Project title:	A gap analysis of soil management research and knowledge transfer in horticulture to inform future research programmes.
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Executive Summary

The aim of this study is to identify key gaps in research and in knowledge transfer mechanisms which currently hinder the development and implementation of best practice guidelines for sustainable soil management. The scope of the review covers temperate horticulture and horticulture/arable/non arable rotations. All soils used for horticultural crops (i.e. field soils, soils under temporary or permanent protection) have been included, but other organic or inorganic substrates are not. The current review defines 'soil management' as practices that involve the direct manipulation of physical, biological and/or chemical soil properties. The study objectives were to:

- Collate and review evidence regarding a) research and b) knowledge transfer mechanisms related to soil management in horticultural crops.
- Consult with horticultural industry representatives via a questionnaire to a) prioritise their current soil management issues, and b) to identify current knowledge transfer mechanisms.
- Highlight gaps in research evidence and knowledge transfer activities which hinder progress towards 'sustainable intensification'.
- Identify whether activities in other agricultural sectors can help fill these gaps or if new research is needed.

A wide variety of materials were used in the review, with over 230 documents scrutinised using a semi-structured, systematic review. The HDC R&D strategy documents and questionnaire responses were used to structure the review. The questionnaire was originally sent to 84 email addresses. Recipients were free to forward the questionnaire on to others. In total, 43 responses were returned. The findings of the research review were combined with questionnaire responses to identify the key gaps in knowledge and understanding of soil management in horticulture.

According to the review, soil management is often not the focus of research studies. Limitations due to scale and or duration of experiments may limit wider applicability of the research outcomes to the horticultural sector. The range of soil types is often limited and most studies only consider a single crop rather than the complete rotation. The main issue appears to be the context-dependency of soil management effectiveness, such that straightforward, universally applicable solutions are not apparent. Also, very few papers consider the cost effectiveness or practicality of the measures used.

We interrogated the literature reviewed (including that from other agricultural sectors) and used the questionnaire responses received to identify where specific research gaps still exist and need addressing. This exercise identified a number of gaps in the research evidence in the following areas:

- Monitoring and measurement: "What gets measured gets managed".
- The use of soil amendments for nutrient management, disease / pest control and environmental protection
- Use of precision agriculture in horticulture
- Limitations of the experimental empirical base: the need for 'big data' approaches

Given this analysis, future research should address the following hypotheses:

1. (Variable input) soil management in horticulture, based on monitoring of key soil metrics in space and time will support production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Identify the key soil metrics that determine soil quality in terms of sustainable crop production.
ii. Determine the required resolution of measurement in space (x, y and z coordinates) to inform soil management decisions.
iii. Determine the required resolution of measurement in time to inform soil management decisions.

iv. Test different techniques to identify the most cost effective (e.g. cost v. accuracy), user-friendly techniques (e.g. cost v. ease of use v. accuracy) to measure and monitor key soil metrics (physical, biological and chemical properties).
v. Present how the measurements can be interpreted into soil management decisions.

2. Appropriate application of soil amendments will support production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Investigate the cost effectiveness of organic fertilisers to reduce reliance on inorganic fertilisers and their associated carbon/energy footprint.
ii. Study the interaction effects of soil nutrient and water management in soils.
iii. Investigate the role of tillage / cultivation in the nutrient cycling efficacy of soil amendments
iv. Investigate the effects of soil amendments on indigenous microbial community and pathogens such as Fusarium
v. Investigate the role of tillage / cultivation in the efficacy of soil amendments in controlling pests and diseases.
vi. Extend the findings of the recent Defra project SP1106: "Quantification of the potential changes in soil carbon in England from soil protection measures within the Soil Protection Review 2010" for application in horticultural crops.

3. Precision agriculture in horticulture will deliver production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Quantify and evaluate the economic, social and environmental costs and benefits of precision agriculture techniques over conventional practice in horticultural systems.

4. *A soil management information system for horticulture, incorporating the concepts of 'big data' will support production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).*

Specific research objectives should:

1. Develop a soil management information system (SMIS) that will hold, manipulate and manage data to provide information on the benefits of soil management practices on crop productivity and environment protection. The SMIS will also capture policy-oriented and best-practice guidelines.
2. Develop relationships between soil management practices and field and farm-level outcomes (e.g. economic costs and benefits; environmental impacts).
3. Develop a system capable of capturing the concepts of 'integrated farm management'.

Scientific papers are a key knowledge transfer mechanism, but they may not be accessible to all. Despite the expansion of social media, these are seldom used for knowledge transfer. This might represent an underused resource, although these are not a popular means for seeking advice currently. A large number of respondents found websites and eNewsletters effective in gaining soil management information and advice. KE/KT approaches that can lead to uptake of research findings include:

- Involvement in grower groups that seek out and share knowledge;
- Engaging the whole farm team in understanding soil management and its effects on crop performance (and thus financial margins);
- Investment in training
- More effective hardware and technology to capture and then analyse information;
- Better access and making more use of agronomists or specialist advisors to help improve the farming system.

"There are known knowns; there are things we know that we know.
There are known unknowns; that is to say, there are things that we now know we don't know.
But there are also unknown unknowns – there are things we do not know we don't know."

Donald Rumsfeld, United States Secretary of Defence (2001-2006)

Glossary

Defra	Department of Environment, Food and Rural Affairs
EC	Electrical conductivity
ECa	Apparent electrical conductivity (ECa).
EMI	Electrical Magnetic Induction
HDC	Horticultural Development Company
ISE	Ion Selective Electrode
ISFET	Ion Selective Field Effect Transistor
KE	Knowledge exchange
KT	Knowledge transfer
LIDAR	(as acronym) LIght Detection And Ranging / Laser Imaging, Detection and Ranging.
MC	Moisture content
NDVI	Normalised Difference Vegetation Index
NIR	Near-infrared
NSRI	National Soil Resources Institute
OC	Organic carbon
R&D	Research and Development
SQI	Soil quality indicator(s)
SWIR	Shortwave infrared
UAV	Unmanned aerial vehicle
VIS	Visible spectrum
vis-NiR	Visible Near Infrared

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Report cover shows shallow soil disturbance in asparagus fields to control runoff and erosion by water, Herefordshire, UK (June, 2013).

1. INTRODUCTION

The sustainability of UK horticulture relies on healthy soils that can deliver high productivity (yield quantity, quality and reliability), business profitability and environmental protection. To achieve this, clear, consistent and reliable guidance on sustainable soil management is needed. This advice has to be based on knowledge gained from scientific research and practical in-field demonstrations. Effective soil management is essential to the long-term sustainability and commercial viability of agriculture (Kruse, 2007).

Currently, the development of best practice guidelines for sustainable soil management in horticulture is hindered by uncertainty surrounding the evidence base. Knowledge relating to soil management does exist, but it is dispersed throughout the sector. The current project has collated and reviewed research from the past 20 years (both fundamental science and field-based experience) related to soil management in horticulture and rotations that include horticultural crops. The study has also considered the effectiveness of knowledge exchange mechanisms in applying science into practice.

The views of representatives of the horticultural industry have been gathered to identify and prioritise their current soil management issues that need to be addressed in any future research programme. This opportunity has also gathered views on knowledge transfer and exchange (KT/KE) regarding soil management practices.

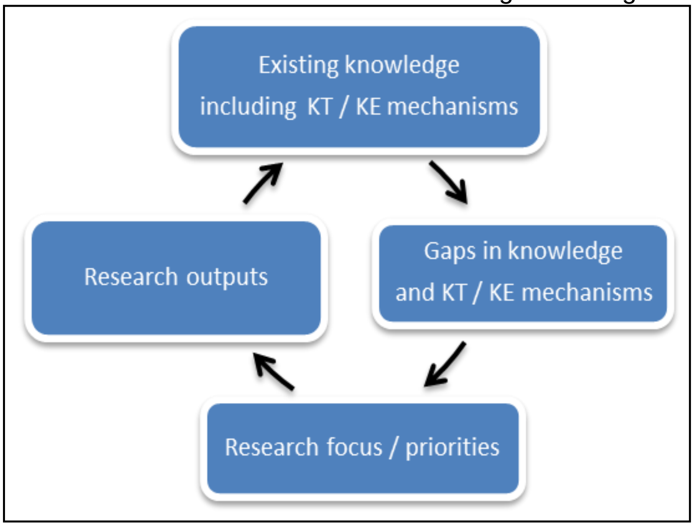


Figure 1. Context of the current gap analysis

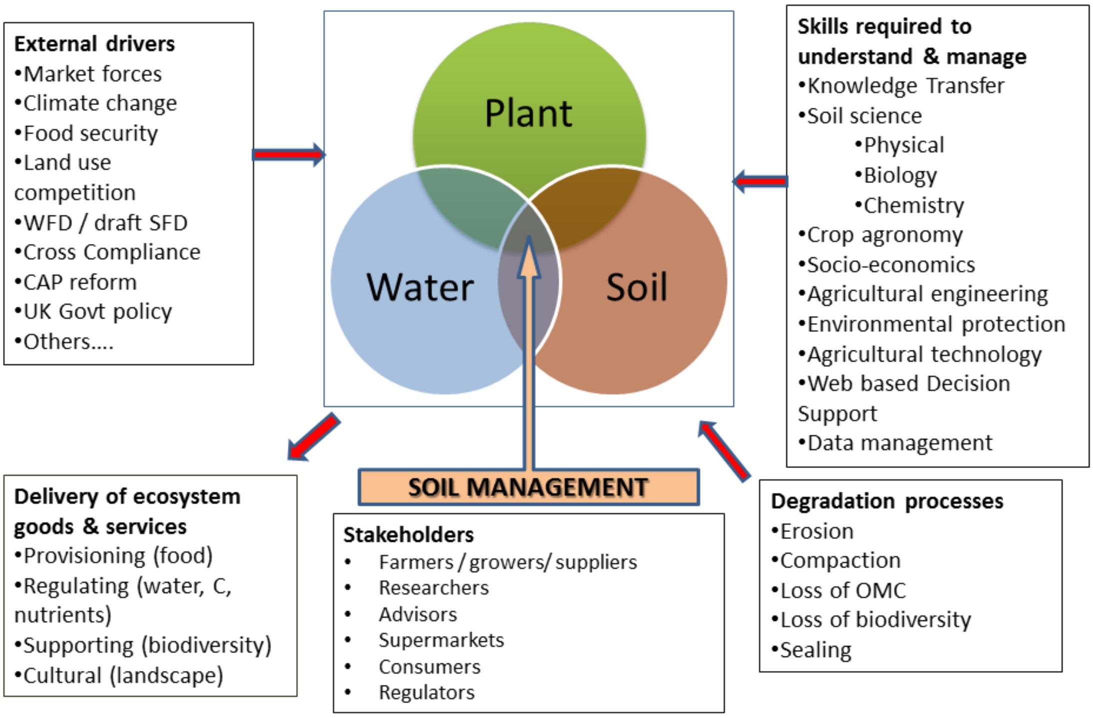
The study will inform strategic direction of future R&D in horticultural production systems in working towards ‘sustainable intensification’ (Pretty, 1997). Key gaps in research and in knowledge transfer mechanisms related to horticultural soil management have to be addressed by future research and development activities to strengthen the scientific and practical robustness of best management guidelines for sustainable horticultural soils (Figure 1).

2. BACKGROUND

In 2010, the RASE report on soil and water management emphasised that sector specific knowledge was important to ensure appropriate and trusted advice (Kibblewhite et al., 2010). The Horticultural Development Company (HDC) have identified that soils should be managed in ways that promote soil health and structure (i.e. physical, biological and chemical properties) to deliver economically and environmentally sustainable, resilient and productive horticultural systems. The ultimate aim is to secure the profitability and environmental sustainability of UK horticulture, whilst ensuring that our soils are fit for purpose, resilient and future proofed. To be sustainable, UK horticulture has to satisfy the often competing demands of productivity (yield and quality), business profitability and environmental protection

Soil management is only one part of a highly dynamic, complex soil-plant-water system (Haynes, 1980). In turn, this system operates within the context of global economic uncertainty, extreme weather patterns, competing demands for water and land resources, and rising consumer expectations regarding the affordability, quality and provenance of produce. Some of the drivers impacting on and impacted by soils and their management are represented in Figure 2.

Figure 2. The diverse drivers impacted by, and impacting on soil management



By changing the physical, biological and chemical properties of soils, soil management can affect soil functioning in both positive and negative ways. It is envisaged that climate change may increase the risks of degradation (e.g. compaction, loss of soil structure, erosion by water), so well informed soil management is imperative if we are to protect our soil resources (Defra, 2009; 2011; EA, 2008). Soils in good condition are able to resist degradation processes such as compaction, soil erosion and losses of organic matter and biodiversity. Improving guidance on soil management will enhance the quality of soils so reducing degradation processes with their on-site and off-site consequences on the environment (Rickson et al., 2010).

Demonstrating robust, evidence based links between inputs (i.e. management) and outputs (e.g. yields, environmental protection) requires research and development activities. Then, ways of transferring the scientific outcomes into practical advice and guidance need to be explored and promoted to 'ensure effective communication between basic science and applied work' (HDC website; Leaver (2010)). Improved knowledge transfer can impact on better soil management (Palmer et al., 2006). These research and knowledge transfer activities have been and continued to be commissioned by HDC and other funding bodies such as Defra, AHDB, UK Research Councils, EU and international sponsors. The collation and review of these studies is the focus of the current study. Indeed, there is a need to 'join up' this extensive and sometimes disparate body of work to:

a) establish the current knowledge and understanding of soil management theory and practice in the horticultural sector;
b) integrate technical aspects of the research with socio-economic aspects;

c) demonstrate the fundamental importance of soils as a finite natural resource (Jones et al., 2012);
d) identify any overlaps / synergies in research activities, including with other agricultural sectors (e.g. arable, combinable crops and potatoes);
e) highlight the critical gaps which hinder the industry's progress towards 'sustainable intensification'; and
f) suggest priorities for future research and knowledge transfer activities.

3. AIM AND OBJECTIVES

The aim of this study is to identify key gaps in research and in knowledge transfer mechanisms which currently hinder the development and implementation of best practice guidelines for sustainable soil management in horticulture. The scope of the review covers temperate horticulture and horticulture/arable/non arable rotations. All soils used for horticultural crops (i.e. field soils, soils under temporary or permanent protection) have been included. Organic or inorganic substrates such as peat, rock wool and coir are beyond the scope of the review. Inevitably, management of horticultural crops involves interactions of crop, soil and water interventions. The current review defines 'soil management' as practices that involve the direct manipulation of the physical, biological or chemical properties of the soil. (For example, irrigation practice is considered a water management practice rather than a soil management practice *per se*).

The following objectives were identified to meet this aim:

1. A collation and review of UK and international evidence regarding a) research (from fundamental science through to practical demonstration) and b) knowledge transfer mechanisms related to soil management for temperate horticultural crops (including when grown in rotation). To date no attempt has been made to integrate and synthesise the current state of knowledge.

2. A consultation with representatives from the horticultural industry to a) identify and prioritise their current soil management challenges (that should be addressed in any future research programme), and b) to identify current knowledge transfer mechanisms.

3. From the outputs of Objectives 1 and 2, identification of the key gaps in research and knowledge transfer related to soil management in horticulture and horticulture/arable rotations.

4. Indicate how exchange of knowledge both between the different horticultural sectors and from other agricultural sectors (e.g. potatoes, cereals and other combinable crops) might fill any gaps identified in Objective 3.

5. Evaluate the importance of each of the research and knowledge transfer gaps identified in Objective 3, given the R&D priorities of the HDC panels.

The ultimate aim is for better evidence on which to base guidance on economically and environmentally sound soil management practices which support soils' capacity (both now and in the future) to deliver goods and services. In turn, these are directly linked to individuals' and national socio-economic wellbeing (Daily, 1997).

4. APPROACHES AND METHODS

The project took the following steps:

- Identify key soil management issues in horticulture and rotations that include horticultural crops
- Review the literature regarding these issues
- Identify where the key issues are poorly addressed in the literature (i.e. gaps in research)
- Evaluate existing knowledge transfer mechanisms: is adoption of best practice hindered by lack of evidence or by poor access / knowledge of that evidence?

4.1. Identifying key issues in soil management.

Any future research programme will only be useful if it addresses the key issues as perceived by the potential beneficiaries of that research. We used 2 approaches to identify the key issues in soil management in horticulture and rotations that include horticultural crops: the current HDC panels R&D strategy documents and a questionnaire aimed primarily at farmers and growers.

4.1.1. HDC R&D strategy documents

The R&D strategy documents for all 8 HDC panels[1] and associated Grower Associations[2] were accessed on line via the HDC web pages (http://www.hdc.org.uk/). These documents were assumed to represent the industry's perception of the key issues of soil management in horticultural production that future research will have to address. The documents were scrutinised to identify and understand these issues. The results of this analysis are shown in Section 5.1.1.

4.1.2. Questionnaire

The purpose of the questionnaire was to augment the information contained in the HDC R&D strategy documents. The questionnaire was aimed at gathering individual's perceptions of:

a) The key soil management issues in horticulture and rotations that include horticultural crops; and

b) The effectiveness of knowledge transfer and exchange mechanisms related to soil management in horticulture (see section 4.2.1. below)

The questionnaire was devised by the project team, in consultation with the HDC Project Manager (Appendix A). There were 18 questions in total: Questions 1 – 6 concerned the respondents' background and involvement in the horticulture sector. Questions 7 – 11 were focused on soil management issues. Questions 12 – 17 related to how respondents' are informed about soil management practices.

With the assistance of HDC Panels and other contacts in the horticultural sector, a list of individuals was collated who were then invited to participate. The questionnaire was aimed primarily at farmers and growers, although the survey was also sent to others in the sector including supermarket representatives and horticultural consultants. Primary access to the questionnaire was on-line, hosted by Qualtrix (http://www.qualtrics.com/research-suite/#enterprise). The questionnaire was also available in hard copy or as a semi-structured telephone survey. The questionnaire went live on 28/06/13, with a closing date of 31/07/13.

The questionnaire was originally sent to 84 email addresses (51 via the HDC Panels; 33 to other industrial contacts). Recipients were free to forward the questionnaire on to others, but this final number was not monitored. In total, 43 responses were returned (Appendix B). Of the original distribution list, this represents a 51% return rate, which is higher than for many on-line questionnaire surveys (Nulty, 2008). Mean survey response time was 11 minutes. The breakdown by each of the horticultural sectors is shown in Table 1. Not all respondents answered all questions; hence the number of responses for each question may be less than 43.

[1] Field Vegetables; Protected Edibles; Bulbs and Outdoor Flowers; Mushrooms; Soft Fruit; Hardy Nursery Stock; Tree Fruit; Protected Ornamentals.
[2] e.g. British Carrot Growers Association; Cucumber Growers Association; Leafy Salad Association; Outdoor salad & radish technical group; Pepper Technology Group; Plant Propagators Ltd; Protected Leafy Salad Group; Tomato Growers Association

Table 1: HDC panels / horticultural sectors represented by the respondents

Horticultural sector	n	%
Field Vegetables	11	33%
Bulbs & outdoor flowers	2	6%
Soft fruit	0	0%
Protected edibles	3	9%
Protected ornamentals	3	9%
Tree fruit	1	3%
Mushroom	0	0%
Hardy nursery stock	6	18%
Other (please specify)	7	21%
Total	33	100%

Most respondents only grew horticultural crops (57%), whilst 30% grew horticultural crops in rotation with other crops. Thirty five per cent of respondents owned their land; 15% rented land and half of the respondents (50%) both owned and rented their land. Area of land farmed ranged from 0.8 to 6,600 ha, with mean area of holdings for owned, rented (>5 year lease) and rented (<5 year lease) being 471 ha, 224 ha and 702 ha respectively. Thus the largest mean and median sized land area used for horticultural crops is rented on short term leases (<5 years). This concurs with the experience of our industry representative who informs us that traditional land use patterns with planned rotations has and is giving way to five year farm business tenancies or one year vegetable lets. The consequence is likely to be exploitative of organic matter rather than productive. Short term lets are certainly negative for the landscape, land drainage, probably wildlife and soil erosion etc. as there is less incentive for tenants to invest in soil protection measures (e.g. drainage, erosion control) that will only bring long term returns.

All data collected were stored in accordance with the UK Data Protection Act (1998) in a secure folder, only accessible to Cranfield University staff. All personal information was treated with the strictest confidence and questionnaire data remained anonymous. Participants were free to withdraw their data without explanation by emailing the project team, at any point up to two weeks after completion of the questionnaire. The results are shown in Section 5.1.2.

4.2. Review the literature regarding soil management issues

A wide variety of materials were used to review the literature. This included existing guidance manuals, trade magazines, farmer responses, scientific data, reports, conference proceedings and scientific papers related to soil management practices used in horticulture and in rotations incorporating horticultural crops. These sources included HDC / HGCA reports and factsheets, information arising from government and regulators (e.g. Defra, EA, Natural England), extension officers/advisors (e.g. ECSFDI), industry representatives (NFU, RASE, HGCA, AHDB, PDC, HDC), assurance schemes (AFS, LEAF), research groups (e.g. Natural Environmental Research Council), and other sources (e.g. purchasers, suppliers, retailers and environmental groups). The review focused on evidence from the UK, although where relevant information was found from outside the UK, this was also included in the review.

For general searching on the internet, we used Google, Google Scholar and Bing as search engines, using the terms ‘soil management’, ‘horticulture’, ‘soil management and water’, ‘soil management and environmental impacts’, ‘horticulture and composts, mulches, green wastes, green manures’, ‘horticulture and productivity, fertility, yield, quality’, ‘horticulture and pest, diseases, weeds and volunteers, organic amendments, biofumigants, rotations, soil sterilisation’, ‘horticulture and precision farming’, and ‘horticulture and monitoring’. To access the peer reviewed, scientific literature and databases, a series of searches were trialled using Web of Knowledge (http://wok.mimas.ac.uk/) and Scopus (http://www.scopus.com/home.url) (Table 2). The aim was to select a search term that was not too broad (exhaustive and time consuming) and not too restrictive (with the risk that not all relevant articles would be captured).

Table 2. Search terms trialled in Web of Knowledge / Scopus (15th September 2013) and number of hits (* and ? denote wildcards).

Search term(s)	In topic	In title	Comment
(("Soil") AND ("horticultur*"))	Approx. 146,409	383	Search term too broad in topic and titles, but will capture all relevant papers
(("Soil") AND ("manage*") AND ("horticultur*"))	Approx. 47,790	2	Search term too broad, and too few papers with relevant title
(("Soil manage*") AND ("horticultur*"))	553	0	Search term reasonable, but with no papers with search term in the title
(("Soil") AND ("manage*") AND ("vegetable*"))	Approx. 33,964	52	Search term too broad in topic, but with reasonable number of titles with search term
(("Soil") AND ("manage*") AND ("fruit*"))	Approx. 21,854	40	Search term too broad, but reasonable number of titles with search term
(("Soil") AND ("manage*") AND ("mushroom*"))	663	2	Search term reasonable in topic, but too few papers with relevant title
(("Soil") AND ("manage*") AND ("protected crop*"))	20	0	Search term in topic too narrow, with no papers with search term in the title

Where material was not accessible on-line, or in the Cranfield library, or by post, we used the British Library Inter Library loan scheme. We contacted Defra (Science.Search@defra.gsi.gov.uk) for access to reports that were not available on their website. We were told that some of the reports from the 90's were on their system, but are currently not available to the public. We were also told that some of the reports that were only produced in paper format might have now been destroyed. This is because there is "increasingly limited space to hold the tens of thousands of paper files Defra has produced and only an obligation to keep records for a certain amount of time". We also contacted Warwick Crop Centre which holds a central archive of material from 2000 onwards, but a number of reports pre-date this and therefore probably reside with the original researchers (now retired, dispersed etc.). This is of concern, revealing that an unknown amount of research evidence and knowledge has been lost (let alone any return on funds invested), possibly before any findings were transferred to / exchanged with the intended audience. With better archiving protocols and increased data storage through digital archiving methods, this should not be an issue for current and future research findings. Indeed, the development of computer information systems allows opportunities to integrate and interrogate vast amounts of data from disparate sources (the concept of 'big data') – as discussed further later in the report). The full list of references / bibliography can be found at the end of this report.

We used the information in the HDC R&D strategy documents and questionnaire responses to organise the literature review. This took the format of a matrix, with HDC panel on one axis and soil management issues identified as being important on the other (Table 3). The number of articles by HDC Panel and soil management issue is shown in Figure 3. Each paper / document / source was scrutinised using a semi-structured, systematic review process, based on a modified template devised by Denyer and Tranfield (2008; Appendix C).

Table 3. Summary of available literature accessed for the review (1993 to 2013) – last updated 09/10/2013

	Soil management issue (as identified in HDC R&D strategy documents and the on-line questionnaire)															
	1. Increased productivity				2. Control of pests, diseases, weeds and volunteers	3. Use of automation /precision agronomy /smart mechanisation	4. Improved monitoring techniques		5. Surface/subsurface water management	6. Control of environmental impacts					7. Use of composts, mulches, green wastes, green manures	8. Mechanisms and routes of knowledge exchange
HDC Sectors	i	ii	iii	iv			i	ii		i	ii	iii	iv	v		
Field Vegetables	✓	✓	✓		✓			✓	✓		✓	✓	✓		✓	✓
Bulbs & Outdoor Flowers			✓		✓										✓	
Soft Fruit			✓		✓			✓	✓						✓	
Protected Edibles	✓	✓	✓		✓				✓		✓	✓			✓	✓
Protected Ornamentals	✓	✓			✓				✓							
Tree fruit	✓	✓	✓		✓	✓					✓	✓	✓		✓	✓
Mushroom		✓		✓												
Hardy Nursery Stock		✓			✓						✓	✓				
Cross sector	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓		✓	✓
Other agricultural sectors			✓		✓	✓	✓				✓	✓			✓	✓
Arable and horticultural rotations			✓												✓	

Key: ✓ = articles / papers / sources found
1. Increased productivity:
i. Nutrients / fertilisers ii. Water iii. Soil health / ecology iv. Alternative substrates
2. Control of pests, diseases, weeds and volunteers
3. Use of automation / precision systems / smart mechanisation
4. Improved monitoring techniques:
i. remote sensing (satellite, air borne and ground based methods) ii. field sampling and mapping
5. Surface / subsurface water management (conservation, drainage and coping with drought)
6. Control of environmental impacts:
i. reduced gaseous emissions ii. control of soil degradation processes iii. reduced diffuse pollution iv. reduced carbon footprint and sequestration of carbon v. control of odours
7. Use of composts, mulches, green wastes, green manures for better soil structure
8. Mechanisms and routes of knowledge exchange

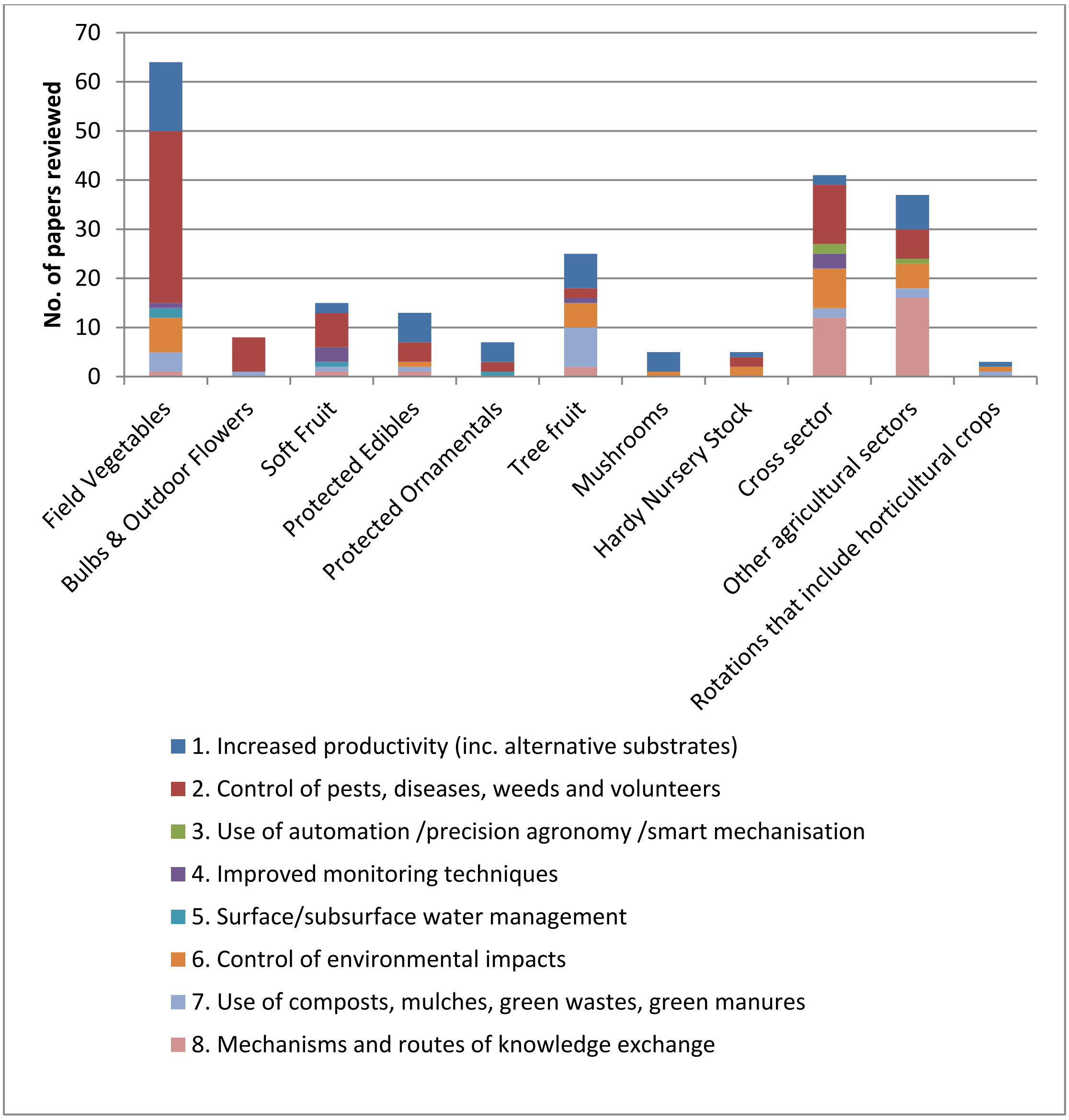


Figure 3. Number of relevant articles by HDC Panel and soil management issue (total = 223)

4.3. Evaluate existing knowledge transfer mechanisms

We used the HDC R&D strategy documents, questionnaire responses and literature review as evidence on knowledge transfer / exchange mechanisms related to soil management in horticulture and rotations that include horticultural crops (Appendix A).

5. IDENTIFYING KEY ISSUES IN HORTICULTURAL SOIL MANAGEMENT.

The findings of the literature / research review (Objective 1) have been combined with questionnaire responses (Objective 2; Appendix B) and HDC R&D strategy documents to identify the key issues in horticultural soil management which need to be addressed by any future research programme.

<u>5.1. Key issues in soil management according to HDC Panel R&D strategy documents</u>

All 8 HDC panels make specific reference to a number of issues either directly or indirectly related to soil management in their R&D strategy documents (Table 4). The role of soil management for increased productivity (quantity, quality and reliability) is raised by all 8 panels. Using soil management for the control of pests and diseases etc., and environmental impacts are also mentioned by most panels. This implies that these issues are of highest priority across the horticultural sector. It is not surprising that the effect of soil management on crop productivity is of particular importance, as this is directly related to (short term) financial returns to the grower. This is supported by the short term tenancy associated with many horticultural lands (see 4.1.2. above). The importance of environmental impacts however has longer term implications in terms of land and water protection.

Table 4. Soil management issues mentioned in HDC Panels' R&D strategies

	HDC Panel								
Soil management issue	Field Vegetables	Bulbs & Outdoor flowers	Soft fruit	Protected edibles	Protected ornamentals	Tree fruit	Mushrooms	Hardy nursery stock	Total
Increased productivity	✓	✓	✓	✓	✓	✓	✓	✓	8
Control of pests, diseases, weeds and volunteers	✓	✓	✓	✓	✓	✓			6
Use of automation /precision agronomy /smart mechanisation	✓	✓		✓	✓				4
Improved monitoring techniques	✓			✓			✓		3
Surface/subsurface water management			✓	✓	✓	✓		✓	5
Control of environmental impacts	✓	✓		✓	✓		✓	✓	6
Use of composts, mulches, green wastes, green manures		✓			✓	✓			3
Use of alternative growing media	✓		✓		✓			✓	4

Improved monitoring techniques and use of composts etc. were only mentioned explicitly by 3 panels. It is assumed that these are regarded as less important issues overall: this might be because their effects are perceived to be only indirectly related to crop production, too costly, too innovative (in terms of monitoring technologies) or too ambivalent in their effects on soil condition (e.g. perceived negative effects of using composts), particularly in the short term.

Inevitably there will be overlap between some of the issues. For example, “Increased productivity” (1) will overlap with “Control of pests, diseases, weeds and volunteers” (2), and “Improved monitoring techniques” (4) overlaps with “Use of automation / precision agronomy and smart mechanisation” (3). However, as far as was possible, we consider the evidence base for each of the issues separately.

From this analysis, the priorities in the R&D documents seem to emphasise the need for robust evidence on how soil management can increase crop productivity, reduce the environmental impacts of farming activities, and control pests and diseases.

5.2. Key issues in soil management according to questionnaire responses

Respondents to the questionnaire also identified a wide range of issues related to soil management (Table 5). The most frequent response (23 responses) was ‘soil compaction’, followed by ‘lack of organic matter’ (18), ‘nutrient management’ (17), ‘soil borne diseases’ (14) and ‘yield quantity’ (14). (The role of soil management in maintaining ‘Yield quality’ and ‘yield reliability’ was not so frequently cited, with 5 and 9 responses respectively).

Table 5. Current soil management challenges by HDC panel as identified in the questionnaire

	HDC Panel									
	Field Vegetables	Bulbs & outdoor flowers	Soft fruit	Protected edibles	Protected ornamentals	Tree fruit	Mushroom	Hardy nursery stock	Other	Total
Soil erosion by water	3	1	0	0	0	1	0	1	4	10
Soil erosion by wind	4	0	0	0	0	0	0	1	1	6
Soil compaction	10	2	0	0	0	1	0	3	7	23
Too little organic matter	8	0	0	1	0	1	0	2	6	18
Drought	5	0	0	1	0	1	0	2	4	13
Drainage	3	0	0	2	1	0	0	3	4	13
Accessing wet soil	3	1	0	0	0	0	0	2	4	10
Soil-borne diseases	7	0	0	0	0	0	0	2	5	14
Yield quantity	5	1	0	2	0	1	0	1	4	14
Yield quality	1	0	0	1	0	0	0	0	3	5
Yield reliability	3	0	0	0	0	1	0	1	4	9

Nutrient management	4	1	0	2	0	1	0	4	5	17
Soil water management	4	2	0	1	0	0	0	1	5	13
Other	1	0	0	0	1	0	0	0	1	3
Others specified	Soil-borne pests				No crops are grown in soil				Systems to reduce fuel costs	

Question 8 then asked about what is being done to tackle these issues, demonstrating a number of approaches are being taken. Question 9 then asked whether current practice is effective or not in addressing these issues. This was taken to indicate the current state of knowledge on which to base soil management decisions. The responses to Question 9 revealed that not all these practices are effective, indicating there is either research gaps or lack of knowledge transfer mechanisms in these areas (Table 6). In 3 cases, there were more responses stating soil management was 'ineffective' compared with being 'effective'. These were: lack of organic matter, accessing wet soil and yield reliability. This indicates a clear gap in research evidence or knowledge transfer, which is picked up in the gap analysis below (Section 6). The breakdown of responses to this question per panel is given in Table B.8, Appendix B.

Table 6. Indication of whether soil management practice is effective or not across all panels

Soil management issue	Soil management practices are effective	
	Yes	No
Soil erosion by water	7	3
Soil erosion by wind	3	2
Soil compaction	13	7
Too little organic matter	6	11
Drought	5	4
Drainage	7	4
Accessing wet soil	2	5
Soil-borne diseases	6	6
Yield quantity	7	3
Yield quality	2	2
Yield reliability	2	4
Nutrient management	10	1
Soil water management	7	2
Other (please specify)	0	1

5.3. Combining the HDC Panels' R&D strategy documents and questionnaire responses

By combining the HDC panels' R&D strategy documents and questionnaire responses, we were able to identify objectively the current soil management issues in horticulture. Yield quantity and reliability appeared to be more of an issue than yield quality. Related issues of nutrient management and soil borne diseases were also identified. Using soil management to control environmental impacts such as soil degradation (erosion, compaction, lack of organic matter) was also common in both the strategy documents and grower questionnaire. Water management (dealing with droughty and wet soils) was also a priority, including accessibility / trafficability of wet soils – no doubt reflecting the previous year's very wet autumn (2012). Timeliness of operations can have significant effects on productivity. Timeliness costs are the main source of annual variation in total costs of cereal production. They range from 0 to €150 ha^{-1} (de Toro, 2005).Yield losses of up to 40% were predicted for cereals due to late sowing in the (wet) autumn of 2012 and subsequent cold temperatures in the spring of 2013 (Will Foss, Agrii, pers.comm). Clearly this will have significant financial impacts for growers. To reflect the importance of this issue, the Institution of Agricultural Engineers Annual Council meeting in May 2013 chose the theme of soil management to mitigate the effects of extreme weather events on crop production (http://www.iagre.org/conferences/SoilWaterManagement230513).

Having identified the issues as perceived by the industry, the next step is to ascertain whether existing knowledge can address these: this is the purpose of the review of research evidence below.

6. FINDINGS OF THE REVIEW OF UK AND INTERNATIONAL RESEARCH EVIDENCE REGARDING SOIL MANAGEMENT IN HORTICULTURE

For clarity, the results of the review have been organised according to the R&D targets given in the HDC Panels' R&D strategy documents. Many of the sources cover multiple topics. Most relate to work done in the UK, although a few documents relate to horticultural systems outside the UK including Argentina, Italy, Poland, New Zealand, Australia and the USA. The review results for each HDC panel and for each soil management issue are presented in Appendix D, which gives details of each of the 223 sources reviewed. Of the HDC Panels, most sources referred to Field Vegetables (64). Only 5 papers referred specifically to soil management in mushroom production, but this low number is not surprising as mushrooms are usually grown on other substrates. Only 7 papers referred specifically to soil management in Protected Ornamentals. Regarding the soil management issues identified in Section 5.1., most of the literature reviewed related to the control of pests, diseases, weeds and volunteers (77), and 48 papers deal directly with increased productivity and fertility. Fewest sources were found for the use of automation / precision agronomy / smart mechanisation in soil management (3). This might reflect the fact that in horticulture, these technologies are still in technical development and results are yet to be published extensively either in the grey or peer-reviewed literature.

Although all the literature reviewed (Table 3) mentions soil management, it is quite often only a limited part of the research, sometimes only mentioned as a passing coincidence of the work undertaken. For example, tillage may only be mentioned because the protocol of the experiment included a tillage cycle, rather than being an experimental variable. A synthesis of the findings for each soil management issue identified by the HDC sector panels is given below.

6.1. Increased productivity and fertility (yield quantity, quality and consistency) through better (soil) resource efficiency

i. Nutrients / fertilisers

Most of the papers refer to nutrient management (both supply and crop requirements) and how critical levels in the soil affect crop yield (both quantity and quality). A number of papers demonstrate the need for more meaningful measurement of soil nutrient status and for careful monitoring of nutrient levels (N, P and K) in the soil profile, especially at shallow depth. A single point measurement is often used to characterise soil conditions throughout the profile and thus assess nutrient requirements. However, spatial variations in nutrient distribution and concentrations occur with soil depth. It should be recognised that nutrient status is especially important in the shallow active root zone at the critical early stages of crop growth. Specifically, there is concern over Fertiliser Manual RB209 not being appropriate in its current form for herbs or shallow rooting vegetable requirements.

Optimal use of fertilisers is acknowledged to increase uptake, reduce diffuse pollution (including leaching, especially in the light of NVZ regulations) and save on production input costs. Over application of fertilisers can be detrimental to quality and yield as well as expensive and damaging to the environment (diffuse pollution through leaching and overland flow / runoff losses). Reducing fertiliser inputs caused no visual signs of nutrient deficiency (Else, 2013). Field experiments, conducted in HGCA Project 267 in 2002, suggested that the financial benefits of variable N management could be as much as £22/ha (£48/ha at current prices).

Nutrient status is related to management practice in many (but not all) papers, through the manipulation of the soil microbial population and fluxes of N and P. Green mulches and animal manures can help mineralise N and P and can replace mineral N applications (see 5.2.7 below). Cover cropping and groundcover management are also seen to increase available N.

ii. Water

Although effective ways of managing water in horticulture are discussed, the role of soil management in this is not often explicitly included. A soil's ability to receive, retain and release water is vital as this affects the timeliness of operations (opportunities to access the land) and crop productivity (yield and quality). Soil moisture affects crop storage quality, harvest times, fruit size, quality, reliability and storage life. Soil moisture content also affects rates of leaching of nutrients and thus the system efficiency. Conversely, water stress can lead to yield losses of 30% in bulb onions for example.

iii. Soil health / quality (physical, biological and chemical)

Soil health or quality has been linked directly to seedling emergence and growth (e.g. HRI, 2003a; 2003b). Soil physical structure is linked to root development and growth, nutrient uptake and plant emergence (because well-structured soils are less liable to slumping and capping through aggregate breakdown). Soil physical, biological and chemical condition is related to cultivations, including the role of reduced tillage. Evidence for yield effects of minimum tillage over a long period is sparse (Knight et al., 2012), but estimates from non-horticultural sectors (i.e. wheat) show yield reductions have ranged from 0 to 4%. Knight et al. (2012) consider two scenarios for the period 1996 - 2012. Assuming a continuing 3% penalty from reduced tillage, a decline in yield of about 0.007 t/ha per year is indicated. A larger, short-term yield penalty was observed during the transition from ploughing to non-inversion. This may be a year effect, but assuming a 12% penalty in the year of transition only, a yield decline of 0.004 t/ha per year is indicated.

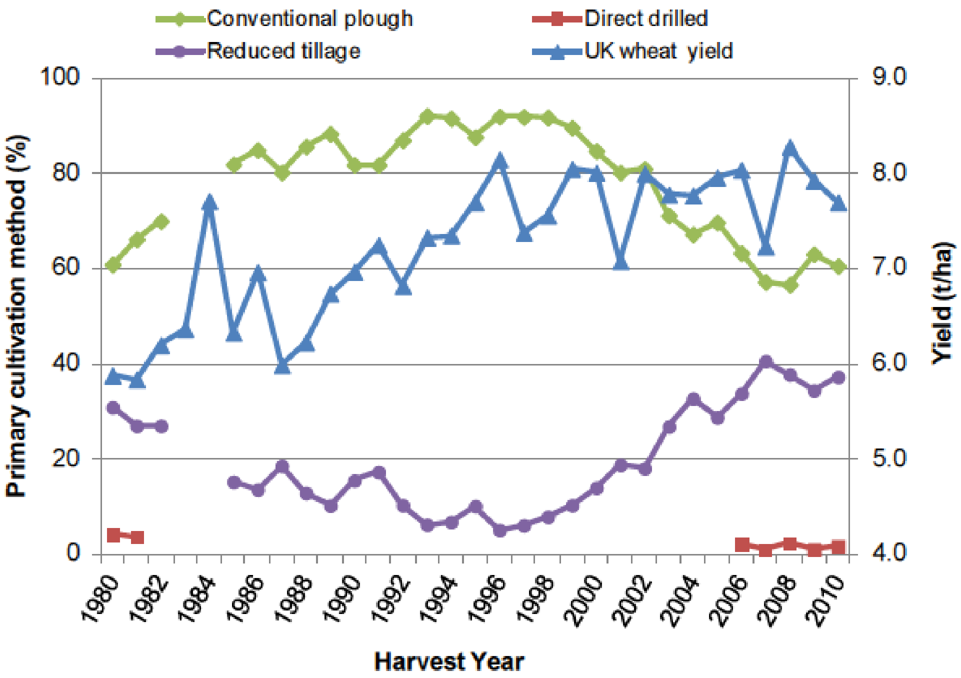


Figure 4. Role of cultivation practice on wheat yields (from Knight et al., 2012)

UK research has indicated that soil compaction from trafficking can reduce cereal yields by an average of 16%, but there are no data to quantify the incidence and severity of compaction (Knight et al., 2012). Reporting for arable crops, machinery wheel loads have progressively increased, inducing high stresses in deep soil horizons irrespective of the tyres or tracks used. Soil compaction below sub-soiling depth may remain for a long time.

The condition of the uppermost millimetres is also significant, as this is where critical processes which affect productivity take place (soil detachment, aggregate breakdown, oxygen diffusion, seedling emergence, water infiltration, etc.). This is the subject of an on-going BBSRC funded project (Soil Surface Matters; BB/J006092/1). Stronger evidence comes from the potatoes sector about the benefits of good soil structure and health (Mallory and Porter, 2007). In a review by Chapmen (2005) there was overwhelming evidence that compaction created by vehicles running randomly over the soil had a negative impact on crop yield and quality. It also increases production costs because of the increased draft energy requirements and has wider environmental implications. Crop benefits can be achieved through limiting the area of soil damaged by vehicular traffic.

Soil biology is the focus for many papers. Tabuchi et al. (2008) state that the use of soil amendments such as composts and chemical fertilisers can be used to manipulate the size, diversity and community structure of fungal and bacterial populations to improve soil and hydroponic productivity (see 5.2.7). The soil microbial community improves nutrient fluxes in the root zone. Ground cover has a similar role. Soil biology can be used as an indicator of soil health; earthworms' abundance and biomass is sensitive to changes in weed populations, pests and soil fertility management. Reduced, less diverse populations (e.g. as a result of mono-cropping) reduces yields due to slow crop establishment and development, although this is less marked on freshly steam sterilised soil (See section 5.1.2. on Control of pests etc. below). Stenberg (1999) reviewed microbiological indicators for soil quality in arable land and suggested a scheme for including such indicators for soil quality monitoring. The primary benefits of including microbiology in soil monitoring is its sensitivity to environmental change.

Alyokain et al. (2005) reinforced the concept that soil organic matter in balance with microbial activity brings benefits to crop quality. Bailey and Lazarovits (2003) have also demonstrated the benefits of improving soil structure through the use of organic matter amendments.

An on-going (2013-16) HGCA project “Improvement of soil structure and crop yield by adding organic matter to soil” (RD-2012-3787) aims to find the minimum addition of external sources of organic matter, including making use of on-farm wastes such as straw, which brings about the maximum improvements in crop yield (grain and straw), and soil and environmental quality. The project calls on recent research at Rothamsted Research which shows that addition of Farm Yard Manure (FYM) can improve yield of barley grain and straw by more than 1 t/ha each within two years. These results suggest that striking benefits from adding the right kind of organic matter can be achieved relatively rapidly in soils. The quality of such addition seems important because other long-term experiments on straw incorporation show little benefit following addition of far more organic carbon. The hypothesis is that crop yields increase quickly (within four years) as a result of improved soil physical condition which results from feeding soil organisms (especially earthworms) with relatively small amounts of suitable organic matter additions. There is scope for the same hypothesis to be tested on horticultural crops.

<u>6.2. Control of pests, diseases, weeds and volunteers (less dependency on chemicals), including the use of organic amendments, biofumigants, rotations, soil sterilisation techniques and optimisation of the growing environment</u>

“As the soil is the reservoir for most weed seeds, insects, nematodes and disease, soil management should be an integral component of pest management”. Indeed, the control of pests, diseases, weeds and volunteers in horticulture has more substantial coverage in the literature than other soil management issues (77 / 223 sources). Most of the literature covers experimental research conducted either in pot, plot or field experiments. Other sources include reviews of literature in the subject area and factsheets derived from experimental work.

The diseases covered in these papers include: soil sickness in Narcissus, Fusarium basal rot, Rhizoctonia, Sclerotinia, Sclerotium spp., lettuce big vein disease, asparagus spear rot (Phytophthora), carrot cavity spot, black scurf, root blemishes in parsnip, white rot in Alliums and bulb onions, clubroot, Pythium spp., canker in parsnips, asparagus purple spot. Pests include herbivores (Alyokain et al., 2005), nematodes, plant parasitic nematodes, slugs and cabbage root fly.

One paper argues that weeds have both positive and negative effects in orchards. Regarding pest control, they act as a habitat for both pests and their predators (Forge et al., 2003), as well as mitigating soil degradation processes such as compaction and erosion. They add organic matter content and nutrients. However, they also compete for water and nutrients with the main crop. Volunteers that compete with main crops include potatoes in vegetable crops.

O'Neill, 2013 argues it is important to determine the levels of pathogens that will cause damage to crops, but this is likely to vary widely over space and time.

To control pests and diseases, the aim is to increase soil suppressiveness against diseases and pests. Many of the papers refer to non-chemical control measures often devised as replacements of traditional practice, now restricted by recent regulations and legislation e.g. use of Telone. Many soil fumigants are coming under increased scrutiny from the EU and are being withdrawn (e.g. methyl bromide). What is needed is an alternative to chemical soil sterilisation that is reliable, has a high level of efficacy, is environmentally benign, is acceptable to the consumer and can be incorporated into standard farming practice, including organic production (Hall, 2010). Even so, it is noted that "Life without methyl bromide is possible, although new and re-emerging diseases do occur on its removal".

A number of soil properties that can be manipulated by soil management have significance on pests and diseases. These include:

a) Soil texture. Although this cannot be changed in a field, a conscious choice of field selection based on texture may have benefit e.g. clubroot detection, the effectiveness of biological control agents against white rot and the effectiveness of steam cleaning.
b) Soil moisture. While none of the literature discusses in any detail how soil moisture may be regulated by soil management, there were several sources that mention the importance of soil moisture on pests and diseases control. Water management has been used to control *P.violae* in field vegetables, slug numbers (Lole 2010), white rot (HRI 2002) and cavity spot (Barbara & Grant 2010). Such strategies can be effective - the importance of soil moisture control for potato scab is well established and guidelines are clear (Wilson et al. 2001; Stalham et al 2010). The control of nematodes by flooding has been advocated (Sotomayor et al. 1999; Nelson et al. 2002), but results have not always been successful (Asjes et al. 1996; McSorley 1996).
c) Soil physical condition is cited as a factor affecting incidence of disease such as Verticillium wilt, root knot nematodes, and gall in tomato and cucumbers. Soil ridging can reduce canker in parsnips. The presence of a pan (e.g. cultivation or plough pan) can affect the distribution of the disease. Soil compaction is associated with Verticillium wilt although the mechanisms for this are unclear. Mechanically working the soil via tillage has been shown to reduce the prevalence of soil-borne fungal diseases in cereals, hypothesised to be related to the physical disruption of mycelia curtailing infection potential, but there are no apparent reports of this phenomenon specifically in the horticultural sector. Sánchez-Moreno et al. (2006) explored the links between soil management and nematode community composition as a bioindicator of soil management practices on the soil food web. Different tillage practices and cropping systems were found to determine soil properties and associated nematode abundance. Cultivation can also exacerbate the spread of soil-borne disease via a spreading of inoculum (McPherson et al., 2013), and yet there is some conflicting evidence that increased tillage may also be a means to control slug populations in horticultural systems (Lole, 2010). The effects of cultivation on nematode numbers are inconsistent. Cultivation can reduce volunteers in a fallow year, but not to a commercially acceptable level.
d) Soil temperature. Heat treatment of soil to reduce pest, pathogen or weed populations can be achieved by solarisation (Katan 1981), where the soil surface is covered with a membrane of some form (e.g. plastic sheet), and solar energy is duly transmitted to the soil surface. It is recommended that temperatures of >65°C should be attained to induce effective control (Stapleton 2000). For effective weed control, these covers are required to be in place for several weeks (Bond and Grundy 2001). However this technique is only applicable where sufficient quantities of solar energy are manifest, which restricts efficacy in the UK. Thermal / laser weeding devices can be effective in control but have very high requirements for energy and consequently can be costly (Bond and Grundy 2001). Many systems are at the experimental phase only (Simon Blackmore, Professor of Agricultural Engineering, Harper Adams University, pers. comm.).
e) Soil nutrient content has been related to control of purple spot in asparagus and basal rot in narcissus, linked to the avoidance of nutrient depletion through mono-cropping.
f) Soil organic matter content may increase populations and activity of pests and diseases, or create the right habitat for predator species, so reducing pests and diseases. Alyokain et al. (2005) found fewer Colorado potato beetles in soil where manure had been applied

in combination with inorganic fertiliser, compared to plots where only inorganic fertiliser was applied. Importantly the organic matter seems to cause beneficial changes in nutrient concentrations in the plant tissues that protect them from attack. This work demonstrates the importance of a 'systems approach' to soil management and its outcomes – here the interactions of soil management practice (application of manure and of fertiliser) affect crop growth and hence resilience against pests. Linked to this is:

g) Soil biology – entomopathogenic fungi offer biological control of pests. Microbial communities can be key to the capacity of soils to suppress soil-borne plant diseases (Van Elsas et al., 2002). These authors found considerable diversity in microbes and the microbial functions on arable and grassland plots. However, no clearly visible difference in function in terms of mechanisms of disease suppression was found.

Control measures indirectly involving soil management include the use of soil amendments. Bonanomi et al. (2010) conducted a detailed review of 2,400 peer-reviewed published studies, across 252 papers (Bonanomi et al., 2008) to assess the capability of specific organic amendments to control a range of specific soil-borne plant diseases, many of which are implicated in attacking horticultural crops. These authors also considered the effects of such materials upon invoking disease suppressiveness of soils in a more general sense. Organic matter amendment was only found to be *consistently* suppressive to specific pathogens in a few instances. In most cases a material suppressive to a pathogen was ineffective or even conducive to other pathogens, suggesting that organic-matter based suppressiveness is often pathogen-specific. It was apparent that the degree of organic matter decomposition is crucial in affecting such relationships, and that during decomposition, disease suppression either increased, decreased, was unchanged or showed more complex responses, such as a 'hump-backed' relationship. More decomposed materials, such as mature composts, were on an average more suppressive. Specific properties of the organic materials across a range of chemical, biochemical and microbiological parameters showed no general correlation to disease suppressiveness.

Olanya et al. (2006), found that although microbial activity was significantly enhanced by the addition of manure and compost soil amendment, lower disease incidence was not associated with increased microbial activity. They also found soil amendment to increase selected tuber diseases and microbial activity in soils. However, Bailey and Lazarovits (2003) suggest that disease suppressive soils can be achieved by introducing organic amendments and crop residual management. The process takes time but the benefits accumulate across successive years improving soil health and structure, and as a consequence also is detrimental to pathogen viability and distribution. A similar approach is being trialled in an on-going HGCA funded project on "Improvement of soil structure and crop yield by adding organic matter to soil" (RD-2012-3787).

Natural predators and pests abundance is affected by the type of compost used (Chandler, 2009). Vermicomposts comprised of cattle manure, paper and / or food waste have been used to reduce plant parasitic nematodes. Other soil amendments for disease control include herb residues, Medicago meal and agricultural waste products.

Some composts and green manures incorporate biocontrol agents, such as glucosinolate (a biocide) and the T. *Hamatum* strain of T382. Leandro et al (2007) report that biocontrols introduced with compost are more cost effective than using fungicides and composts separately.

Pre-crop biofumigation on cavity spot in carrots and companion planting to control cavity spot. Soil biofumigation includes crops such as *Brassica juncea*, *Sinapis alba* and BioFencein. Other biological control includes the use of French marigolds (*Tagetes patula*) to reduce nematode infestation.

Rye grass mulch is used to suppress weeds in asparagus (Brainard et al., 2012). Their results suggest that 1) soil-improving rye cover crops can partially suppress weeds but may also compete with asparagus for soil moisture in dry years unless irrigation is used; and 2) successful use of rye living mulches for weed management will depend on identification of complementary weed management practices to avoid build-up of the summer annual weed seed bank. This highlights the need for multiple, integrated and possibly synergistic soil management practices. In the Hardy Nursery Stock sector, chemicals are used to control nematodes and Verticillium wilt, but biological control such as the use of Sudan grass as a mulch does not appear to be as effective.

Soil disinfection methods can prevent the growth of pathogens. These methods include novel techniques such as electromagnetic radiation in the microwave range to reduce populations of fungal and nematode pathogens, weeds and volunteer potatoes. The use of steam sterilisation as the basis for zero herbicide (e.g. replacement of methyl bromide) appears realistic (Pinet et al., 1999). The effectiveness of this latter technique depends on soil depth and texture (and the extent of steam penetration; Pinet et al., 1999). Steam sterilisation of soil is sometimes followed by the introduction of organic amendments to enhance biological control of pests and diseases.

The effectiveness of these measures is assessed by their cost, ability to avoid pathogen resistance and longevity over several seasons. Many authors encourage a broad range of products and active ingredients as this will reduce the chance of fungicide resistance developing. Often the efficacy of the measure depends on very particular sites condition e.g. soil type, soil moisture content, degree of soil preparation (O'Neill et al., 2007). The wide ranging literature demonstrates the importance of detailed knowledge of pathogens, crops and environment (e.g. soil properties, water availability) as evidence on which to base management decisions. The main issue appears to be the context-dependency of the effectiveness of control measures such that straightforward, universally applicable solutions are not apparent.

<u>6.3. Use of automation / precision systems / smart mechanisation (for planting, weeding, harvesting operations) to control traffic and reduce compaction</u>

Very few papers could be sourced on this topic (3 / 223), although Roberson (2000; now over 10 years old) points out the potential of precision agriculture in horticultural production systems. Relatively high crop values per unit area for some horticultural crops and crop response to variability in soil and nutrients make precision agriculture an attractive production system, and yet few research papers are available, let alone the widespread use of commercially viable systems. Computer vision has been successful in precision control of mechanical weeding (Tillett et al. 2008). Mechanized soil sampling and variable rate control systems are readily adapted to horticultural crops. Improved monitoring of in-field variability of soil and crop conditions via remote sensing (see 6.4 below) can lead to better management through variable rate application of fertilisers, water, seeding rates etc. This leads to costs savings and reduced environmental impacts such as diffuse pollution over applied nutrients. GIS can be used to map the results for precise targeting of management treatments. Field experiments, conducted in HGCA Project 267 in 2002, suggested that the financial benefits of variable N management could be as much as £22/ha (£48/ha at current prices).

Precision planters are designed to accurately measure and place seeds in the seedbed. Precise control of population, spacing, and depth are hallmarks of precision planting (Roberson, 2000). Advantages of precision planting over conventional planting include lower thinning costs, reduced seed usage, reduced competition between young plants, and reduced shock to plants during thinning. Disadvantages include protection of stand after emergence, seedbed preparation is more critical and seed treatment is often necessary to improve planter performance. Once the decision to use precision planters has been reached, the opportunity to apply site-specific management principles can be considered. Variable rate controls can be added to the planter to give the operator the ability to adjust seed population on the go to match optimum field requirements. For example, Maguire et al. (2003) investigated the use of an automated system capable of varying onion seed rates according to pre-determined application plan. An AGCO Fieldstare variable rate controller used on planters was adapted for use with a Stanhay Singulaire 780 precision drill, which resulted in satisfactory performance with a mean error in seed spacing between actual and required of 2.57% in the laboratory and 3.15% in the field. This led to a 10% increase in the saleable yield of onion.

One aspect of precision agriculture that is seldom discussed is raised by Roberson (2000), who points out that total usage of lime and fertilizer may not necessarily be reduced under precision agriculture systems - on average the application rate over the whole field may be similar as that under conventional systems. However, inputs will be used more effectively in the field by matching application rates to specific site requirements. Also, it should be noted that equipment that cannot perform adequately in conventional production will not be acceptable in precision agriculture.

6.4. Improved monitoring techniques

One questionnaire respondent said “What gets measured gets managed”. The measurement of properties and characteristics of horticultural crops, pests and diseases, and soils using sensors is critical for improving soil management in terms of timeliness of intervention and the required nature of that intervention. These data are also the foundation of precision agriculture approaches described above (5.2.3.) and are to some extent the topic of an on-going HGCA funded project on ‘Exploiting yield maps and soil management zones’ (RD-2012-3785).

Whilst there is an extensive evidence base on improved plant monitoring techniques for better crop management, our review specifically focused on those technologies directly targeted at improving soil management practices.

i) Detection of canopy characteristics as related to soil management practice
One of the ultimate goals of estimating canopy volume by the Normalised Difference Vegetation Index (NDVI) is site specific variable rate applications of fertilizers and pesticides. Canopy volume has been assessed using different methods, such as ultrasonic, laser scanning, aerial sensing, LIDAR, light penetration, satellite imagery or synthetic aperture radar (SAR). However, these studies assume crop canopy will indicate nitrogen status without direct reference to soil nitrogen content. Crop water status can be mapped by thermal imaging (thermography) techniques, which also detect crop diseases and fruit loadings in tree canopies, all of which have implications for soil management, but the links are not explicitly explored in any of the papers reviewed. In any case, monitoring of canopy temperature alone for example cannot be an absolute indicator of water stress since it is affected by the meteorological conditions at the time of measurement.

ii) Disease and stress detection in crops in relation to soil management
If soil management is to be effective in controlling pests and diseases (see above), then accurate and reliable assessment of the problem(s) is vital. Disease and stress detection in crops based on spectral reflection information relies on the properties of the light emerging from the canopy after multiple interactions, i.e., reflections, transmissions, and absorptions, with the tissues of the plant. As the primary effects of different diseases vary (chlorophyll, water and temperature effects), different wavebands are suitable for detection of different diseases (Bryson et al., 1998; Dudka et al., 1998). A list of pests and diseases detectable by remote sensing techniques is given in Appendix D (Literature review pages). However, none of this work links these diagnoses with associated soil management practice.

A number of other ‘novel’ techniques are described to monitor diseases which may be linked to soil management. These include the use of mass DNA to test nematode presence (O’Neill, 2013) and a molecular test for Verticillium wilt. Another study describes the detection and quantification of *Phytophthora rubi* in soil and plant tissue. However, again disease detection in crops is often the goal of the research rather than how soil management practice may cause or control such disease.

iii) Crop yield monitoring
The effectiveness of soil management practice on crop yield can be assessed indirectly by remote sensing. Machine vision technologies, based on digital images can provide information about the status of crop stands and individual plants (including weeds and volunteers), and how this is related to nutrients, water status, fruit load, yield and fruit maturity. The technology used in nutrient and water status detection can produce information to aid soil management decisions (precision agriculture).

In other sectors (e.g. cereal production), combine harvesters have yield monitors fitted as standard and many farmers are exploiting them to create yield maps for their fields. These maps contain important information about the variation of fields, but as Marchant et al. (2012) point out, it is not clear how this information can be fully exploited for management decisions. This is being addressed in an on-going HGCA funded project (2013-16) 'Exploiting yield maps and soil management zones' (RD-2012-3785). A limitation is that yield monitor data is often noisy and contain artefacts and there is no general consensus on the best methods for analysis. When a low-yielding region is identified the farmer is often unsure how to respond because there are many factors which could limit the yield. There is also variation between maps from different seasons, so a single map does not capture the full variability. The main aim of RD-2012-3785 is to determine when it is cost-effective for farmers to use yield maps and management zones to guide soil management decisions. The work will devise protocols for the robust and efficient implementation of yield maps and management zones. The project will investigate existing yield maps and complementary soil data to determine the best methods of exploiting yield information and when this is cost-effective. Clear guidelines will be produced so that farmers are able to analyse yield monitor data. Improved yield mapping software will also be produced and made freely available in the project. However, the project researchers accept that this might be not possible if tests show that complex statistical algorithms are required. A similar approach could be used in other AHDB sectors, where yield mapping and soil management zones are reported (See Gap analysis below).

iv) Sensor networks for field monitoring and relation to soil management
The use of sensor networks in horticulture is less documented than in arable crop production systems. There is some evidence of integrated agricultural monitoring systems using high-spatial-resolution remote sensing imagery and data from sensor networks. These systems can produce maps displaying information such as crop growth, temperature, volumetric moisture content and salinity. These data can then be used for soil / land management decisions, particularly with regard to variable rate application of fertilizers.

v) Measurement of soil properties with proximal soil sensors
More direct than the other methods listed above, proximal or ground-based (invasive or non-invasive) soil sensors can collect high resolution data rapidly, and in certain cases allow real-time analysis and processing. Sensor-based soil analysis potentially has lower costs, increased efficiency, more timely results, and better collection of dense datasets compared with conventional (manual) soil sampling. Mouazen (2012) advocates the use of on-line soil sensors for their potentially faster, cost effective method of describing within field soil variability. Cambouris et al. (2006) suggest that in potatoes production, electrical conductivity (EC) has the potential to be used to delineate within-field management zones based on soil deposits and soil physical properties that control soil moisture availability. The technique can be used to produce management maps based on kriged EC data. However, sources of error for these methods currently include temperature, dust, roots and stones, and accuracy is predetermined by adequate calibration. It is acknowledged that few sensors are able to measure physical and/or chemical soil properties directly. Due to the complex nature of agricultural soils, successful measurement of soil properties has to account for co-variation with other soil properties e.g. with OC in NIR spectroscopy (Stenberg *et al*., 2010). As the origin of these co-variations is not yet understood nor documented in details, further research is needed.

The spatial variation of within field soil properties in horticultural fields using proximal soil sensors is rarely reported. A new HDC project does address this (CP93, The use of vis-NIR spectroscopy for on-line measurement of selected soil properties in field vegetables; Mouazen, 2012), which is evaluating the implementation of vis-NIR spectroscopy using on-line measurements of selected soil properties to improve fertiliser recommendations based on variable rate application.

6.5. Surface / subsurface water management (conservation, drainage and coping with drought)

It was difficult to differentiate many sources as relating to 'soil' management as opposed to 'water' management. The role of 'soil water management' on crop productivity is described above (5.2.1.). Clearly, yield and quality of crops are related to water management, which can affect nitrate uptake in cover crops too. The effect of water distribution on economic yield, water losses and nitrate leaching can be modelled.

There are concerns as to the wastage of water and nutrients through the irrigation systems used in horticulture. One source reported growers are presently wasting water and money through inefficient production systems. Alternatives are available but a significant investment cost may be required. More intelligent irrigation systems can maintain yields, improve fruit quality and reduce waste. Water savings of 80% had no effects on Class 1 yields. Water savings helped efficient nutrient use too. Whilst the effectiveness of these practices will be determined by soil condition (e.g. water holding capacity, infiltration rate etc.), they are more related to management of water (e.g. application of irrigation) rather than soil management / manipulation *per se*. A more holistic approach to future research programmes would ensure better linkage and integration between best practice in soil, plant and water management.

6.6. Control of environmental impacts

i. reduced gaseous emissions

Very few papers addressed the role of soil management in reducing gaseous emissions from horticultural land. One source described in passing (with no details) how carbon emissions can be controlled through appropriate ploughing operations, driver behaviour and tractor suitability. Defra project SP1106: “Quantification of the potential changes in soil carbon in England from soil protection measures within the Soil Protection Review 2010” linked soil management with gaseous emissions. Although focussed on soil organic carbon content (see below), the report found some evidence to suggest zero/reduced tillage can increase N2O emissions on heavy land, and this may mean a net increase in greenhouse gas emissions. The report also identified a potential problem in that cover crop incorporation in the spring may exacerbate nitrous oxide (N2O) emissions. However, maintaining land drainage in medium and heavy soils may decrease N2O emissions.

ii. control of soil degradation processes (compaction, erosion by water and wind, loss of biodiversity and organic matter content)

Degradation processes identified in the literature review and questionnaires include: soil carbon losses, soil quality degradation, desertification, wind and water erosion, runoff and compaction. These processes have been shown to have a direct effect on marketable yield e.g. in onions. Less is reported on other forms of soil degradation such as loss of biodiversity. Organic amendments can increase soil biological activity and so reduce bulk density, soil erosion and leaching. They also increase infiltration, earthworm populations and biodiversity. Grass strips both across the slope and as downslope grassed waterways can be used to control erosion by water, regulate N levels and reduce leaching, and were identified as erosion control measures in questionnaire responses. Wind erosion can be controlled by planting strips of barley which is then selectively sprayed off, but the residues still control erosive wind speeds, so minimising wind abrasion on crops. Shallow soil disturbance and straw mulching result in 97-99% and 92-96% reductions in soil loss and runoff volume respectively, when compared with the bare soil control. This work is unusual in that it considers the effectiveness of two soil management measures (cultivation and mulching) and their interactions on controlling runoff and erosion (Niziolmski, 2011). Appropriate use of ground pressures in tyres reduces compaction risks.

Regarding improving soil organic carbon contents through soil management, a recent Defra report (SP1106; 2012) assessed the effects of the measures listed in the Soil Protection Review 2010 that potentially enhance soil organic carbon (SOC) storage. Using modelling and expert opinion, the following measures were found to increase SOC content by increasing C inputs to the soil or by decreasing rates of SOC oxidation: applying bulky organic manures to low organic matter soils; drilling autumn-sown crops early; growing temporary autumn-sown cover crops; and the BPEX soil management plan for outdoor pig production. However, with each of these there are issues. Regarding manures, the overwhelming majority of livestock manures and biosolids are already recycled to land. Even so, there is scope to increase the amount of compost and paper crumble produced and applied, though the amounts currently recycled are small. Drilling autumn-sown crops early could potentially increase SOC levels at the farm scale but there is limited scope to increase uptake at the regional and national scales, mainly due to practical limitations. For example, it is logistically impossible to drill all autumn-sown crops one month early due to the work load on farm. Also, disease risk can be increased through early drilling of some crops; and where early drilling is favourable most farmers are already doing so to maximise yield potential, particularly for oilseed rape and first wheat crops. The report found significant scope to increase the area of autumn-sown cover crops, although adoption may be impaired by practical difficulties associated with carrying out additional field activities/cultivations at a busy time of year (crop harvest and drilling of autumn-sown crops), when weather and soil conditions can limit opportunities to work the land, and so incentives would be required. Another potential problem is that cover crop incorporation in the spring may exacerbate nitrous oxide (N2O) emissions (see above). The BPEX soil management plan for outdoor pig production is likely to have a small but significant beneficial effect on SOC by increasing C inputs. There may also be a small effect by reducing erosion losses, particularly on sloping land with sandy and light silty soils.

The research found that maintaining land drainage in medium and heavy soils may decrease SOC by increasing rates of SOC oxidation, but potentially off-setting this are (a) decreased erosion losses of SOC with better drainage; and (b) decreased N2O emissions. The scope for increasing or up-grading under-drainage systems in England and Wales is uncertain because there is limited information on the current extent and condition of artificial under drainage systems. The following measures did not change SOC significantly either by adding C to the soil or affecting oxidation rates: Introduction of grass leys into the rotation where organic matter is low; Introduction of cover crops/green manures into rotations where organic matter is low; Under-sowing maize with a cover crop.

The results for the first two of these do not agree with experimental findings, and the lack of significant changes at regional and larger scales may be due to the measure being restricted to low organic matter soils. However, these measures could be effective in reducing erosion and associated SOC losses on sloping land.

The report shows that reduced-tillage systems have some C storage potential, but that this will not be cumulative because arable (and most horticultural) land in the UK is typically cultivated every 3‐4 years to reduce the build-up of weeds, diseases, and soil compaction.

iii. reduced diffuse pollution (N, P, pesticides, other agrochemicals, silt)

Soils were seen as important buffers to nutrient transfers. Application of fertiliser should only be applied at a rate appropriate to the needs of the crop and residual fertiliser still available in the soil. Diffuse pollution includes the leaching of agrochemicals (e.g. atrazine) and nutrients (e.g. N; although few sources referred to pollution caused specifically by high P levels in watercourses). Developing control measures is often driven by EU regulations (e.g. Water Framework Directive). Some studies argue that increased organic matter helps control diffuse pollution as it will allow lower applications of pesticides and fertilizers and reduced soil cultivation, due to improved soil structure. Run-off and therefore diffuse pollution loss from irrigated plug plants under glass prior to planting is only believed to be minimal because duration of irrigation is short and of low intensity. Risk of diffuse pollution from field vegetables can be reduced by knowing what levels of nutrient are in the field at the start, and monitoring uptake and utilisation. Timeliness of nutrient applications can reduce leaching. A decision support tool has been developed to optimise N fertiliser application, to avoid excess application and associated risks of N leaching and diffuse pollution.

iv. reduced carbon footprint and sequestration of carbon

Carbon losses through runoff erosion and CO_2 emissions are covered, but only indirectly by some papers. Biochar is mentioned although its benefits or otherwise are still uncertain.

v. control of odours

No papers were found that related soil management practice to odour generation or control.

6.7. Use of composts, mulches, green wastes, green manures for better soil structure

Twenty papers were reviewed on the use of these materials in horticulture. Most papers referred to tree fruit production (8) or were generic (Cross sector; 2; other agricultural sectors, 2). No studies were found on the use of composts etc. in Protected Ornamentals or Hardy Nursery Stock. Materials used in the different sectors include: green waste, composts, mulches (pine bark, conifer bark, aged manures, Sudan grass, wood chips, sawdust, shredded paper, plastics and hairy vetch), biosolids, organic wastes, recycled vegetable wastes, non-woven polypropylene and peat. There is some overlap with the papers reviewed under 'Increased productivity and fertility' and 'Control of pests and diseases' etc. above.

The work has often been initiated by the Agricultural Waste Regulations (2006), which restricts the disposal of waste material in landfill. Another key driver for this research has been the need to replace products such as methyl bromide. Biocidal-containing green manures have been identified as one alternative, in the control of Fusarium basal rot for example. In an attempt to replace non-renewable plastic covers and mulches, biodegradable products have been used.

Application of manures and soil amendments do seem to have positive effects and may in the long term reduce reliance on chemical alternatives. Reported benefits include increased soil organic matter content and biological activity in the soil due to the presence of the organic material on the surface. Grandy et al. (2002) reported that a green manure crop consisting of oat, pea and hairy vetch, grown in rotation with potatoes can increase soil C. Bailey and Lazarovits (2003) have also demonstrated the benefits of improving soil structure through the use of organic matter amendments. Green manures including grasses and legumes seem to have soil nutrient, organic matter, moisture and structural benefits as well as control of leaching and erosion, and nutrient supply in the spring. This can result in improved yields and crop quality. Tejada et al. (2008) found benefits to maize crop yield with the application of green manures such as *Trifolium pratense* and *Brassica napus*. The green manures had a positive effect on soil biological properties, plant nutrition and crop yield parameters. However, in one case, these benefits occurred only in the first year and do not seem to carry over to a second cropping year.

Nutrient status is reported to also improve (i.e. levels of C, N and microbial biomass) through the use of cattle manure compost for example. Biosolids can have marked effects on soil fertility and nutrient status. Mulching (shredded paper) was seen to both increase temperature at the beginning of the season and reduce it at the end of the season. This has a beneficial effect on narcissus production. Shredded paper mulch also improved tree performance. The size, number and nutrient contents of tree crops have been related to applications of compost, although these effects can be variety specific. Compost use also affects time of harvest. Natural mulches perform better than black plastic sheets in terms of vegetative growth. Pathogen suppressant or pest / pathogen free composts can reduce the number of soil borne pathogens. Some papers consider the economics of using these products However, it is also acknowledged that mulches are expensive and difficult to use.

One rare example of the interaction effects between 2 different soil management techniques is presented, relating to the use of mulches and ridging in orchards (Szewczuk and Gudarowska, 2006a; see also Niziolmski (2011)).

6.8. Conclusions of the review of UK and international research evidence regarding soil management in horticulture

Overall, very few sources specifically set out to consider the influence of soil management on crop productivity and soil fertility as the main focus of the article. Examples include how seed germination and emergence of field vegetables are affected by levels of oxygen in the soil (a function of porosity and thus soil management such as tillage practice) and the impact of waterlogging and compaction on carrot yields (Knight et al., 2005), also a function of soil management practice. Many sources make little or no comment on how soil management practices might actually cause or solve these impacts on production. One exception to this is a paper by Drost and Wilcox (2000) on tillage effects on root distribution and asparagus yields. Questionnaire responses mention the use of shallow subsoiling to control erosion by water, but no empirical evidence of its effectiveness was sourced.

The evidence base suggests there has been more research on soil management effects on crop productivity in terms of yields, rather than on crop quality, consistency or reliability of supply. As retailers and consumers are demanding higher quality products (e.g. uniformity in product appearance, size, etc.), this is an area for further exploration. Also, very few papers consider the cost effectiveness or practicality of the measures used.

Often the efficacy of a soil management measure depends on very particular site conditions such as soil type, soil moisture content or degree of soil preparation (O'Neill et al., 2007). The main issue appears to be the context-dependency of the effectiveness of control measures such that straightforward, universally applicable solutions are not apparent.

O'Neill (2009) identifies the following priorities for future research on soil management in horticulture, which concur with the present reviews findings:

- further developments and better understanding of biological control, organic amendments and anaerobic soil disinfestations
- improvement of diagnostic tools
- developing tests for soil suppressiveness
- better understanding of soil biology population dynamics with crop rotation.

Questionnaire replies show that additional information is being sought on all of the soil management issues identified in Table 4 (Appendix B; Table B.18). Assuming this information can be used to reflect where gaps need to be addressed, the most common issue in this regard is the 'Use of compost, green manures and green wastes' (19 responses), followed by 'control of pests and diseases' (18) and use of automation / precision agriculture (18).

7. RESULTS FROM THE REVIEW OF KNOWLEDGE TRANSFER / EXCHANGE MECHANISMS

Current knowledge transfer mechanisms relating to soil management in horticulture were reviewed by combining the findings of the literature review (Objective 1; Appendix D) and the results of the end user questionnaire (Objective 2; Appendix B). The purpose was to identify the key gaps in knowledge transfer relating to soil management practices.

Figure 5 shows the mechanisms of knowledge exchange mentioned in the literature reviewed. A number of sources made no mention of disseminating results, with no direct reference to knowledge exchange mechanisms (41). Many used scientific papers to disseminate the results, which ensures the results are scientifically robust (having passed the peer review process), but these may not be freely accessible to all, due to the costs of subscriptions to relevant academic journals[3]. Grower / industry meetings were a common way of sharing research results (to a greater extent than more formal scientific meetings and conferences). Use of smart phone technology for dissemination of information and tips was mentioned in only one paper (Wedgwood et al., 2012).

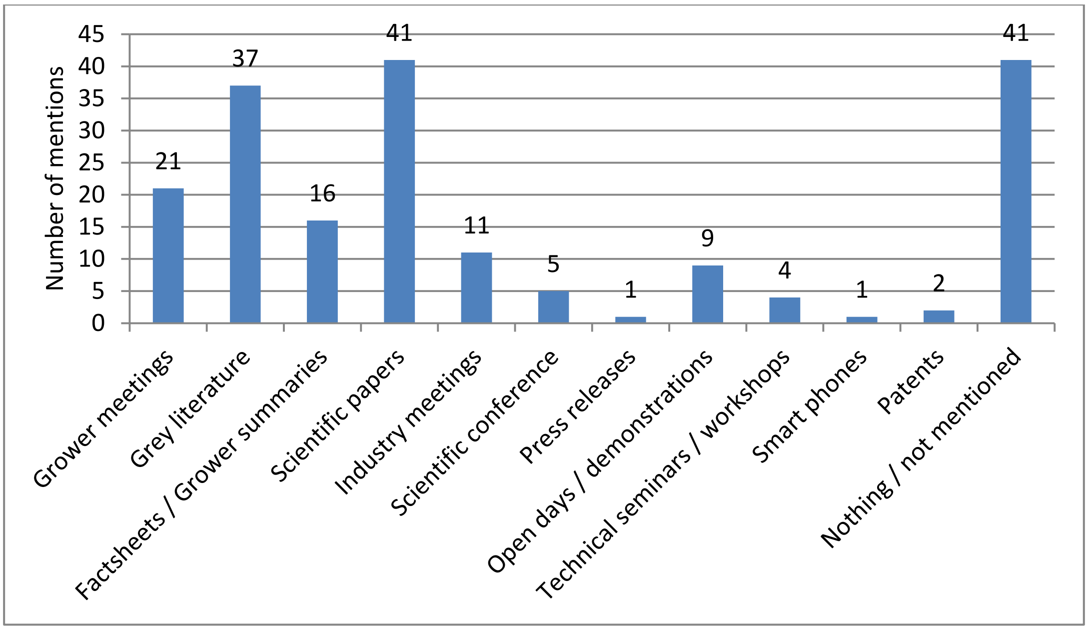


Figure 5. Mechanisms of knowledge exchange cited in the literature review

From the end user questionnaire (Appendix B), most knowledge exchange occurs from grower to grower or by talking to trusted sources such as the HDC, especially via websites and e-newsletters (Table 7). Scientific papers and demonstration days are also listed as effective knowledge exchange mechanisms. Social media (Facebook, Twitter etc.) appear to be less favoured (only 1 response), which mirrors the results found from the literature review. Paper documents (pamphlets, trade articles) are still an important method of receiving information, as also reflected in the literature review, especially ‘grey’ literature published outside of the academic community. Table B.20 in Appendix B presents the level of confidence afforded to the different sources of advice. Most responses demonstrate a confident level of trust in the information that is offered, no matter from which source. Interestingly, most wariness is directed to more the modern technologies of on-line discussion forums, social media, and radio and television.

[3] For example, the Journal of Horticultural Science and Biotechnology (ISSN 1462 0316) subscription costs £360 for 6 issues (2014).

Table 7. Sources of soil management advice by sector

	Field Vegetables	Bulbs & outdoor flowers	Soft fruit	Protected edibles	Protected ornamentals	Tree fruit	Mushroom	Hardy nursery stock	Other	Totals
Talking to other farmers	10	2	0	2	0	0	0	4	4	22
Talking to other trusted sources (e.g. Defra/ AHDB/ HDC/ HGCA/ PC)	8	1	0	1	1	1	0	6	4	22
Trusted web sites and e-newsletters (e.g. Defra, AHDB/ HDC/ HGCA/ PC)	9	1	0	2	0	1	0	4	5	22
Scientific papers	5	0	0	2	1	0	0	3	3	14
Hard copy (e.g. pamphlets, posters, trade articles)	6	0	0	1	0	0	0	3	3	13
On-line discussion forums	1	0	0	0	0	0	0	1	1	3
Social media (e.g. Facebook or Twitter)	0	0	0	0	0	0	0	0	1	1
Media (radio, television)	1	0	0	0	0	0	0	1	1	3
Web search	4	0	0	0	0	1	0	3	3	11
Demonstration days (e.g. LEAF)	7	0	0	1	0	0	0	2	4	14
Trade events	4	0	0	1	1	0	0	3	3	12
Other*	1	0	0	1	0	1	0	1	1	5

Other
Agronomists / Specialist advisers / consultants
The UK is under resourced in soil scientists
Own observation and experience of one's own crop is perhaps more important than all the above but this is rarely quantified.
Cambridge University Farms
Natural England

8. ANALYSIS OF GAPS IN RESEARCH EVIDENCE REGARDING SOIL MANAGEMENT IN HORTICULTURE

The purpose of this section of the report is to highlight the critical gaps in research evidence which are judged to hinder the industry's progress towards 'sustainable intensification'. The report will then identify whether research activities in other agricultural sectors (e.g. arable, combinable crops and potatoes) can help to fill these gaps. However, in relation to research learning from arable crop production for example, Knight et al. (2012) point out that 'there has been little emphasis on soil management studies undertaken or interpreted in the context of today's production systems'.

It might be that new research is needed. If this is the case, recommendations for future research projects / programmes will be made, taking into account the current drivers affecting soil management. These include the issues raised by growers / farmers in the questionnaire, cross compliance, soil policy at the EU and national level (e.g. draft Soil Framework Directive (2006), and Natural Environment White Paper (2011)) and key documents such as the Foresight Report (Future of Food and Farming, 2011). The analysis will also consider current UK government initiatives such as the TSB / BIS / Defra Agri-Technology Strategy and research programmes such as Defra's Sustainable Intensification Research Platform, which is due to start in early 2014. Finally, any research required to develop guidelines for better soil management in horticulture must account for external drivers such as climate change and recent extreme weather events as evidence from the arable sector show these to have effects (both negative and positive) on crop yields (Knight et al., 2012). Ultimately, all research should have the end result of reducing unit costs of production (Robin Buck, pers.comm.).

The simplest and most apparent gap analysis is to use Table 3 to identify where only limited research evidence could be found in the review (Table 8). For each issue researched, we classified the degree of evidence into 'good', 'average' and 'poor'.

Table 8. Identifying where there is a 'good', 'average' or 'poor' research evidence base, according to sources found for the literature review.

	Soil management issue (as identified in HDC R&D strategy documents and the on-line questionnaire)															
	1. Increased productivity				2. Control of pests, diseases, weeds and volunteers	3. Use of automation /precision agronomy /smart mechanisation	4. Improved monitoring techniques		5. Surface/subsurface water management	6. Control of environmental impacts					7. Use of composts, mulches, green wastes, green manures	8. Mechanisms and routes of knowledge exchange
	i	ii	iii	iv			i	ii		i	ii	iii	iv	v		
Count for all Panels	5	7	8	2	9	3	2	2	4	0	6	6	3	0	8	5
'Good', 'average' or 'poor'	A	G	G	P	G	A	P	P	A	P	G	G	A	P	G	A

1. Increased productivity:
i. Nutrients / fertilisers ii. Water iii. Soil health / ecology iv. Alternative substrates
2. Control of pests, diseases, weeds and volunteers
3. Use of automation / precision systems / smart mechanisation
4. Improved monitoring techniques:
i. remote sensing (satellite, air borne and ground based methods) ii. field sampling and mapping

5. Surface / subsurface water management (conservation, drainage and coping with drought)
6. Control of environmental impacts:
i. reduced gaseous emissions ii. control of soil degradation processes iii. reduced diffuse pollution iv. reduced carbon footprint and sequestration of carbon v. control of odours
7. Use of composts, mulches, green wastes, green manures for better soil structure
8. Mechanisms and routes of knowledge exchange

We found a poor evidence base for the following issues:
- use of substrates
- improved monitoring techniques.
- control of gaseous emissions
- use of automation / precision agronomy / smart mechanisation; control of odours.

In some Panels, we found no research activities or evidence relating to these topics. We suspect the issue of 'surface / subsurface water management' is under-represented in the review because, although many papers considered soil conditions as a result of water management (e.g. application of irrigation), we excluded papers that did not consider direct management or manipulation of the soil. With this logic, installing field structures to control surface runoff would be in scope, but comparing trickle and sprinkler irrigation on soil water would not be, as there has been no direct or deliberate alteration of the soil *per se.* Even so, few sources focus on soil moisture status as specifically affected by soil management practices (as opposed to application of irrigation etc.). The use of substrates was poorly reported, but in any case this is outside the scope of the review.

This simplistic 'absence / presence' approach fails to acknowledge that there may be flaws in the search process used (i.e. relevant papers did not meet the criteria of the search terms used – see Table 2) or that research has been undertaken, but this has not been published in easily accessed sources (as yet). It is likely that some of the more innovative techniques (e.g. precision agriculture in horticulture) may fall into this latter category.

So, to develop the gap analysis further, we interrogated the literature reviewed and used the questionnaire responses received to identify where specific research gaps still exist and need addressing. This exercise identified a number of gaps in the research evidence in the following areas:
- Monitoring and measurement: "What gets measured gets managed".
- The use of soil amendments for nutrient management, disease / pest control and environmental protection
- Use of precision agriculture in horticulture
- Limitations of the experimental empirical base: the need for 'big data' approaches

<u>8.1. Monitoring and measurement: "What gets measured gets managed".</u>

A number of papers and questionnaire replies demonstrate the need for more meaningful measurement of soil conditions to inform decisions on soil management. The state of the soil in space and time will dictate timeliness of operations, degree of cultivation, depth of tillage (e.g. subsoiling requirements), energy used (draught force required for cultivations) and rate of agro-chemical applications, including nutrients and pesticides, etc. In short, soil condition affects production costs and returns to the grower. Similar consultation in the arable sector regarding soil measurements identified 'attention to detail', 'getting everything right' and 'continuing improvement' were seen as vital to achieve positive yield trends on individual farms (Knight et al., 2012).

Relevant, related research projects from other agricultural sectors (primarily arable production) are shown in Table 9.

Table 9. Relevant research projects on monitoring and measurement from other agricultural sectors.

Title	Year	Description of research
Cost-effective sampling strategies for soil management	2012	Current recommendations for soil sampling are based primarily on anecdotal evidence of what sampling is sufficient. They do not relate the sampling effort to the consequences of erroneous soil nutrient information. These consequences might include reduced profitability or the long term development of nutrient excess or deficiency. A previous HGCA project showed that it is possible to optimize the sample designs to perform better than the W in terms of sampling errors per core taken. However such schemes might not be as simple to implement in the field. These factors suggest there is a need to assess the sampling requirements for soil nutrient management so that the best sampling design and the rational sampling effort (i.e. number of cores) can be determined.
Detecting soil nitrogen supplies by canopy sensing	2008 / 2009	Research that tested whether soil nitrogen supplies to cereal crops can be detected using canopy sensors; the first season was reported in HGCA Project Report No. 427.
Developing methods to improve sampling efficiency for automated soil mapping	2005	The goal of this project was to develop methods to sample spatial variables, such as soil or crop properties, which are efficient and cost-effective despite the fact that we start with little or no information about the spatial variability of the variable.
Description of spatial variation in soil to optimize cereal management	2004	The aim of this project was to determine through detailed soil, crop and environmental surveys some of the causes of the variation in yield and to indicate which of these the farmer might ameliorate.
Evaluation of non-intrusive sensors for measuring soil physical properties	2003	Knowledge of soil physical properties has always been important for decisions concerning cropping and crop management inputs, especially the use of fertilisers and lime.
Developing a cost-effective procedure for investigating within-field variation of soil conditions	2003	The aim of this project was to develop a cost-effective procedure for investigating the variability of soils within fields as an aid to farm-level decisions on the adoption of variable rate management of inputs.
Extraction and identification of weed seeds and plant-parasitic nematodes from soil samples collected from 98 cereal fields throughout Scotland	1998	Monitoring work on weed seeds and nematodes is useful in providing an indication of long- term trends of the build-up or reduction in species occurrence.
The development of cost-effective methods for analysing soil information to define crop management zones	1998	Yield maps of winter-sown cereal crops were obtained from five sites in England for two or more seasons.
Variation within fields of potentially available soil nitrogen using the hot KCl technique	1996	In February 1996, ten fields in the Lothians were chosen which had been ploughed but not yet sown with spring barley.
Assessing within-field soil variability	2003	To provide a data set of soil nitrogen and crop nitrogen uptake analyses through which the Rothamsted cereal nitrogen model could be validated for higher OM soils and in higher rainfall conditions than in Eastern England. Many soil physical and chemical properties vary within fields. Where this variation is large, and can be managed at practical scales, variable management within a field, eg for lime, fertiliser or cultivations, may be worthwhile.

The question arises as to what soil properties should be measured? One questionnaire reply complained of the lack of key metrics that determine whether the soil is in 'optimal condition'. Research elsewhere on soil quality indicators (SQIs) and 'soil health' is pertinent here (e.g. Merrington et al., 2006; Black et al. 2008, Rickson et al., 2013). It is acknowledged that soil physical, biological and chemical properties affect soil functions (e.g. water holding capacity, infiltration) which in turn affect the soils ability to deliver ecosystem goods and services, such as biomass production (yield quantity and quality), nutrient buffering and regulation of carbon and water supplies. However, there has been little research on SQIs in horticulture. Therefore research is needed to determine which soil properties are relevant. This may vary according to HDC panel and will include (but not be limited to) the five pivotal points of soil health: moisture content, nutrient status, organic matter content, soil biota and structure (including compaction) (Ritz et al., 2010).

As an example, soil compaction was identified as a serious issue by many questionnaire respondents. The extent and impact of soil compaction at or below sub-soiling depth needs to be quantified. Knight et al (2012) report that soil compaction from trafficking can reduce cereal yields by an average of 16%. To demonstrate the complexities of monitoring this property, consistent characterisation of the degree and nature of soil compaction is challenging because the various structural conditions associated with compaction are difficult to measure quantitatively. The degree of compaction may vary greatly within a single field, across the landscape and even through the soil profile. Surface soil compaction is ephemeral (especially in cultivated systems) and subsoil compaction can go largely unnoticed until its effects are serious. The upper part of the subsoil (in general the plough pan layer) is the zone of most importance for identifying subsoil compaction (Van den Akker et al., 2003). Furthermore, climatic conditions (precipitation, evaporation) are unpredictable. Vulnerability to compaction should ideally be assessed by direct measurement of soil bearing capacity, but currently no reliable, easily applicable direct practical tests are available.

Once the problem is assessed, appropriate management can be applied. For example, controlled traffic farming is used to alleviate compaction (Chamen, 2006). Continuous measurement of soil properties can then assess the effectiveness of the management technique used.

The research should also determine the resolution of measurements over space (in the X, Y and Z planes) and time needed to detect meaningful changes in soil properties i.e. when soil functions are affected (Rickson et al., 2013).

Given this analysis, future research should address the following hypothesis:

(Variable input) soil management in horticulture, based on monitoring of key soil metrics in space and time will deliver production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).

Research objectives:

1. Identify the key soil metrics that determine soil quality in terms of sustainable crop production. These metrics will include physical, biological and chemical properties, and sub classes of these (e.g. soil biota can be measured and monitored using a range of techniques – see 4. below). Without prejudice, these metrics are likely to include: soil moisture content, organic matter content, nutrient content, soil biota (including pests and diseases) and degree of compaction. However, the importance of each metric may vary for the different HDC panels, so that in some cases, one nutrient may be limiting to yield quantity and quality: for other crops combinations of nutrients and their interactions may be critical for growth. Some research on soil nutrient management for yield quality exists for cereal crops (e.g. N and S dosage for wheat grain quality, Knight et al. 2012): these approaches could apply to horticultural crops too.

2. Determine the required resolution of measurement in space (x, y and z coordinates) to inform soil management decisions. A recent HGCA funded study by Marchant et al. (2012) 'Cost effective sampling strategies for soil management' developed a quantitative framework to study the effectiveness of different sampling designs so that rational sampling

recommendations for phosphorus (P), potassium (K) and nitrogen (N) could be developed. This framework can be used to assess the cost-effectiveness of different sampling designs for the formulation of fertiliser recommendations but also to develop and assess the cost-effectiveness of modifications to these recommendations. The applicability of this approach in horticulture could be explored further. .

3. Determine the required resolution of measurement in time to inform soil management decisions. This will capture the dynamic nature of soil processes and functions. It is especially pertinent given the high proportion of short duration tenancies on horticultural land (the questionnaire responses found that the largest mean and median sized land area used for horticultural crops is rented on short term leases <5 years). It is also important to capture the impacts of changing site conditions over time as a result of climate change (long term; Knight et al., 2012) and incidence of extreme weather events (short term).

Current research on soil resilience could be extended to the horticultural sector. Here, the response of soil properties (notably soil biota) to perturbations (e.g. cycles of heating and cooling; wetting and drying; cultivations, etc.) is taken to reflect soil resilience. One BBSRC funded project "Fundamental bases of biological soil resilience" aims to find better understanding of the basis of such resilience to improve management of soils to enhance their ability to deliver a range of functions and withstand environmental stresses. This research will establish which soil properties underpin the biological resilience of soils, and hence determine the extent to which resilience may then be imparted onto soils through soil management practices.

4. Test different techniques to identify the most cost effective (e.g. cost v accuracy), user-friendly techniques (e.g. cost v ease of use v accuracy) to measure and monitor key soil metrics (physical, biological and chemical properties).

New technologies for soil measurement were the focus of an IAgrE technical workshop, held in 2013. These included applications of medical imaging to soil sciences covering X-ray CT and MRI scanning; measurement of soil water potential associated with thermodynamics; electrical resistive tomography to assess water uptake under growing crops; and site-specific land management of cereal crops based on proximal soil sensing. As Knight et al. (2012) conclude "Current soil testing technology should be checked for its effectiveness in modern arable conditions and further knowledge transfer is needed to reaffirm the benefits of regular soil testing, to ensure effective targeting of fertilisers to fields where yield is at risk, and to avoid low P or K indices becoming a yield limitation in future".

Visualisation techniques have been used to identify optimum seedbed conditions.

The use of sensor networks in horticulture is less documented than that in arable crop production systems. However, some techniques perform better than others and it should be remembered that sensors are presently unable to measure all soil properties essential for the management of the soil-plant-water system. Few sensors are able to measure physical and/or chemical soil properties directly. Sources of error to be overcome include temperature, dust, roots and stones, and accurate calibration. Due to the complex nature of agricultural soils, successful measurement of soil properties has to account for co-variation with other soil properties e.g. with OC in the NIR spectroscopy (Stenberg *et al*., 2010). As the origin of these co-variations is not yet understood nor documented in details, further research is needed.

Research is needed to improve current sensing technologies and develop new sensing techniques including the sensing infrastructure aimed at achieving a stable and consistent environment, which ensures a sensor can operate effectively under varying environments in the field. Some sensing techniques, including acoustic, pneumatic and ground based passive radiometric-based sensing using microwaves, were not considered in the present review, because only marginal advances in the development of these methods for soil analysis have been reported so far. There is potential to investigate these sensing principles further and even explore new techniques being used in other sectors for applications in agricultural soils.

Fusion of data collected on soil and crop properties, weather and topography in horticultural systems is rare, with more research based in the arable sector. For example, Sylvester-Bradley et al. (2009) report that young cereal canopies can signal soil N status where soil mineral N is less than 120-140 kg/ha. Effects were more certain as crops grew, so canopy sensing for soil N supplies should prove more useful as the season progresses. Despite the large and expanding evidence base on new monitoring technologies, very few sources link the target (yield, canopy cover, pests and diseases) directly with soil management practice used.

5. Present how the measurements can be interpreted into soil management decisions. This is being addressed in the current HGCA project 'Exploiting yield maps and soil management zones' (RD-2012-3785; 2013-16). The main aim is to determine when it is cost-effective for farmers to use yield maps and management zones to guide soil management decisions. The work will devise protocols for the robust and efficient implementation of yield maps and management zones. The project will investigate existing yield maps and complementary soil data to determine the best methods of exploiting yield information and when this is cost-effective. Clear guidelines will be produced so that farmers are able to analyse yield monitor data. The same approach could be used in horticulture and for soil metrics rather than crop metrics (in this case yield maps). One example might be the reduced fuel costs associated with variable rate tillage. Fuel cost in medium cultivations now accounts for up to 40% of tractor and labour cost (Robin Buck, pers. comm., 2013). Fuel consumption under no-till is invariably less than under ploughing, though the difference will depend on the soil type, the depth of cultivation and the requirement for secondary cultivations (Knight et al., 2012).

This approach could also develop improved recommendations for N application (rates, point of application in the profile and timeliness) in specific crops – clearly 'one size' does not fit all and international guidance has not been validated for UK soils and climates.

8.2. The use of soil amendments for nutrient management, disease / pest control and environmental protection

Increasing costs of inorganic chemical fertilisers and restrictions on the use of traditional pesticides had led to an increase of soil amendments (including composts and mulches) to enhance nutrient cycling and organic matter content, and to control pathogens. However, these products are expensive and there is very little if any evidence of their effectiveness. Currently, there is no regulation surrounding these products and some unsubstantiated claims have been made by commercial interests. The reality is likely to be that some of them work for specific conditions (e.g. soil type, organic amendments added to the soil, water regime, crop), but many are never going to work. No mechanistic investigation of their effects has been researched, which is needed to ascertain the effect of these supplements on plant growth, crop performance and disease control, as overall performance could not be substantiated in the current evidence base.

These issues are being addressed for cereals and combinable crops as an on-going HGCA project ("Improvement of soil structure and crop yield by adding organic matter to soil" (RD-2012-3787), which aims to find the minimum addition of external sources of organic matter, including making use of on-farm wastes such as straw, which brings about the maximum improvements in crop yield (grain and straw), and soil and environmental quality. The project calls on recent research at Rothamsted Research which shows that addition of Farm Yard Manure (FYM) can improve yield of barley grain and straw by more than 1 t/ha each within two years. These results suggest that striking benefits from adding the right kind of organic matter can be achieved relatively rapidly in soils (which is important, given the short term tenancies often found in horticultural production). The quality of such addition seems important because other long-term experiments on straw incorporation show little benefit following addition of far more organic carbon. The hypothesis is that crop yields increase quickly (within four years) as a result of improved soil physical condition which results from feeding soil organisms (especially earthworms) with relatively small amounts of suitable organic matter additions. There is scope for the same hypothesis to be tested on horticultural crops.

According to Hall (2010), an alternative to chemical soil sterilisation is needed that is reliable, has a high level of efficacy, is environmentally benign, is acceptable to the consumer and can be incorporated into standard farming practice, including organic production. Given the high proportion of short term tenancies in horticulture, an additional requirement might be quick response time. Soil biological condition is often linked to the control of pests / diseases, but without a strong empirical evidence base. It appears that the use of organic amendments to control disease is feasible but rather context-specific, and in general any effects are transient. Natural predators and pests abundance is affected by the type of compost used (Chandler, 2009). The use of steam sterilisation as the basis for zero herbicide (e.g. replacement of methyl bromide) appears realistic (Pinet et al., 1999). The effectiveness of this latter technique depends on soil depth and texture (Pinet et al., 1999), with some studies advocating the introduction of organic amendments after sterilisation to enhance biological control of pests and diseases. This process and the development of a beneficial soil (micro) biological community warrant further attention.

Few studies have considered the role of soil physical condition and the control of soil borne pests and diseases. Tillage has been shown to reduce the prevalence of soil-borne fungal diseases in cereals, hypothesised to be related to the physical disruption of mycelia curtailing infection potential, but there are no apparent reports of this phenomenon in the horticultural sector. For example, the effects of cultivation on nematode numbers are inconsistent. Soil compaction is associated with Verticillium wilt, although the mechanisms for this are unclear. Alleviation of compaction through tillage can expose asparagus roots to Fusarium disease (John Chinn, pers. comm.). There were several sources in the literature that implicate but do not quantify the importance of soil moisture on pests and disease control.

Given this analysis, future research should address the following hypothesis:

Appropriate application of soil amendments will deliver production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Research objectives:
Nutrient management

1. Investigate the cost effectiveness of organic fertilisers to reduce reliance on inorganic fertilisers and their associated carbon/energy footprint. The aim is to harness resource efficiency and adopt the circular economy approach to support sustainable intensification in the horticulture sector.
2. Nutrient uptake is determined by soil moisture content, but few studies explicitly study the interaction effects of soil nutrient and water management in soils. Soil management can create conditions for optimal water delivery (i.e. avoiding waterlogging and drought) which will increase post harvest life, avoid N leaching and reduce the need for irrigation.
3. Investigate the role of tillage / cultivation in the nutrient cycling efficacy of soil amendments

Control of pests and diseases

1. Identify the mechanisms and extent to which pathogens such as Fusarium can be controlled by soil amendments containing inoculations with additional microbiology.
2. Investigate the effects of soil amendments on indigenous microbial community (e.g. nutrient cycling.
3. Investigate the role of tillage / cultivation in the efficacy of soil amendments in controlling pests and diseases.

Environmental protection

1. Extend the findings of the recent Defra project SP1106: “Quantification of the potential changes in soil carbon in England from soil protection measures within the Soil Protection Review 2010” for application in horticultural crops.

8.3. Use of precision agriculture in horticulture

From the review, it appears that much of the technology used in precision agriculture is still in its infancy. More research has been undertaken in the arable sector, where a number of precision farming techniques have the potential to help deliver better targeting of agronomy, facilitating attention to detail while improving the outputs from labour and machinery (Knight et al., 2009; 2012). Precision farming techniques and technologies have the potential to improve the timeliness and targeting of inputs or operations, and to help maintain attention to detail as farms get larger. However, they also need to be more practical and accessible for small or medium-sized farms.

Extending this research to horticultural systems will be necessary to allow the systems to reach maturity. While work so far suggests that these techniques are technically feasible, further research is also needed to clarify the economic and environmental benefits of many elements of precision agriculture, especially when applied to the horticultural industry.

The feasibility of these techniques in horticulture would have to quantify and evaluate the advantages of precision agriculture over conventional planting (e.g. lower thinning costs, reduced seed usage, reduced competition between young plants, reduced shock to plants during thinning and reduced input (water, nutrients, herbicide) requirements). Disadvantages to consider include the protection of the plant stand after emergence, the importance of seedbed preparation and if seed treatments are necessary to improve planter performance. This is an area where precision agriculture techniques developed within the arable sector, including soil and crop monitoring techniques and use of automation may have useful application to the horticultural industry. For example, Tillett et al. (2008) demonstrate how computer vision can be used for mechanical within-row weed control for transplanted crops.

However, the cost effectiveness of these techniques needs to be quantified, not least the investment needed in both hardware and software. Regarding the former, Roberson (2000) points out that equipment which cannot perform adequately in conventional production will not be acceptable in precision agriculture. In arable systems, Knight et al. (2012) report that new cultivation equipment can save time and fuel, and deliver effective establishment.

Relevant, related research projects from other agricultural sectors (primarily arable production) are shown in Table 10.

Table 10. Relevant research projects on the use of precision farming from other agricultural sectors.

Title	Year	Description of research
An up-to-date cost:benefit analysis of precision farming techniques to guide growers of cereals and oilseeds	2009	Economic benefits may result from higher yields, saved inputs or faster work rates, and depend on farm size, cropping and the amount of soil, crop or yield variation as well as crop values and input prices.
'Controlled traffic' farming: Literature review and appraisal of potential use in the U.K.	2006	The review assessed, through international literature, the incidence and impact of soil compaction in cropping systems.
Precision farming of cereal crops: A five-year experiment to develop management guidelines	2002	Precision Farming is the term given to a method of crop management by which areas of crop within a field may be managed with different levels of input.

Given this analysis, future research should address the following hypothesis:

Precision agriculture in horticulture will deliver production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Research objective:
Quantify and evaluate the economic, social and environmental costs and benefits of precision agriculture techniques over conventional practice in horticultural systems. This could follow the approach of Knight et al. (2009) to provide an up-to-date cost/benefit analysis of precision farming techniques to guide growers of horticultural crops. Factors to consider include: machine control; managing limitations to crop performance; crop establishment; nutrient management; crop protection; traceability and record keeping; and the whole farm system.

8.4. Limitations of the experimental empirical base: the need for 'big data' approaches

Despite the volume of research on soil management in horticulture, wider applications of the research outcomes throughout the horticultural sector are limited by the scale and or duration of many studies and experiments. The range of soil types is often limited to only one or two. Most sources reported on a single or at best comparison of two different crop types. Much of the research concentrates on individual crops (e.g. cabbage, broccoli, cauliflower, unspecified Brassicas, herbs (coriander and mint), leek, field grown lettuces, carrots, onions) rather than when grown in rotation (either with other horticultural crops or as part of an arable rotation). This may reflect the relatively short duration of research projects due to limited funding available for long term projects. Despite most of the research focusing on only a single crop, the conclusions and recommendations may be relevant to a wider range of crop types, although this possibility is seldom explored. Very few studies consider any interaction effects between 2 or more different techniques, although an exception to this is the use of mulches and ridging in orchards (Szewczuk and Gudarowska, 2006a), and the use of mulches and shallow soil disturbance in asparagus (Niziolmski, 2011).

The literature demonstrates that horticultural production needs to be seen holistically. Agronomy information tends to focus on comparison of products, doses or techniques, but the implications of mistiming for yield should be made equally accessible (Knight et al., 2012).For example, soil biology affects N mineralisation and nutrient availability (including N, K and Ca), hence improved soil fertility. The uptake of nitrate is affected by moisture content and the soils ability to retain water, which in turn can be controlled by soil condition and irrigation. However, few studies explicitly study the interaction effects of soil nutrient and water management in soils. The development of tools such as EU-Rotate-N and CLOSYS will help the horticultural industry maximise the efficient use of N fertilizer and water efficiency. EU-Rotate-N is particularly useful as it considers multiple combinations of different rotation scenarios.

Concepts such as 'integrated farm management' (IFM) try to capture these synergistic relationships, as reflected in the work by organisations such as LEAF (http://www.leafuk.org/leaf/home.eb). The current Defra Sustainable Intensification Research Platform research call also includes a project on "Integrated farm management for improved economic, environmental and social performance" (LM0201). The project is due to begin in early 2014. Whether this will address the horticultural sector specifically depends on the winning proposal, but in any case its outcomes are likely to have significance for all agricultural sectors.

The wealth of evidential and scientific data generated is difficult to integrate in a semi-systematic but qualitative review. Exploring the possibility of applying the principles of 'big data' to the research outputs has potential. A soil management information system could hold geo-referenced environmental and management information at a variety of geographical scales, incorporating (where available) the data from each study on soils, crops, pest/disease incidence, soil degradation status, climate and meteorology, and management inputs, practices and costs. Using novel data fusion techniques, these inputs would form the 'rule base' of how soil management practices in different scenarios are likely to give different outcomes for the farmer. This will provide information on how current soil management practice affects the functioning of soil processes under the range of scenarios represented by the information system database. This could allow the effects of different soil management options on soil properties to be evaluated for different situations (soil type, rotation, location, etc). The inevitable complexity of such a system is shown in Figure 6.

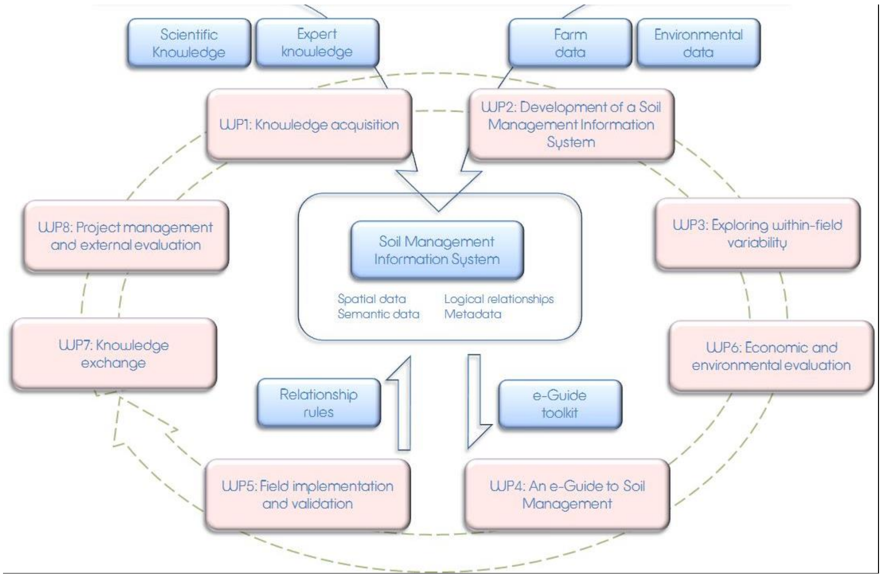


Figure 6. Conceptual structure of a soil management information system incorporating 'big data' methods (Rickson et al., 2012).

'Proof of concept' of this approach is being developed in the 'Soil for Life' project, a 'Knowledge Transfer Partnership' initiative undertaken at Cranfield University and co-funded by Produce World, TSB, Defra, BBSRC and NERC. Ultimately, the aim is to increase revenue through better yield quantity and quality, and reducing waste (e.g. product below quality requirements). The system also identifies best quality land, capable of maximum production with degradation (sustainable intensification), so securing the future resource base (soil). The system allows benchmarking of Produce World's 17,000 ha land bank, including the foundation of the company's soil carbon inventory. The information in the databank includes spatial and temporal monitoring of key soil attributes that affect skin finish, quality and storability of potatoes, onions and root crops; uniformity of plant size and consistency in product (Brassicas) and soil compaction risk. It also includes information on pest and disease incidence (so leading to the development of pest and disease indices), and on nutrient use and uptake (so optimising agro-chemical use and reduced farm costs). The project is due to report in 2014.

A similar (but more geographically limited) approach for cereal production is being developed currently (2013-16) as an HGCA funded project "Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments" (RD-2012-3786). The project acknowledges that the UK currently lacks information from robust experiments that address the agronomic, environmental and economic impacts of soil management practices. The project aims to make best use of existing soil management experimental platforms to build understanding from tillage experiments at three locations that can (a) produce vastly different soil properties, (b) assess commercially-relevant cultivation systems and (c) assess performance of different cereal varieties. It will also compare plough versus reduced tillage in larger-scale farm sustainability experiments. The project aims to develop quantitative indices that are related directly to soil constraints to cereal production. By applying them to long-standing soil tillage trials, that are located in multiple regions and on different soil types, the project aims to demonstrate the pros and cons of different soil management practices under controlled conditions without the artefacts caused by short-term studies. A similar approach, possibly on a larger spatial and temporal scale (including historical data) could be used in other AHDB sectors, including horticulture and potatoes.

Given this analysis, future research should address the following hypothesis:

A soil management information system for horticulture, incorporating the concepts of 'big data' will support production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).

Research objectives:

1. Develop a soil management information system (SMIS) that will hold, manipulate and manage data to provide information on the benefits of soil management practices on crop productivity and environment protection. The SMIS will also capture policy-oriented and best-practice guidelines.
2. Develop relationships between soil management practices and field and farm-level outcomes (e.g. economic costs and benefits; environmental impacts).
3. Develop a system capable of capturing the concepts of 'integrated farm management'.

9. ANALYSIS OF GAPS IN KNOWLEDGE TRANSFER / EXCHANGE MECHANISMS REGARDING SOIL MANAGEMENT IN HORTICULTURE

The purpose of this section of the report is to highlight the critical gaps in knowledge exchange / transfer (KE/KT) mechanisms which are judged to hinder the industry's progress towards 'sustainable intensification'. The report will then identify whether KE/KT activities in other agricultural sectors (e.g. arable, combinable crops and potatoes) can be applied in horticulture, or whether new mechanisms are required. If this is the case, recommendations for future KE/KT activities will be made.

Scientific papers have been identified as a key knowledge transfer mechanism, but they may not be accessible (i.e. free) to all, as they often require an individual or institutional annual subscription. Although they are a means of knowledge transfer in their own right, few papers discuss the ways in which their research findings are disseminated in other, possibly more accessible ways.

Despite the expansion of social media (Facebook, Twitter, LinkedIn), these avenues are seldom used for knowledge transfer. This might represent an underused resource, although these sites do not appear to be popular as a means for seeking advice according to the questionnaire (only 1 reply). This is possibly because the researchers are not using these means for communicating their findings. However, the use of smart phones was mentioned in one study as a means of conveying information and tips to farmers and growers. A large number of respondents did use websites and eNewsletters and found them to be effective in gaining information and advice.

Knight et al. (2012) state there are short-term opportunities to raise farm yields that involve additional knowledge transfer to address apparent shortcomings in agronomic practice. Not all growers will benefit, as many will already be employing best practice, but they may provide quick wins for others to improve crop performance. The KE/KT approaches that can lead to positive yield trends for wheat and oilseed rape were identified as:

- Involvement in grower groups that seek out and share knowledge;
- Engaging the whole farm team in understanding soil management and its effects on crop performance (and thus financial margins);
- Investment in training
- More effective hardware and technology to capture and then analyse information;
- Better access and making more use of agronomists or specialist advisors to help improve the farming system.

The same approaches will apply in the horticulture sector.

10. CONCLUSIONS AND RELEVANCE OF THE REVIEW AND GAP ANALYSIS

The collation and review of evidence regarding a) research and b) knowledge transfer mechanisms related to soil management in horticulture crops has identified a number of gaps in the current state of knowledge. Consultation with representatives from the horticultural industry in the form of an on-line questionnaire has highlighted their current soil management challenges and preferred knowledge transfer mechanisms. These challenges concur with those identified as the R&D priorities of the eight HDC panels.

Of the documents reviewed, soil management is often not the main focus of research work and is often only a limited part of a project. The (spatial) scale and / or duration of many of the experiments involving soil management may limit wider applicability of the research outcomes within the horticultural sector. The range of soil types is often limited and most studies only consider a single crop rather than the complete rotation. Few studies consider interaction effects between two or more soil management practices, such as the use of soil amendments and tillage. The main issue in reviewing soil management practices appears to be the context-dependency of their effectiveness, such that straightforward, universally applicable solutions are not apparent. Also, very few papers consider the cost effectiveness or practicality of the measures used.

Gaps in the current evidence relate to:

- Monitoring and measurement: There is a need for more meaningful measurements of soil condition, such as moisture content and nutrient status, to address the lack of key metrics that determine whether the soil is in ‘optimal condition’ for production.
- Nutrient management: Improved recommendations are needed for N application (rates, point of application in the profile and timeliness) in specific crops – ‘one size’ does not fit all and international guidance has not been validated for UK soils and climates. More investigation is needed on the effect of nutrient supplements on plant growth, crop performance and disease control as overall performance could not be substantiated in the current evidence base.
- Control of pests and diseases: Few studies have considered the role of soil physical and biological condition and the influence of these on the presence and control of soil borne pests and diseases. Both have been linked to the control of pests / diseases, but without a strong empirical evidence base.
- Use of precision agriculture in horticulture: More research is needed to allow the systems to reach technical maturity, and to clarify the economic and environmental benefits of many elements of precision agriculture.
- Environmental impacts and their mitigation: better environmental auditing will help identify environmental impacts of horticultural production, and target solutions accordingly. There are still quality and yield issues around soil amendments, which suggest the need to expand research in this area.
- Productivity and fertility: The evidence base suggests there has been more research on soil management effects on crop productivity in terms of yields, rather than on crop quality, consistency or reliability of supply. As retailers and consumers are demanding higher quality products (e.g. uniformity in product appearance, size, etc.), this is an area for further exploration.
- Data generation, analysis and use: The wealth of evidential and scientific data generated is difficult to integrate in a semi-systematic but qualitative review.

By analysing these gaps and referring to research undertaken in other agricultural sectors, a number of research hypotheses have been formulated to strengthen the evidence base:

1. (Variable input) soil management in horticulture, based on monitoring of key soil metrics in space and time will deliver production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Identify the key soil metrics that determine soil quality in terms of sustainable crop production.

ii. Determine the required resolution of measurement in space (x, y and z coordinates) to inform soil management decisions.
iii. Determine the required resolution of measurement in time to inform soil management decisions.
iv. Test different techniques to identify the most cost effective (e.g. cost v. accuracy), user-friendly techniques (e.g. cost v. ease of use v. accuracy) to measure and monitor key soil metrics (physical, biological and chemical properties).
v. Present how the measurements can be interpreted into soil management decisions.

2. Appropriate application of soil amendments will deliver production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Investigate the cost effectiveness of organic fertilisers to reduce reliance on inorganic fertilisers and their associated carbon/energy footprint.
ii. Study the interaction effects of soil nutrient and water management in soils.
iii. Investigate the role of tillage / cultivation in the nutrient cycling efficacy of soil amendments
iv. Investigate the effects of soil amendments on indigenous microbial community and pathogens such as Fusarium
v. Investigate the role of tillage / cultivation in the efficacy of soil amendments in controlling pests and diseases.
vi. Extend the findings of the recent Defra project SP1106: "Quantification of the potential changes in soil carbon in England from soil protection measures within the Soil Protection Review 2010" for application in horticultural crops.

3. Precision agriculture in horticulture will deliver production (quantity and quality) that is socially and economically viable and environmentally friendly (so addressing the 3 pillars of sustainability).

Specific research objectives should:

i. Quantify and evaluate the economic, social and environmental costs and benefits of precision agriculture techniques over conventional practice in horticultural systems.

4. *A soil management information system for horticulture, incorporating the concepts of 'big data' will support production (quantity and quality) that is socially and economically viable, and environmentally friendly (so addressing the 3 pillars of sustainability).*

Specific research objectives should:

i. Develop a soil management information system (SMIS) that will hold, manipulate and manage data to provide information on the benefits of soil management practices on crop productivity and environment protection. The SMIS will also capture policy-oriented and best-practice guidelines.
ii. Develop relationships between soil management practices and field and farm-level outcomes (e.g. economic costs and benefits; environmental impacts).
iii. Develop a system capable of capturing the concepts of 'integrated farm management'.

Scientific papers are a key knowledge transfer mechanism, but they may not be accessible to all. Despite the expansion of social media, these are seldom used for knowledge transfer. This might represent an underused resource, although these are not a popular means for seeking advice currently. A large number of respondents did use websites and eNewsletters and found them to be effective in gaining soil management information and advice. Uptake of research findings could be improved by strengthening grower groups that seek out and share knowledge; engaging the whole farm team in understanding soil management effects on crop performance (and thus improved financial margins); investment in training; more effective hardware / technology to capture and then analyse information; and better access to agronomists or specialist advisors to help improve the farming system.

The findings of this review have relevance to different audiences and will bring the following benefits:

a) Benefits to levy payers

The gaps highlighted in this report have pinpointed where future soils research and knowledge transfer activities are needed for the industry to progress towards sustainable intensification. This gap analysis will enable more effective and efficient targeting of future research and development funding. The return on this investment will be robust, practical and economically viable soil management guidance aimed at reducing production costs (e.g. energy, fuel, seeds, water, labour, nutrients, pesticides, herbicides, soil resources, waste) and increasing outputs (e.g. yield quality, quantity and consistency, and environmental protection). These are tangible benefits to levy payers.

Simply put, well-managed, healthy soils lead to greater business profitability. Soils in good condition are associated with increased income (higher prices paid for higher yields and better crop quality) and reduced costs associated with production and environmental protection (e.g. dredging of eroded sediments, water treatment costs, alleviation of compaction, withdrawal of single farm payments).

b) Benefits to consumers

This report is likely to be of marginal direct benefit to consumers. However, as a step on the path towards sustainable intensification, it is an essential stage in the process. Future research and knowledge transfer activities recommended in the report will lead to more sustainable soil management. In turn, this should lead to an increase in product quantity and quality at an affordable price to consumers, without incurring increased costs to society as a whole due to environmental degradation. We estimate that in the long term, benefits of effective soil management will accrue to society, as healthy soil delivers diverse ecosystem goods and services needed for sustainable living (including the provision of food and protection of the environment; Kibblewhite et al., 2008), and continued socio-economic growth and stability (GOS, 2010). Also, delivering safer, more affordable, more reliable produce is a cornerstone of the improving public health agenda (Defra, 2010).

c) Benefits to the environment

This report offers better access to current information on how soil management practices are linked to environmental protection, especially the sustainable use of soil and water resources. Poor soil management is associated with environmental degradation processes. These include soil compaction, soil erosion by water and wind, loss of organic matter and biodiversity, GHG emissions, poor energy use and efficiency, diffuse pollution (e.g. nitrate leaching, pesticides in runoff) and ammonia volatilisation. These processes jeopardise the sustainability of agricultural production.

The gap analysis has identified the research and knowledge transfer activities that can support clear and reliable guidance on soil management practices which avoid environmental degradation. The ultimate aim is to maintain or restore healthy soils that are capable of producing horticultural crops economically, whilst reducing ecological footprints (e.g. carbon, water) and building resilience against future environmental degradation. The guidance must ensure that the way we manage our soils today will not compromise their capacity to deliver ecosystems goods and services in the future (Powlson et al., 2011).

d) Financial benefits of the research

It is not possible to quantify the immediate financial benefits expected to accrue from the review findings, nor at this stage, those resulting from the best practice guidelines that are the ultimate purpose of the review. However, the financial impacts of such guidelines will include:

- Improved soil health leading to greater business profitability, as a result of increased income (higher prices paid for higher yields and better crop quality)

- Cost savings due to the reduced inputs associated with better soil management (e.g. savings in fuel, machinery maintenance, water use, nutrient and pesticide applications, and wastage at harvest)
- Better protection of soil and water resources, so requiring less investment in remedial works (e.g. dredging of eroded sediments, water treatment costs, alleviation of compaction) and fewer financial penalties (e.g. withdrawal of single farm payments)
- A safer, more affordable, more reliable food supply, resonating with the government's agenda of improving public health

The benefits of sustainable soil management can also be valued in terms of the reduced costs of soil degradation, which is often associated with poor soil management. Although not attributable to any one agricultural sector, these have been estimated at the national scale in a recent report for Defra (Table 8; Graves et al., 2011).

Table 11. Costs of soil degradation processes (after Graves et al., 2011)

£ million per year , 2010	**Ecosystem Service**								
Degradation process	**Provisioning**		**Regulating**			**Cultural**	**Total**		
	agric prod	flooding	water quality	GHG	other		Range	Central estimate	%
Erosion	30-50	46-80	55-62	8-10	-	?	139-187	165	13%
Compaction	180-220	120-200	60-80	30-40	-	?	390-540	481	39%
Soil organic content	2	?	?	360-700	-	?	362-702	558	45%
Diff Contamination**	?	?	?	?	25*	?	25	25	2%
Soil biota loss	?	?	?	?	-	?			
Sealing	?	?	?	?	-	?			
Total	212-270	166-280	115-142	398-750	25	?	916-1454	1229	
%	20%	19%	11%	49%	2%				100%

* cost of regulation to protect soils from contamination ? Estimates not available at national scale
**diffuse soil contamination

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Appendices – separate files