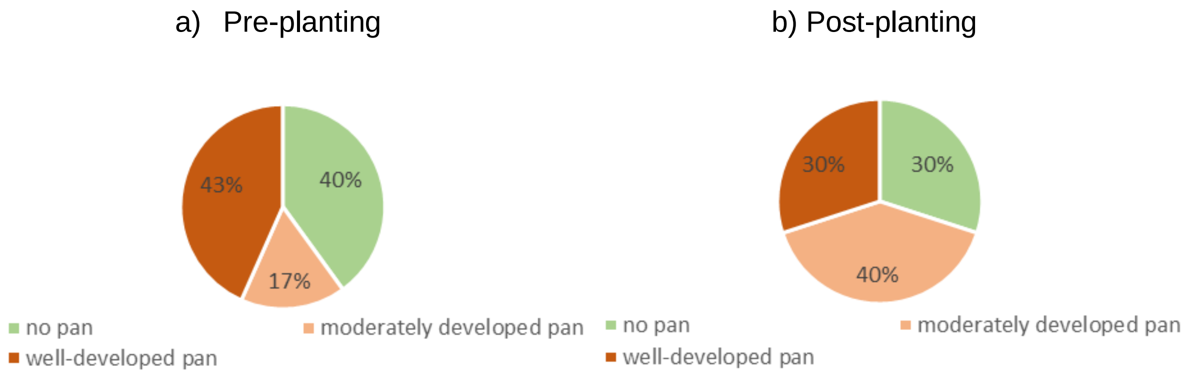


Figure 34. Presence of a tillage pan in allium fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 35. Presence of a tillage pan in leafy salad fields: a) pre-planting and b) post-planting.

VSA – earthworm numbers

Earthworm numbers in the topsoil are a useful indicator of good soil structure and soil health, and were assessed as part of the VSA. Earthworm numbers can vary from less than 100 individuals per m^2 (<4 per 20 cm x 20 cm block) to more than 750 individuals per m^2 (>30 per spade full), depending on the degree of cultivation and the quantity, nutritional quality and continuity of food supply (Smith *et al*., 2008). The VSA assessment distinguishes between soils with <100, 100-200 and >200 earthworms per m^2. Soil moisture can affect local patterns of earthworm distribution and activity, and so all the VSA assessments were carried out when the soil was at field capacity. For annual crops, 81% of sites pre-planting, and 85% of sites post-planting had on average less than 100 earthworms per m^2 (*Figure 36*). Frequent cultivations are likely to be an important factor in the relatively low number of earthworms observed at annual cropping sites (Ernst and Emmerling, 2009). Interestingly, in vining pea fields pre-planting, over half of the assessments found more than 200 earthworms per m^2 (Figure 41). Some of the highest counts (up to 350 earthworms per m^2) were made in fields growing a mustard cover crop.


a) Pre-planting
b) Post-planting

Figure 36. Earthworm numbers in annual cropping fields: a) pre-planting and b) post-planting.

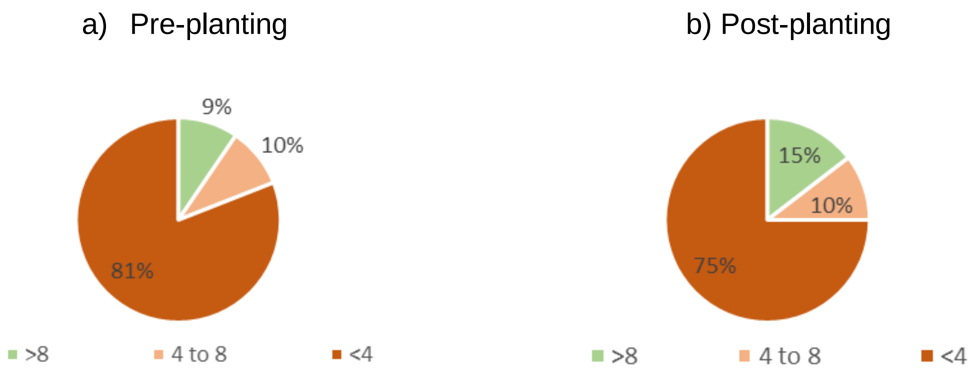

a) Pre-planting
b) Post-planting

Figure 37. Earthworm numbers in brassica fields: a) pre-planting and b) post-planting.

a) Pre-planting

b) Post-planting

Figure 38. Earthworm numbers in root crop fields: a) pre-planting and b) post-planting.

a) Pre-planting b) Post-planting

Figure 39. Earthworm numbers in allium crop fields: a) pre-planting and b) post-planting.

a) Pre-planting b) Post-planting

Figure 40. Earthworm numbers in leafy salad fields: a) pre-planting and b) post-planting.

a) Pre-planting b) Post-planting

Figure 41. Earthworm numbers in vining pea fields: a) pre-planting and b) post-planting.

Visual Evaluation of Soil Structure (VESS) – annual crops

For annual crops as a group (n = 47) the ‘limiting’ soil layer was ‘friable’ or ‘intact’ in 62% of fields at pre-planting and in 70% of fields post-planting (Figure 42). The ‘limiting’ layer was ‘compact’ in 4% of fields pre-planting and 5% post-planting. In most annual crop groups (root crops, alliums, leafy salads and vining peas) there was a general improvement in soil structure with the number of ‘firm’ or ‘compact’ soils decreasing between pre-planting and post-planting. Root crops showed the greatest improvements between visits with sites scoring ‘friable’ or ‘intact’ increasing from 67% pre-planting to 100% post-planting (Figure 44). The exception was brassicas for which the percentage of fields with a ‘firm’ or ‘compact’ soil layer increased from 31% pre-planting to 35% post-planting (Figure 43).


a) Pre-planting

b) Post-planting

Figure 42. VESS score of ‘limiting’ topsoil layer in annual cropping fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 42. VESS score of ‘limiting’ topsoil layer in brassica fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 43. VESS score of ‘limiting’ topsoil layer in root crop fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 44. VESS score of ‘limiting’ topsoil layer in allium fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 45. VESS score of ‘limiting’ topsoil layer in leafy salad fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 46. VESS score of ‘limiting’ topsoil layer in vining pea fields: a) pre-planting and b) post-planting.

Visual Evaluation of Subsoil Structure (SubVESS) – annual crops

For the subsoil visual evaluation of soil structure (SubVESS) in annual crops there was a general trend of improving subsoil structure between visits. There were signs of ‘some compaction’ pre-planting in some fields coming into brassicas (23%; Figure 48) and vining peas (67%; Figure 52), but for all crop groups other than alliums, all subsoils scored as ‘friable’ or ‘firm’ at post-planting. For alliums there were signs of ‘some compaction’ in the subsoil at one site post-planting (Figure 50).

In general, it was more difficult to pick out signs of compaction using the SubVESS assessment compared with the VESS assessment for which a block of soil is extracted and assessed. Indeed, the SubVESS results do not reflect the relatively high subsoil BD values measured in some crops such as brassicas, alliums and leafy salads.

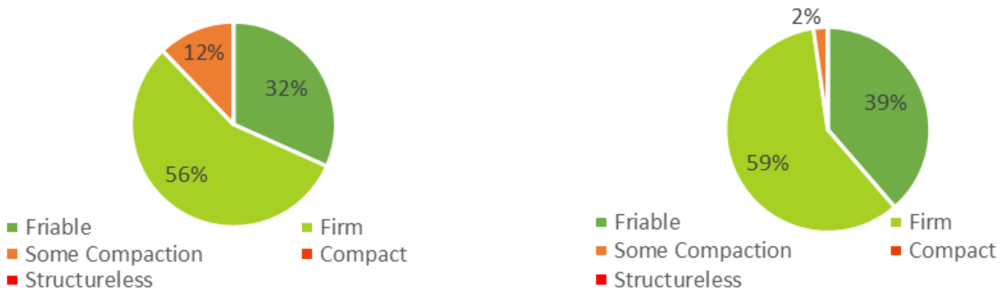

a) Pre-planting b) Post-planting

Figure 47. SubVESS scores for annual crops: a) pre-planting and b) post-planting.

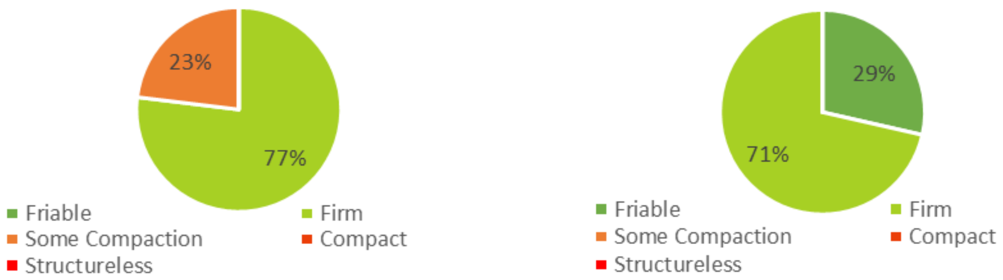

a) Pre-planting b) Post-planting

Figure 48. SubVESS scores for brassica fields: a) pre-planting and b) post-planting.

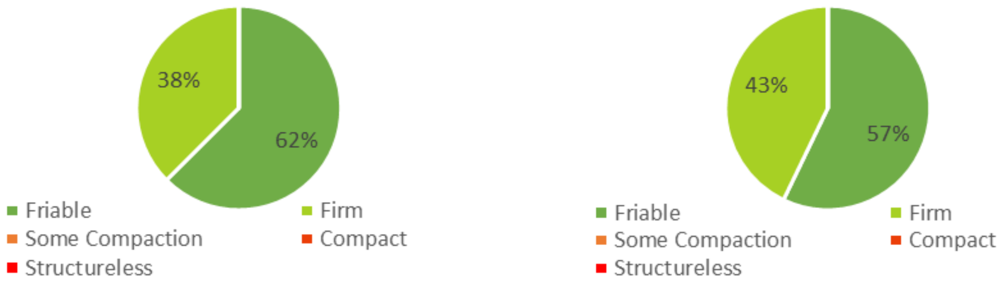

a) Pre-planting b) Post-planting

Figure 49. SubVESS scores for root crops: a) pre-planting and b) post-planting.

a) Pre-planting b) Post-planting

Figure 50. SubVESS scores for allium fields: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 51. SubVESS scores for leafy salads: a) pre-planting and b) post-planting.


a) Pre-planting

b) Post-planting

Figure 52. SubVESS scores for vining pea fields: a) pre-planting and b) post-planting.

Soil management practices – annual crops

The annual crop growers were asked a range of questions about soil structural and drainage issues; their soil assessment and soil management activities; and their use of soil mapping and other practices. Almost all the growers (95%) felt soil structural condition was an issue for crop production, with topsoil compaction (74%) and capping (45%) the most commonly perceived problems. Interestingly, only 18% of the growers thought subsoil compaction was an issue (Figure 53).

Although most growers felt soil structure was an issue, a smaller proportion (57%) were confident they could assess the structure of their soil, while 33% were keen to learn more about assessing soil structure (Figure 54). A large number of growers (90%) were visually assessing their soil, with most of them using a spade.

Around half of growers used soil mapping for the variable rate application of lime and/or nutrients. A smaller number of growers (14%) had commissioned electrical conductivity (EC) maps, while 5% were actually using the information on soil variability to manage their soils and/or crops (Figure 55).

Waterlogging was one of the key issues identified by growers. It is therefore not surprising that over half of growers surveyed (62%) had invested in new drainage or maintained existing drainage, and an even greater number (95%) were improving drainage through mole draining or subsoiling on a regular basis (Figure 56). A similar proportion (90%) had infrastructure in place to irrigate horticultural crops.

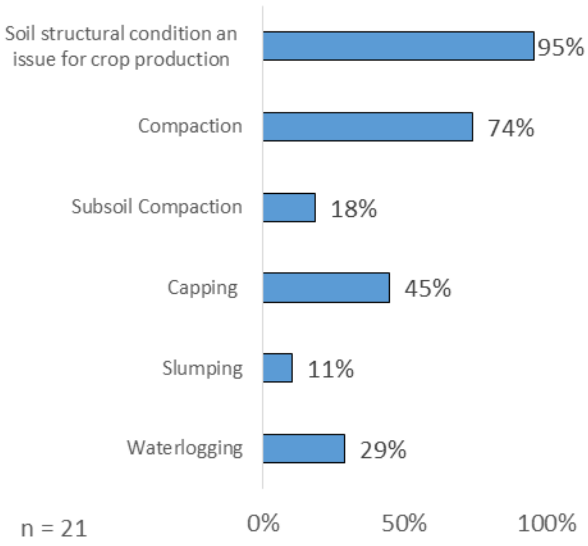


Figure 53. Key structural issues affecting crop production across annual crop sites.

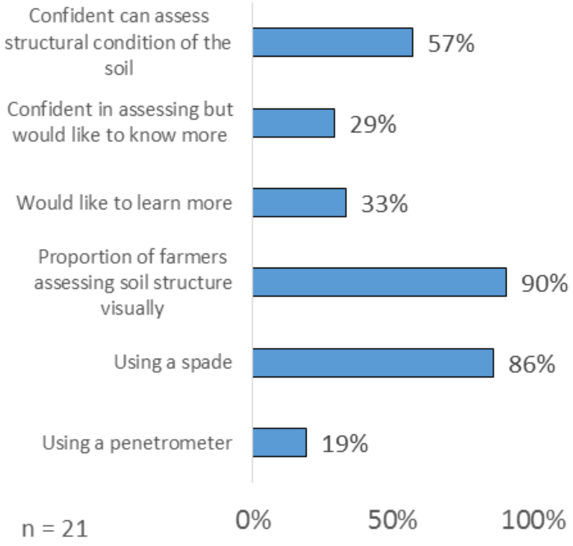


Figure 54. Grower attitudes to assessing soil structure across annual crop sites.

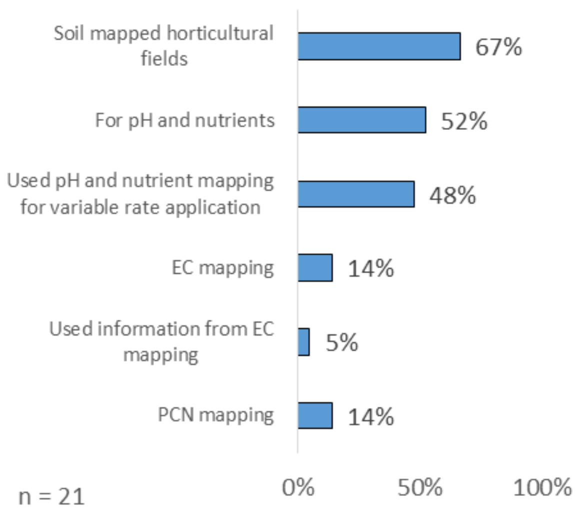


Figure 55. Proportion of growers using soil mapping technology on annual crop sites.

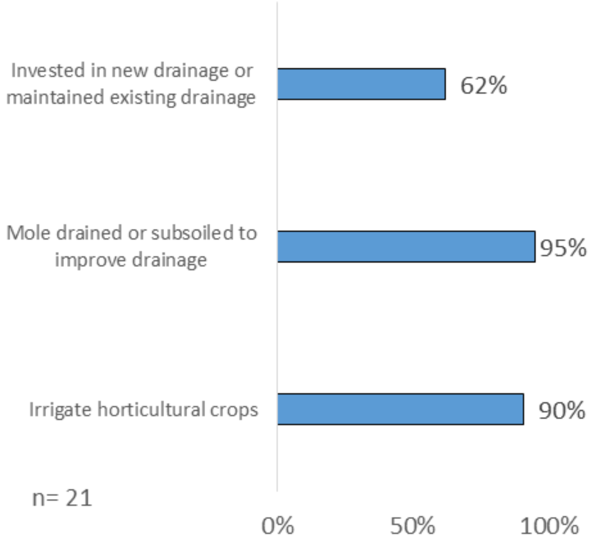


Figure 56. Proportion of growers improving drainage and irrigating at annual crop sites.

Growers used a wide range of methods to try and improve soil structure across their farms, with cover cropping and organic amendments most widely used (Figure 57). Many growers felt cultivations were an important tool for tackling soil structural issues, in particular subsoiling to depth was specifically mentioned by 43% of growers (*Figure 57*). Although conventional cultivation methods were popular with growers around a quarter (24%) were using reduced tillage and 5% using controlled traffic farming to improve soil structure (Figure 57).

Of the growers surveyed, 92% carried out deep cultivations (below 25-30 cm depth), with 70% of these adjusting the depth of cultivation based on visual assessments and around 10% making the adjustment “more on feel”.

Data from VSA and VESS assessments in combination with soil management information from 43 annual cropping fields indicated that a third of growers had deep cultivated (e.g. subsoiled or ‘flat lifted’) where there was evidence of a tillage pan (Figure 58). A higher proportion of growers (40%) did not deep cultivate where a pan was present, and a small proportion (7%) deep cultivated with no pan present. Given the prevalence of tillage pans (in *c*. 70% of annual cropping fields; Figures 31 and 58), it is not surprising that many growers subsoil on a regular basis. However, subsoiling where there are no clear signs of compaction is costly (£55-£65 per hectare; Nix, 2015) and is likely to do more harm than good (Hallett *et al*., 2012).

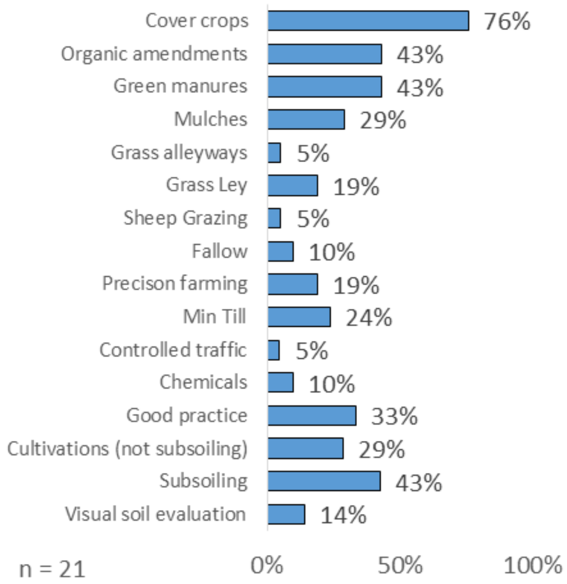


Figure 57. Other practices farmers are adopting to improve soil structure across annual crop sites.

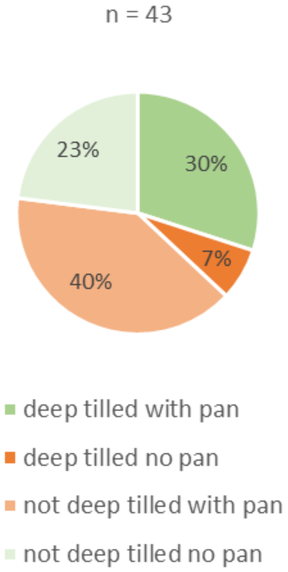


Figure 58. Deep cultivation timings relative to presence of a tillage pan across annual crop sites.

Twenty nine growers provided data on the number, type and depth of cultivation for 36 annual cropping fields (Table 5). Around two thirds (70%) of fields were ploughed and half (47%) were subsoiled; 9% of fields were not ploughed or subsoiled, with a wide range of other cultivation equipment used to an average depth of around 13 cm. Ploughing depth ranged from 13 to 38 cm depth and subsoiling from 28 to 50 cm depth. The depth of subsoiling was on average below the depth of the topsoil tillage pan found at pre-planting on annual cropping sites (Table 5). Interestingly, the depth of the topsoil tillage pan was, on average, lower at post-planting (on sites that had a tillage pan post-planting) than at pre-planting. In some cases (e.g. leafy salads), the average ploughing depth coincided with the depth of the deeper post-planting topsoil tillage pan (Table 5).

Table 5. Cultivation techniques and depths being used by annual crop growers

Crop type	Fields ploughed (%)	Average ploughing depth (cm)	Fields subsoiled (%)	Average subsoiling depth (cm)	Growers not ploughing or subsoiling (%)	Pre-planting mean depth of topsoil tillage pan (cm)[1]	Post-planting mean depth of topsoil tillage pan (cm)[1]
All annual crops (n=38)	70	27	47	43	9	7-23	9-28
Brassicas (n=7)	71	22	29	43	14	11-24	10-28
Root Crops (n=7)	71	27	71	43	0	7-23	-
Alliums (n=10)	100	31	50	44	0	1-24	7-26
Leafy Salads (n=11)	45	26	36	39	27	2-23	15-27
Vining Peas (n=3)	100	25	100	37	0	11-22	3-30

[1] Data only from sites scoring between firm and very compact on VESS assessments

Results – perennial crops

Sample characteristics – perennial crops

The survey of soil structure and soil management of perennial crops covered farms ranging in size from 16 ha to 1,821 ha. The survey covered a range of locations (*Figure 1*) and soil types. At each site, field level information was collected on soil pH, P index, K index, Mg index, soil organic matter content and clay content.

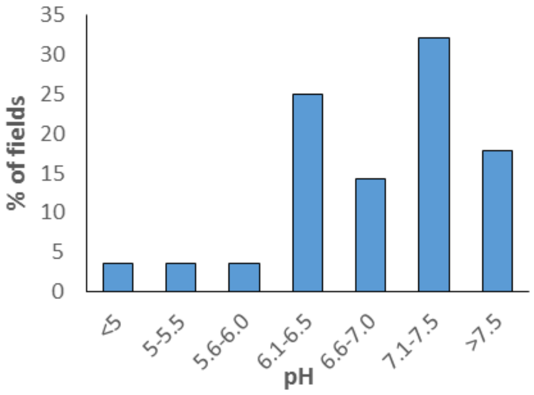


Figure 59. Frequency distribution of soil pH levels in perennial crop fields.

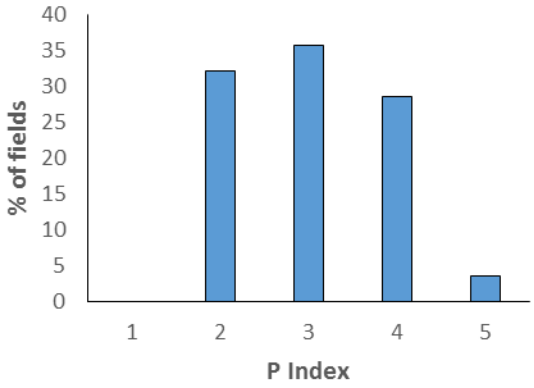


Figure 60. *Frequency distribution of* soil P indices in perennial crop fields.

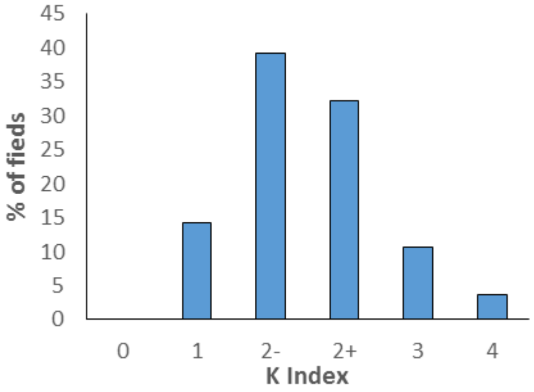


Figure 61. Frequency distribution of Soil K indices perennial crop fields.

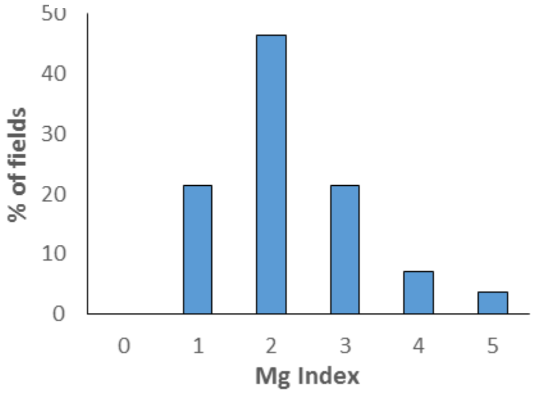


Figure 62. Frequency distribution of Soil Mg indices perennial crop fields.

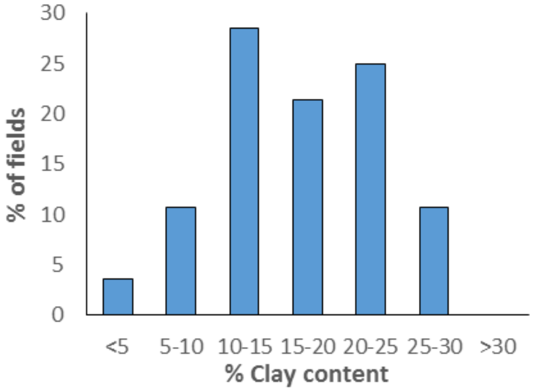


Figure 63. *Frequency distribution of Clay content in perennial crop fields.*

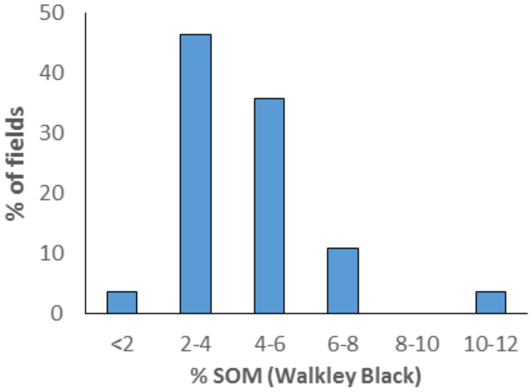


Figure 64. *Frequency distribution of SOM in perennial crop fields.*

Around two thirds (64%) of fields surveyed were above the optimum soil pH 6.0—6.5 recommended in RB209 (AHDB, 2017) for perennial vegetable and fruit crops (*Figure 59*), although pH 6.5—6.8 is recommended before planting for fruit crops. Of the fields surveyed, 68% were at or above target P index 3, 46% at or above target K index 2+; and 80% at or above target Mg Index 2 (*Figures 60 to 62*).

Most of the sites had sandy or light silty soils, as indicated by 64% of topsoils with a clay content less than 20%; all the topsoils were less than 30% clay (Figure 63). All the perennial crops were grown on mineral soils, with only 15% of the fields having a topsoil organic matter content greater than 6% (*Figure 64*).

Bulk density – perennial crops

The perennial crop sites assessed pre-planting were different from the sites assessed post-planting so it was not possible to assess the effectiveness of cultivations for the establishment of perennial crops. Nevertheless, it was interesting to compare soil physical properties at sites that were at the pre-planting stage with those that had an established perennial crop.

It is important to note that soil measurements in established asparagus crops were taken at the edge of the asparagus beds to determine whether the beds themselves provided good conditions for rooting. Interestingly, topsoil and subsoil BD values were higher at pre-planting sites compared with post-planting sites (*Figure 65*). Indeed, mean BD results were above trigger values at pre-planting sites and below trigger values (no concern) at post-planting sites (*Figure 66*), indicating that the post-planting sites were in good condition below the asparagus beds.

At soft fruit sites, topsoil and upper subsoil BD values were above trigger values at both pre-planting sites and post-planting sites (Figures 67 to 70). However, average BD values in the mid subsoil at established raspberry sites were below trigger values, indicating that the soil below the ‘transition’ layer was in good condition (Figure 70).

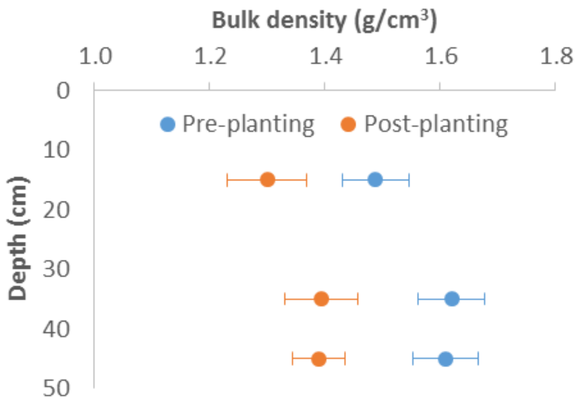


Figure 65. Mean bulk density profile for asparagus

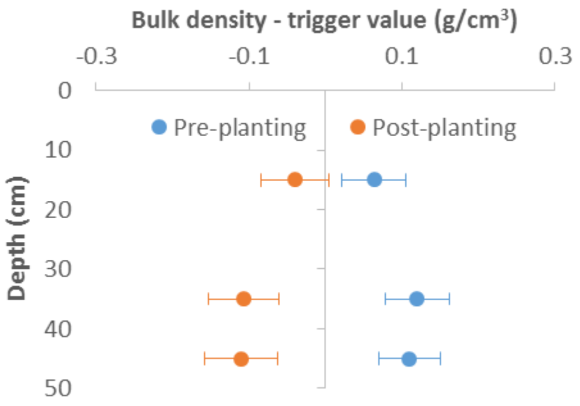


Figure 66. Mean bulk density profile for asparagus crops relative to soil trigger values.

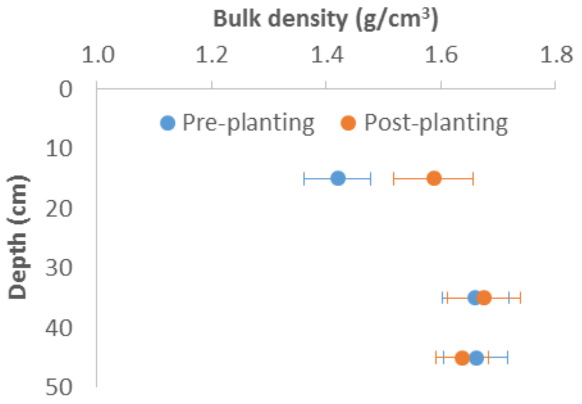


Figure 67. Mean bulk density profile for blackcurrants.

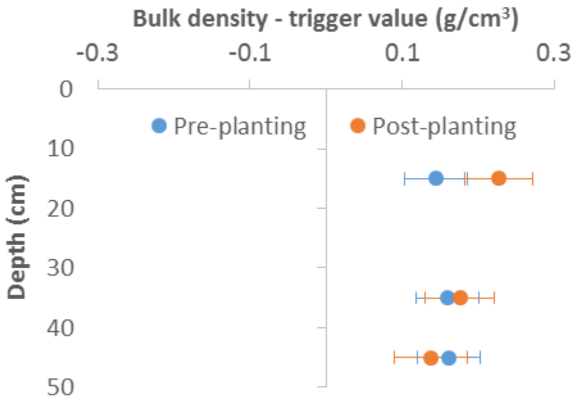


Figure 68. Mean bulk density profile for blackcurrants relative to soil trigger values.

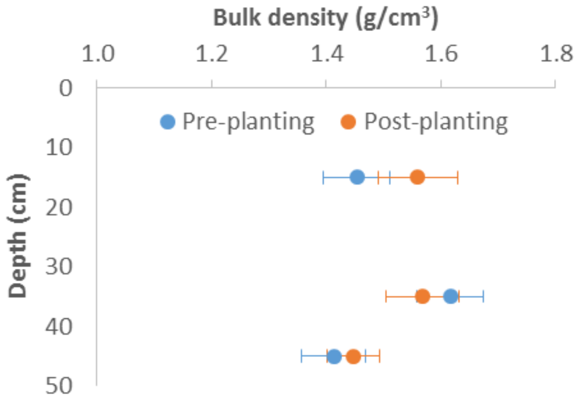


Figure 69. Mean bulk density profile for raspberries.

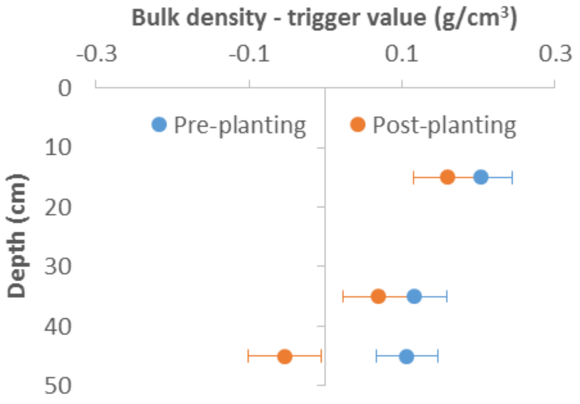


Figure 70. Mean bulk density profile for raspberries relative to soil trigger values.

For apple orchards, topsoil and subsoil BD values were relatively high at both pre-planting and post-planting sites. However, in established apple orchards there appeared to be a contrast between the topsoil and subsoil, with topsoil BD clearly higher than trigger values and subsoil values either side of concern levels, indicating that subsoil condition (and porosity) may be better than topsoil condition (Figures 71 and 72).

For cut flowers, topsoil mean BD values at both pre-planting and post-planting sites were at or just below trigger values, whereas subsoil BD values were clearly below concern levels, indicating that soils, and particularly subsoils, were in generally in good condition (Figure 74).

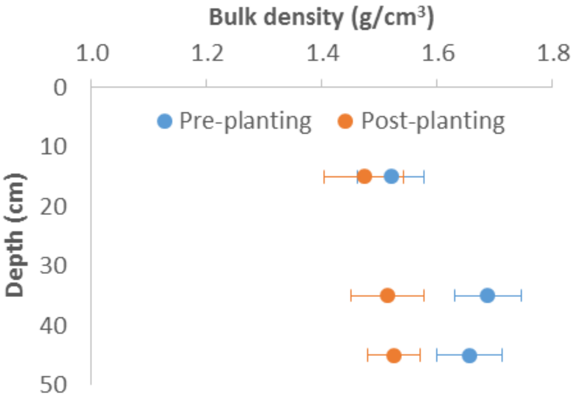


Figure 71. Mean bulk density profile for apples.

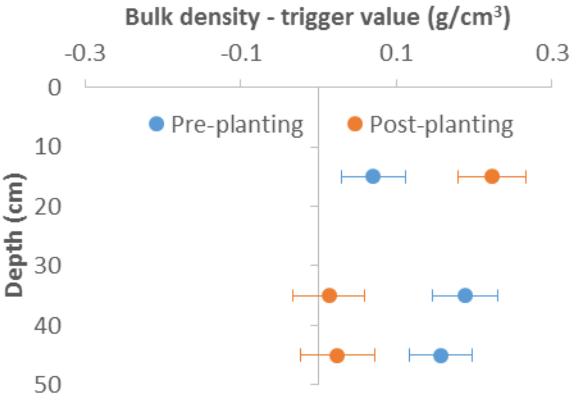


Figure 72. Mean bulk density profile for apples relative to soil trigger values.

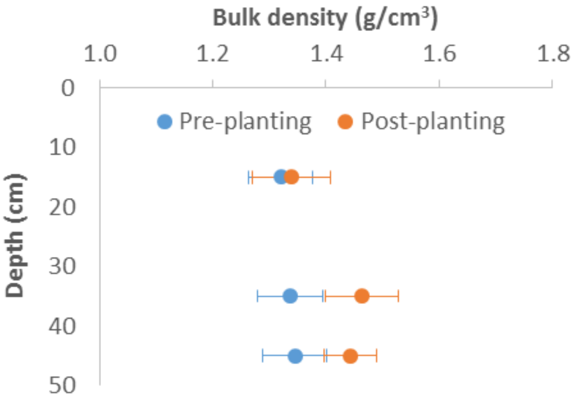


Figure 73. Mean bulk density profile for cut flowers.

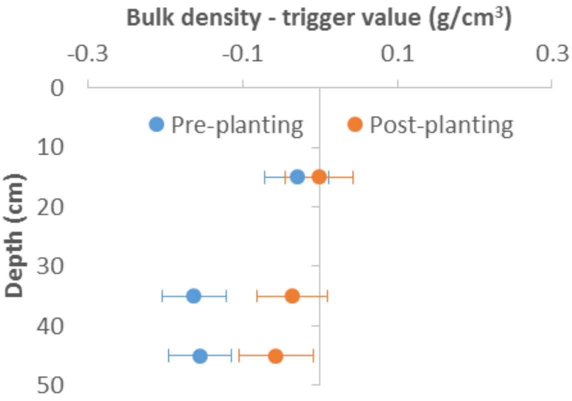


Figure 74. Mean bulk density profile for cut flowers relative to soil trigger values.

Penetrometer resistance – perennial crops

The depth of maximum resistance at established asparagus sites was on average lower in the soil than at pre-planting asparagus sites, indicating that any more resistant layers (detected using a penetrometer) at established sites were below topsoil depth (*Figure 75*). The same was true of established raspberries (Figure 77) and cut flower (Figure 79) sites. Only for blackcurrants was there an indication that the depth of maximum PR was shallower in the soil at established sites (Figure 76).

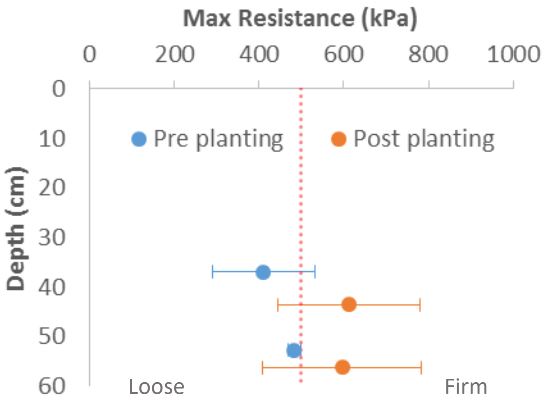


Figure 75. Penetrometer resistance profile: asparagus.

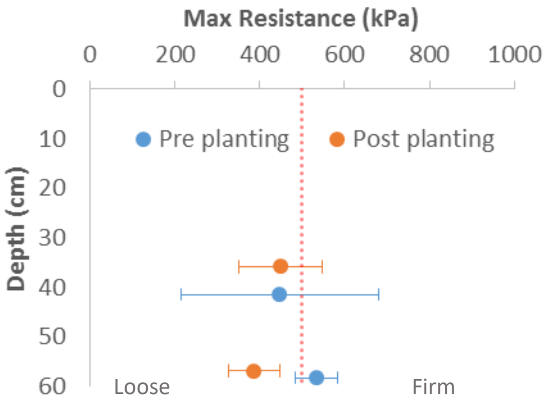


Figure 76. Penetrometer resistance profile: blackcurrants.

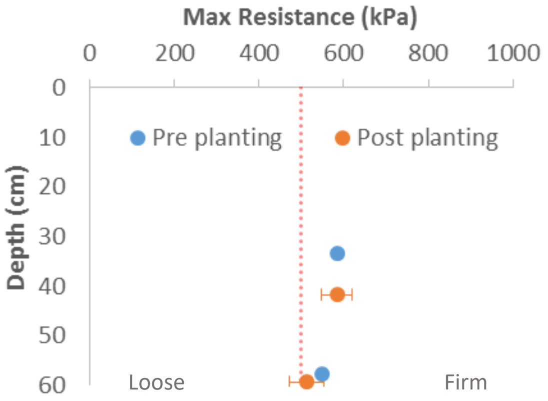


Figure 77. Penetrometer resistance profile: raspberries.

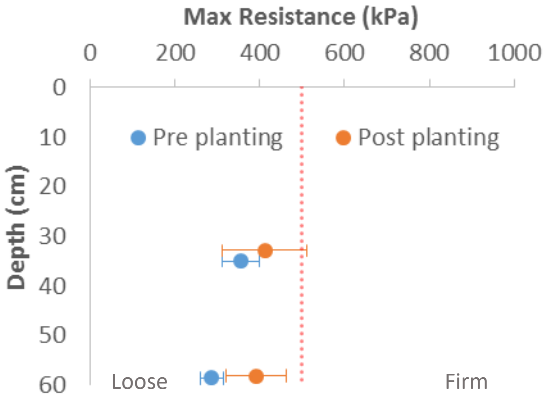


Figure 78. Penetrometer resistance profile: apples.

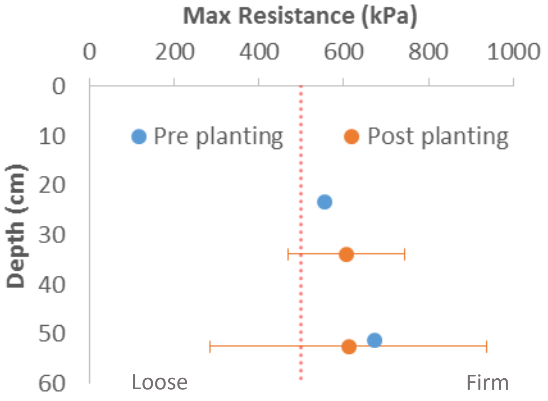


Figure 79. Penetrometer resistance profile: cut flowers.

Visual Soil Assessment (VSA) - perennial crops

Based on the Visual Soil Assessment (VSA) method, topsoils at all nine pre-planting perennial sites were in either moderate or good condition (Figure 80). None of the sites were in poor condition (severely degraded). Indeed, based on the ‘structure and consistence’ score the asparagus, narcissus and cut flower sites were all mainly in good structural condition; and in general the perennial crop sites visited pre-planting had more earthworms than the annual cropping sites (Table 6). However, five out of the nine pre-planting sites had a tillage pan, with two sites (apples in Kent and blackcurrants in Glos) having a well developed tillage pan. Furthermore, based on the ‘structure and consistence’ score, one of the blackcurrants sites (Glos), the raspberries site (Kent), and one of the apple sites (Herefords.) were in poor structural condition.

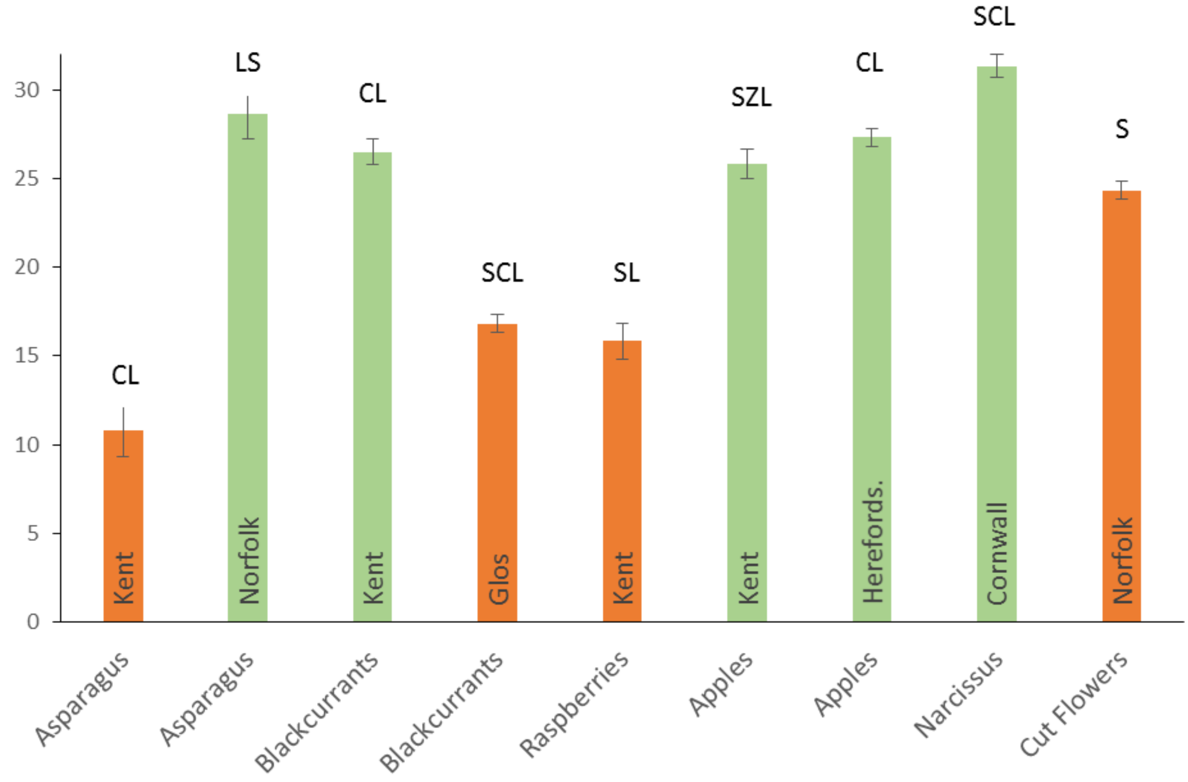


Figure 80. VSA Ranking Scores for perennial crop pre-planting sites; by location, crop type and soil type (S = sand; LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; CL = clay loam; SZL = sandy silt loam). Error bars indicate the standard error of the mean.

All twenty established perennial crop sites were in either moderate or good condition (Figures 81 and 82). None of the topsoils were in poor condition (i.e. severely degraded).

Two asparagus sites were in good condition and two in moderate condition (Figure 81), although the two in good condition (Herefords and Lincs) had a moderately developed tillage pan. The VSA score did not appear to relate to the age of the asparagus crop. All the blackcurrant sites were in good condition whether they had been established for one or seven years (Figure 81); although ‘structure and consistence’ was generally ‘moderate’ and two of the sites (Essex & Borders) had a clearly developed tillage pan under the beds. The established raspberries, apple, narcissus and cut flower sites were all in moderate condition (Figures 81 and 82). The soft fruit sites were in their first or second year while the apple orchards had a greater range of ages. Even so, there did not appear to be a clear pattern between the age of the orchard and soil condition. There were signs of a tillage pan at two of the raspberry sites (Cheshire & Staffs); three of the established apple sites (the three year old Kent site, Glos and Cambs); one narcissus site (Norfolk); and one cut flower site (Norfolk). Earthworm numbers were similar to levels in annual cropping topsoils, although there did appear to be some differences between perennial crop types. All the asparagus, narcissus and cut flower sites had fewer than 100 earthworms per m^2 (<4 worms per extracted block). The soft fruit sites were more variable with three sites (Herefords, Staffs & Borders) having fewer than 100 earthworms per m^2; three sites (Kent, Essex and Cheshire) 100-200; and one site (Norfolk) >200 (390 per m^2). Three of the apple orchards (in Kent and Cambs) had over 200 earthworms per m^2 (range = 225-290) with the other (in Glos) having 120*.*

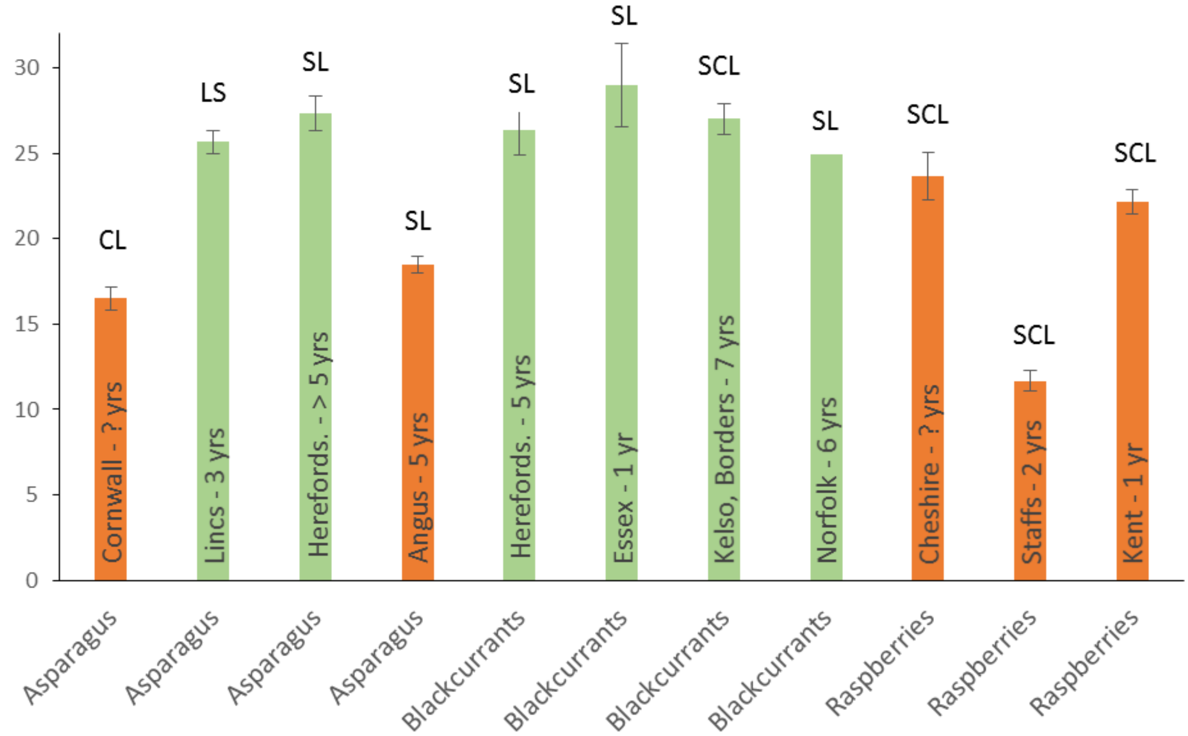


Figure 81. VSA Ranking Scores for established perennial crop sites (asparagus and soft fruit); by crop type, location, years in crop and soil type (S = sand; LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; CL = clay loam; SZL = sandy silt loam). Error bars indicate the standard error of the mean.

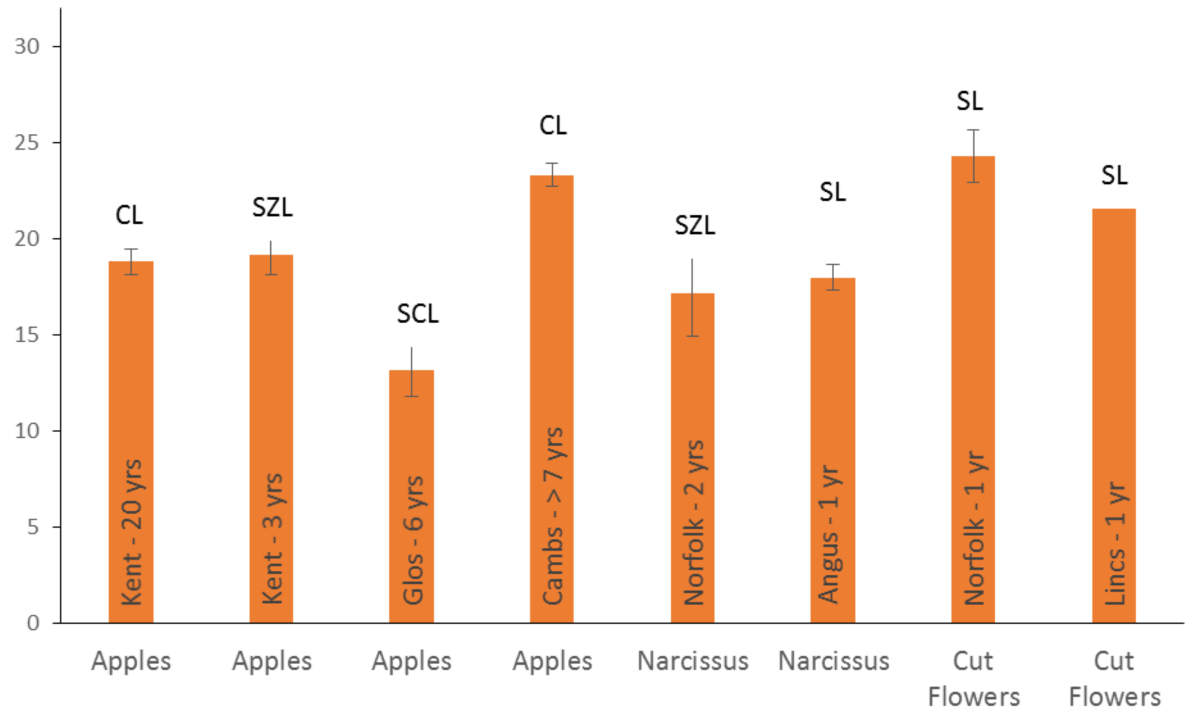


Figure 82. VSA Ranking Scores for established perennial crop sites (apples, narcissus and cut flowers); by crop type, location, years in crop and soil type (S = sand; LS = loamy sand; SL = sandy loam; SCL = sandy clay loam; CL = clay loam; SZL = sandy silt loam). Error bars indicate the standard error of the mean.

VESS – perennial crops

Three of the nine pre-planting perennial crops sites (Table 6) had a topsoil layer that scored compact or very compact in the VESS assessment: the blackcurrants site in Gloucestershire, the raspberries site and the apples site (both in Kent).

Similarly, seven of the nineteen established perennial sites had a compact or very compact topsoil layer, with all crop types represented (Table 7): the Herefordshire (>5 year) asparagus site; the Essex (first year) blackcurrant site; the Cheshire raspberries site (age of crop unknown); the Kent (3 year) and Cambs (>7 year) apple sites; the Norfolk (second year) narcissus site; and the Norfolk (first year) cut flower site. The age of the crop did not appear to have an important influence on whether or not there were clear signs of soil compaction.

Around two thirds of pre-planting and established perennial crop sites, therefore, did not have a compacted topsoil layer, indicating that at the majority of perennial crop sites soil structure was not a significant limitation to drainage, nutrient use efficiency or productivity.

Table 6. Results for pre-planting perennial crop sites

Previous crop	***Next crop***	***Location***	***Soil type***	***Mean VSA score***	***VSA – tillage pan***	***VSA – earthworms (per m^2)[1]***	***VESS – compact or v compact***	***Mean SubVESS score[2]***
Cover crop	Asparagus	Kent	clay loam	10.8	Yes	250	No	**2.7**
Winter barley	Asparagus	Norfolk	loamy sand	28.7	No	0	No	2.0
Winter wheat	Blackcurrants	Kent	clay loam	26.5	No	270	No	**2.9**
Winter wheat	Blackcurrants	Glos	sandy clay loam	16.8	Yes	30	Yes	2.4
Strawberries	Raspberries	Kent	sandy loam	15.8	Yes	25	Yes	**2.6**
No data	Apples	Kent	sandy silt loam	25.8	Yes	110	Yes	1.6
No data	Apples	Herefords.	clay loam	27.3	Yes	80	No	2.0
Calabrese	Narcissus	Cornwall	sandy clay loam	31.3	No	370	No	2.3
Sugar beet	Cut Flowers	Norfolk	sand	24.3	No	20	No	1.1

[1] Earthworm number per 20 x 20 cm block multiplied by 25.

[2] SubVESS scores: 1 = friable; 2 = firm; 3 = some compaction; 4 = compact; 5 = structureless.

Table 7. Results for established perennial crop sites.

Crop	***Age of crop (years)***	***Location***	***Soil type***	***Average VSA score***	***VSA – tillage pan***	***VSA – earthworms (per m^2)[1]***	***VESS – compact or v compact***	***Mean SubVESS score[2]***
Asparagus	No data	Cornwall	clay loam	16.5	No	<100	No	2.0
Asparagus	3	Lincs	loamy sand	25.7	Yes	<100	No	1.9
Asparagus	>5	Herefords.	sandy loam	27.3	Yes	<100	Yes	**2.9**
Asparagus	5	Angus	sandy loam	18.5	No	<100	No	No data
Blackcurrants	5	Herefords.	sandy loam	26.3	Yes	<100	No	2.4
Blackcurrants	1	Essex	sandy loam	29.0	Yes	100-200	Yes	1.9
Blackcurrants	7	Borders	sandy clay loam	27.0	Yes	<100	No	**2.7**
Blackcurrants	6	Norfolk	sandy loam	25.2	No	>200	No	2.2
Raspberries	No data	Cheshire	sandy clay loam	23.7	Yes	100-200	Yes	**2.6**
Raspberries	2	Staffs	sandy clay loam	11.7	Yes	<100	No	**2.6**
Raspberries	1	Kent	sandy clay loam	22.2	No	100-200	No	1.6
Apples	20	Kent	clay loam	18.8	No	>200	No	2.0
Apples	3	Kent	sandy silt loam	19.2	Yes	>200	Yes	1.5
Apples	6	Glos	sandy clay loam	13.2	Yes	100-200	No	2.3
Apples	>7	Cambs	clay loam	23.3	Yes	>200	Yes	1.7
Narcissus	2	Norfolk	sandy silt loam	17.2	Yes	<100	Yes	**3.0**
Narcissus	1	Angus	sandy loam	18.0	No	<100	No	**2.8**
Cut Flowers	1	Norfolk	sandy loam	24.3	Yes	<100	Yes	**2.5**
Cut Flowers	1	Lincs	sandy loam	22.2	No	<100	No	**2.9**

[1] Earthworm number per 20 x 20 cm block multiplied by 25.

[2] SubVESS scores: 1 = friable; 2 = firm; 3 = some compaction; 4 = compact; 5 = structureless.

SubVESS – perennial crops

Although none of the subsoils at the pre-planting perennial crop sites were ‘compact’ or ‘structureless’, there were some ‘signs of compaction’ at three of the nine sites (Table 6): an asparagus site, a blackcurrants site and the raspberries site (all in Kent).

Similarly, there were signs of subsoil compaction at nine of the nineteen established perennial crop sites (Table 7): the Hereford asparagus site (>5 years); the Borders blackcurrants site (7 years); the raspberries in Cheshire (age unknown) and Staffordshire (second year); the Gloucestershire apple orchard (6 years); and all four established narcissus/cut flower sites (all first or second year crops). All these crops were established on sandy loam, sandy clay loam or sandy silt loam soil types.

Soil management practices – perennial crops

As with annual crop growers a large percentage (87%) of perennial crop growers surveyed felt soil structural condition was an issue for crop production, with the key issues again being compaction, capping and waterlogging (*Figure 83*).

Although most growers felt soil structure was an issue only 59% were confident they could assess the structure of their soil (Figure 84). Even though 71% of growers were visually assessing their soil, predominantly using a spade, three quarters (76%) were keen to learn more about assessing soil structure (Figure 84).

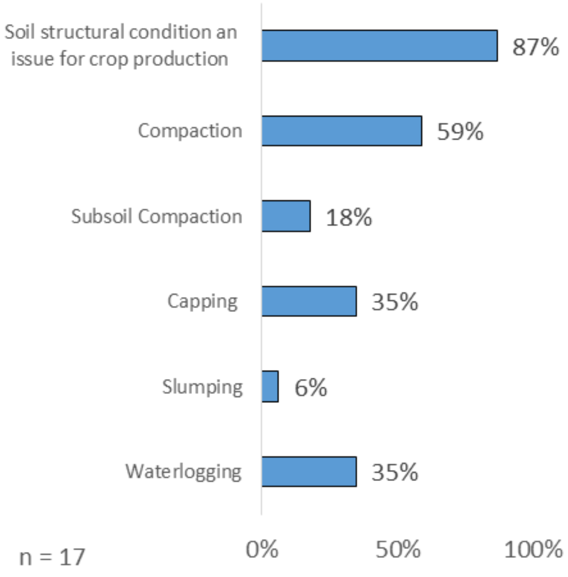


Figure 83. Key structural issues affecting crop production on perennial cropping farms

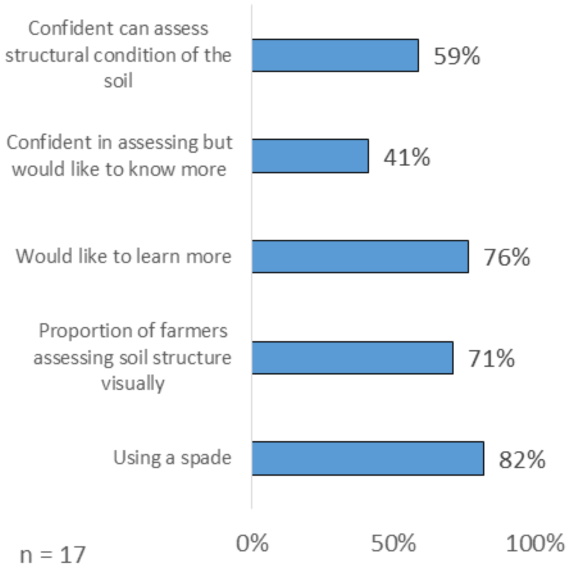


Figure 84. Grower attitudes to assessing soil structure on perennial cropping farms.

Soil mapping was being used by nearly half (47%) of perennial crop growers, principally for pH and nutrients (41%), with 18% variably applying nutrients or lime (Figure 85). However, none of the growers surveyed were using electrical conductivity (EC) mapping to guide soil zoning. A small number of growers were mapping potato cyst nematode (PCN) and using UAV (unmanned aerial vehicle/drone) technology to monitor crop health (*Figure 85*).

As was the case for annual cropping farms, over half the perennial crop growers surveyed (61%) had maintained or invested in new drainage in recent years, and an even greater number (92%) mole drained or subsoiled to improve drainage (*Figure 86*).

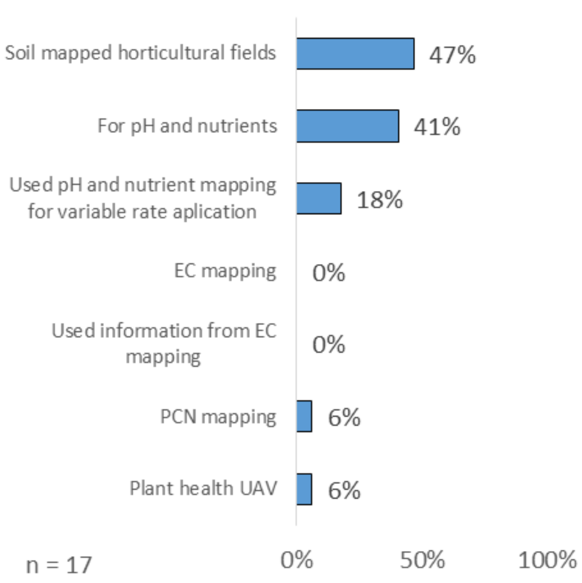


Figure 85. Proportion of growers using soil mapping technology on perennial cropping farms.

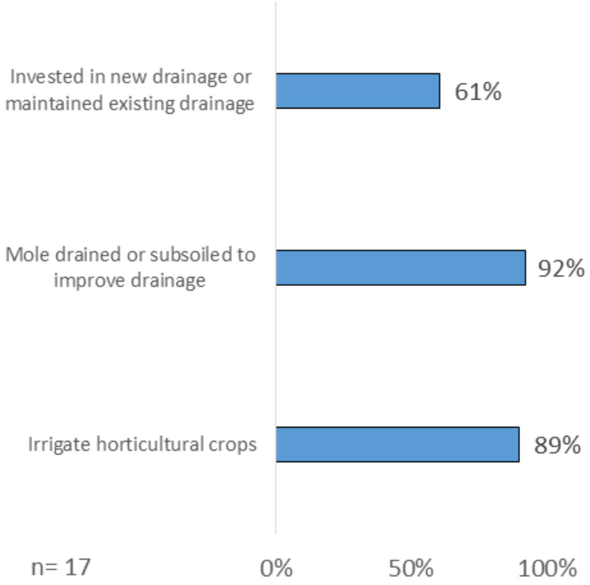


Figure 86. Proportion of growers improving drainage and irrigating on perennial cropping farms.

Perennial crop growers used a similar range of methods to annual crop growers to improve soil structure on their farms, with organic amendments most widely used. Certain measures that lend themselves to perennial systems, such as grass alleyways, were more widely used in perennial crop fields (Figure 87).

Although many growers felt that cultivations were still the major tool for tackling soil structural issues (e.g. 65% mentioned subsoiling), growers were using a number of other methods (Figure 87). None of the perennial crop growers surveyed were using reduced tillage, but 6% were using controlled traffic farming to help improve soil structure (Figure 87).

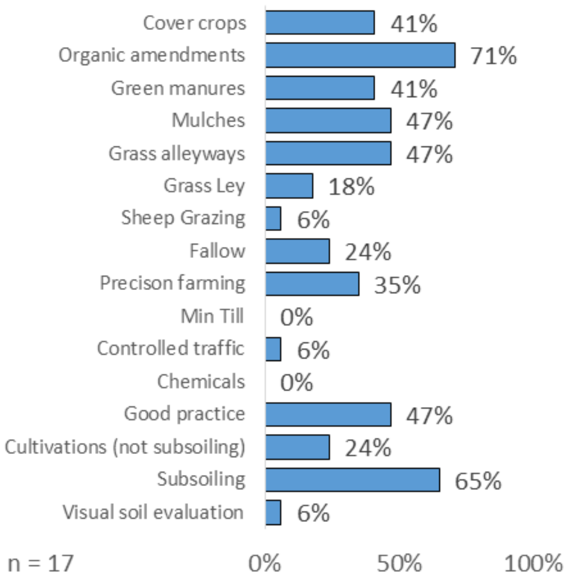


Figure 87. Other practices growers are adopting to improve soil structure across perennial crop sites.

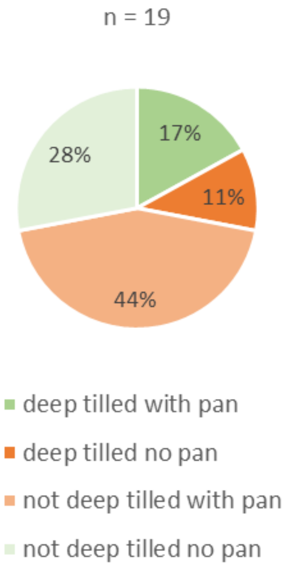


Figure 88. Deep cultivation in the presence or absence of a tillage pan on perennial crop sites.

Data from VESS assessments in combination with field information showed that only 17% of sites visited were deep cultivated when there was evidence of a tillage pan. A large proportion of sites (44%) were not deep cultivated when a pan was present, with a smaller number (11%) deep cultivated with no pan present (Figure 88). Although there are limited opportunities for deep cultivation on established perennial crop sites, the results indicate that compaction may be a common issue limiting management and productivity.

Data collected on cultivations used to prepare perennial crop sites for planting showed that 71% of growers surveyed were ploughing and 43% subsoiling, to average depths of 28 and 38 cm respectively. Other cultivations included rotavating and bed ridging in asparagus; and use of a boat planter (5-15 cm depth to move soil to wheelings and then back in to cover bulbs), deep ridging, bed formers (20-25 cm depth) and destoners (20-25 cm depth) in soil preparation for cut flowers and narcissus. In general, ploughing depth appeared to coincide with the depth of tillage pans and subsoiling depth was well below it (Table 8).

Table 8. Cultivation methods and depths used to prepare the ground for perennial crops.

Crop type	**Growers Ploughing (%)**	**Average ploughing depth (cm)**	**Growers subsoiling (%)**	**Average subsoiling depth (cm)**	**Growers not ploughing or subsoiling (%)**	**Average cultivation depth (cm)**	**Pre-planting average depth of topsoil tillage pan (cm)[1]**	**Post-planting average depth of topsoil tillage pan (cm)[1]**
Pre-planting perennial crops (n=14)	71	28	43	38	14	10	10-27	5-25
Asparagus (n=3)	33	30	0	-	66 (rotovator)	10	0-25	8-25
Blackcurrants & raspberries (n=4)	50	28	75	38	0	0	10-30	3-25
Apples (n=2)	100	25	1	no data	0	0	14-27	0-26
Cut Flowers / narcissus (n=5)	100	28	40	38	0	0	0	16-32

[1] Data only from sites scoring between firm and very compact on VESS assessments

Discussion

The use of robust soil physical quality indicators (e.g. dry bulk density) and visual evaluation methods has resulted in a comprehensive overview of the structural condition in a range of horticultural soils. For annual crops, the majority of topsoils were in moderate condition pre-planting and cultivation resulted in a general improvement in topsoil condition, including the disruption of tillage pans in many cases (e.g. for root crops and alliums). However, there were a few differences between crop types. For example, vigorous cultivation in root crops (71% of fields subsoiled to an average depth of 43 cm) resulted in complete removal of tillage pans and widespread improvement in soil condition scores post-planting. This was also reflected in penetrometer resistance measurements. However, the high VSA scores for structure and consistence (abundant small aggregates) post-planting may also reflect a degree of soil structural instability, which is reflected in the contrast between pre-planting and post-planting scores and the relatively low number of earthworms in carrot and parsnip cropping topsoils.

Leafy salad fields were notable in that the proportion of topsoils with a tillage pan actually increased post-planting, indicating that cultivations may have been carried out in ‘wet’ soil conditions. Similarly, under brassica crops the proportion of topsoils that were either firm or compact (VESS assessment) increased post-planting. Brassicas and vining peas were the only annual crops that had topsoil bulk density values clearly above UKSIC trigger values post-planting, indicating low topsoil porosity. Interestingly, this was also reflected in no change in the proportion of fields with a tillage pan after cultivation and planting.

In general, subsoil bulk density values under annual cropping were slightly above UKSIC concern levels, particularly in alliums and leafy salads, although this was not reflected in poor SubVESS scores, which in general detected ‘some compaction’ rather than ‘compact’ or ‘structureless’ subsoils. The management of soil structure within the ‘transition’ layer between the topsoil and subsoil is still open to question. Where compaction at this depth limits rooting and drainage in more stable, medium-textured soils, subsoiling is advised, but in more sensitive loamy sand or sandy silt loam soils a degree of compression may provide bearing strength and stability without compromising rooting or drainage, and deep subsoiling of these soils in the wrong conditions could result in ‘slumping’, instability and related management problems (Batey, 2009).

Most pre-planting perennial crop sites were in good soil structural condition, although a third of sites had a compacted topsoil layer and/or some signs of compaction in the subsoil. Although it was difficult to compare due to low sample numbers, a higher proportion of established perennial crop sites had signs of topsoil and/or subsoil compaction. Based on bulk density values, asparagus and cut flower beds had good topsoil and subsoil porosity. However, the majority of established sites were in moderate rather than good condition based on visual assessments. Relatively high bulk density values indicated low porosity in soft fruit and apple orchard topsoils and in soft fruit upper subsoil. About a third of established sites had a compacted layer in the topsoil and around a half had some signs of compaction in the subsoil, but there was no clear pattern between the age of the perennial crop and soil condition. Earthworm numbers were similar to levels in annual crops, but there were some differences between perennial crop types with numbers generally lower in asparagus and flower beds and higher under apple orchards.

The pressures of late harvesting and establishment schedules to meet market requirements inevitably lead to some soil structural damage. The challenge within horticulture systems is to avoid or limit this damage where possible and use efficient methods to alleviate compaction when it occurs. Methods also need to match the degree of compaction and should include methods to improve soil health and resilience as well as those to repair damage. The industry is still fairly reliant on subsoiling as a means of alleviating compaction, with 92% of growers deep cultivating. It is encouraging that 70% of annual cropping growers adjust the working depth based on visual assessments, but there may be scope to reduce the amount of unnecessary subsoiling, particularly if controlled traffic systems are more widely adopted. Interestingly, based on our assessments, around 8% of sites were deep tilled where no tillage pan was present and 40% of sites were not deep tilled when a pan was present, so there may be a case for more rather than less subsoiling as long as cultivations are based on the use of a spade to check soil structure (or EC/EMI scanning in combination with spade use).

Around 5% of annual crop and 6% of perennial crop growers are already using controlled traffic farming (CTF) principles to improve soil structure. In some cases this has been adopted in combination with the use of cover crops and reduced tillage systems. CTF systems are well adapted to some horticulture systems (McPhee *et al*., 2015), but given the extent of compaction indicated in this survey (70% of annual cropping sites and 60% of perennial crops had a tillage pan) it is important that soil structural degradation is addressed before a system reliant on cover cropping and reduced depth tillage is fully adopted. It may take a number of years of deep cultivation, and cover cropping before soil structure is sufficiently improved to rely on a reduced tillage CTF approach. Indeed, in many horticulture rotations it may be difficult to achieve the full benefits of complete CTF, with seasonal CTF (all operations apart from harvest on the same track gauge) being a more realistic option.

The soil structure survey outputs will be used as a tool for dissemination to raise awareness of the state of UK horticultural soils and how practices can be improved. With 33% of annual cropping growers and 76% of perennial crop growers interested in learning more about visual assessment it will be important to develop guidance materials that are tailored to horticulture systems. Ideally visual assessment guides should link to the management and cultivation options specific to each sector and crop type, and should be adapted to UK soil types and conditions. The VSA and VESS methods form a good basis from which to develop a soil structure assessment and management toolkit for horticulture sector growers.

Conclusions

- The survey of soil structure identified that the majority of soils under annual and perennial cropping were in moderate condition. None of the soils were in poor condition (i.e. topsoil and subsoil severely degraded).
- In many cases, moderate topsoil condition was related to the presence of a tillage pan (around 70% of annual crops and 60% of perennial crops), and low earthworm numbers.
- In general, cultivations resulted in an overall improvement in soil condition, although in some cases (e.g. soil preparation for carrot and parsnip crops) the contrast in condition between pre-planting and post-planting indicated a degree of instability in soil structure (i.e. large aggregates broke down very readily).
- It was clear that the majority of soil cultivation practices addressed the common soil structural issues encountered in horticulture cropping systems. However in some cases cultivation had no effect or resulted in deterioration of soil structural condition.
- On average, subsoil bulk density values were above UKSIC concern levels under annual crops such as alliums and leafy salads. Further work is needed to determine whether or not this indication of low porosity has significant implications for system efficiency and productivity and how these high bulk density soils should be managed.
- Cultivations were not always matched to soil conditions or the need for subsoiling, with some soils (*c*.10%) deep cultivated when there were no signs of compaction and other soils (*c*.40%) not deep tilled when there were clear signs of a compacted layer.
- Growers acknowledged that soil structural condition is an issue for crop production and used a variety of methods to improve soils, including the use of cover crops and organic amendments. There was widespread reliance on subsoiling with relatively few growers investigating controlled traffic (c.5%) or reduced tillage (24%) approaches.
- Around a third of annual crop growers and three quarters of perennial crop growers are keen to learn more about visual assessment of soil structure to inform soil management decisions.

- The results of the soil survey provide a useful tool for dissemination, discussion and knowledge exchange that will help stimulate interest and develop awareness and industry expertise in soil management practices.

Knowledge and Technology Transfer

Demonstration open days

The results of the soil structure survey were presented and discussed at three demonstration open days in year 2 of the project:

- Canopy sensing for variable rate N management: 22nd September 2016 at Glassford Hammond Farming, Notts.
- Controlled traffic farming: 3rd November 2016 at Barfoots, West Sussex
- Options for soil mapping: 7th February 2017 at F.B. Parrish & Son, Beds.

A further three events are planned for 2017. Dissemination and knowledge exchange activities at the demonstration plot sites will help growers to assess tools and techniques that would be most likely to improve soil and nutrient management practices and production efficiency on their farms. Each field demonstration open day will include soil pits for the demonstration of visual soil evaluation and information on methods to avoid and alleviate compaction.

Other project meetings and knowledge transfer activities

There were a number of additional project meetings, events and press articles in year 2 of the project (April 2016 to March 2017).

Meetings & events

- GREAT soils event, 21st September 2017 at Riviera Produce Cornwall. Presentation:
    - ‘Taking the compact out of compaction’
- Elsoms open day 12-13th October 2016. ‘Mini’ presentations:
    - ‘Soil structural condition in horticultural systems’
    - ‘How can we use precision faming tools to improve soil and nutrient management in horticulture?’
- Brassica and leafy salads conference, 25th January 2017. Presentation:
    - ‘State of our soils and potential for precision farming to improve soil and nutrient management’

Press articles

- AHDB Grower magazine, June 2016
    - ‘AHDB demonstrates soils research results’ (in news section)

- AHDB Grower magazine, June 2016
    - ‘Breaking new ground’ (feature article including results from soil structure survey and precision farming review).
- Vegetable Farmer magazine, August 2016
    - ‘Increased awareness of soil health does not make management easier’ (feature article)
- AHDB Grower magazine, December 2016/January 2017
    - ‘Take the pressure off’ (feature article from CTF demonstration day at Barfoots).
- AHDB Grower magazine, March 2017
    - Cover crops and precision farming feature in soils events (in news section)
- Vegetable Farmer magazine, March 2017
    - ‘Precision farming project demonstrates savings’ (in news section based on CTF demonstration at Barfoots)
- AHDB Grower magazine, April 2017 (in press)
    - ‘Does it pay to be precise?’ (Feature article on variable rate N demonstration at Glassford Hammond Farming).

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A total of 56 growers across England and Scotland have contributed to the soil structure survey and have provided information on soil management on their farm.

Appendices

This will include all supporting statistical analyses, raw data, and additional relevant photographs not incorporated elsewhere.