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Soil Biology and Soil Health Partnership Project 14: Rectifying Soil Structural Damage

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This is the final report of a 10-month project (Project 14) within the Soil Biology and Soil Health Partnership (AHDB: 91140002), which started in October 2020. The work was funded by a contract for £16,450 from AHDB and BBRO.

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1. Abstract

This project is part of a suite of integrated projects (Soil Biology and Soil Health Partnership) specifically aimed at addressing the AHDB and BBRO Soils Programme call - "Management for Soil Biology and Soil Health". This project was one of a number of activities funded through the Innovation Fund, designed to address knowledge gaps that arose over the 5-year duration of the programme (see Figure 1).

Keeping soils in good condition improves production efficiency, reduces costs and increases productivity. Preventing soil compaction occurring is the best strategy. However, harvesting crops in wet conditions is sometimes unavoidable and can result in significant structural damage that could compromise productivity for years. Similarly, cultivating soils, establishing crops, grazing livestock or silaging in sub-optimal conditions can cause compaction. This project summarises current guidance on how to rectify soil structural damage, including the use of vigorous rooting green crops for this purpose, and provides sign-posting for a farmer/grower using the soil health scorecard on the options available for improving soil physical condition. It is divided into 3 core sections: i) a review of vigorous rooting green crops to improve soil structure; ii) rectifying soil structure guidance; and iii) three case studies evaluating the use of the Soil Biology and Health Partnership soil health scorecard where soil structural damage is evident.

Vigorous rooting green crops (cover crops, catch crops, green manures and short-term herbal leys) are often promoted as a strategy to improve soil structure. However, evidence for this approach is unclear and there is a lack of guidance, for example, regarding which vigorous rooting crop species should be selected and how crops should be managed for optimal benefit to soils. The review therefore aimed to summarise the available evidence of the ability of vigorous rooting green crops to remediate soil structural damage. Recent studies (published from 2010 onwards) quantifying effects of vigorous rooting crops on indicators of soil structure (soil bulk density, penetration resistance and visual evaluation of soil structure scores), that were based in the UK or similar climate systems were reviewed. In total, 11 studies were found that were directly relevant to this review.

The results highlight the lack of evidence of a clear and consistent effect of vigorous rooting crops on soil structure. Some evidence suggests that when integrated into reduced or no till cropping systems for multiple years, vigorous rooting crops can be of benefit to topsoil structure. However, there is a lack of longer terms studies (> 1.5 years) and studies which quantify changes to soil structure at depths > 30 cm. There is some evidence that tap-rooted species are most suited to improving soil structure in compacted soils, however more evidence is needed to determine which species and species mixtures perform best, the levels and depths of soil compaction that can be remediated and the timescales for these changes. Improved understanding of the benefits and

limitations of using vigorous rooting crops for remediating soil structure is required to guide best practice so that optimal agronomic and environmental benefits may be achieved.

Soil structural damage is sometimes unavoidable, but when it happens remember to assess, consider the appropriate response (right action; right conditions) and then reassess the effectiveness of any field operation. In many cases all you need is vegetation cover, roots and earthworms to improve soil conditions over time. Indeed, on soils that crack, no action is often sufficient. If using metal, carefully consider whether it is necessary and whether you have the right conditions for an effective operation.

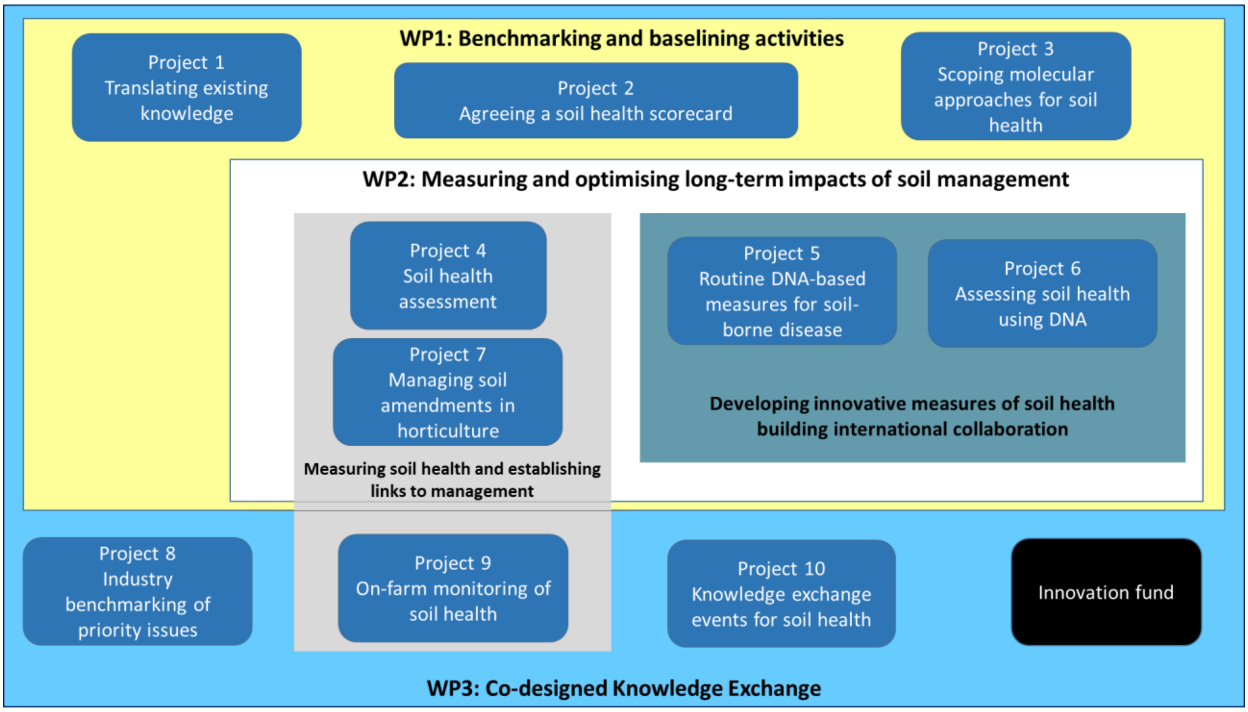

Figure 1. Diagram to show how this project fits into the organisation of the Soil Biology and Soil Health Partnership: Project 14 is one of the projects funded under the "Innovation fund"

2. Introduction

Changes in the pattern and intensity of rainfall over recent years have left farmers struggling to harvest and establish crops in difficult conditions. In many circumstances, delaying harvest is not often possible because of the impact on crop quality and/or requirements to maintain supply to supermarkets. This has resulted in soil structural damage which may impact the following crops in the rotation. Soil structural damage is particularly problematic in field vegetable rotations and those involving late harvested root crops and field-grown hardy nursery stock. However, it has also been evident across the arable sector, for example in autumn 2019 where farmers struggled to get winter crops drilled due to an exceptionally wet autumn. It can also be an issue for grassland farms applying slurry and that aim to extend livestock grazing into late autumn.

The causes and consequences of soil structural damage (i.e. compaction, capping, slumping, puddling, smearing, erosion, runoff and flooding) are well understood and there is good guidance across sectors about how to avoid, identify and alleviate it (e.g. AHDB Soil management for horticulture, Healthy Grassland Soils, Arable soil management: Cultivation and crop establishment, Field drainage guide). Rectifying soil structural damage often involves improving drainage and using targeted cultivations to remove compacted layers. The use of vigorous rooting green crops (green manures, cover crops, catch crops, temporary herbal leys) is also being promoted. However, the effectiveness of this approach is unclear, and there is a lack of guidance on the use of green crops for this purpose (e.g. when to use, what to use and how to manage).

The soil health scorecard being developed as part of the Soil Biology and Soil Health Partnership (SBSH) aims to help farmers evaluate the soil chemical, physical and biological condition of their soils in an integrated way. Visual evaluation of soil structure (VESS) is used to assess soil physical condition, with texture, soil organic matter content and earthworm numbers also providing an indication of how resilient a soil might be to soil structural damage. The scorecard is being tested across a variety of experimental and on-farm sites, but none where soil structural damage is known to be an issue.

2.1. Objectives

This project summarises current guidance on how to rectify soil structural damage, including the use of vigorous rooting green crops for this purpose, and provides sign-posting for a farmer/grower using the soil health scorecard on the options available for improving soil physical condition. It has been divided into three sections in line with the following three objectives:

1. Review the UK evidence (extended to studies undertaken in temperate cropping systems where appropriate) for the use of green crops to repair structural damage following harvesting/trafficking in wet conditions.
2. Summarise the current advice on rectifying soil structural damage (across the range of sectors), outlining the potential options available to farmers and growers and providing sign-posting to existing relevant guidance that is specific to the sector in question.
3. Evaluate and test the soil health scorecard approach at three case study sites where soil structural damage is evident:
    - Barfoots Farms Ltd (field vegetables)
    - Wyevale Nurseries Transplant Division (hardy nursery stock)
    - SoilCare project compaction study at GWCT (arable cropping)

3. Evidence review of the use of vigorous rooting green crops to rectify soil structural damage

3.1. Method

This review has focused on UK-based evidence published in the last 11 years (publication date of 2010 or after). The review has included scientific and grey literature as well as popular press articles relevant to the subject. Where appropriate, studies undertaken in other temperate regions with similar crop rotations to the UK were also included.

The review addressed the following research questions:

1. To what degree are vigorous rooting crops grown as catch/cover crops, green manures or short-term herbal leys effective in rectifying soil structural damage in the topsoil and subsoil in UK and temperate oceanic agro-climatic conditions?
2. What degree (as defined by soil physical quality indicators such as penetration resistance, dry bulk density or visual score) and depth of soil compaction can catch/cover crops, green manures or short-term herbal leys rectify?
3. Under which cropping, crop rotation and soil type conditions are vigorous rooting crops grown as catch/cover crops, green manures or short-term herbal leys most effective in rectifying soil structural damage?
4. Which plant species, plant species traits or plant species mixtures grown as catch/cover crops, green manures or short-term herbal leys, are most effective for rectifying soil structural damage?
5. What is the optimal method for establishing and managing species or species mixtures of vigorous rooting crops grown as catch/cover crops, green manures or short-term herbal leys for rectifying soil structural damage?

3.1.1. Search terms and search method

The following search terms were applied to the Web of Science search engine:

"catch crop*" OR "cover crop*" OR "green manure*" OR "herb* ley*" OR "grass ley*"

AND

"soil structur*" OR "soil qualit*" OR "soil physical properties" OR "penetration resistance" OR "bulk densit*" OR "visual score*" OR (compact* AND soil*)

AND

"crop rotation*" OR species OR trait* OR mixture* OR establish* OR manag*

AND

Timespan: 2010:2020

This search returned 760 articles.

Articles were further refined to include only those within the following research categories: soil science, agronomy, environmental sciences, agricultural multidisciplinary, plant sciences, ecology, horticulture, water resources, green sustainable science technology, biodiversity conservation, biology and environmental studies. This returned 641 articles.

Articles were then refined to include only those which met both the below criteria which returned 312 articles.

1. Study location must have a temperate oceanic climate according to the Köppen climate classification (Kottek *et al.*, 2006) which used the following definition of a temperate oceanic climate: coldest month averaging above 0 °C (or −3 °C), all months with average temperatures below 22 °C, and at least four months averaging above 10 °C with no significant precipitation difference between seasons.
2. Study location must be within the temperate latitude range (35°- 60° N or S).

These articles were then each examined based on title and abstract to select those relevant to the review. In total 11 scientific papers/reports were relevant, and the results are detailed in this review (see summary Table 3.1 (bulk density), Table 3.2 (soil penetration resistance) and Table 3.3 (Visual Evaluation of Soil Structure). Some additional relevant articles including grey literature were found using further search terms and are referred to in the review text. For simplicity, throughout this review the term 'vigorous rooting crop' is used to refer to all cover crops, catch crops, green manures and grass/herbal ley species.

Table 3.1 Summary of literature review papers quantifying effects of vigorous rooting (VR) green crops on soil bulk density (BD). Rows shaded grey provide site and other metadata per site for the unshaded cells below, nd = no data, ns = no statistically significant effect.

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
Washington State, USA	1060	10.3	Sandy loam	24 (BD measured at 24 months all treatments)	Oct 2014- autumn 2015, Oct 2015 - autumn 2016	*Triticum aestivum* 'Norwest' (hard red winter wheat)	ns	1.20	0-7.5	Red raspberry (perennial alley system)	Mowed	Drilled	Sub-soiled/roto-tilled	(Rudolph *et al.*, 2020)[a]
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Triticum aestivum* 'Rosalyn' (soft white winter wheat)	ns	1.18	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Avena sativa* 'Nora' (winter hardy oat)	ns	1.18	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Avena sativa* 'TAM 606' (winter hardy oat)	ns	1.16	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Lolium perenne* (perennial ryegrass mix)	ns	1.18	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Triticosecale* sp. 'Trical 103BB' (triticale)	ns	1.12	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - autumn 2016	*Triticosecale* sp. 'TriMark 099' (triticale)	ns	1.18	0-7.5					
				24	Oct 2014 - autumn 2015, Oct 2015 - Autumn 2016	*Secale cereale* (rye)	ns	1.18	0-7.5					
				24	Oct 2014 - autumn 2016	2 sp. mix: *Lolium hybridum*, *Lolium*	ns	1.17	0-7.5					

[a] Results reported in the table are from the second year of growth. The first year of the experiment also reported no significant effect of any of the cover crops on bulk density.

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
						perenne (intermediate and tetraploid perennial ryegrass)								
Samsun, Turkey	685.5	14.5	Clay loam	24+ (BD measured in second year, all treatments)	Apr 2012 - autumn 2014	*Festuca rubra* (red fescue)	ns ns	~1.21 -	0-20 20-40	Hazelnut orchard	Mowed	Broadcast seeding and shallow cultivation	nd	(Demir & Işik, 2020)
				24+	Apr 2012 - autumn 2014	*Trifolium repens* (white clover)	Decrease (9.2%) ns	~1.18 -	0-20 20-40					
				24+	Apr 2012 - autumn 2014	*Festuca arundinacea* (tall fescue)	ns ns	~1.20 -	0-20 20-40					
				24+	Apr 2012 - autumn 2014	3 sp. mix: *Trifolium repens* (white clover), *Festuca rubra* (red fescue) and *Festuca arundinaceae* (tall fescue) (40:40:20)	Decrease (8.5%) ns	~1.19 -	0-20 20-40					
				24+	Oct 2012 - autumn 2013, Oct 2013 - autumn 2014	*Vicia villosa* (hairy vetch)	Decrease (9.2%) ns	~1.18 -	0-20 20-40					
				24+	Oct 2012 - autumn 2013, Oct 2013 - autumn 2014	*Trifolium meneghinianum* (agean clover)	ns ns	~1.20 -	0-20 20-40					
Andisleben, Germany (II)	500-550	8.5-9.0	Silty clay loam	9 (BD measured in April 2011, 9 months)	Jul 2010 - winter 2010	3 sp. mix: *Vicia faba* (field bean), *Pisum sativum* (field pea), *Vicia sativa* (vetch)	ns	1.16-1.27	9-12	Cereal	Mulching	Direct seeding	Frost	(Rücknagel *et al.*, 2016)
Rothenberga, Germany (I)	500-550	8.5-9.0	silt loam	8 (BD measured in Apr 2012, 8 months)	Aug 2011 - winter 2011	*Vicia faba* (field bean)	ns	1.13-1.16	9-12	Cereal	Mulching	Direct seeding	Frost	

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
Rothernberga, Germany (II)	500-550	8.5-9.0	silt loam	7 (BD measured Mar 2014, 7 months)	Aug 2013 - winter 2013	3 sp. mix: *Vicia faba* (field bean), *Pisum sativum* (field pea), *Vicia sativa* (vetch)	ns	1.11-1.13	9-12	Cereal	Mulching	Direct seeding	Frost	
British Columbia, Canada	1483	10.4	Sandy loam	45 (BD measured Sept 2010, 12 months)	Sept 2009 - March 2010	*Hordeum vulgare* (barley)	ns	1.18	10-15	Raspberry	nd	Subsoiled and ploughed before sowing	Roto-tilled	(Forge *et al.*, 2016)
Maryland, USA	1033	14.4	Silt loam	156 (BD measured after 13 years)	Autumn - winter (annually)	*Secale cereal* (rye)	Decrease (11%)	1.26	1-7	Continuous corn	nd	nd	nd	(Steele *et al.*, 2012)
Maryland, USA, (Exp 1)	1125	14.4	Fine loam	24 (BD measured March 2008, 20 months all treatments)	Aug 2006 - winter 2006, Aug 2007 - winter 2007	*Raphanus sativus* (radish)	ns	nd	0-40	Arable rotation	N fertiliser at planting	Disked to 8 cm depth, no till drill	Frost	(Chen & Weil, 2011)
					Aug 2006 - Apr 2007, Aug 2007 - Apr 2008	*Brassica napus* (rapeseed)	ns	nd	0-40				Paraquat dichloride Apr 2007, glyphosate Apr 2008	
					Aug 2006 - Apr 2007, Aug 2007 - Apr 2008	*Secale cereale* (rye)	ns	nd	0-40				Paraquat dichloride Apr 2007, glyphosate Apr 2008	
(Exp 2)	1125	14.4	Coarse loamy sand	12 (BD measured March 2008, 7 months, all treatments)	Aug 2007 - Sept 2008	*Raphanus sativus* (radish)	ns	nd	0-40	Arable rotation	N fertiliser at planting	Disked to 8 cm depth, no till drill	Frost	
					Aug 2007 – Apr 2008	*Brassica napus* (rapeseed)	ns	nd	0-40				Glyphosate	
					Aug 2007 - Apr 2008	*Secale cereale* (rye)	ns	nd	0-40				Glyphosate	

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
Leicestershire, UK	664	9.7	Clay loam	7 (BD measured Feb 2016, 5 months all treatments)	Sept 2015 - Apr 2016	2 sp, mix: *Avena sativa* (oat), *Phacelia tancetifolia*	ns	1.10	0-10	Arable rotation, no till	None	Direct drilled and rolled with a segmented ridged roller	Glyphosate (2 applications)	(Crotty & Stoate, 2019)
				7	Sept 2015 - Apr 2016	4 sp. Mix: *Avena sativa* (oat), *Secale cereale* (rye), P*hacelia tancetifolia,* (Phacelia), *Raphanus sativus* (radish)	ns	1.06	0-10					
				7	Sept 2015 - Apr 2016	7 sp. mix: *Avena sativa* (oat), *Phacelia tancetifolia, Raphanus sativus* (radish), *Vicia sativa* (vetch), *Trifolium incarnatum* (crimson clover), T*rifolium alexandrium* (berseem clover), *Fagopyrum esculentum* (buckwheat)	ns	1.06	0-10					
North Yorkshire, UK	674	9.2	Silt loam, loam, sandy loam	19[b]	May 2015 - Nov 2016	6 sp. mix*: Lolium* x *boucheanum* (hybrid ryegrass), *Lolium perenne* (perennial ryegrass), *Festulolium* spp.,	Decreased (7.4%) ns	1.38 1.37	2-7 0-22	Arable rotation	Cutting	Glyphosate, direct drill	Diquat (as dibromide)	(Berdeni *et al.*, 2021)

[b] Bulk density measured 10 months after termination of the 19-month-old grass-clover ley vegetation.

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.-month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
						Trifolium repens (white clover), *Trifolium pratense* (red clover) (28:36:16:5:15)								
Cambridgeshire, UK	568	10.2	Sandy loam	24	Sept 2016-Feb 2017	*Raphanus sativus* (radish)	ns	Site mean: 1.26 (post cover cropping). 1.15-1.37 (1 year later, in the winter crop)	25-30	Arable rotation	Slug control	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al*., 2020)
						Avena sativa (spring oat)	ns							
						Secale cereale (rye)	ns							
						Vicia sativa (vetch)	ns							
						Trifolium incarnatum (crimson clover)	ns							
						Fagopyrum esculentum (buckwheat)	ns							
						Phacelia tanacetifolia (phacelia)	ns							
						2 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum* (crimson clover) (83:17)	ns							
						3 sp. mix: *Raphanus sativus* (radish), *Phacelia tanacetifolia* (phacelia),	ns							

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	VR crop species/ species mix grown	Significant change in bulk density compared to control (decrease/ increase/ no effect)	Bulk density (g cm^{-3})	Depth of soil studied (cm)	Cropping system/rotation	VR crop management	VR crop establishment	VR crop destruction	Study reference
						Fagopyrum esculentum (buckwheat) (30:20:50)								
						5 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum* (crimson clover), *Raphanus sativus* (radish), *Phacelia tanacetifolia* (phacelia), *Fagopyrum esculentum* (buckwheat) (53:11:11:6:19)	ns							
Nottinghamshire, UK	650	9.7	Clay loam	24	Aug 2017 - Feb 2018	Identical treatments to site in Cambridgeshire detailed above	ns	Site mean: 1.36 (post cover cropping); 1.15-1.23 (1 year later, in the winter crop)	25-30	Arable rotation	Slug control	Light cultivation; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al*., 2020)
Yorkshire, UK	751	8.6	Sandy loam	24	Aug 2017 - Mar 2018	Identical treatments to site in Cambridgeshire detailed above	ns	Site mean: 1.37 (post cover cropping); 1.28-1.35 (1 year later following a second cover crop (mustard) established over the whole site	25-30	Arable rotation	none	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al*., 2020)

Table 3.2 Summary of literature review papers quantifying effects of vigorous rooting (VR) green crops on soil penetration resistance (PR). Rows shaded grey provide site and other metadata per site for the unshaded cells below, nd = no data, ns = no statistically significant effect.

Study Location	Average annual rainfall (mm)	Average annual temperature (°C)	Soil texture (topsoil)	Study duration (months)	Growing period (month est.- month dest.)	Vigorous rooting crop species/ species mix grown	Direction of change in penetration resistance compared to control (significant decrease/ increase or no significant effect	Penetration resistance (MPa)	Depth of soil studied (cm)	Cropping system/ rotation	VR crop management	VR crop establishment	VR crop destruction	Study ref
Leicestershire, UK	664	9.7	Clay loam	7 (PR measured Feb 2016, 5 months all treatments)	Sept 2015 - Apr 2016	2 sp, mix: *Avena sativa* (oat), *Phacelia tancetifolia*	ns Increased (>20%) ns	~ 0.2 ~ 0.4 to 0.7 0.7-1.5	0-2.5 5-12.5 15-45	Arable rotation, no till	None	Direct drilled and rolled with a segmented ridged roller	Glyphosate (2 applications)	(Crotty & Stoate, 2019)
				7	Sept 2015 - Apr 2016	4 sp. mix: *Avena sativa* (oat), *Secale cereale* (rye), *Phacelia tancetifolia* (phacelia), *Raphanus sativus* (radish)	ns Increased (>20%) ns	~ 0.2 ~ 0.4-0.7 0.7-1.5	0-2.5 5-12.5 15-45					
				7	Sept 2015 - Apr 2016	7 sp. mix: *Avena sativa* (oat), *Phacelia tancetifolia*, *Raphanus sativus* (radish), *Vicia sativa* (vetch), *Trifolium incarnatum* (crimson clover), *Trifolium alexandrium* (beseem clover),	ns Increased (>20%) ns	~ 0.2 ~0.4-0.7 0.7-1.5	0-2.5 5-12.5 15-45					

						Fagopyrum esculentum (buckwheat)								
Cambridgeshire, UK	576	10.5	Loamy peat topsoil (to 40 cm), heavy clay subsoil	4 (PR measured April 2017, 8 months) (4 months of growth)	Aug 2016 - Dec 2016	3 sp. mix: *Avena strigosa* 'Cadence' (black oat), *Raphanus sativus* 'Final' (radish), *Sinapsis alba* 'Braco' (white mustard), 60:35:5, (frost sensitive mix)	ns ns Increased ns ns	~2.02 ~2.08 ~1.74 ~1.69 ~1.89	1-10 11-20 21-30 32-40 41-50	Arable rotation	None	Drilled into wheat stubble (25 kg ha^{-1})	Frost	(Storr *et al.*, 2017)
				8 (PR measured Apr 2017, 8 months from est.) (8 months of growth)	Aug 2016 - April 2017	3 sp. mix: *Secale cereale* 'Protector' (rye), *Raphanus sativus* 'Evergreen' (radish), *Trifolium alexandrium* (berseem clover), 60:30:10, (winter hardy mix)	ns ns Increased Increased Increased	~2.21 ~2.22 ~1.79 ~1.93 ~2.0	1-10 11-20 21-30 32-40 41-50	Arable rotation	None	Drilled into wheat stubble (30 kg ha^{-1})	Herbicide	
Maryland, USA, Exp 1	1125	14.4	Fine loam	24 (PR measured Mar 2008, 20 months, all treatments)	Aug 2006 - winter 2006, Aug 2007 - winter 2007	*Raphanus sativus* (radish)	ns	nd	0-40	Arable rotation	N fertiliser at planting	Disked to 8 cm depth, no till drill	Frost	(Chen & Weil, 2011)
					Aug 2006 - Apr 2007, Aug 2007 - Apr 2008	*Brassica napus* (rapeseed)	ns	nd	0-40				Paraquat dichloride Apr 2007, glyphosate Apr 2008	
					Aug 2006 - Apr 2007, Aug 2007 - Apr 2008	*Secale cereale* (rye)	ns	nd	0-40				Paraquat dichloride Apr 2007,	

													glyphosate Apr 2008	
Exp 2	1125	14.4	Coarse loamy sand	12 (PR measured Mar 2008, 7 months all treatments)	Aug 2007 - Sept 2008	*Raphanus sativus* (forage radish)	ns	nd	0-40	Arable rotation	N fertiliser at planting	Disked to 8 cm depth, no till drill	Frost	
					Aug 2007 - Apr 2008	*Brassica napus* (rapeseed)	ns	nd	0-40				Glyphosate	
Cambridgeshire, UK	568	10.2	Sandy loam	24	Sept 2016 - Feb 2017	*Raphanus sativus* (radish)	ns	Site mean: 1.7 (post cover cropping); 2.8-3.0 (1 year later, in the winter crop)	Maximum to 30 cm depth post cover cropping; maximum to 45 cm a year later	Arable rotation	Slug control	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al*., 2020)
						Avena sativa (spring oat)	ns							
						Secale cereale (rye)	ns							
						Vicia sativa (vetch)	ns							
						Trifolium incarnatum (crimson clover)	ns							
						Fagopyrum esculentum (buckwheat)	ns							
						Phacelia tanacetifolia (phacelia)	ns							
						2 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum* (crimson clover) (83:17)	ns							
						3 sp. mix: *Raphanus sativus* (radish),	ns							

						Phacelia tanacetifolia (phacelia), *Fagopyrum esculentum* (buckwheat) (30:20:50)								
						5 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum* (crimson clover), *Raphanus sativus* (radish), *Phacelia tanacetifolia* (phacelia), *Fagopyrum esculentum* (buckwheat) (53:11:11:6: 19)	ns							
Nottinghamshire UK	650	9.7	Clay loam	24	Aug 2017 - Feb 2018	The same 10 treatments were tested as detailed above for the Cambridges hire site.	ns (all 10 treatments)	Site mean: 1.1 (post cover cropping); 1.7-2.1 (1 year later, in the winter crop)	Maximum to 30 cm depth post cover cropping; maximum to 45 cm a year later	Arable rotation	Slug control	Light cultivation; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al.*, 2020)

Yorkshire UK	751	8.6	Sandy loam	24	Aug 2017 - March 2018	The same 10 treatments were tested as detailed above for the Cambridgeshire site.	ns (all 10 treatments)	Site mean: 1.7 (post cover cropping); 4.6-5.2 [c](1 year later following a second cover crop (mustard) established over the whole site	Maximum to 30 cm depth post cover cropping; maximum to 45 cm a year later	Arable rotation	none	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al*., 2020)

[c] The exceptionally high penetration resistance values reported were attributed to measurements being undertaken in January following a period of cold temperatures.

Table 3.3 Summary of literature review papers quantifying effects of vigorous rooting (VR) green crops on soil structure using VESS (Visual Evaluation of Soil Structure). Rows shaded grey provide site and other metadata per site for the unshaded cells below, nd = no data, ns = no statistically significant effect.

Study Location	**Average annual rainfall (mm)**	**Average annual temperature (°C)**	**Soil texture (topsoil)**	**Study duration (months)**	**Growing period (month est.-month dest.)**	**Vigorous rooting crop species/species mix grown**	**Direction of change in VESS score compared to control[d]**	**VESS score**	**Depth of soil studied (cm)**	**Cropping system/rotation**	**VR crop management**	**VR crop establishment**	**VR crop destruction**	**Study reference**
Cambridgeshire, UK	576	10.5	Loamy peat topsoil (to 40 cm), heavy clay subsoil	4 (VESS measured May 2017, 9 months) (4 months of growth)	Aug 2016 - Dec 2016	3 sp. mix: *Avena strigosa* 'Cadence' (black oats), *Raphanus sativus* 'Final' (oil radish), *Sinapsis alba* 'Braco' (white mustard), 60:35:5, (frost sensitive mix)	Decreased[e] Control (3.5)	3.0	0-25	Arable rotation	none	Drilled into wheat stubble (25 kg ha^{-1})	Frost	(Storr *et al.*, 2017)
				9 (VESS measured May 2017, 9 months) (8 months of growth)	Aug 2016 - April 2017	3 sp. mix: *Secale cereale* 'Protector' (rye), *Raphanus sativus* 'Evergreen' (oil radish), *Trifolium alexandrium* (berseem clover), 60:30:10, (winter hardy mix)	Decreased Control (3.5)	3.0	-0-25	Arable rotation	none	Drilled into wheat stubble (30 kg ha^{-1})	Herbicide	
Unspecified, UK (trial 1)[f]	nd	nd	nd	approx. 8 months	Aug/Sept 2014 - spring 2015	Brassica cover crop	Decreased Control (3.8)	~3.1	0-25	Arable rotation	nd	nd	nd	(Stobart *et al.*, 2015)[g]

[d] Direction of change - no statistical analysis reported by either study.
[e] 9 replicate plots per cover crop treatment, one VESS assessment per plot
[f] Cover crop studies within 17 fields in England, VESS results are only reported for 2/17 fields.
[g] VESS replication per treatment not reported. Reported VESS 'control' values are for stubble with no cover crop. VESS score of 'farm standard' autumn cultivated soil with no cover crop was ~2.6.

Unspecified, UK (trial 2)[g]	nd	nd	nd	approx. 8 months	Aug/Sept 2014 - spring 2015	*Raphanus sativus* (radish), *Avena sativa* (oat)	Decreased Control (3.0)	~2.5	0-25	Arable rotation	nd	nd	nd	
				approx. 8 months	Aug/Sept 2014 - spring 2015	*Raphanus sativus (*radish),	Decreased Control (3.0)	~2.5	0-25					
				approx. 8 months	Aug/Sept 2014 - spring 2015	*Raphanus sativus* (2 varieties - radish & tillage radish), *Avena sativa* (oat)	Decreased Control (3.0)	~2.5	0-25					
Cambridgeshire, UK	568	10.2	Sandy loam	24	Sept 2016 - Feb 2017	*Raphanus sativus* (radish)	ns	2-3 (1 year after cover cropping, in the winter crop)	0-25	Arable rotation	Slug control	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al.*, 2020)
						Avena sativa (spring oat)	ns							
						Secale cereale (rye)	ns							
						Vicia sativa (vetch)	ns							
						Trifolium incarnatum (crimson clover)	ns							
						Fagopyrum esculentum (buckwheat)	ns							
						Phacelia tanacetifolia (phacelia)	ns							
						2 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum*	ns							

						(crimson clover) (83:17)								
						3 sp. mix: *Raphanus sativus* (radish), *Phacelia tanacetifolia* (phacelia), *Fagopyrum esculentum* (buckwheat) (30:20:50)	ns							
						5 sp. mix: *Avena sativa* (spring oat), *Trifolium incarnatum* (crimson clover), *Raphanus sativus* (radish), *Phacelia tanacetifolia* (phacelia), *Fagopyrum esculentum* (buckwheat) (53:11:11:6:19)	ns							
Nottinghamshire, UK	650	9.7	Clay loam	24	Aug 2017 - Feb 2018	The same 10 treatments were tested as detailed above for the Cambridgeshire site.	ns (all 10 treatments)	2-4 (1 year after cover cropping, in the winter crop)	Maximum to 30 cm depth post cover cropping; maximum to 45 cm a year later	Arable rotation	Slug control	Light cultivation; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al.*, 2020)
Yorkshire, UK	751	8.6	Sandy loam	24	Aug 2017 - Mar 2018	The same 10 treatments were tested as detailed above for the Cambridgeshire site.	ns (all 10 treatments)	3-4 (1 year after cover cropping following a second cover crop (mustard) established over the whole site	Maximum to 30 cm depth post cover cropping; maximum to 45 cm a year later	Arable rotation	none	Light cultivation & glyphosate to remove volunteers; drilled with Suffolk coulters set on a power harrow to move the trash only	Glyphosate	(Bhogal *et al.*, 2020)

3.2. Results and Discussion

3.2.1. Effectiveness of vigorous rooting green crops for rectifying soil structural damage

The literature review showed a paucity of studies reporting the effect of vigorous rooting crops on soil structure in experimental locations with a climate similar to that of the UK (temperate oceanic climate). In total, 11 relevant studies were found. Nine studies[h] reported effects of vigorous rooting crops on soil bulk density (Table 3.1**Error! Reference source not found.**) of which only 3 studies reported results from experiments within the UK. In total, 4 studies reported effects of vigorous rooting crops on penetration resistance (Table 3.2), and 3 studies reported effects on soil structure using a Visual Evaluation of Soil Structure (VESS) methodology (Table 3.3).

Depth of soil studied

Most studies that quantified soil structural properties during or after growth of vigorous rooting crops measured the upper topsoil layer (0-25 cm depth) with only 5 studies reporting metrics for soil properties at depths > 25 cm. Of the studies which measured soil bulk density, 6/9 studies reported bulk density values at < 25 cm depth, with soil bulk density measured to 30 cm depth by one study (Bhogal *et al.,* 2020) and to 40 cm depth by two studies (Chen & Weil, 2011; Demir & Işik, 2020). Similarly, all three studies reporting VESS scores (Stobart *et al.*, 2015; Storr *et al.*, 2017 and Bhogal *et al*., 2020) did this based on the upper 0-25 cm of soil (topsoil VESS). The four studies measuring penetration resistance of soils supporting vigorous rooting crops, measured penetration resistance to 40 cm depth (Chen & Weil, 2011), 45 cm depth (Storr *et al.*, 2017 and Bhogal *et al.*, 2020) and 50 cm depth (Crotty & Stoate, 2019) respectively. This demonstrates a relative lack of data quantifying effects of vigorous rooting crops on soil structure, particularly below topsoil depth.

Studies of vigorous rooting crops on bulk density

Of the 9 studies which measured bulk density, the performance of 60[i] vigorous rooting crop treatments were compared against a control treatment (no vigorous rooting crop) (Table 3.1). A significant reduction in bulk density was reported for 5/60 vigorous rooting crop treatments whilst 55/60 treatments reported no significant effect. No comparisons reported a significant increase in bulk density during or following growth of a vigorous rooting crop.

Where a significant reduction in bulk density was reported, the size of reduction ranged from 7.4% to 11%, averaging 9.1 %. Significant reductions in bulk density were only reported in the upper topsoil layer. Of the five vigorous rooting crop treatments where a significant reduction in bulk density was reported, two of the bulk density reductions were at 2-7 cm depth and three were at 0-20 cm depth.

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[h] Nine papers (results from 14 field sites).

[i] 'treatment' = a vigorous rooting crop that was measured against a control (no vigorous rooting crop) treatment. Where multiple crop species/species mixes are tested in the same experiment, each treatment is counted separately. Effect of the treatment on soil properties may be quantified at multiple depths/time points.

Due to the limited data it was not possible to determine a threshold bulk density at which vigorous rooting crops were able to remediate compaction: of the treatments where soil bulk density was significantly reduced by vigorous rooting crops, bulk density averaged 1.24 g cm^{-3} (min = 1.18 g cm^{-3}, max = 1.38 g cm^{-3}) whilst bulk density of soils where vigorous rooting crops had no effect, averaged 1.13 g cm^{-3} (min = 1.06 g cm^{-3}, max = 1.37 g cm^{-3})[j]. There was also no clear effect of soil texture; reductions in bulk density were reported in some clay loam, sandy loam and silt loam soils. However, other studies on a range of soil textures (coarse-loamy sand, clay loam, fine loam, sandy loam, silt loam, silty-clay loam) reported that bulk density was unaffected by vigorous rooting crops.

Demir & Işik, (2020) reported significant reductions of 9.2 %, 8.5% and 9.2% bulk density at 0-20 cm depth in clay loam soil following 24 months of cover cropping with *Trifolium repens* (white clover); a mixture of *Trifolium repens, Festuca rubra* (red fescue) and *Festuca arundinacea* (tall fescue)*;* and *Vicia villosa* (vetch) respectively. In this case bulk density was reduced to 1.18, 1.19 and 1.18 g cm^{-3} respectively. However, no difference in bulk density between cover cropped and none cover cropped treatments was found at 20-40 cm depth. Similarly, Berdeni *et al.*, (2021) reported a 7.4% reduction in bulk density at 2-7 cm depth following 19 months of grass and clover ley growth (mixture of *Lolium* spp., *Festulolium* spp., and *Trifolium* spp.) compared to an arable control in soils with a silt loam, loam and sandy loam texture. In this experiment bulk density was reduced to 1.38 g cm^{-3} in the ley treatment. However, overall bulk density at 0-22 cm depth was not significantly different from the arable control. In a comparatively longer-term experiment, which quantified changes in soil properties with 13 years of rye grown annually as a winter cover crop in a silt loam soil, Steele *et al.* (2012) reported a 11% reduction in bulk density at 1-7 cm soil depth in the cover cropped treatment compared to the control treatment (13 years conventional cropping with no cover crop). In this case, bulk density was reduced to 1.26 g cm^{-3} in the cover cropped treatment.

The results of this review are similar to those of Chapman *et al.* (2018) who reviewed evidence for the impact of cover crops on indicators of soil health (6 soil health indicators: bulk density, soil organic carbon storage, aggregate stability, total porosity, hydraulic conductivity, earthworm populations) using studies with sites based in temperate climates published from 1900-2018. Chapman *et al.* (2018) reported that out of 23 studies that compared changes in soil bulk density with a cover crop against a control (no cover crop) treatment, 20 studies reported no change, two studies reported a significant decrease, and one study reported a significant increase. Of the bulk density studies, only one was from an experiment in the UK and the authors noted that despite being a commonly promoted agricultural practice, there is limited information on the benefit of cover crops on soil structure in UK systems. Similarly, this literature review (approx. 2.5 years later) found only five

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[j] Bulk density values reported were measured in the vigorous rooting crop treatment rather than the control.

studies based in the UK that quantified the effect of vigorous rooting crops on soil structural properties, showing there is still a deficit of research in this area.

Studies of vigorous rooting crops on penetration resistance

Studies quantifying changes in soil penetration resistance with vigorous rooting crops were limited; of the four studies which measured penetration resistance (41 comparisons were made against control treatments), two studies (36/41 comparisons) reported no significant difference in penetration resistance between the control (no vigorous rooting crop) and the vigorous rooting crop treatment, while two studies (5/41 comparisons) reported some incidences of increased penetration resistance with the vigorous rooting crop (Table 3.2). None of the studies reported a reduction in penetration resistance following or during growth of a vigorous rooting crop. However, penetration resistance values should be interpreted with a degree of caution as soil moisture is a key driver of penetration resistance. Indeed, in an otherwise uniform soil, penetration resistance can be used as an empirical index of soil moisture. This is an important consideration when using penetration resistance values to measure changes in soil structure arising from vigorous rooting crops, particularly if the measurements are taken whilst the crop is in the ground, as vigorous rooting crops can affect soil moisture (generally by drying the soil due to increased evapotranspiration, although in some situations they can increase soil moisture), thus potentially confounding the penetration resistance results due to indirect effects on soil water content. Soils with a high density of root may also produce higher penetration resistance values as more pressure is needed to penetrate through the root mass. Nevertheless, where soil moisture and rooting are equal, more compact soils will produce higher penetration resistance values.

Crotty & Stoate (2019) compared penetration resistance (to 45 cm depth) of three different cover crop species mixtures, five months after sowing in a no-till system on clay loam in Leicestershire. This study reported an approximate 20% increase in penetration resistance at 5.0-12.5 cm depth in all three cover crop treatments (observations indicated that this was the most compacted soil layer, and the maximum penetration resistance was approximately 1.5 MPa, suggesting a firm soil) compared to the control (no cover crop; bare soil) treatment. The reported increase in penetration resistance in the cover cropped treatment areas was attributed to compaction caused by the direct drill, which seeded the cover crop treatments, travelling on the ‘wet’ clay loam soil in early September following heavy rainfall. However, it is also plausible that the increase in penetration resistance may have been due to evapotranspiration by the cover crop on the cover crop plots resulting in drier soil conditions than on the control plots. Indeed, soil moisture measurements at 0-10 cm depth also recorded in February 2016, (the same month as the penetration resistance values were measured) showed that soils in the cover crop treatment plots may have been drier than the control plots (with average soil moisture content of 43.9%, 43.5% and 42.7% in the 2, 3 and 7 species mix respectively compared to 45.5% in the control) although this difference was not statistically significant.

Additionally, it is possible that increased root density in the cover cropped plots at the 5.0-12.5 cm depth could explain the higher penetration resistance values measured at this depth. In February 2016 the dry above ground biomass was measured as > 120 g m^2 in all cover crop treatments compared to < 40 g m^2 in the control (due to weed regeneration) strongly suggesting differences in root mass would be found in the topsoil, although this was not quantified.

Crotty & Stoate (2019) emphasised that it had been necessary to establish the cover crop under wet conditions as, due to the preceding wet August, harvest of the previous winter wheat crop had been delayed. This study highlights a key challenge faced by growers; the need to establish cover crops as early as possible in the autumn to maximise their growth, balanced against the need for suitable planting conditions to prevent the damage to soil structure that may be caused by machinery travelling over 'wet' soils. In this case it is possible that five months of cover crop growth did not offset the compaction caused by the direct drilling used to establish the cover crops. Similarly, Storr *et al.* (2017) measured penetration resistance eight months after sowing two cover crop species mixtures (both 3-species mixtures, one 'frost sensitive' – 4 months of growth, and one 'winter hardy' mix – 8 months of growth) in a loamy peat soil to 40 cm depth over a heavy clay soil in Cambridgeshire, in August 2016. This study reported increased penetration resistance at 21-50 cm soil depth after the 'winter hardy' cover crop treatment, and increased penetration resistance at 21-30 cm depth after the 'frost sensitive' cover crop mix, compared to the control. It was suggested that the compaction may have been caused by the drilling machinery and tire packer roller which was used to establish the cover crop mix. Notably, due to growth of wheat volunteer plants, greater above ground biomass (9.1 t ha^{-1}) was recorded in March 2017 within the control treatment plots compared to winter hardy cover crop plots (6.4 t ha^{-1}) and frost sensitive cover crop plots (2.1 t ha^{-1}). The authors proposed that the fibrous rooting system of wheat volunteers supported soil pore formation and was of benefit to soil structure within the control plots. In contrast, Chen & Weil (2011) reported no effect of winter cover crop on soil penetration resistance (0-40 cm depth) following *Raphanus sativus* (radish), *Brassica napus* (rapeseed) or *Secale cereale* (rye) winter cover crop treatments grown for either eight months (one winter) on sandy loam soil, or 20 months (two consecutive winters) on loamy sand. Bhogal *et al.* (2020) also reported no effect of ten different winter cover crop treatments (seven species grown as straights and three species mixes) on maximum soil penetration resistance immediately after six months of cover crop growth (measured to 30 cm depth), or in the following winter cereal crop a year later (measured to 45 cm depth). In this study the cover crop mixes were trialled at three sites in the UK; Cambridgeshire (sandy loam), Nottinghamshire (clay loam) and Yorkshire (sandy loam).

Soil mechanical strength can limit root elongation (Zhang and Peng, 2021). This has been clearly demonstrated. For example, Materechera *et al.* (1991) compared the ability of seedlings of 22 plant species to penetrate a strongly compacted growth medium (4.2 MPa siliceous sand) compared to control plants grown in vermiculite (0 MPa resistance). In the compacted soil, root elongation of all species was reduced by over 90%. The mechanistic basis for reduced rooting in compacted soil is unresolved, however, Pandey *et al.* (2021) recently demonstrated that ethylene accumulation in root tissue triggers a plant hormonal response which limits root growth. The authors proposed that plants sense soil compaction by responding to ethylene accumulation, which occurs when ethylene diffusion is limited due to lack of air-filled pore space in compacted soils. This suggests that the potential for vigorous rooting crops to remediate soil structural damage will be limited where soil is compacted to the extent that air-filled pore space (and therefore ethylene diffusion) is limited. Soil penetration resistance is indicative of the soil resistance to air, water and heat flow and dynamic processes including root growth. It is generally considered that root development becomes increasingly limited at penetration resistance values above 2 MPa. Penetration resistance values measured by Storr *et al.* (2017) ranged from 1.7-2.2 MPa showing a firm, moderately compacted soil, while values measured by Crotty & Stoate (2019) ranged from 0.2 to 1.5 MPa, suggesting a loose to well-structured soil.

Studies of vigorous rooting crops on VESS

Three UK-based studies reported topsoil VESS assessment scores with and without cover crops (Table 3.3). In total 37 vigorous rooting treatments were measured, seven of which reported small reductions in VESS score with cover crops compared to 'no cover crop' controls, indicating small improvements in soil structure. Storr *et al.* (2017) reported reductions in VESS from 3.5 (no cover crop control) to 3.0 with both 'winter hardy' and 'frost sensitive' cover crop mixes, grown for seven and four months respectively, suggesting some improvement in soil structure. Similarly, Stobart *et al.* (2015) reported reductions in topsoil VESS scores from 3.0 (no cover crop control) to *c*. 2.5 following eight months of cover cropping with each of five different cover crop mixtures (Table 3.3). Together, these results suggest that small improvements in soil structure may be achieved in moderately compacted soils (topsoil VESS of 3-3.5). However, it is important to note that neither study statistically analysed the difference in VESS scores between control and cover crop treatments and that (where reported) replication of VESS assessments was limited[k]. Replication is important for accurately quantifying effects of treatments on soil properties due to the potential spatial variability of soils within treatment areas. In contrast, Bhogal *et al.* (2020) reported no significant effect of six months of winter cover crop growth on topsoil VESS scores measured immediately after cover crop removal or a year later in the following winter crop, on sandy loam soils (Yorkshire and Cambridgeshire) or clay loam soils (Nottinghamshire).

[k] Storr *et al*. (2017): one VESS assessment from each of 9 replicated plots per treatment; Stobart *et al.* (2015): replication not reported.

3.2.2. Effect of soil and cropping conditions on vigorous rooting green crops

Establishment, management and termination of vigorous rooting crops

Appropriate planting and destruction of vigorous rooting crops is required to derive associated environmental and agronomic benefits (Zhang & Peng, 2021). There is clearly variation in the management and establishment of vigorous rooting crops reported in the reviewed literature and it is difficult to determine optimal management practices. Many of the vigorous rooting crop treatments were established by direct drilling into no-till arable cropping systems. As discussed in section, measured increases in compaction (soil penetration resistance) have been attributed to autumn cover crops being drilled in wet conditions (Storr *et al.,* 2017; Crotty & Stoate, 2019). Where reported, most studies have relied on herbicide application or frost to terminate the vigorous rooting crop growth. This is an area where further research is required to inform best practice as there could be environmental and human health impacts associated with the widespread application of herbicides such as glyphosate (e.g. development of herbicide resistance (Heap, 2014), potential impacts on soil biodiversity (Gaupp-Berghausen *et al.*, 2015) and water pollution (Van Bruggen *et al.*, 2018)). There are several options for destruction of vigorous rooting crops including grazing, mowing and roller crimping. The latter method was promoted by Zhang & Peng (2021) due to potential additional benefits for soil conservation including providing mulch, weed suppression and moisture retention, however the authors emphasised that use of the roller crimper needs to be correctly timed (late flowering/early pod set) as if rolled too early (in the vegetative state) the crop with not be terminated effectively.

The magnitude of soil improvement by vigorous rooting crops is management and site specific (Blanco-Canqui & Ruis, 2020). It has been suggested that vigorous rooting crops may be of most benefit to soil structure when integrated into a no-till cropping system (Blanco-Canqui & Ruis, 2018; Blanco-Canqui & Ruis, 2020).

Effects of conditions e.g. weather/soil moisture

As detailed in 3.2.1, there is limited evidence reported of the benefit of vigorous rooting crops on soil structure in temperate climates. These results are broadly similar to those of a recent review by Blanco-Canqui & Ruis (2020), which summarised the results of studies quantifying impacts of cover crops on soil structural properties covering a range of climates worldwide. This review by Blanco-Canqui & Ruis (2020) assessed data on the impact of cover crops on soil bulk density measured at 51 study locations globally and reported a significant reduction in bulk density at 16 of the study locations (with reductions in bulk density ranging from 3 to 24% and averaging at 1.5%). Most of these studies[l] (11 studies) quantified bulk density in the upper topsoil (< 20 cm depth) with bulk density measured to 30 cm depth by three studies and to 60 cm depth by one study. No difference

[l] Depth of bulk density measurement was detailed in 15/16 studies.

between cover cropped and control treatments was reported at 35 study locations (69% of study locations), which were again restricted to the measurement of the upper topsoil (bulk density measured to <20 cm depth by 32 studies, to 30 cm depth by two studies and to 40 cm depth by one study) and no studies reported increased bulk density in cover cropped treatments. This is broadly similar to the literature only from temperate oceanic climates, reported in this review, where only small improvements in bulk density (7.4% to 11.0% averaging at 9.1%) were found, while the majority (92%) of vigorous rooting crop treatments had no effect on soil bulk density. This suggests that effects of vigorous rooting crops on soil structure in temperate oceanic climates may be similar to effects in other climatic systems. It may also indicate that dry bulk density is a relatively insensitive measure of changes in soil structure, particularly when the number of replicate samples is low.

Blanco-Canqui & Ruis (2020) also reported that out of 17 study locations where soil penetration resistance was measured following/during cover crop treatments (measurements to 20 cm, 30 cm and 60 cm depth by 13, three and one study/studies respectively), penetration resistance was reduced in 11 locations (65% of locations) with the reduction in penetration resistance ranging from 5 to 29% and averaging at 5.1%. There was no effect at four study locations, and mixed effects at two study locations. By contrast, our review of temperate oceanic climates found an increase in penetration resistance following/during cover crops in five out of 41 treatments, potentially due to drier soil or a greater root mass in the cover cropped treatments, or soil compaction caused by the additional machinery traffic required to drill/establish the vigorous rooting crops, with no effect on penetration resistance in 36 treatments. However, these results were from a limited number of studies (four studies).

Duration of growth

It is of note that all three of the studies which reported effects of vigorous rooting crops on bulk density had green manure crops grown for at least 19 months and that in the other studies, where no effect was shown, all treatments were established for 12 months or fewer; with the exception of Chen & Weil (2011) who reported that in one experiment bulk density was measured after 20 months – two consecutive winters of winter cover cropping. This supports the suggestion by Blanco-Canqui *et al.* (2015) that vigorous rooting crops generally need to be integrated into cropping systems for >1 year before clear benefits to soil structure and porosity are found. When cover crops are grown in late autumn and winter months only, plant growth is limited by light and temperature, and while some visual changes in soil structure may be observed, changes to soil bulk density and porosity are far less common. Similarly, Jokela *et al.*, (2009) considered that four or more years of cover crop growth may be required for indicators of soil quality such as penetration resistance and bulk density to be improved.

Unsurprisingly, the duration of crop growth is important in determining the degree of change in soil quality (White *et al.*, 2016; Blanco-Canqui & Ruis, 2020; Zhang & Peng, 2021). Vigorous rooting crops that have a longer period of growth or are integrated into the cropping system for multiple years have more time for root systems to develop and interact with soil properties (Zhang & Peng, 2021). This is particularly important for winter cover crops where good autumn establishment is needed prior to winter months when growth is limited by lack of light and low temperatures. Stobart *et al.*, (2015) reported a strong positive relationship between green area index (GAI) of cover crops (measured in October of the year of establishment) and August-September planting dates at eight cover crop trial sites in the UK, with earlier sown cover crops associated with a greater GAI. Similarly, Bhogal *et al.* (2020) reported that early establishment of cover crops was positively related to improved performance (growth and N recovery).

Indirect effects of cover crops on soil properties and interactions with soil biology

Although beyond the scope of this review, it is important to note the potential indirect effects of use of cover crops/leys on soil structure. For example, earthworm populations are generally positively impacted by use of vigorous rooting crops (Roarty *et al.*, 2017), due to the provision of ground cover and organic inputs from root and crop residue. Earthworm population recovery can in turn directly affect soil properties, including bulk density and macropore structure (Bertrand *et al.*, 2015). Jarvis *et al.*, (2017) reported increases in the biomass and number of epigeic and endogeic earthworms in the topsoil following growth of grass-clover leys (one to five years) in a silt loam soil in Northern Sweden. Likewise, Hallam *et al.*, (2020) reported increased earthworm numbers after one year of grass-clover ley conversion in silt loam, loam and sandy loam soils in North Yorkshire, which corresponded with changes in topsoil properties including reduced bulk density and increased macropore flow. Similarly, arbuscular mycorrhizal fungi form symbiosis with many species of vigorous rooting crops and have been shown to promote macro-aggregate formation and stability (Lehmann *et al.*, 2017; Morris *et al.*, 2019).

3.2.3. Species or species mixtures most suited for rectifying soil structural damage and how to manage them

Plant species/species mixtures and rooting traits

In total, the review found that 33 different vigorous rooting species/ species mixtures have been tested in studies quantifying the effect of vigorous rooting crops on soil structural properties (bulk density, penetration resistance and VESS) (

Table 3.4). The reviewed studies included 20 species grown as straight crops and 13 different species mixes (with seven species within the most diverse mix). In total, the plant species tested represented five plant families: the Poaceae, Fabacea, Brassicaceae, Polygonaceae and Boraginacaea families. Species where bulk density was significantly improved were: *Secale cereale* (rye), *Trifolium repens* (white clover), *Vicia villosa* (vetch), a 3 species mix (*Trifolium repens, Festuca* *rubra* (red fescue) and *Festuca arundinaceae* (tall fescue)), and a 6-species mix (*Lolium* x *boucheanum* (hybrid ryegrass), *Lolium perenne* (perennial ryegrass), 2 x *Festulolium* spp., *Trifolium repens* and *Trifolium pratense* (red clover)). Due to the lack of common species tested in multiple vigorous rooting crop treatments and the variability between experimental sites, it is difficult to deduce which species are most effective from the literature reviewed.

Multi-species mixes

It has been suggested that multispecies mixtures may provide more benefit to soil structure due to functional complementarity (being able to occupy more ecological niches and therefore able to become more productive with limited resource) (Deyn *et al.*, 2011; Fischer *et al.*, 2015; Husse *et al.*, 2016). Mixtures with multiple rooting strategies are thought to be of more benefit to soil structure due to the complementary development of different root structures (e.g., tap roots creating macropores/bio-drilling, fibrous roots supporting micropore formation and soil aggregation). However, there is currently little data supporting this (Table 3.4). For example, of the three vigorous rooting species mixtures tested by Crotty & Stoate, (2019) one mixture which consisted of *Avena sativa*, *Secale cereale*, *Phacelia tancetifolia* and *Raphanus sativus* (oats, rye, phacelia and radish) was marketed as a 'soil structure building mix'. However, neither penetration resistance nor bulk density measurements showed a reduction in compaction when measured five months from sowing this mix.

Kemper *et al.*, (2020) suggested that due to complementary rooting characteristics, combining crop root types with different rooting strategies would increase overall root length density (RLD) and maximise cover crop benefits to soil structure. Kemper *et al.*, (2020) compared rooting traits between seven cover crop species (*Trifolium incarnatum* (crimson clover), *Secale cereale* (winter rye), *Avena strigosa* (bristle/black oat), *Lupinus angustifolius* (blue lupin), *Raphanus sativus* (oil radish), *Brassica rapa* (winter turnip rape) and *Phacelia tancetifolia (phacelia)*, at two time points (October and March) for two years in a field experiment in Germany (silt loam, 60 – 200 cm depth). Differences in root length density (RLD), distribution of roots between subsoil and topsoil and, in the autumn of the first-year, differences in rooting depth were found between species. The results showed that the tap rooted species generally had greater subsoil growth than the fibrous rooted species. However, this was not the case for bristle oat (intermediate between fibrous rooted and tap-rooted) and lupin (low RLD in topsoil and subsoil). Bhogal *et al*., (2020) measured RLD to 50 cm depth in 10 cover crop species/species mixtures and found that *Secale cereale* (rye) and *Phacelia tancetifolia (*phacelia) achieved the highest topsoil RLD (0 - 30 cm depth).

Table 3.4. Summary of reported treatment effects per species. Grey cell: number of vigorous rooting treatments which reported no significant effect on the soil structural property, green cell: significant effect reported (positive), orange cell: significant effect reported (cause of effect is unclear).BD = bulk density; PR = penetration resistance; VESS = Visual evaluation of soil structure

Plant family/ families	**Species grown**	**BD no effect**	**BD reduced**	**PR no effect**	**PR increased**	**VESS no effect**	**VESS[m] reduced**	**Study reference**
Poaceae	*Avena sativa*	5		3		3		(Bhogal *et al.*, 2020; Rudolph *et al.*, 2020)
Brassicaceae	*Brassica napus*	2		2				(Chen & Weil, 2011)
Brassicaceae	*Brassica sp.*						1	(Stobart *et al.*, 2015)
Polygonaceae	*Fagopyrum esculentum*	3		3		3		(Bhogal *et al.*, 2020)
Poaceae	*Festuca arundinacea*	1						(Demir & Işik, 2020)
Poaceae	*Festuca rubra*	1						(Demir & Işik, 2020)
Poaceae	*Hordeum vulgare*	1						(Forge *et al.*, 2016)
Poaceae	*Lolium perenne*	1						(Rudolph *et al.*, 2020)
Boraginaceae	*Phacelia tancetifolia*	3		3		3		(Bhogal *et al.*, 2020)
Brassicaceae	*Raphanus sativus*	5		5		3	1	(Chen & Weil, 2011; Stobart *et al.*, 2015; Bhogal *et al.*, 2020)
Poaceae	*Secale cereale*	6	1	5		3		(Chen & Weil, 2011; Steele *et al.*, 2012; Bhogal *et al.*, 2020; Rudolph *et al.*, 2020)
Fabaceae	*Trifolium incarnatum*	3		3		3		(Bhogal *et al.*, 2020)
Fabaceae	*Trifolium meneghinianum*	1						(Demir & Işik, 2020)
Fabaceae	*Trifolium repens*		1					(Demir & Işik, 2020)
Poaceae	*Triticosecale*	2						(Rudolph *et al.*, 2020)

[m] A reduced VESS score indicates improved soil structure; Note, no statistical analysis performed - interpret with caution.

Plant family/ families	**Species grown**	**BD no effect**	**BD reduced**	**PR no effect**	**PR increased**	**VESS no effect**	**VESS[m] reduced**	**Study reference**
Poaceae	*Triticum aestivum*	2						(Rudolph *et al.*, 2020)
Fabaceae	*Vicia faba*	1						(Rücknagel *et al.*, 2016)
Fabaceae	*Vicia villosa*		1					(Demir & Işik, 2020)
Fabaceae	*Vicia sativa*	3		3		3		(Bhogal *et al.*, 2020)
Poaceae	*Lolium spp. mix*	1						(Rudolph *et al.*, 2020)
Boraginaceae Poaceae	2 spp. mix*: Avena sativa*, *Phacelia tancetifolia*	1			1			(Crotty & Stoate, 2019)
Poaceae Fabaceae	2 spp. mix: *Avena sativa, Trifolium incarnatum*	3		3		3		(Bhogal *et al.*, 2020)
Brassicaceae Poaceae	2 spp. mix*: Avena sativa, Raphanus sativus*						2	(Stobart *et al.*, 2015)
Fabaceae Poaceae	*2 spp. mix: Secale cereale, Vicia* sp.						1	(Stobart *et al.*, 2015)
Fabaceae	3 spp. mix: *Vicia faba, Vicia sativa, Pisum sativum*	2						(Rücknagel *et al.*, 2016)
Poaceae Fabaceae	3 spp. mix: *Festuca arundinaceae, Festuca rubra, Trifolium repens*		1					(Demir & Işik, 2020)
Brassicaceae Poaceae	3 spp. mix: *Avena strigosa, Raphanus sativus, Sinapsis alba*				1		1	(Storr *et al.*, 2017)
Brassicaceae Fabaceae Poaceae	3 spp. mix: *Raphanus sativus, Secale cereale*, *Trifolium alexandrium*				1		1	(Storr *et al.*, 2017)

Plant family/ families	Species grown	BD no effect	BD reduced	PR no effect	PR increased	VESS no effect	VESS[m] reduced	Study reference
Boraginaceae Brassicaceae Polygonaceae	3 spp. mix: *Fagopyrum esculentum, Phacelia tanacetifolia, Raphanus sativus*	3		3		3		(Bhogal *et al*., 2020)
Boraginaceae Brassicaceae Poaceae	4 spp. mix: *Avena sativa*, *Phacelia tancetifolia*, *Raphanus sativus, Secale cereale*	1			1			(Crotty & Stoate, 2019)
Boraginaceae Brassicaceae Fabaceae Poaceae Polygonaceae	5 spp. mix: *Avena sativa, Fagopyrum esculentum, Phacelia tanacetifolia, Raphanus sativus, Trifolium incarnatum*	3		3		3		(Bhogal *et al*., 2020)
Fabaceae Poaceae	6 spp. mix: *Festulolium* spp., *Lolium* x *boucheanum, Lolium perenne, Trifolium repens*, *Trifolium pratense*		1					(Berdeni *et al*., 2021)
Boraginaceae Brassicaceae Fabaceae Polygonaceae	7 spp. mix*: Avena sativa*, *Fagopyrum esculentum, Phacelia tancetifolia*, *Raphanus sativus*, *Trifolium alexandrium, Trifolium incarnatum, Vicia sativa*	1			1			(Crotty & Stoate, 2019)

Due to the lack of data available in this review it is not possible to determine whether there is a benefit of multispecies mixtures on rectifying soil structure. Variable effects on soil structure were reported with both single species and species mixtures and this is an area which clearly requires further investigation. However, it is important to note that for other ecosystem services, for example biodiversity support, more diverse mixes are likely to be of increased benefit.

Rooting traits

Species with a thick root diameter such as tap-rooted species, are generally considered to be the most appropriate vigorous rooting crops for improving soil structure to depth, due to the size of the root system and depth of rooting that can potentially be achieved (Chen & Weil, 2010; Zhang & Peng, 2021), however evidence for this is limited. Zhang & Peng (2021) considered that the optimal traits for a vigorous rooting crop were: deep roots with thick diameter, rapid decomposition rate of the roots, the ability to establish well with a rapid growth rate and suitability for soil and environmental conditions.

Biopores produced by tap rooted species are thought to benefit soil structure by improving conductivity of air and water and by providing channels of least resistance that can be exploited by subsequent crop roots (Colombi *et al.*, 2017; Blanco-Canqui & Ruis, 2020). There is some evidence to support this, for example Chen & Weil, (2010) measured root penetration of compacted soils (>2 MPa penetration resistance) to depths of 45 cm by species with contrasting root structure (*Raphanus sativus* (radish), *Brassica napus* (rapeseed) and *Secale cereale* (rye)) and found that the tap rooted species (radish) was better able to grow through compacted soil compared to other species (rapeseed and rye), with the fibrous rooted rye least able to penetrate through the compacted soil. It was also noted that in the most compacted soil treatment of this experiment (penetration resistance of > 2 MPa at 15 - 45 cm depth) deep rooting of the subsequent maize crop was improved when following the rapeseed and fodder radish cover crop treatments. Similarly, Munkholm & Hansen, (2012) compared root development of three catch crop species in a relatively compact soil and found that at the end of the second growing season *Raphanus sativus* (radish) and *Isatis tinctoria* (dyer's woad) were able to achieve a greater depth of rooting (175 cm and 113 cm respectively) compared to *Lolium perenne* (perennial ryegrass) (65 cm rooting depth) when grown in a sandy loam soil in Denmark for two years. The soil had a distinct compacted plough pan at 25 - 40 cm depth (with a penetration resistance of 2 - 3 MPa) and a firm subsoil (penetration resistance of > 2 MPa at depths >50 cm depth). Likewise, Chan & Heenan, (1996) reported that after four seasons within a crop rotation, tap rooted species reduced bulk density and penetration resistance more than fibrous rooted species. Critchley & Kirkham, (2011) reviewed evidence in the scientific literature of grassland plant species that were able to ameliorate grassland soil compaction in UK climatic conditions and suggested that species with tap roots were well suited to this purpose, being capable of deep soil penetration and radial expansion. Previous studies of soybean, wheat and maize crops in compacted soils have shown that roots preferentially grow into/across artificial macropores, which provide a route of less resistance (Colombi *et al.*, 2017).

Differences in the ability of species to penetrate compacted soil layers have been demonstrated. Materechera *et al.*, (1993) compared the root penetration ability of eight crop species and found that *Lupinus* sp. (lupin) had greater root penetration than the seven other crops in compacted soil. Dicotyledonous species usually have a wider root diameter than monocotyledonous species and are generally better able to penetrate compacted soil. For example, Materechera *et al.*, (1991) found that dicots were generally better able to penetrate a strong medium than the roots of grasses (graminaceous monocotyledons), with a significant positive correlation found between root thickness and elongation. Bodner *et al.*, (2014) tested the effect of coarse and fine roots on pore size distributions (micro-pores and macro-pores) in a silt loam soil, comparing 10 plant species (from six different families; Fabaceae, Brassicaceae, Boraginaceae, Linaceae, Polygonaceae, Poaceae) and two species mixtures (containing plant species from different families). This experiment showed that macro-porosity was increased by 30% by the coarse rooted species (at the 2-7 cm depth). In comparison, species with fine dense root systems increased the micropore volume and heterogeneity of the pore space. Changes in soil pore characteristics were attributed to coalescence of soil aggregates and re-orientation of soil particles.

3.3. Conclusions

- Most studies reported no effect of vigorous rooting crops on bulk density, however in some instances (5/60 vigorous rooting treatments) a small reduction in bulk density was shown in the upper topsoil (0-20 cm depth).
- A limited number of studies (four studies) measured the effect of vigorous rooting crops on penetration resistance. Vigorous rooting crops either had no effect on penetration resistance compared to a no cover crop control (36/41 vigorous rooting comparisons) or resulted in an increase in penetration resistance at some of the depths measured (5/41 vigorous rooting treatments). These were attributed to increased compaction caused by machinery travelling on wet land in autumn to drill the cover crop but may potentially also have been influenced by changes in soil moisture and rooting compared to the control treatments. No reductions in penetration resistance were reported with vigorous rooting crop treatments.
- A limited number of studies (three studies) compared topsoil VESS scores in cover cropped areas and no cover crop controls. Seven of the cover crop treatments tested (7/37 comparisons) showed small improvements in soil structure compared to the no cover crop controls (indicated by lower topsoil VESS scores). However, it is important to note that in both trials which reported reductions in VESS scores (i.e. improvement in soil structure), replication was limited and no statistics were performed.

- This review has highlighted the lack of evidence of a clear and consistent effect of vigorous rooting crops on soil structure. There is some evidence that when integrated into reduced or no till cropping systems for multiple years, vigorous rooting crops can be of benefit to soil structure. However, there is a lack of longer terms studies.
- More studies are required to quantify the effect of vigorous rooting crops at depths > 30 cm and in compacted soils, so that the extent to which soil structure can be ameliorated in compacted conditions can be quantified. There is some evidence that tap-rooted species are most suited to improving soil structure in compacted soils. However, more evidence is needed to determine which species and species mixtures perform best and the levels of soil compaction that can be remediated.
- A recent survey of UK farmers attitudes to cover crops by Storr *et al.* (2019) identified that one of the principal reasons for a lack of cover crop use was the difficulty of measuring cover crop benefit (other reasons were expense and problems with incorporating the cover crop into the planned rotation). Improved understanding of the benefits and limitations of using vigorous rooting crops may thus improve farmer uptake and will help to guide best practice so that optimal agronomic and environmental benefits may be achieved.

4. Guide to rectifying soil structural damage

Keeping soils in good condition improves production efficiency, reduces costs and increases productivity. Preventing soil compaction occurring is the best strategy. However, harvesting crops in wet conditions is sometimes unavoidable and can result in significant structural damage that could compromise productivity for years. Similarly, cultivating soils, establishing crops, grazing livestock or silaging in sub-optimal conditions can cause compaction. So, what is the best course of action when you suspect your soils have been damaged?

There are four basic steps to alleviating soil compaction:

1. Assess the damage
2. Select the most appropriate action
3. Implement the action in the right conditions
4. Assess the effectiveness of the action

4.1. Assess the damage

If you suspect that a soil is compacted, wait for the right conditions (not too wet or too dry), and then use a spade or fork to assess the degree and depth of compaction. Also consider how widespread the compaction is. For example, it may be restricted to tramlines or headlands only. This is crucial to deciding the correct course of action. There is plenty of guidance to help you do this, including Visual Evaluation of Soil Structure (VESS) and Visual Soil Assessment (VSA).

For grassland soils, try the Healthy Grassland Soils assessment sheet and pocketbook or GrassVESS to see what works for you. It's particularly important to determine whether any compaction is limited to the topsoil (top 20-25 cm; 8-10 inches) or if it is deeper; in the 'transition layer' between topsoil and subsoil or even in the upper subsoil. If the compaction is affecting root growth or drainage, then you need to consider what action may be required.

4.2. Options for rectifying soil structural damage

If you have identified clear signs of soil compaction, consider the best course of action, which will be dependent on the soil type, the degree and depth of compaction, and land use. Remember that most medium and heavy soils (with a clay content > 18%) will naturally shrink and crack in dry conditions, and a dry spring or summer may be enough to rectify the worst of any damage caused in a wet autumn/winter. In this case, the best course of action may be no action. Again, use a fork or spade to assess this, looking at the extent and depth of cracks, rooting and any compacted layers.

If soil structural damage persists there are a few options available to you and plenty of guidance, depending on your sector. See:

- Field drainage guide for all sectors
- Soil management for horticulture
- Arable soil management: Cultivation and crop establishment
- Healthy Grassland Soils

If the soil structural damage is moderate and restricted to the topsoil, cover crops, green manures or grass leys may be all you need to improve soil conditions. Indeed, avoiding the use of 'metal' will also encourage earthworm populations, which are the most reliable 'cultivators'. However, it may take a few years to see noticeable change.

If compaction is restricting drainage or crop/grass roots at 20 cm (10 inches) depth or below, subsoiling or sward lifting may be required. The guidance listed above stresses the importance of dry (friable or cemented) conditions at cultivation depth. Just as working soil in wet conditions causes damage, you need dry conditions to rectify it. See the Healthy Grassland Soils pocketbook for more information on the right conditions and aftercare when sward lifting. See Arable soil management and the Field drainage guide for more technical guidance on subsoiling.

Remember, subsoiling or sward lifting soils that are in good condition will do more harm than good. Only consider using a chisel plough or subsoiler in wet conditions in emergency situations, to create a channel to move water away, as you would do in a moling operation.

Also think about the costs associated with the different options compared with the intended benefits:

Option	**Materials and operations**	**Overall cost (£/ha)[1]**
Subsoiling or sward lifting	Single pass	£55-£65
Cover cropping	Cost of seed plus: • Cultivated/not cultivated • Broadcast/drilled • Rolled	£89-£244
Grass or herbal ley	Cost of seed plus: • Cultivated/not cultivated • Broadcast/drilled • Rolled	£173-£364

[1] Redman, G. (2019). The John Nix Pocketbook for Farm Management 2020. 50th Edition. Melton Mowbray: Agro Business Consultants.

The guidance listed above also provides information on costs and benefits of alleviation strategies in different sectors.

4.3. Assess the effectiveness of the action

When subsoiling or sward lifting, it is always worth assessing the effectiveness of the operation on a small area before lifting the whole of the affected area. Check the working depth and the amount of lift and cracking achieved. Always have a spade or fork and a tape measure to hand.

4.4. Summary

Soil structural damage is sometimes unavoidable, but when it happens remember to assess, consider the appropriate response (right action; right conditions) and reassess the effectiveness of any field operation. In many cases all you need is vegetation cover, roots and earthworms to improve soil conditions over time. Indeed, on soils that crack, no action is often sufficient. If using metal, carefully consider whether it is necessary and whether you have the right conditions for an effective operation.

5. Case Study 1: Use of the soil health scorecard to evaluate the impact of controlled traffic farming within field vegetable rotations at Barfoots

5.1. Background

Barfoots Farms Ltd. is a horticultural business based in southern England (Hampshire and West Sussex) with farms at Trotton, Chichester and Little Abshot in Hampshire, growing a range of field vegetables including sweetcorn, tenderstem broccoli (TSB), courgettes, pumpkins, dwarf beans and broad beans. The company has developed a long-term soil management strategy including the use of cover crops, controlled traffic farming (CTF) and reduced tillage. The main drivers for this strategy were reducing costs (reduced fuel consumption – minimal cultivation, fewer machinery passes, reduced depth of cultivation where possible); soil quality benefits; and associated increases in crop yield. In 2016, the farm at Abshot was in the initial stages of adopting a CTF system and the condition of soils in a number of fields was measured as part of the AHDB Horticulture PF-*Hort* project which looked at the structural condition of soils in horticultural rotations. The PF-*Hort* project demonstrated that moving to a 5 m-based CTF system at the farm would result in a permanent 30% reduction in tracked area across the whole farm and a 63% reduction for the majority of the area, and that reducing tillage intensity would result in a 10-15% reduction in fuel use per hectare (Chamen et al., 2019; https://ahdb.org.uk/knowledge-library/soil-management-strategies-to-improve-soil-quality-and-cut-operating-costs-in-sweetcorn-production). Baseline soil assessments were undertaken in November 2016 within three fields at Little Abshot with contrasting landuse/management: CTF, inversion tillage and temporary grassland. These fields were re-sampled in November 2020 as part of the Soil Biology and Health Partnership, with the aim of evaluating if and how soil conditions had changed since 2016, interpreting the findings in the light of the soil health scorecard that has been developed by the partnership.

5.2. Methodology

5.2.1. Study sites

Table 5.1 provides details of the cropping and management of the three fields at Little Abshot since the baseline sampling in November 2016. Parrett 1 has used partial CTF since 2016, incorporating cover crops into the rotation and reducing tillage intensity, with targeted subsoiling of headlands and tramlines where needed. However, in autumn 2018 and again in spring 2020 (pre and post the courgette crop) the whole field was subsoiled (2018 only) and ploughed (to 8 inches; 2018 & 2020) to remove compaction and correct damage incurred following the courgette harvest; this operation did not follow the 5m CTF working width. Chilling 3 was a non-CTF field, with soils typically ploughed post-harvest and left bare over winter. Meon was intended to be in permanent grassland for the duration of the study, but had to be cultivated in 2017 due to excessive weed growth and thereafter followed a spring crop rotation (cereals, sweetcorn) with grass cover crops and reduced tillage, but without CTF. The non-inversion tillage methods used in Parrett 1 and Meon included a 'top-down' cultivator and power harrow typically working between 7.6 to 15cm (3 and 6 inches), depending on the crop.

Table 5.1 Crop rotation and soil management practices in the three study fields at Little Abshot farm

	Parrett 1 (Partial CTF & cover crops)	Chilling 3	Meon
Soil management practices	Partial CTF, cover crops ahead main crop since 2016, reduced tillage[1]	Plough-based, no cover crops	Grass leys & cover crops since 2016, reduced tillage
2019/20[2]	Cover crop Sweetcorn	Pumpkins	Grass cover crop Sweetcorn
2018/19	Cover crop Courgette	Sweetcorn	Grass cover crop Spring wheat
2017/18	Cover crop Sweetcorn	Sweetcorn	Grass cover crop Spring wheat
2016/17[2]	Cover crop Sweetcorn	Winter wheat	Grass/bean catch crop[3]
2015/16	Tenderstem broccoli	Sweetcorn	Grass
2014/15	Sweetcorn	Tenderstem broccoli	Sweetcorn
2013/14	Tenderstem broccoli	Winter wheat	Pumpkins

[1]Harvest of sweetcorn in 2017 and courgettes in 2018 in wet conditions caused soil compaction which the farm addressed by ploughing before the next crop. The plough system did not follow the 5m CTF system. This highlights a challenge of CTF systems in vegetable rotations requiring periodic ploughing to remove compaction.

[2]Baseline soil assessments conducted in November 2016 (i.e. cover crop, winter wheat and grass in Parrett 1, Chilling 3 and Meon, respectively), repeated in November 2020 (i.e. sweetcorn stubbles, bare ploughed, grass cover crop in Parrett 1, Chilling 3 and Meon, respectively).

[3]The grass established in 2015/16 was sprayed off in spring 2017 due to a weed problem and the field was used for a green bean trial that wasn't harvested so acted as a 'catch crop'. Thereafter, the field has been spring cropped with an overwinter grass cover crop; all crops were established using non-inversion tillage methods.

5.2.2. Soil sampling

A topsoil (0-15cm) sample was taken in November 2020 from each of the long-term study fields from the same sampling area used in autumn 2016 (using GPS records of the 2016 sampling locations). Samples were analysed for pH, extractable P, K & Mg, organic matter (by loss on ignition - LOI); CO_2-C respiration burst and potentially mineralisable N (PMN). Visual soil evaluation was used to determine soil structural condition, using both VESS (as used by soil health scorecard approach; Guimaraes *et al.*, 2011) and VSA (Shepherd, 2000) methodologies, to match what was done in 2016. Three assessments were made in each field, corresponding to the points of maximum, median and minimum penetration resistance, as determined from 20 penetration resistance measurements (to

30cm) taken across the topsoil sampling area. Earthworm counts were conducted on each of the three VESS assessment blocks. The SBSH soil health scorecard uses the VESS methodology to evaluate soil physical condition. The PF-*Hort* study also undertook a detailed survey of soil physical condition in each of the fields in 2016, by taking bulk density measurements across a 10 x 10m grid, with samples taken every five metres (nine sampling points in total). This sampling was repeated in 2020 at the exact same locations, with bulk density measured at 15-20cm depth and a penetrologger used at each of the points to measure penetration resistance down the profile to 60cm depth, in order to evaluate subsoil structural condition.

5.3. Results and discussion

Above average rainfall in autumn 2020 meant that the sweetcorn harvest was delayed and was conducted in very wet conditions (particularly in Parrett 1 and Chilling 3), causing considerable structural damage, as can be seen in the case of Parrett 1 field which had deep ruts containing standing water (Figure 5-1a). Chilling 3 was ploughed soon after the pumpkin harvest (Figure 5-1b), and although sampling was timed for 4 weeks after this ploughing event, the soil condition was described as 'marginal' for visual soil assessments in particular. In Meon, the grass cover crop had just established (Figure 5-1c).

Table 5.2 compares topsoil soil chemical, physical and biological properties measured in 2016 and 2020, using the SBSH partnership soil health scorecard approach to interpret the findings (i.e. the 'traffic light coding').

Table 5.2 Topsoil chemical, physical and biological properties in autumn 2016 and 2020, reported as a soil health scorecard.

Field name	Parrett 1		Chilling 3		Meon	
Texture	Sandy silt loam		Clay loam		Clay loam	
% clay	14		20		19	
Year	2016	2020	2016	2020	2016	2020
Current crop	Cover Crop	Stubble	WW	Ploughed	Grass	Grass reseed
pH	6.4	6.7	7	7.2	6.9	7.1
SOM % (LOI)	2.0	2.3	2.5	2.8	2.8	3.1
Ext P mg/l (Index)	42 (3)	49 (4)	44 (3)	38 (3)	23 (2)	26 (3)
Ext K mg/l (Index)	159 (2-)	184 (2+)	156 (2-)	237 (2+)	125 (2-)	113 (1)
Ext Mg mg/l (Index)	84 (2)	84 (2)	130 (3)	152 (3)	74 (2)	66 (2)
PMN (mg/kg)	nd	10	nd	24	nd	16
CO_2-C (mg/kg)	nd	76	nd	79	nd	93
VESS (limiting layer)	4.2	1.8	2.2	2.0	2.7	1.8
Earthworms (No/pit)	4	4	3	5	8	4

No action needed Monitor Investigate

Figure 5-1 Soil conditions in a) Parrett 1; b) Chilling 3; c) Meon, at the time of sampling (November 2020)

There was little change in soil pH and nutrient status between 2016 and 2020. Topsoil pH was close to or above optimum levels of 6.5 recommended in the Nutrient Management Guide (RB209; AHDB, 2017) and nutrient levels (extractable P, K and Mg) were at or above target levels (i.e. P index 2-3, K index 2-/2+, Mg index 2-3). The only exceptions were for extractable P in Parrett 1 and extractable K in Meon. In Parrett 1 topsoil extractable P was at index 4 and given an 'amber' flag; levels in excess of index 4 can pose a risk to the environment, so manufactured fertiliser P should not be applied to this field. In Meon extractable K was at index 1 ('amber') which suggests additional K in the form of manufactured fertiliser or manures is required to build soil levels for crop production.

Soil organic matter (SOM) levels were marginally higher in 2020 compared to 2016, but this difference is unlikely to be significant (this could not be tested statistically as only a single sample was analysed). As in 2016 SOM reflected the soil types and land use, with higher levels in Meon (successive grass leys and cover cropping) compared to the annual horticultural cropping undertaken in Parrett 1 and Chilling 3. All three fields however had below average SOM contents for the soil type and rainfall region (using SBSH scorecard thresholds, Griffiths *et al.,* 2018). This is supported by both the potentially mineralisable N (PMN) and respiration burst (CO_2-C) measurements in 2020 (not measured in 2016), which give an indication of the level of biological activity within a soil and are related to SOM content. Both of these assessments suggested low microbial activity.

Topsoil structural condition is evaluated using the VESS method in the scorecard. Here the limiting layer score is reported (rather than the overall block average) which enables detection of the extent and depth of the poorest (most compact) soil structural condition. In 2016, a 'compact' (Sq 4) layer with large, sub-angular aggregates and few macropores was detected at 13-25cm in Parrett 1 (Figure 5-2a). Similarly in Chilling 3 and Meon the poorest layers were detected at this depth, although there was less compaction: Sq 2 ('intact') for Chilling 3 and Sq 3 ('firm') for Meon (Figure 5-2c&e). In all three fields the topsoil near the soil surface was relatively friable, with abundant plant roots present. In 2020, soils were wetter when assessed (Figure 5-3), but scored more favourably Sq2: ('intact') in all three fields, with no obvious layering in Meon, but slightly lower (i.e. 'better') scores (Sq1.5: friable/intact) recorded in the top 20 cm of Parrett 1 and Chilling 3 (Figure 5-2b,d,e). This corresponds with the depth of ploughing (8 inches/20cm). As Parrett 1 was ploughed in spring 2020, it is more likely that the improvement in soil structural condition is the result of cultivation, rather than the period of CTF and cover cropping that preceded this operation.

a) Parrett 1 (2016) Sq = 4

b) Parrett 1 (2020) Sq = 2

c) Chilling 3 (2016) Sq = 2

d) Chilling 3 (2020) Sq = 2

e) Meon (2016) Sq = 3

f) Meon (2020) Sq = 2

Figure 5-2 VESS assessments in 2016 and 2020 (with limiting layer scores)

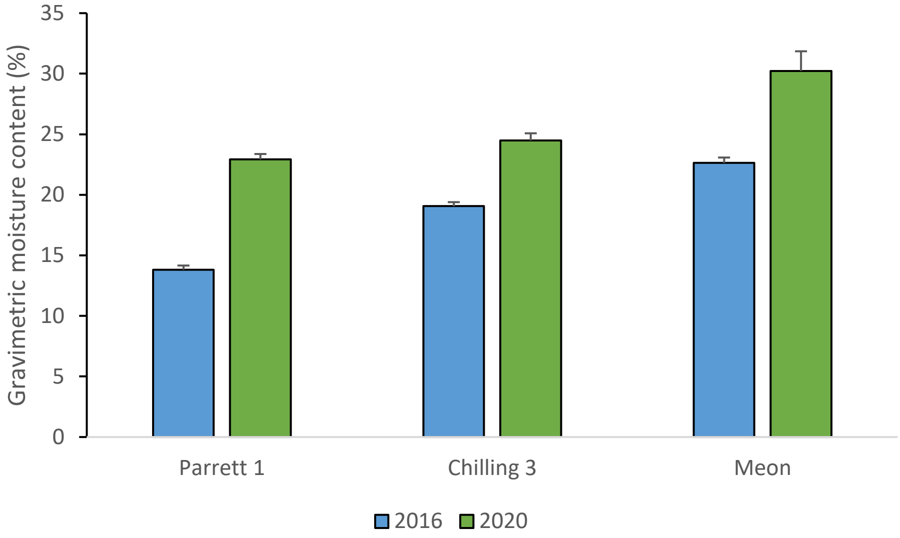

Figure 5-3 Mid topsoil (10-15cm) gravimetric moisture content at the time of sampling

VSA was also used to assess structural condition, and in contrast to the VESS assessment, Parrett 1 had similar scores in 2020 to those recorded in 2016 ('moderate'), whereas both Chilling 3 and Meon showed a slight deterioration in condition between the two samplings, dropping from 'good' to 'moderate' (Figure 5-4). This is probably related to soil moisture (wetter soils in 2020) and in the case of Chilling 3 due to the recent harvest and ploughing which was undertaken when soils were wet.

Parrett 1. VSA (2016) score = 21

VSA (2020) score = 19

Chilling 3. VSA (2016) score = 27 VSA (2020) score = 20

Meon. VSA (2016) score = 26 VSA (2020) score = 23

Figure 5-4 VSA 'structure and consistence' photos from Parrett 1, Chilling 3 and Meon in 2016 and 2020, with VSA scores (<10 = poor, 10-25 = moderate, >25 good soil structure)

5.3.1. Detailed soil structural assessments

In 2016, mean bulk density (BD) values in Parrett 1 (horticultural cropping) and Meon (grass ley) were above the UK Soil Indicator Consortium (UKSIC; Merrington, 2006) trigger values in all topsoil and subsoil layers, and in Chilling 3 the lower topsoil (15-20cm) was the only soil layer in the three fields in which soil BD was below the trigger value. Bulk densities greater than the trigger values are an indication that soils are potentially compacted and some action may be required to remediate the issue, or plant growth could be impaired.

Bulk density was only measured in the mid-topsoil (10-15cm) in 2020. As can be seen from Figure 5-5 BD had improved in Parrett 1 and had decreased to below the UKSIC trigger value (i.e. < 1.50g/cm^3 for soils containing 2-3% SOM). This improvement matches the VESS assessments undertaken in this field, but it is likely that the spring ploughing would have had the greatest influence on this outcome, rather than the adoption of CTF, reduced tillage and cover cropping. Bulk density was also lower in Meon compared to 2016 values, again dropping to below the UKSIC trigger value (i.e. <1.4 g/cm^3 for soils containing 3-4% SOM). In Chilling 3 BD was below the UKSIC trigger value on both sampling occasions, but had improved (i.e. was lower) at the 2020 sampling (Figure 5-5).

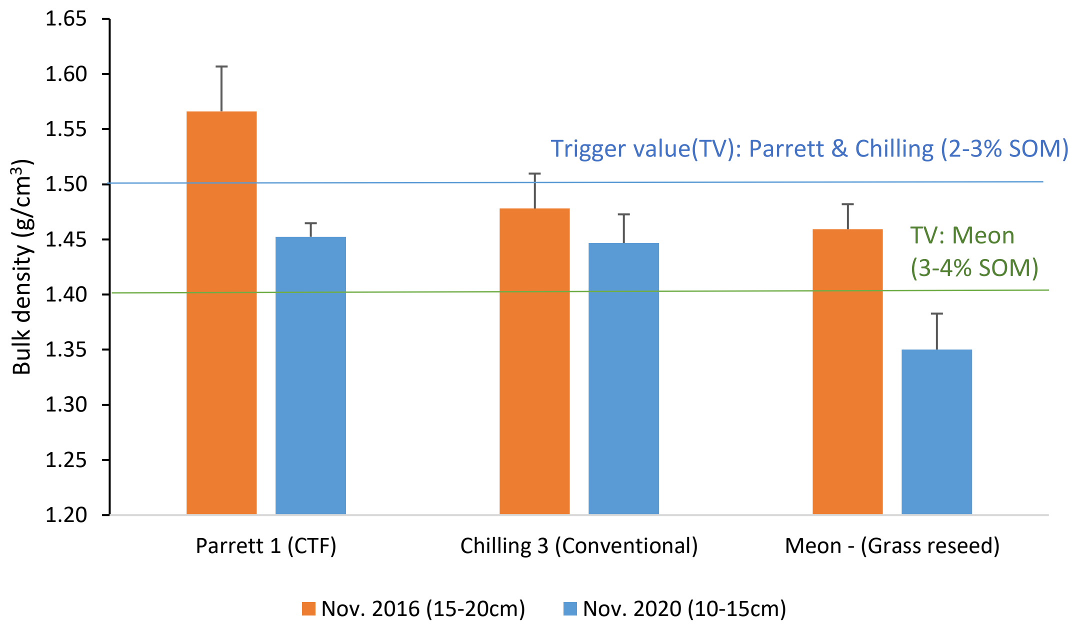

Figure 5-5 Mid-lower topsoil bulk density in 2016 and 2020, in comparison to the UKSIC Trigger values (TV).

Penetration resistance to depth was also measured across the bulk density grid-sampling positions. In all three fields, there were high levels of resistance at 30-35cm depth, with the penetrologger unable to be pushed below this depth at most points within Parrett 1 in particular (Figure 5-6). Resistances above 1.25 MPa indicate moderate levels of compaction, whilst those above 2MPa suggest levels of compaction will significantly impede root growth (Valentine et al., 2012, Griffiths et al., 2018). Soil pits dug in each field clearly showed this compacted layer, with some mottling also observed suggesting impeded drainage (Figure 5-7). Penetration resistance measurements and subsoil visual evaluation of soil structure (SubVESS; Ball et al., 2015; https://www.sruc.ac.uk/media/4qgfjtuh/valuing-your-soils.pdf) undertaken in 2016 also found this resistant layer in the upper subsoil. This suggests that the measures employed to improve soil structure between 2016 and 2020 (CTF, reduced tillage, cover crops) only had an impact on topsoil condition. As the visual soil assessment methodologies (VESS/VSA) only evaluate the topsoil horizon, this subsoil compaction would not have been captured within the soil health scorecard assessments.

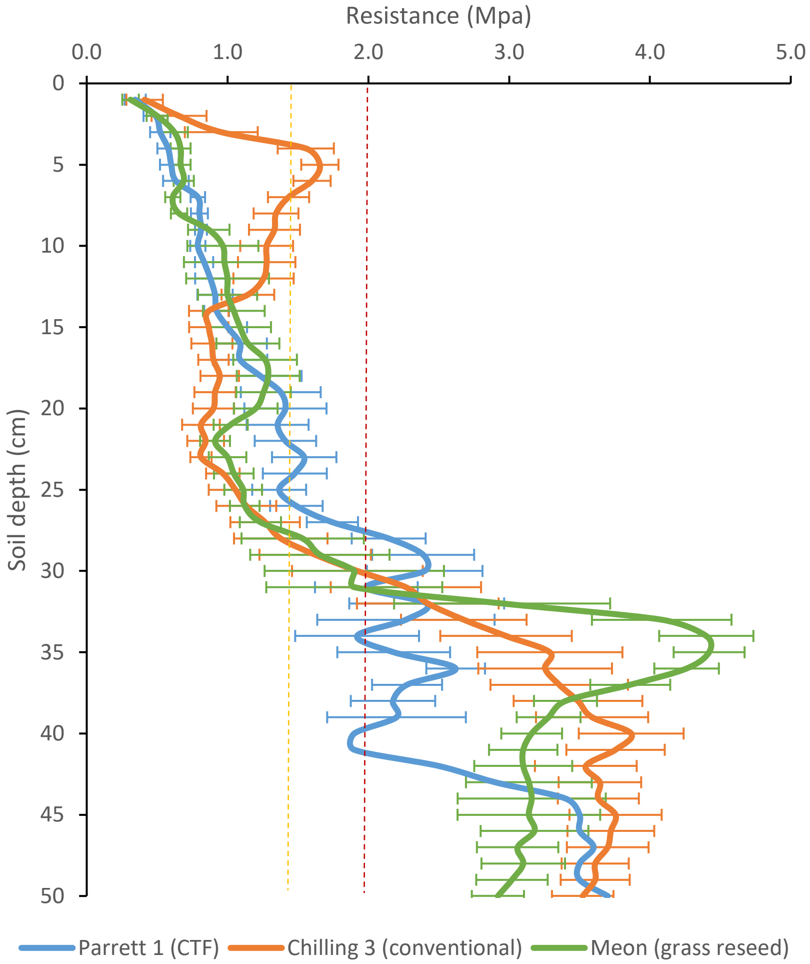

Figure 5-6 Penetration resistance profiles (November 2020); resistances>1.25 MPa indicate moderate compaction (amber dotted line) and >2MPa high compaction with the potential to significantly impede root growth (red dotted line)

Note the penetrologger could only be inserted below 30cm at 4 of the 9 measurement points in Meon and Parrett 1, dropping to just 1 measurement position in Parrett 1 below 38cm in Parrett 1 (hence the lack of error bars at this point in the chart). Recordings were possible at all locations within Chilling 3.

Figure 5-7 Soil pits showing subsoil structural conditions (hardened layer at 30-35cm with some mottling)

5.4. Conclusions

It was encouraging that the visual soil evaluation scores agreed with the more detailed bulk density assessments, confirming its usefulness as a practical method for field assessment of soil structural condition. Although there appeared to have been an improvement in topsoil structural condition in both Parrett 1 (CTF, reduced tillage & cover cropping) and Meon (short term grassland + reduced tillage) since 2016, it is not possible to attribute this to the long-term soil management practices put in place within these fields, due to recent tillage practices (ploughing in spring 2020 within Parrett 1, and cultivations ahead of establishing the grass cover crop in Meon). This demonstrates the challenge of CTF systems in vegetable rotations where periodic ploughing may be required to remove compaction.

The soil health scorecard only focuses on topsoil condition, whereas subsoil compaction remains problematic across all three fields. Alleviation of this level of compaction may be achieved through long-term continuation of the soil improving practices adopted within Parrett 1, i.e. CTF, cover cropping and reduced tillage. Soil organic matter remained low in all fields and supported low levels of microbial activity and earthworm numbers; the continued use of cover crops and addition of organic materials is recommended to build soil organic matter levels.

This case study shows that use of soil health scorecard provides a useful tool to evaluate topsoil physical, biological and chemical ‘health’ and monitor change over time. This, together with an assessment of subsoil condition (e.g. using SubVESS and penetration resistance measurements) is recommended in another 4-5 years, to enable continued evaluation of the use of these soil management techniques for improving soil health.

6. Case Study 2: Use of the soil health scorecard to evaluate changes in soil health under hardy nursery stock

6.1. Background

Wyevale Nurseries' Transplant Division is a horticultural company based in Herefordshire who specialise in raising hedges and tree transplants, which are typically established in outdoor seedbeds until they are around 30 cm tall. Young plants are lifted between October and February and cold stored prior to being transplanted into beds in the spring (March-May). The plants are then grown on for 1 to 2 years before autumn-winter harvesting and selling on into various markets. Soils are sandy (Bromsgrove Association) and many of the fields are sloping. One of the greatest challenges for soil management at Wyevale is the fact that plants are harvested in the autumn-winter period when soils are 'moist' to 'wet'; and in the absence of any mulch, soils are left bare over winter. Soil erosion is therefore a significant issue at the site, resulting in loss of soil organic matter and topsoil nutrients, and a major pollution risk for watercourses. Slumping, resulting in soil compaction, and capping, also reduce production at the nursery. Wyevale have explored several erosion mitigation options (e.g. grassed headlands, sedimentation ponds and sediment traps) with the aim of protecting sensitive receptors (neighbours and local watercourses) from surface runoff. The nursery has also been exploring ways to improve the resilience of their soils by growing grass leys and applying green compost.

The nursery was included as a demonstration site as part of the AHDB Horticulture *PF-Hort* project in 2018 looking at the structural condition of soils in horticultural rotations. A baseline survey of three fields at the Nursery was undertaken in January 2018, selected to represent the range of tree and hedge species grown at Wyevale Nurseries' Transplants (https://ahdb.org.uk/knowledge-library/control-soil-erosion-and-improve-soil-conditions-in-nursery-stock-production). Results showed that soil compaction generally extended to below the effective working depth of most agricultural subsoilers (*c*. 45 cm depth). The same three fields were re-sampled in December 2020 as part of the Soil Biology and Health Partnership, with the aim of evaluating if and how soil conditions had changed since 2018, interpreting the findings in the light of the soil health scorecard that has been developed by the partnership.

6.2. Methodology

6.2.1. Study sites

Table 6.1 and Figure 6-1 provide details of the location and cropping of the three fields at Wyevale since the baseline sampling in January 2018. Bed establishment usually involves subsoiling 2 or 3 times before ploughing (in the furrow), power harrowing, bed forming, sterilisation and drilling/transplanting. However, the farm managers have been considering ways of reducing the number of cultivations to reduce soil instability. Sampling was undertaken between the rows of nursery stock in Northbank, in a recently established grass ley in Vinnings field and from a fallow (recently harvested and cultivated) section of the field in Upper Foxbury.

Table 6.1 Crop rotation in the three study fields at Wyevale

	Northbank	Vinnings	Upper Foxbury
2020/21	50% field area: grass ley 50% field area: nursery stock	Grass ley	Nursery stock in the process of being harvested at the time of sampling
2019/20	50% field area: grass ley 50% field area: nursery stock	75% field area: grass ley 25% field area: nursery stock	Nursery stock
2018/19	50% field area: grass ley 50% field area: nursery stock	70% field area: grass ley 30% field area: nursery stock	Mustard cover crop
2017/18	Hawthorn (*Crataegus monogyna*)	Hawthorn (*Crataegus monogyna*)	Guelder rose (*Viburnum opulus*)

All 3 fields had been in annual cropping prior to 2017/18; note c. 6 t/ha horse manure applied to Vinings in October 2020

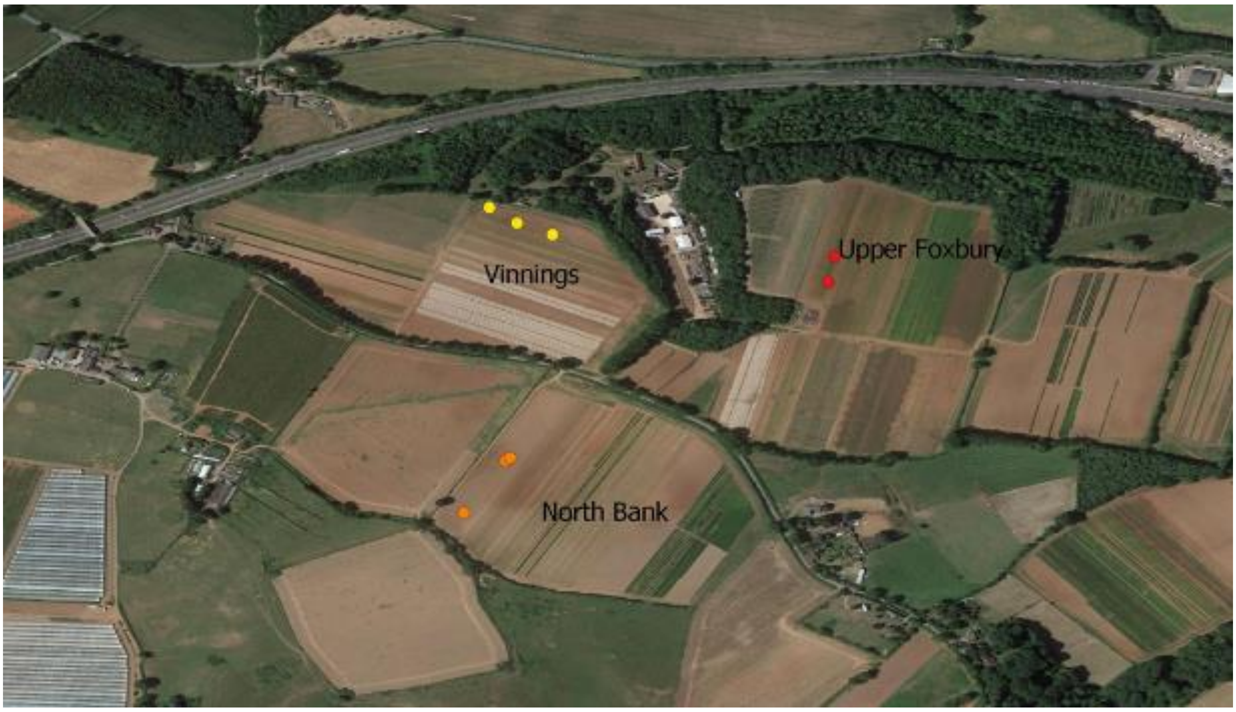

Figure 6-1 Study field location and sampling points

6.2.2. Soil sampling

A topsoil (0-15 cm) sample was taken in December 2020 from each of the study fields from the same sampling area used in January 2018 (using GPS records of the 2018 sampling locations). Samples were analysed for pH, extractable P, K & Mg, organic matter (by loss on ignition - LOI); CO_2-C respiration burst and potentially mineralisable N (PMN). Visual soil evaluation was used to determine soil structural condition, using VESS (as used in the soil health scorecard approach; Guimaraes *et al*., 2011) and SubVESS (Ball et al., 2015) methodologies, to include an assessment of subsoil structural condition. Penetration resistance to 60 cm and mid topsoil (10-15 cm depth) and upper subsoil (30-35 cm depth) bulk density was also determined to give a more detailed evaluation of soil structural condition and match the baseline assessments undertaken in 2018. Three assessments were made in each field, corresponding to the points of maximum, median and minimum penetration resistance, as determined from 20 penetration resistance measurements (to 30 cm) taken across the topsoil sampling area. Earthworm counts were conducted on each of the three VESS assessment blocks.

6.3. Results and discussion

Table 6.2 compares topsoil soil chemical, physical and biological properties measured in 2018 and 2020, using the SBSH partnership soil health scorecard approach to interpret the findings (i.e. the 'traffic light coding').

Table 6.2 Topsoil chemical, physical and biological properties in winter 2018 and 2020, reported as a soil health scorecard.

Field name	Northbank		Vinnings		Upper Foxbury	
Texture	Sandy loam		Loamy sand		Loamy sand	
% clay	9		7		7	
Year	2018	2020	2018	2020	2018	2020
Current crop	Nursery stock	Nursery stock	Nursery stock	Grass	Nursery stock	Fallow
pH	6.2	6.8	6.7	7.1	6.5	6.9
SOM % (LOI)	1.7	1.8	1.7	1.7	2.1	1.7
Ext P mg/l (Index)	42 [3]	66 [4]	41 [3]	40 [3]	73 [5]	82 [5]
Ext K mg/l (Index)	237 [2+]	298 [3]	266 [3]	152 [2-]	249 [3]	180 [2+]
Ext Mg mg/l (Index)	70 [2]	56 [2]	38 [1]	35 [1]	66 [2]	56 [2]
PMN (mg/kg)	nd	17.2	nd	14.3	nd	9.6
CO_2-C (mg/kg)	nd	64	nd	105	nd	62
VESS (limiting layer)	2.1	1.3	2.3	1.0	2.3	1.0
Earthworms (No/pit)	0	0	0	0	0	0

No action needed | Monitor | Investigate

Topsoil pH increased in all three fields compared to the measurements undertaken in 2018 and was slightly above optimum levels of 6.5 recommended in the Nutrient Management Guide (RB209; AHDB, 2017). There was very little change in topsoil nutrient status; extractable K was at or above target levels i.e. K Index 2-/2+ in all fields, whereas extractable Mg remained low in Vinnings (Index

1) and extractable P was high in Upper Foxbury (Index 5). Extractable P levels in excess of Index 4 can pose a risk to the environment, so manufactured fertiliser P should not be applied to Upper Foxbury or Northbank.

Soil organic matter (SOM) levels were similar at both samplings, dropping slightly between 2018 and 2020 in Upper Foxbury, with all three fields having below average SOM contents for the soil type and rainfall region (using SBSH scorecard thresholds, Griffiths *et al.,* 2018). This is supported by both the potentially mineralisable N (PMN) and respiration burst (CO_2-C) measurements in 2020 (not measured in 2016), which give an indication of the level of biological activity within a soil and are related to SOM content. Both of these assessments suggested low microbial activity. There were also no earthworms found in any of the soil pits. This is probably a reflection of the light textured soils, the low organic matter content and residue return, plus the cultivations required to establish and harvest the transplants.

Topsoil structural condition is evaluated using the VESS method in the scorecard. Here the limiting layer score is reported (rather than the overall block average) which enables detection of the extent and depth of the poorest (most compact) soil structural condition. In 2018, all three fields had a limiting layer score of 2 (‘intact’). The topsoil generally broke up relatively easily and was friable (due to its light texture) with mainly fine aggregates and occasional larger, sub-angular aggregates. However, a moderately developed tillage pan was observed in the lower topsoil (10-25cm depth; Figure 6-2a,c,e). This tillage pan was not observed in 2020, with all three fields having very friable rounded aggregates (Figure 6-2b,d,f). This is probably a reflection of the soil texture, rather than evidence of good soil structure. Moreover, although the scorecard suggests the structure was ‘good’ (i.e. given a ‘green’ traffic light), there was evidence of surface capping and significant surface erosion, particularly in Northbank and Upper Foxbury where there was limited vegetative cover (Figure 6-3 & Figure 6-4). Use of VESS on light textured, unstable arable and horticultural soils can therefore sometimes give rise to misleading conclusions about soil structural stability, due to the ease of break-up into friable aggregates. It is therefore recommended that VESS scores should also be evaluated in the light of soil surface condition on these soil types (e.g. evidence of erosion, capping, waterlogging etc). The grass ley grown in Vinnings field appeared to be offering some protection against soil loss, but where nursery stock was being harvested in the adjacent field, there was evidence of severe rutting and erosion (Figure 6-5).

a) Northbank (2018) Sq = 2.1

b) Northbank (2020) Sq = 1

c) Vinnings (2018) Sq = 2.3

d) Vinnings (2020) Sq = 1

e) Upper Foxbury (2018) Sq =2.3

f) Upper Foxbury (2020) Sq = 1

Figure 6-2 VESS assessments in 2018 and 2020 (with limiting layer scores)

Figure 6-3 Sampling area and evidence of erosion in Northbank field

Figure 6-4 Sampling area and evidence of erosion in Upper Foxbury field

Figure 6-5 Sampling area in Vinnings field and adjacent field area undergoing harvesting of the nursery stock

6.3.1. Detailed soil structural assessments

In 2018, mean bulk density (BD) values in mid topsoil horizon were close to the UKSIC (Merrington, 2006) trigger value of 1.6 g/cm^3, whereas bulk density in the upper subsoil (30-35cm) exceeded this value, demonstrating the influence of topsoil cultivation in creating a more porous structure. Bulk densities greater than the trigger values are an indication that soils are potentially compacted and some action may be required to remediate the issue, or plant growth could be impaired.

As can be seen from Figure 6-6, BD had increased in the mid topsoil in 2020 and upper subsoil of Northbank field. Bulk densities in the upper subsoil of Vinnings and Upper Foxbury had declined relative to the measurements undertaken in 2018, but were still above the UKSIC trigger value.

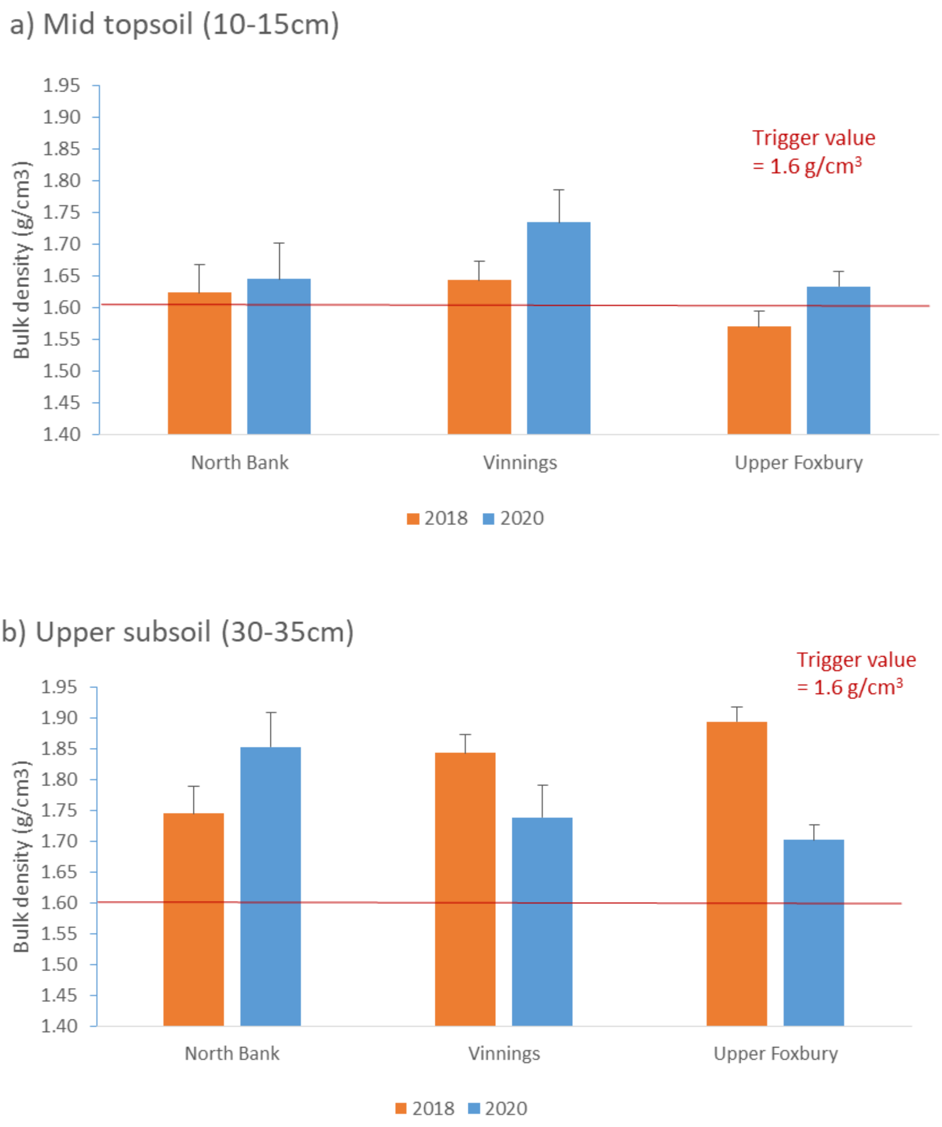

Figure 6-6 Bulk density in the mid topsoil and upper subsoil measured at Wyevale Nurseries in 2018 and 2020.

Penetration resistance to depth was also measured. In all three fields, there were high levels of resistance (> 2MPa) below 10 cm depth increasing further to resistances in excess of 3 MPa at 20-25 cm depth, with the penetrologger unable to be pushed below 30 cm depth (Figure 6-7).

Resistances above 1.25 MPa indicate moderate levels of compaction, whilst those above 2 MPa suggest levels of compaction that can significantly impede root growth (Valentine et al., 2012, Griffiths et al., 2018). SubVESS assessment of the subsoil gave an overall score of 1 ('friable') for Northbank and Upper Foxbury and 2 ('Firm') for Vinnings, although a firm layer at around 30-45 cm was detected where aggregates were harder to obtain, more angular and of a lower porosity (Figure 6-8). This was also observed in 2018.

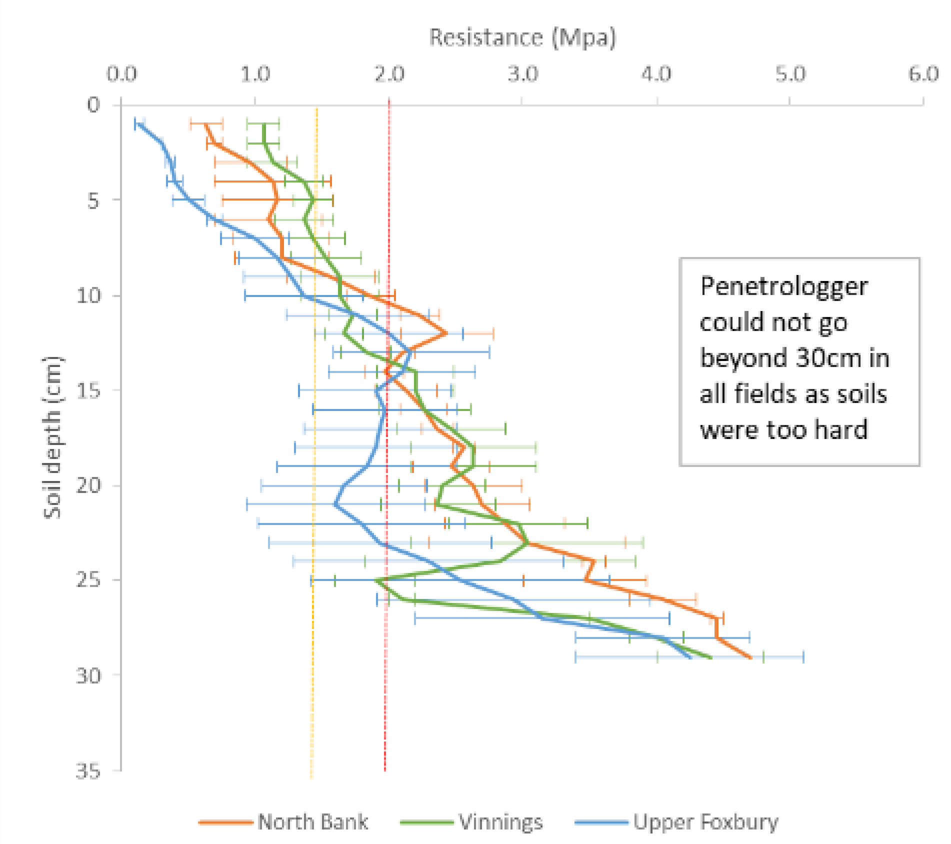

Figure 6-7 Penetration resistance profiles (December 2020); resistances >1.25 MPa indicate moderate compaction (amber dotted line) and >2 MPa high compaction with the potential to significantly impede root growth (red dotted line)

Figure 6-8 Soil pits in Northbank (left), Vinnings (central) and Upper Foxbury (right) fields showing subsoil structural conditions.

6.4. Conclusions

The repeat sampling at Wyevale Nurseries, suggested that there had been a slight improvement in topsoil structure, as determined by the VESS scores. However, there was still evidence of compaction from the mid-topsoil downwards, with very high resistances recorded below 25 cm depth, as well as topsoil erosion where there was low ground cover (e.g. between the rows of nursery stock and in the bare fallow field). The nature of production and winter harvesting operations exacerbate these issues and a reduction in cultivation intensity and trafficking would help alleviate the problem. Soil organic matter concentrations also remained low, with low levels of microbial activity and earthworm numbers. The use of green compost, mulches and grass leys/strips between rows is recommended to build organic matter levels and protect the soil surface.

This case study shows that the soil health scorecard provides a useful tool to evaluate topsoil physical, biological and chemical 'health' and monitor change over time. However, use of VESS on light textured, unstable arable and horticultural soils can sometimes give rise to misleading conclusions about soil structural stability, due to the ease of break-up into friable aggregates. It is therefore recommended that VESS scores should also be evaluated in the light of soil surface condition on these soil types (e.g. evidence of erosion, capping, waterlogging etc). Targeted assessment of subsoil condition (e.g. using SubVESS and penetration resistance measurements) is also recommended, particularly where there is evidence of erosion and compaction.

7. Case study 3: Use of the soil health scorecard to detect soil compaction on a heavy clay soil at Loddington

7.1. Background

The EU funded ‘SoilCare’ project https://www.soilcare-project.eu/ aimed to identify and evaluate promising soil improving cropping systems and agronomic techniques that increase the profitability and sustainability of European agriculture. As part of this work, GWCT established an experiment at Loddington (Leicestershire) in 2017 which compared the effect of cultivation method (plough vs. direct drilling) with or without a biological amendment (mycorrhizal inoculation) on a compacted soil. Plots were deliberately compacted by repeated trafficking prior to drilling in each 3 consecutive seasons. This resulted in both compacted (topsoil penetration resistance > 1.5MPa) and un-compacted areas (penetration resistance < 1MPa) of the field, providing a useful test-bed for the prototype soil health scorecard that is currently being evaluated by a number of farmer groups across the country within Project 9 of the Soil Biology and Soil Health Partnership. The aim of this case study was therefore to provide additional data for the overall evaluation of the scorecard approach and to see whether the approach picks up more subtle differences in soil compaction levels.

7.2. Methodology

7.2.1. Study site

The SBSH farmer protocol and scorecard assessment (i.e. topsoil chemistry, VESS and earthworm counts) was evaluated in two contrasting areas of an arable field (‘Townsend’ field) at GWCT Loddington, Leicestershire. This field was part of the SoilCare project, and each year, since autumn 2017, part (100 m X 50 m) of the field has been deliberately compressed with tractor wheels before drilling, by driving a tractor (Massey Ferguson 7720, weighing *c.* 8 tonnes) up and down, so each tyre covered all of the ground twice. The field is in an arable rotation comprising largely of winter cropping (winter barley, winter beans and winter wheat), although in 2019-20 spring wheat was grown, due to wet autumn conditions preventing establishment of a winter crop. The soils are heavy clays (56% clay) and all crops were established using a direct drill (“Eco M,” Dale Drills) and rolled with a segmented ridged roller (Cambridge rolled) to ensure seed to soil contact. Plough plots were ploughed to a depth of 25 cm then disked to a depth of 10 cm (Väderstad carrier) in autumn, while direct drill plots only received a straw rake before drilling. Standard farm practice was used for the application of manufactured fertiliser and plant protection products, and this was consistent across all plots. For this study the compressed plots without any compaction alleviation (i.e. direct drilled) were compared with the surrounding field which had not had any compression treatment, and had been ploughed after harvest, one month prior to sampling. Plots within the SoilCare experiment that had been compressed then alleviated using plough or low disturbance subsoiler (LDS) were not sampled.

7.2.2. Soil sampling

A topsoil (0-15cm) sample was taken in November 2020 from across a circular area approximately 5-10 m in diameter in each of the compressed and un-compressed parts of the field, in line with the protocol being developed to go alongside the SBSH soil health scorecard (with the central point GPS located for future sampling of the site). Samples were analysed for pH, extractable P, K & Mg, organic matter (by loss on ignition - LOI); CO_2-C respiration burst and potentially mineralisable N (PMN). Within each sampling area, three 25 X 25 X 25 cm blocks of soil were extracted for visual soil evaluation (VESS; Guimaraes *et al*., 2011) and the extracted blocks were used for an earthworm count.

The SBSH soil health scorecard currently uses the VESS methodology to evaluate soil physical condition. However, bulk density and penetration resistance were also proposed as indicators (Griffiths et al., 2018 – SBSH project 2 report), but subsequently 'dropped' as being potentially too complex for a simple scorecard approach (in the case of bulk density) or too dependent on other conditions (e.g. soil moisture and organic matter content) to make interpretation and comparisons over time difficult. These two measurements (i.e. resistance to 50 cm depth and mid-topsoil bulk density) were therefore undertaken at Loddington to evaluate whether they would provide a more robust assessment of soil compaction levels compared to visual soil evaluation. If this is the case, these assessments could potentially be used as supplementary indicators to the scorecard, for more in-depth analysis of soil condition, where compaction has potentially been identified visually. Bulk density was measured adjacent to each VESS pit by taking a soil core from 10-15 cm depth extracted using a core cutter; a metal cylinder (5 cm diameter) knocked into the soil using a hammer. Penetration resistance was conducted using a field penetrometer (Field Scout, SC900) to a depth of 45 cm with 10 measurements taken per plot and averaged. Alongside this, soil moisture measurements were taken to a depth of 20 cm using a moisture meter (Field Scout, TDR 100) with 5 measurements taken per plot and averaged. Penetration resistance was measured in September 2019 after the compression treatment, then again in May 2020 at drilling, and finally in November 2020 after harvest, alongside other measurements of VESS, earthworms and bulk density.

7.3. Results and discussion

Penetration resistance profiles measured in September 2019 and May 2020 identified a considerable difference in topsoil compaction as a result of the repeated trafficking, with the compacted areas having resistances in excess of 1.5 MPa at *c.* 5cm depth, compared to *c.*1 MPa at an equivalent depth on the un-compacted areas (Figure 7-1 & Figure 7-2). Resistances above 1.25 MPa indicate moderate levels of compaction (given an amber 'traffic light' on the soil health scorecard according to Griffiths et al., 2018), whilst those above 2 MPa suggest levels of compaction will significantly impede root growth (Valentine et al., 2012) and would result in a red 'traffic light' (Griffiths et al., 2018).

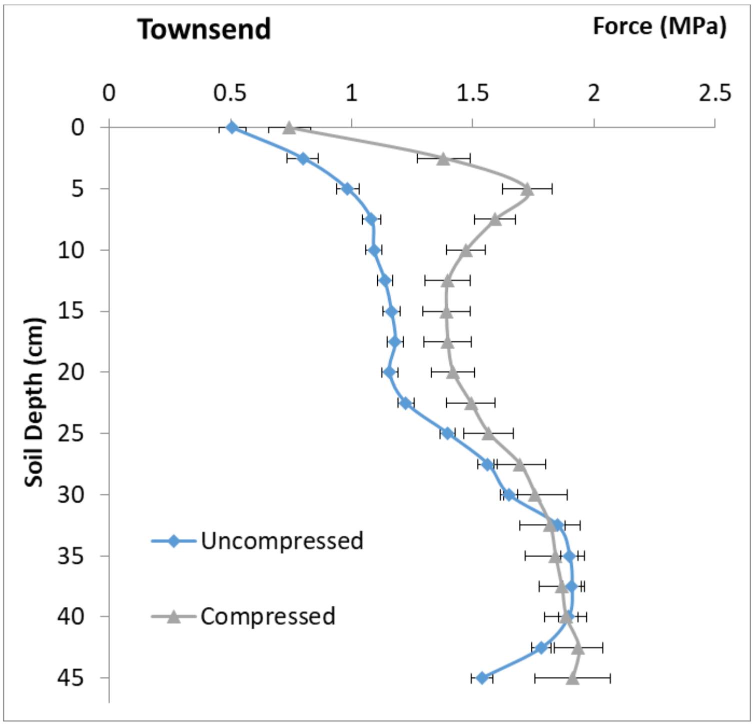

Figure 7-1 Penetration resistance profile measured in September 2019 (soil moisture at 23%)

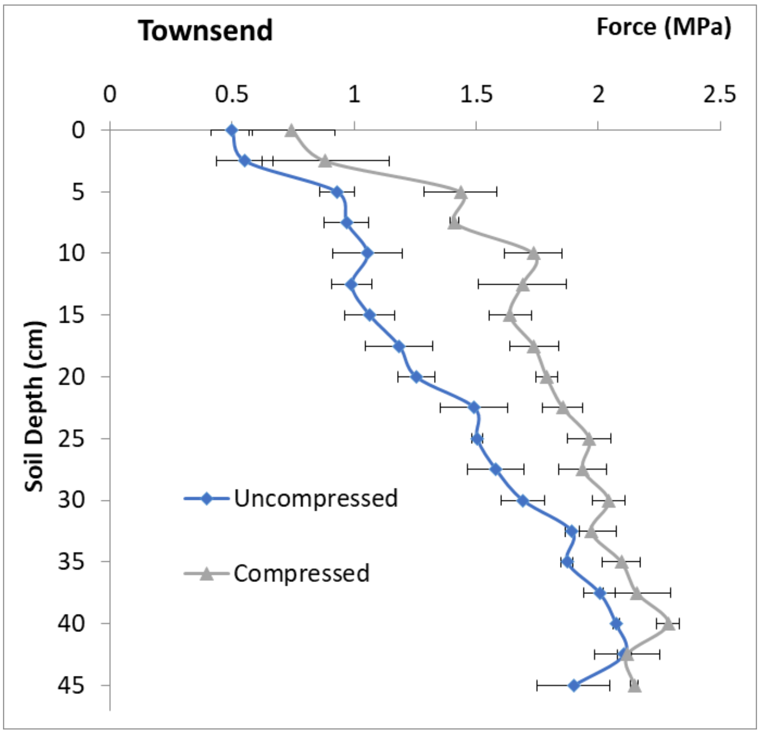

Figure 7-2 Penetration resistance profile measured in May 2020 (56.7% moisture)

The soil health scorecard from the autumn 2020 sampling of both the compressed and un-compressed areas of Townsend field is shown in Table 7.1

Table 7.1 Topsoil chemical, physical and biological properties of Townsend Field, Loddington, reported as a soil health scorecard.

Treatment area	Compressed	Un-compressed
Texture	Clay	Clay
% clay	57	56
pH	7	6.7
SOM %	10.6	8.6
Ext P (mg/l)	43	40
Ext K (mg/l)	135	116
Ext Mg (mg/l)	85	85
PMN (mg/kg)	53	39
CO_2-C (mg/kg)	132	137
VESS	2	3
Earthworms (No/pit)	4	7

No action needed

Monitor

Investigate

Somewhat surprisingly, the VESS indicated slightly poorer structure in the soils which had not received the compression treatments, with a limiting layer score of 3 ('moderate'), found at *c*. 20cm depth (layer 3 in Figure 7-3 right), whereas in the compressed soils a limiting layer score of 2 ('intact') was observed at *c*. 20cm depth (layer 3 in Figure 7-3 left). This could be due to the development of a plough pan at 20 cm in the uncompressed plots (with the plough depth set at 15-20cm and the compressed plots not ploughed). Soil moisture content (measured using a moisture meter as part of the more detailed soil structure assessments) was higher in the compressed soils (at 50%) compared to un-compressed soils (35%), which may explain why the 'un-compressed' soils had a higher VESS score (drier soils tend to be more 'firm'). SOM was also numerically lower in the un-compressed soil, although SOM content as a whole was above average for a heavy textured soil in this rainfall region. Differences in SOM contents were reflected in the PMN results, but not CO_2-C respiration. However, earthworm numbers were marginally higher in soils which had not been deliberately compressed. Note, the comparison undertaken was not replicated, so we cannot attribute the differences observed to the 'treatments' imposed. Crop yields in 2018 and 2020 appeared higher in the compressed and direct-drilled plots (Table 7.2), however this result may have been confounded by the sampling method. Yields were taken from the combine, which for the direct-drilled area were from nine 20m plots, whereas for the un-compressed area they were calculated from the rest of the 5.4 ha field, so more variability would be included. The plots were set up in a uniform area of the field so didn't suffer from poor emergence, high weed burden or headland effects that would have been included in the rest of the field measurement.

Figure 7-3 Example VESS profiles from a compressed plot (left) and a non-compressed plot (right). Numbers show location of VESS layers.

Table 7.2 Grain yields from the compacted an un-compacted areas of Townsend Field, Loddington.

Year	Crop	Yield un-compressed t/ha	Yield compressed t/ha
2018	winter barley	5.78	6.58
2019	winter beans	4.72	4.11
2020	spring wheat	6.44	7.15

7.3.1. Additional soil structural assessments

There was no difference in mid-topsoil bulk density which was 1.26 g/cm^3 in the compressed soils and 1.28 g/cm^3 in the control. These values however, are above UKSIC trigger values (Merrington, 2006), which Griffiths et al. (2018) also suggested could be used on the soil health scorecard (i.e. these values would be given a red 'traffic light'). Bulk densities greater than the trigger values are an indication that soils are potentially compact, and some action may be required to remediate the issue, or plant growth could be impaired.

Differences in the penetration resistance at 5-10cm observed in May and September (Figure 7-1 and Figure 7-2), were no longer apparent in November (Figure 7-4), despite a big difference in topsoil moisture content (i.e. drier in the 'un-compressed' control). There were still slightly higher resistances in the 'compressed' soils deeper down the profile (between 20-25cm in particular), but these only reached levels of potential concern (i.e. > 1.5 MPa) at *c*. 25 cm depth, at which point there was no difference between the two treatment areas. The September (2019) measurements were taken straight after the compression treatment, and this most likely contributed to the higher resistance values measured at that time. The May 2020 measurements were taken before significant plant growth, so it is possible that by November the action of crop growth had alleviated some of the differences between the treatments. No cultivations were carried out on the 'compressed' plots before measurements were taken.

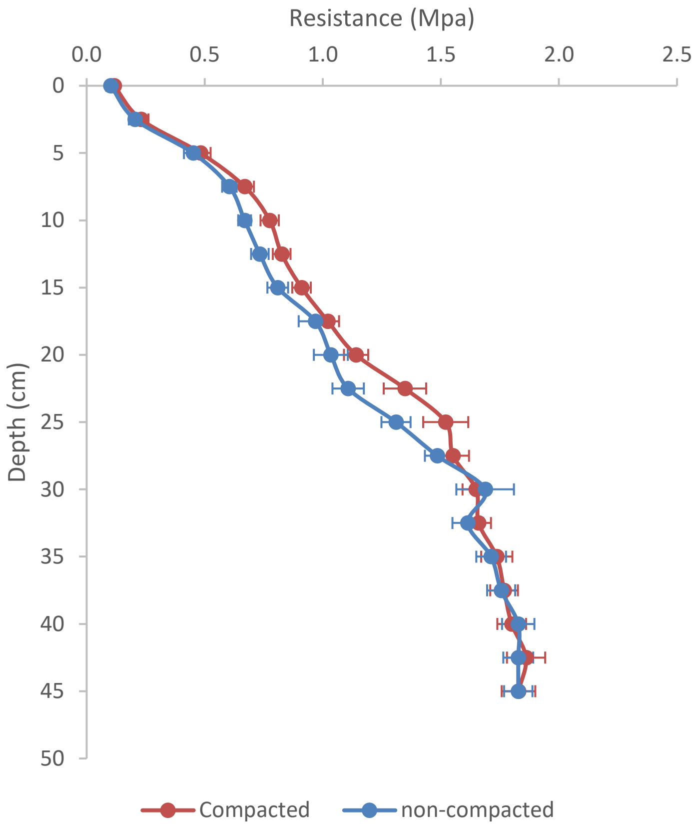

Figure 7-4 Penetration resistance profile, November 2020 (50% moisture – compacted plots; 35% moisture – non-compacted)

7.4. Conclusions

Previous results from the 'Soil Care' compaction study showed a healthier VESS score and higher earthworm numbers where 'compressed' soils had been left uncultivated, compared with plough cultivation in other areas, suggesting that the ploughing to alleviate any compaction was having a detrimental effect on soil structure and worm numbers. As the rest of the field used as the 'uncompressed' plots in the present study had plough cultivation in autumn each year, this could explain the higher VESS score when compared to the 'compressed' plots, which have had three years of minimal soil disturbance, despite the yearly compression treatment using tractor wheels. Differences in soil resistance measured using a penetrometer clearly reduced over the season, with no visible difference by November after crop harvest, suggesting that the soil was able to recover over the season, perhaps with the help of crop growth. The lack of yield differences also suggests that the crop did not suffer from the compression treatment. VESS and earthworms are clearly useful indicators of soil health, as they also show that despite the compression treatment the soil was able to sustain a healthy crop that suffered no yield loss. Using penetrometer resistance as an indicator of compaction also gave an accurate indication of the physical effect of the compression treatment. This could help farmers monitor and make decisions on cultivations.

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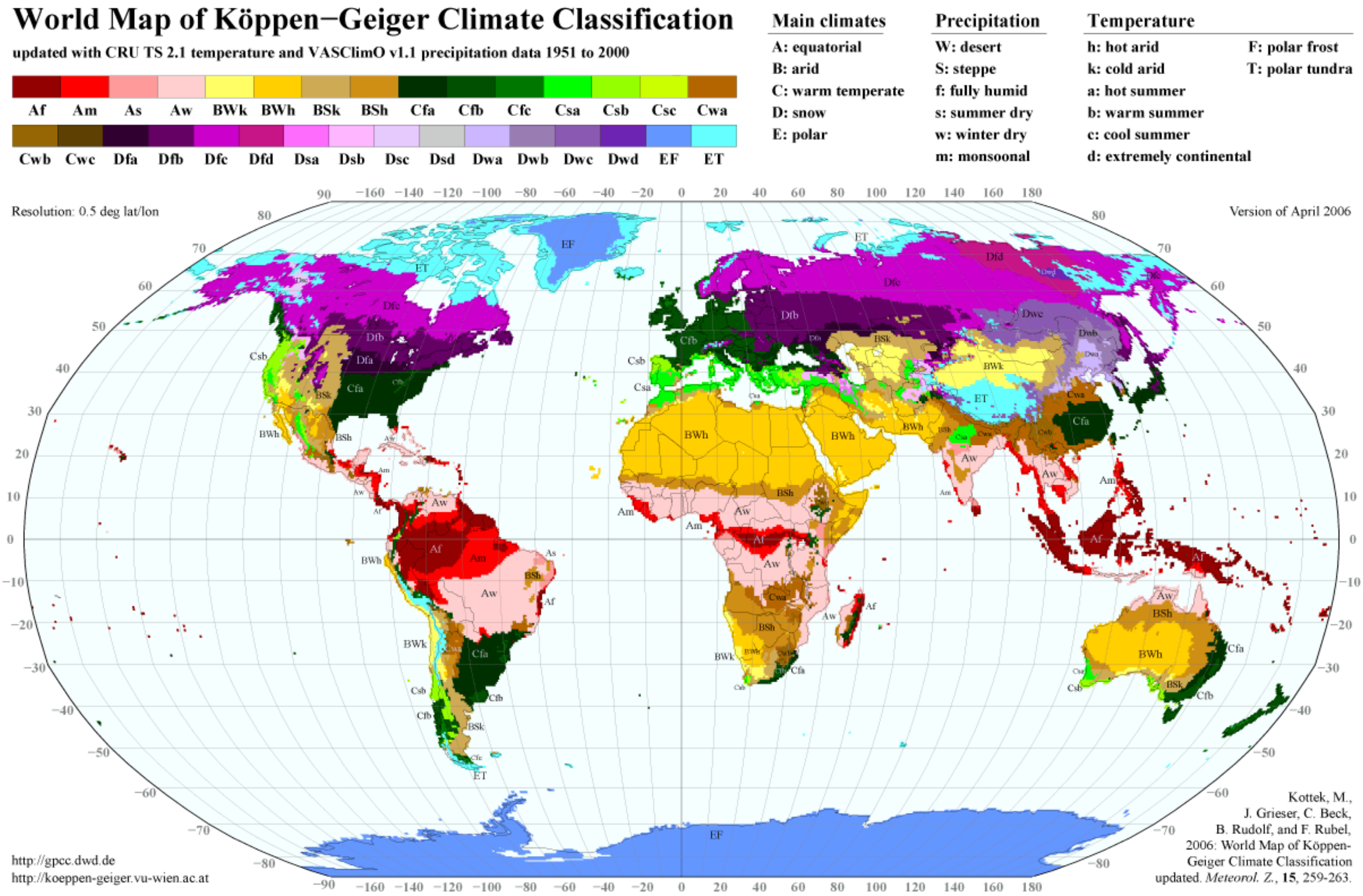
9. Appendix



Map 9-1 Word map of Köppen-Geiger climate classification. Cfb =Temperate oceanic climate (Kottek et al.*, 2006).*