Project title:	The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems (PF-*Hort*)
Project number:	CP 107c
Project leader:	Dr Lizzie Sagoo & Dr Paul Newell Price, RSK ADAS Ltd
Report:	Final Report, July 2018
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Location of project:	Field demonstrations at grower sites around the country
Industry Representative:	Andy Richardson, Allium & Brassica Centre

Date project commenced: 01/04/2015

Date project completed 31/03/2018

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

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headline

- Soil mapping, canopy sensing and yield mapping provide soil and crop variability data which can be used as a decision support aid for soil and crop management plans (eg to quantify and target nutrient applications to crops).
- Controlled traffic farming reduces the field area wheeled by machinery and can lead to improvements in soil structure, efficiency and productivity.

Background

Precision techniques can help to improve the efficiency of operations in horticulture production systems, including cultivation and accurate fertiliser and agrochemical applications. Precision farming involves measuring and responding to variability in soils and crops to optimise returns on inputs. Potential increases in marketable yield of high value crops makes this approach an attractive option for many growers. Anecdotal evidence suggests that whilst uptake of GPS and soil mapping in horticulture is increasing, the development and uptake of other precision farming techniques such as controlled traffic farming (CTF), canopy Nitrogen (N) sensing and yield mapping has largely been focussed in cereals and oilseed rape. Some of these precision farming techniques have direct relevance to horticulture and there is interest from growers in their potential to increase yields and improve profitability.

The aim of this project was to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management in horticulture, and to encourage greater uptake of commercially available techniques.

Phase one of the project included a field survey of soil structural conditions under horticultural cropping as well as a review of precision farming techniques. In Phase Two the precision farming techniques with the greatest potential for uptake were evaluated through demonstration activities and/or field experiments on six commercial farms.

Summary

Soil structure survey

The soil structure survey was carried out between September 2015 and October 2016 on 75 fields located on 49 holdings. The survey was stratified by crop type and included annual crops and perennial crops. For the annual crops the survey was carried out twice (pre- and post-planting/drilling). For the perennial crops, the survey was carried out prior to establishment at some sites and in the growing crop at others. The structural survey report is available on the CP 107c project page of the AHDB Horticulture website.

Precision farming review and KT Guide

The precision farming review engaged with precision farming companies and machine manufacturers, growers, consultants and researchers to evaluate the potential for precision farming techniques such as CTF, soil mapping, remote sensing of crop canopies, variable rate inputs and yield mapping, to increase crop marketable yield and profitability. The review provides a comprehensive overview of the precision farming techniques available to growers to improve soil and nutrient management and more specifically how these techniques may be applied to horticultural crops. The precision farming review is also available on the CP 107c project page of the AHDB Horticulture website.

The results from the soil structure survey and precision farming review have also been collated into an AHDB GREATSOILS ‘Soil management for horticulture’ guide.

Field demonstrations

In Phase Two the precision farming techniques with the greatest potential to improve soil and nutrient management in horticulture were evaluated in demonstrations and/or field experiments on six commercial farms.

- ***Options for soil mapping – F.B. Parrish & Son Ltd.***

Soil variability is one of the key factors determining differences in crop yield potential within and between fields. Soil mapping can be used to delineate the boundaries between soil types and to define or characterise the soil types themselves (e.g. pH or soil nutrient indices). F.B. Parrish & Son Ltd. hosted a demonstration focussing on soil mapping in their Avenue Field (10 ha) at Chicksands in Bedfordshire. The aim of this field demonstration was to demonstrate options for soil mapping, including soil sensing techniques (i.e. soil electrical conductivity/electro-magnetic induction scans and soil brightness) and soil nutrient mapping, and compare the effect of soil sampling intensity and a grid-based compared to zone-based approach to soil sampling on the soil nutrient maps produced.

A soil EC survey was conducted and satellite soil brightness imagery sourced for the field. Topsoil samples (0-15 cm) were taken in November 2016 using a number of different sampling approaches. These soil samples showed significant within field variability in soil pH and nutrients.

The soil analysis results were used to create soil pH and soil extractable P, K and Mg maps to demonstrate grid and zone based sampling strategies and the impact of sampling intensity. Once created, soil pH and nutrient maps can be converted into maps for variable rate fertiliser or lime application. This type of soil nutrient mapping is of most value in variable fields where it identifies lower soil index areas, which would otherwise have been under-fertilised or under-limed. Where soil pH or nutrient levels vary above target soil indices, such variation should not be expected to affect crop yields, however variable rate fertiliser application may still offer cost savings through not over-applying nutrients to higher Index areas.

- ***Controlled traffic farming – Barfoot Farms Ltd.***

CTF aims to improve soil structure by reducing the proportion of each field area that is compacted by wheeled machinery. These improvements can lead to fewer and less energy-intensive cultivations, reduced fuel use, improved seedbeds, better drainage, more machinery work days, improved water/nutrient use efficiency and increased yields in some years. These benefits can be accrued within a few years of adopting CTF systems.

Barfoot Farms Ltd. have converted the majority of their machinery to a CTF system as part of a new soil management strategy that also includes the adoption of reduced tillage systems and the use of cover crops to improve soil structure. The CTF field demonstration at Barfoots contained three elements:

i) Capturing detailed technical information on machinery to compare the extent of tracking under the previous conventional and recently adopted CTF systems;
ii) A short term field study to investigate within-field soil quality and crop variability under the recently adopted CTF system;
iii) A field study to investigate the long term effects of the recently adopted CTF system on soil quality.

The tracking study was based on a rotation of sweetcorn, pumpkins, tenderstem broccoli and beans with the addition of cover crops at Barfoots' Little Abshot Farm. Detailed technical information was collated for all the machinery before and after CTF adoption, including track gauges (i.e. distance between wheels on an axle) and implement working widths. The gathered data was used to provide a graphical representation of tracking in the four-year rotation prior to and after CTF implementation. CTF adoption resulted in a potential 63% reduction (37% versus 100%) in tracked area.

The farm is in the early stages of transition towards a CTF system, incorporating the use of cover crops. The demonstration therefore provided the opportunity to capture the soil and crop management challenges encountered in the first few years of the transition. Detailed soil measurements taken within the 2017 sweetcorn crop in two fields (one field in the second year of CTF and a second field in the 5th year of CTF) showed that the base of the topsoil was firm to compact in both fields, indicating that it can take more than 5-10 years for soils to recover from a conventional system of random traffic with deep cultivation to a reduced tillage CTF system.

- ***Soil management strategies – Wyevale Transplants (Forestry) Ltd.***

Wyevale Transplants (part of Wyevale Nurseries) specialises in raising tree and hedging transplants in Herefordshire. Soils are sandy, many of the fields are sloping and plants are harvested in the autumn-winter period when soils are moist or wet, leaving soils bare over winter. In the past, soil erosion and runoff has had a significant impact on local watercourses and properties. One of the principal challenges for the business is therefore to improve resilience through increasing soil organic matter and reducing soil erosion risk. Demonstration activities focused on assessing soil condition and investigating the potential for various soil management strategies including the use of controlled traffic principles.

Detailed soil assessments carried out in three fields showed that the upper topsoil was generally well structured, with a firmer layer at 10-25 cm depth and a moderately-developed tillage pan. Despite recent subsoiling operations, the upper subsoil at around 30-45 cm depth was the firmest layer (probably associated with in-furrow ploughing), with soil compaction generally extending to below the effective working depth of most agricultural subsoilers.

Wyevale Transplants have introduced a range of measures to slow down and capture surface-runoff, including wide grass margins, sediment ponds and filter barriers. Additional measures have included the introduction of 18-month grass leys into the rotation and the application of green compost every two years; and the nursery is considering a reduced tillage trial in which cultivations will be carried out without subsoiling.

A tracking study indicated that there may be some potential to reduce the extent of compaction using controlled traffic, but establishing permanent trackways is challenging with machinery harvesting on sloping land in wet conditions over winter. The first quick win to reduce compaction would be to upgrade tyres to one of the latest designs to reduce tracking and ground contact pressure.

- ***Canopy sensing for variable rate N applications – Savoy cabbage (2016) and Brussels sprouts (2017)***

Canopy sensing measures reflectance from the crop surface. This information is presented as a vegetation index, which can relate to crop biomass and crop N uptake. Information on crop canopy variation across a field can be used to vary the N rate. This technology may have the potential to improve nitrogen use efficiency in horticultural crops. Two project demonstrations therefore focused on variable rate N management for brassica vegetables: one on Savoy cabbages in 2016 at Glassford Hammond Farming LLP and a second on Brussels sprouts in 2017 at W Clappison Ltd’s Park Farm, Risby. The overall aim of these field experiments was to demonstrate the potential for canopy sensing for variable rate N management on brassica vegetables.

The demonstrations included N response experiments and tramline comparisons of uniform and variable rate N application to address the following questions:

(i) Does the optimum N rate for the crop vary across the field?
(ii) Can we relate canopy sensing information to crop biomass and N uptake during the growing season?
(iii) Can we demonstrate a benefit from variable rate N application?

Statistical analysis of N response data from the replicate N response experiments showed that for both the Savoy cabbage and Brussels sprouts N response was similar between the experiments and there was no evidence to indicate a difference in optimum N rates.

There was a good relationship between crop reflectance measurements (NDVI) and above ground biomass and N uptake early in the season. The results indicate that canopy sensing can be used to provide a good proxy measure of variation in brassica vegetable crop biomass and N uptake and may be used as the basis to vary N applications, but may not be as effective in identifying biomass/N uptake differences later in the season as the crop develops a larger number of overlapping leaves.

Comparison of marketable head weights and total marketable yields from the uniform and variable rate N tramline comparisons on the Savoy cabbage did not provide any evidence that varying the N rate increased total marketable yield or produced a more consistent sized crop. However, the variable rate N tramline comparisons in the Brussels sprouts showed slighter higher yields and a greater proportion of large sprouts from the variable rate compared to uniform N treatment. However, the yield difference (1.4 t/ha) was considered small and it was not possible to assess whether the difference in yield between the two tramlines was statistically significant.

- ***Focus on variability – G's Growers Ltd. Cambridgeshire (lettuce)***

Consistency of crop size and quality are key issues for growers. The aim of this field demonstration was to use a case study field to show growers the various precision farming tools available to them to measure variation in their soils and crops. Information on soil variability was collected via a soil EC survey, soil brightness maps, soil sampling and analysis, soil structural assessments and soil moisture probes. Information on crop variability was collected using crop canopy sensing. Areas of thinner and thicker crop were identified for targeted soil and crop sampling.

The case study field showed significant variation in lettuce head weight. Soil sampling and analysis showed that soil organic matter content varied from 7 to 45% in the fenland soils. The pattern of variation in soil organic matter matched the pattern of variation in crop reflectance data. It is likely that the variation in lettuce head weight was driven by factors related to variation in soil organic matter and this may be a combination of differences in soil moisture availability and nutrient availability. Targeted soil and crop sampling identified a number of trends for lower soil and tissue nutrient concentrations in areas of thinner crop, however it was difficult to confidently identify any specific nutrients as likely causes of yield variation.

Focusing on crop variability can help growers identify and address yield-limiting factors. If the causes of yield limitation can be identified and eliminated, crop productivity in the low-yielding areas can potentially be increased resulting in rapid benefits for all crops grown in the rotation. However, this case study also showed that it can be difficult to disentangle the various soil and other yield-limiting factors to understand which are most important in driving crop variability.

Financial Benefits

This project has provided information on the state of horticultural soils and guidance on precision farming and other techniques to identify, avoid and alleviate soil compaction, thereby increasing opportunities to carry out field operations; reduce cultivation and other input costs; increase crop yields and farm profitability, while minimising environmental impact.

The project has assessed the potential for precision farming techniques to better target soil management and nutrient inputs to horticulture crops. The potential benefit of variable rate inputs is greatest in fields that are inherently variable, where it can result in a more accurate use of inputs, optimising nutrient availability across the field and delivering a greater proportion of marketable product.

Action Points

- Soil compaction can be a key yield-limiting factor. Growers can manage the impact of soil compaction by identifying and alleviating it where it has occurred and where possible, by avoiding it in the first place.
- Precision farming tools such as soil mapping, canopy sensing and yield mapping can provide growers with valuable information about the variability of their soils and crops. Where growers have identified variability in their soil or crop, they should first seek to identify the causal factors before adopting appropriate techniques to provide an effective return on investment.

SCIENCE SECTION

Introduction

Technical innovation offers growers new opportunities to potentially increase the efficiency of soil-based horticulture production systems. The overall aim of this project was to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management for improved profitability and sustainable intensification for a broad range of horticulture crops. The project was delivered in two phases:

Phase One: Field survey of soil structural condition in horticulture and review of precision farming techniques for improved soil and nutrient management (first 14 months)

Objective 1. To assess the structural condition of horticultural soils and to establish baseline information on typical soil management practices across a range of horticultural crops (perennial, biennial and annual).

Objective 2. To review the current commercially available precision farming techniques used for soil and nutrient management and to assess their potential application in horticulture cropping systems.

Objective 3. Collate the outputs from the soil structure survey (Objective 1) and review (Objective 2) into a practical, user-friendly "*Soil management for horticulture*" guide.

Phase Two: Field demonstration experiments to quantify the benefit of selected precision farming techniques for improved soil and nutrient management in horticulture cropping systems (years 2 and 3)

Objective 4. Project steering group meeting to agree the soil and nutrient management techniques to be assessed in field demonstration experiments on commercial farms in Phase Two of the project (Objective 5).

Objective 5. To carry out 6 field demonstrations to quantify the benefits (crop yield and quality and farm profitability) and trade-offs of selected soil and nutrient management precision techniques compared with conventional production on commercial farms (3 sites per year over 2 years).

Field survey of soil structural condition in horticulture

Soil compaction was the principal soil quality issue identified by the AHDB Horticulture panel consulted in AHDB Horticulture project CP107 (Rickson *et al*., 2013). A key objective of the current project was therefore to assess the structural condition of horticulture production system soils and establish baseline information on typical soil management practices across a range of horticultural crops (perennial and annual). The methodology and findings of the survey are published in a separate AHDB Research Review Report. A brief methodology summary and some key results for annual cropping fields are provided here.

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

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

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

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

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

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

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

The soil structure and soil management practice surveys offer case study evidence of soil structural conditions rather than statistical relationships between sectors or cause and effect relationships between soil management practices and soil structural condition. However, the greater number of fields surveyed under annual cropping (47 fields) allowed an approximate assessment of the extent of soil compaction issues for this sector (Figure 1).

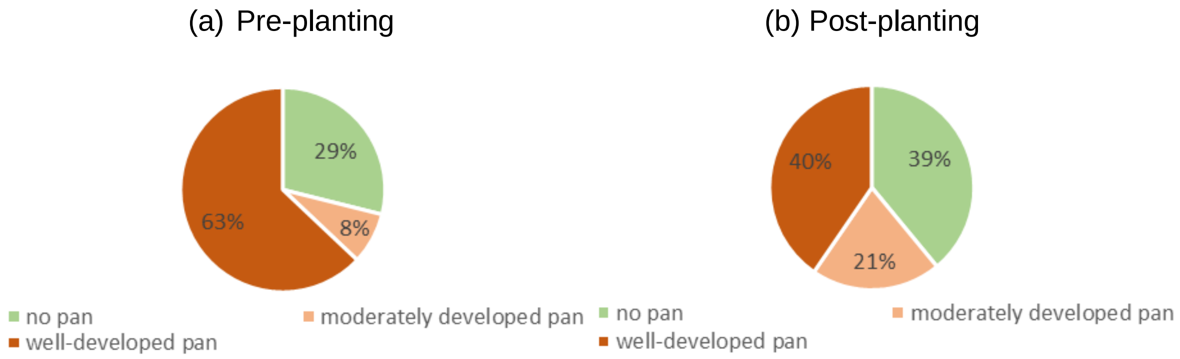


Figure 1. Percentage of annual cropping sites with a tillage pan, (a) pre-planting and (b) post-planting (n = 47).

Review of precision farming techniques for improved soil and nutrient management

The objective of the review was to examine current commercially available precision farming techniques used for soil and nutrient management and to assess their potential application in horticulture cropping systems.

The precision farming review included a literature review, a survey of precision farming companies and machinery manufacturers and a targeted survey of horticulture growers with experience of using precision farming techniques. The review focussed on techniques that can be used to improve soil and nutrient management to increase crop marketable yield and profitability, including:

- Guidance systems.
- Controlled traffic farming.
- Yield mapping – potential to yield map horticultural crops and the potential to use yield maps from combinable crops grown in the rotation to target management of horticultural crops.
- Soil mapping to zone fields: electrical conductivity (EC) and electro-magnetic induction (EMI) mapping and soil brightness imagery.
- Remote sensing of crop canopies and applications for crop surveillance, variable rate N applications, and use of high-resolution imagery to count/size crops.
- Variable rate P, K Mg fertiliser and lime applications.
- Variable rate planting.
- Targeted variable depth sub-soiling to remove compaction.

The combination of the literature review and interviews with precision farming companies, machine manufactures and growers has provided a comprehensive overview of what precision farming techniques are available to growers to improve soil and nutrient management and more specifically how these techniques may be applied to horticultural crops.

Results from the soil structure survey and precision farming review have been collated into an AHDB GREATsoils KT Guide Soil management for horticulture.

Field demonstrations to quantify the benefit of selected precision farming techniques for improved soil and nutrient management in horticulture cropping systems

Background

In Phase Two (years 2 & 3) the precision farming techniques with the greatest potential to improve soil and nutrient management in horticulture were evaluated in demonstrations and/or field experiments on six commercial farms.

Objectives

Objective 4. Project steering group meeting to agree soil and nutrient management techniques to be assessed in field demonstrations on commercial farms (Objective 5).

Objective 5. To carry out 6 field demonstration experiments to quantify the benefits and trade-offs of selected soil and nutrient management precision techniques compared with conventional production on commercial farms (3 sites per year over 2 years).

Approach

The project steering group agreed that the field demonstrations should focus on soil nutrient mapping, techniques to help growers understand variability, canopy sensing for variable N rate and soil management strategies including controlled traffic farming. The six field demonstrations were:

i. **Options for soil mapping**
F.P. Parrish and Son Ltd. (2016/2017)

ii. **Controlled traffic farming**
Field vegetables, Barfoot Farms Ltd. (2016/2017)

iii. **Soil management strategies**
Nursery stock, Wyevale Transplants (Forestry) Ltd. (2017/2018)

iv. **Canopy sensing for variable rate N applications**
Savoy Cabbage, Glassford Hammond Farming LLP (2016)

v. **Canopy sensing for variable rate N applications**
Brussels Sprouts, W Clappison Ltd. Park Farm, Risby (2017)

vi. **Focus on variability – precision farming techniques for measuring soil and crop variability**
Lettuce, G's Growers Ltd. (2017)

Options for soil mapping – F.B. Parrish & Son Ltd.

Background

Soil variability (i.e. spatial variation in soil properties such as soil texture, soil depth, stoniness, soil compaction, soil pH, soil nutrient reserves and soil organic matter content) is one of the key factors determining differences in crop yield potential within and between fields. It can also affect how fields are managed and the effectiveness of field operations, such as cultivation and seed drilling/planting for crop establishment. Soil mapping can be used to delineate the boundaries between soil types and to define or characterise the soil types themselves (e.g. pH or soil nutrient indices). In the past, this has been achieved using soil survey techniques and a knowledge of how soil types vary within the landscape. However, more recently soil mapping has been carried out using a combination of scanning/sensing techniques to define boundaries between soil types; and soil sampling and/or soil survey to determine soil characteristics. Increasing numbers of growers are seeking to map their soil variability as a first step towards trying to understand and manage this variability.

The overall aim of this field demonstration was to choose a field to use as a case study to demonstrate options for soil mapping, including soil sensing techniques (i.e. soil electrical conductivity/electro-magnetic induction scans and soil brightness) and soil nutrient mapping, and comparing the effect of soil sampling intensity and a grid-based compared to zone-based approach to soil sampling on the soil nutrient maps produced.

Methods

Experimental site

This demonstration was hosted by F.B. Parrish & Son Ltd., Chicksands, Bedfordshire on their 10 ha Avenue Field, currently in the following arable and horticultural rotation:

- 2012 Potatoes
- 2013 Wheat
- 2014 Onions
- 2015 Wheat
- 2016 Quinoa
- 2017 Potatoes

The soils in this area of Bedfordshire have developed from glacial and river outwash deposits resulting in significant variability in soil types across the farm from heavier textured Hanslope series clays to the lighter Cottenham series loamy sands (Figure 1).

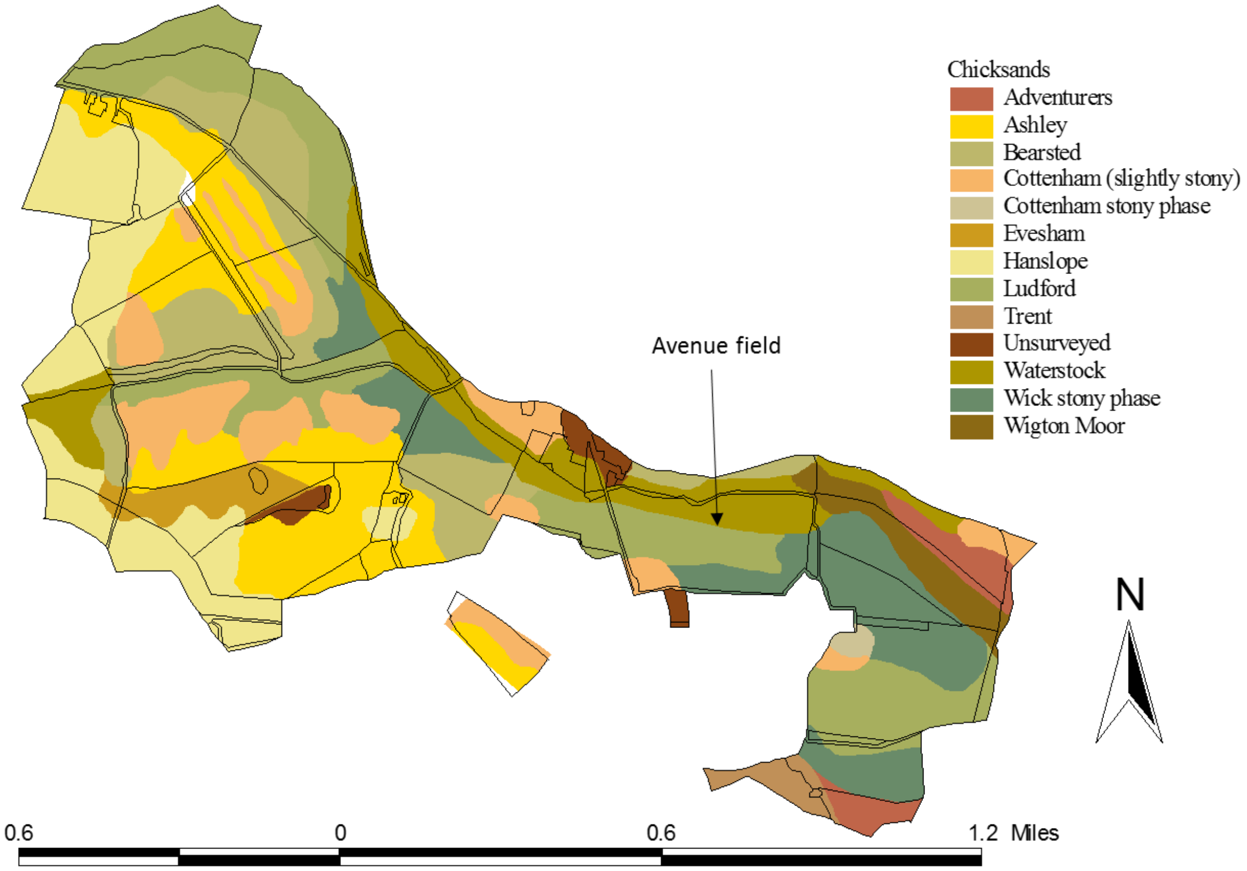


Figure 1. Soil series at Chicksands, Bedfordshire

Soil sensing

Soil electrical conductivity (EC) surveys can be used to map within-field soil variability. The main factors affecting soil EC are soil texture, organic matter content, moisture content and bulk density; light sandy soils have lower EC and heavier textured soils have a higher EC.

Information on soil electrical conductivity (EC) was collected using a non-contact electro-magnetic induction (EMI) scanner by SOYL on 21/10/16 and using a contact Veris MSP3 scanner by Agrovista on 01/11/2016 (Figure 2). Both surveys were carried out when the field was in stubble prior to cultivation, at bout widths of 24 m across the field.

Soil EC data from the Veris MSP3 scanner was used to provide shallow EC values for each of the 143 GPS located soil sampling points. Data interpolation was used to estimate an EC value for each of the measurement points based on actual EC measurements taken at 24 m bout widths across the field. Regression analysis was used to assess the relationship between EC and each of the measured soil parameters.

Satellite soil brightness imagery for the field was provided by Intelligent Precision Farming (IPF – owned by The Courtyard Partnership).

Figure 2. Measuring soil electrical conductivity using a non-contact EMI scanner (left) and a contact Veris MSP3 EC scanner

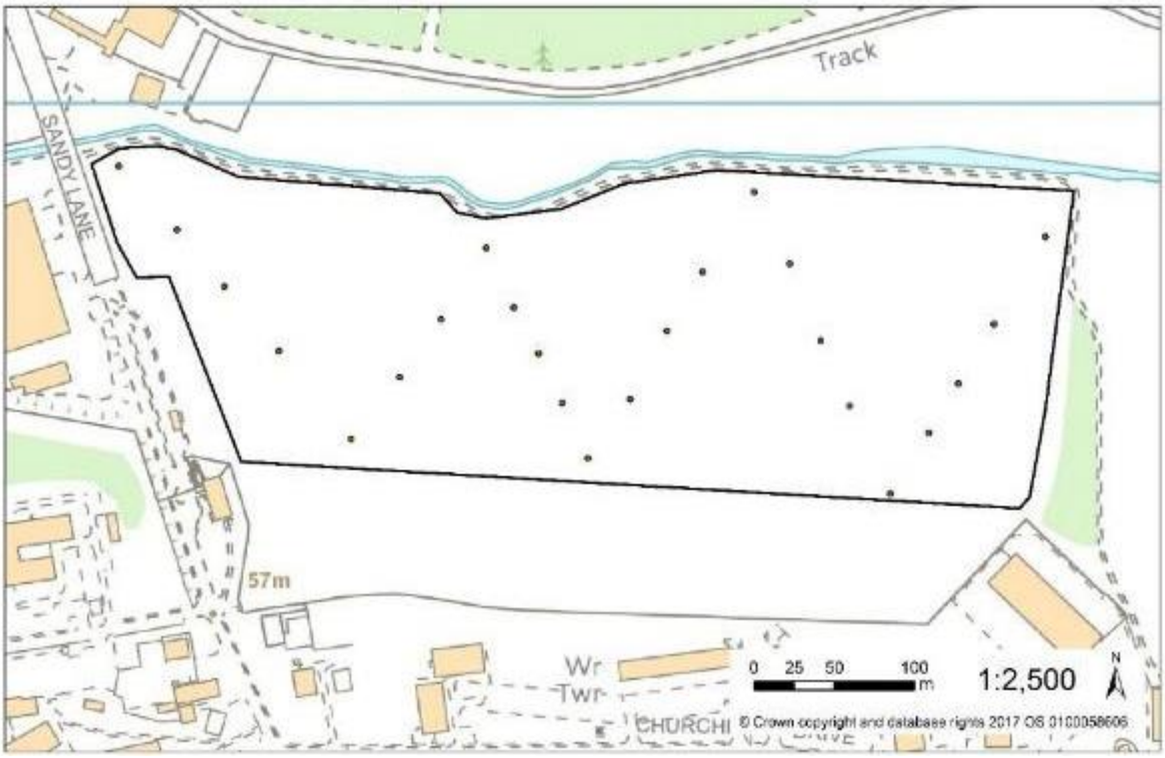
Soil sampling

Topsoil samples (0-15 cm) were taken from Avenue Field in November 2016 using the following sampling methods:

- Single field sample using ‘W’ sampling technique – a single composite sample (of 25 soil cores) was taken by walking a ‘W’ across the field (Figure 3).
- 1 ha soil sampling – the field was divided into approximately 1 ha blocks and a single composite sample (of 25 soil cores) was taken from each 1 ha block by walking a ‘W’ in each block (Figure 4).
- Grid soil sampling – topsoil samples were taken on a 25 m grid across the field (Figure 5), excluding a 10 m ‘no sampling’ buffer zone around the edge of the field, giving a total of 143 soil samples. Each grid sampling point was GPS located. A single composite sample was taken from each GPS located point; each sample consisted of 16 soil cores taken in a spiral within a 3 m radius of the central point.

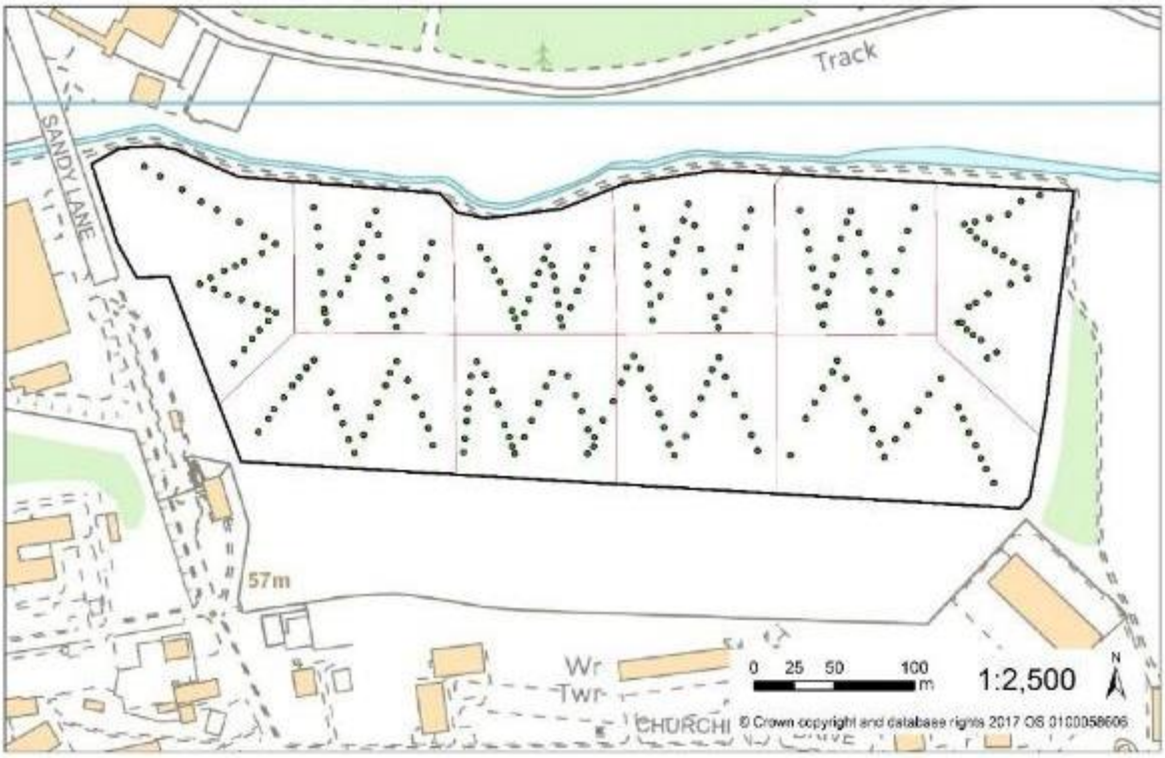
All soil samples were analysed by Natural Resource Management Ltd. (NRM) for pH, extractable P (Olsen’s extraction), K and Mg (ammonium nitrate extract). In addition the following soil samples were also analysed for organic matter (loss on ignition method) and particle size distribution (soil texture):

- Whole field sample (1 sample)
- 1 ha soil samples (10 samples)
- Samples from the 25 m grid closest to the centre point of each 1 ha area (10 samples) (Figure 6).



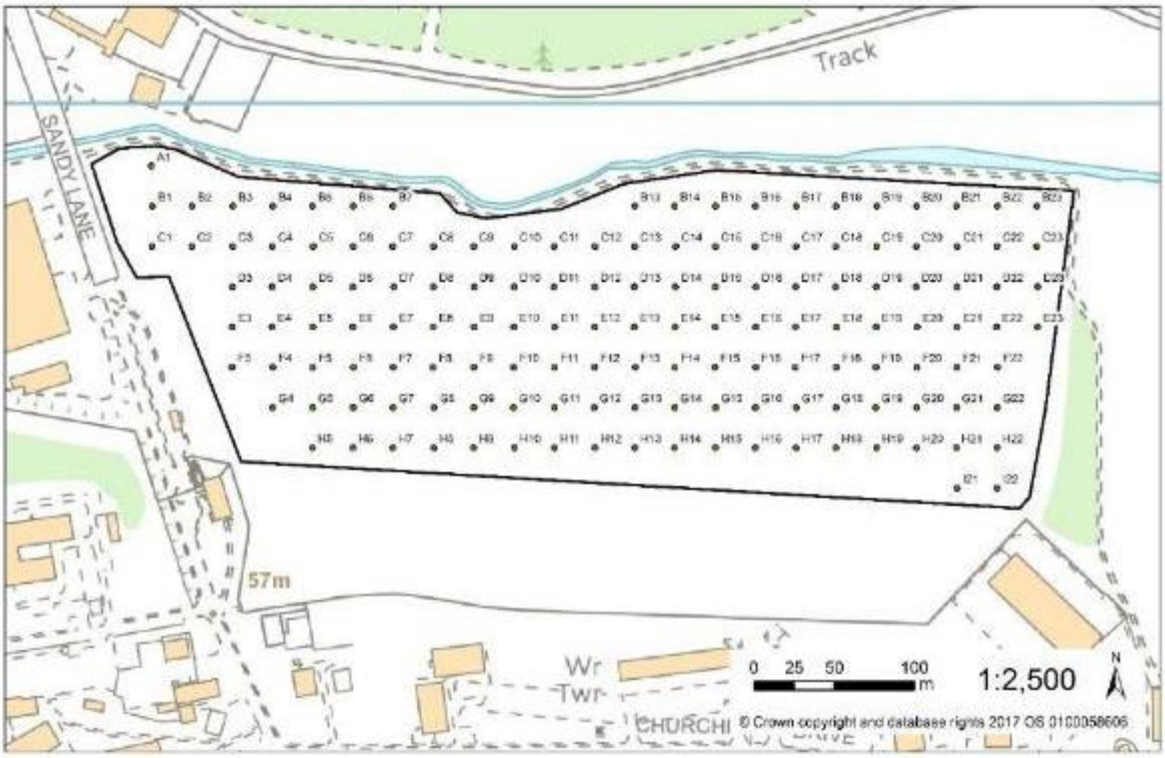
Each green dot represents a single soil core; soil cores were bulked into a single field sample.

Figure 3. Soil sampling at Avenue Field - whole field sample



Each green dot represents a single soil core; soil cores were bulked into a single sample from each 1 ha area.

Figure 4. Soil sampling at Avenue Field - 1 ha sampling



Each numbered green dot represents a sampling point. A single composite sample of 16 soil cores was taken in a spiral within a 3m radius of the central point

Figure 5. Grid based soil sampling at Avenue Field (25 m grid)

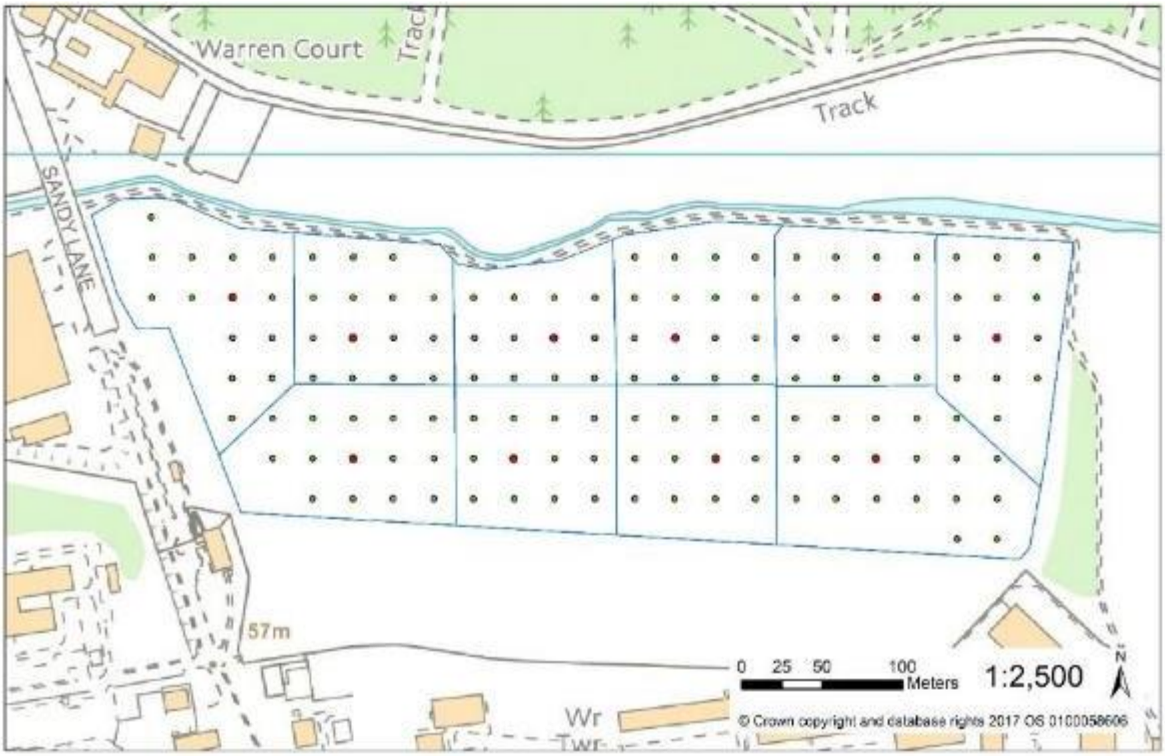


Figure 6. Avenue Field 25 m grid soil sampling points showing the sampling points selected as closest to the centre of each 1 ha area (red dots) – these 10 samples were also analysed for soil texture and organic matter

Soil nutrient mapping

The soil analysis results were used to create soil pH and soil extractable P, K and Mg maps for Avenue Field. Maps were created to demonstrate grid- and zone-based sampling strategies and the impact of sampling intensity.

1. *Regular or grid-based sampling and mapping*

Soil pH and nutrient maps were created based on grid point sampling intensities of:

- 1 sample per hectare (10 samples from the field)
- 2 samples per hectare (20 sampling points from the field)
- Approximately 4 samples per hectare (based on a 50 m grid – 40 sampling points from the field)
- Approximately 16 samples per hectare (based on a 25 m grid – 143 sampling points from the field)

In order to create maps from the individual samples we used a process of spatial interpolation to estimate values at other unknown points to create a contoured map. Soil pH and nutrient maps were created in ArcGIS using four methods of spatial interpolation: inverse distance weighting, kriging, natural neighbour and spline[1]. The soil pH and nutrient maps created using the inverse distance weighting method are presented here, and in addition examples of maps created using the four different methods are also given to show the effect of the different spatial interpolation methods.

2. *Zone-based sampling and mapping*

Zone-based or targeted soil sampling uses existing knowledge of within-field soil variability to direct where soil samples are taken. Field soil management zones can be created based on any available information on soil or crop variability within a field which is likely to impact on or reflect soil pH or nutrient content. Once the soil management zones are defined, each is sampled separately (as a single composite sample representative of the zone). The soil pH and nutrient maps produced will reflect the boundaries between the soil zones.

Soil zones were created for Avenue Field using two approaches:

i. Field soil survey and satellite soil brightness maps.

Soil management zones were created for Avenue Field by IPF based on a field survey and satellite soil brightness maps. Available geological data, Google satellite images, previous national soil survey data and satellite soil brightness maps were collected and used to guide

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[1] A description of each of the methods of data interpolation available from http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/an-overview-of-the-interpolation-tools.htm

the field survey. The field survey used standard soil survey techniques and one observation point per hectare (using a soil auger up to 1 m depth). This information was combined to delineate seven soil management zones in Avenue Field (Figure 7).

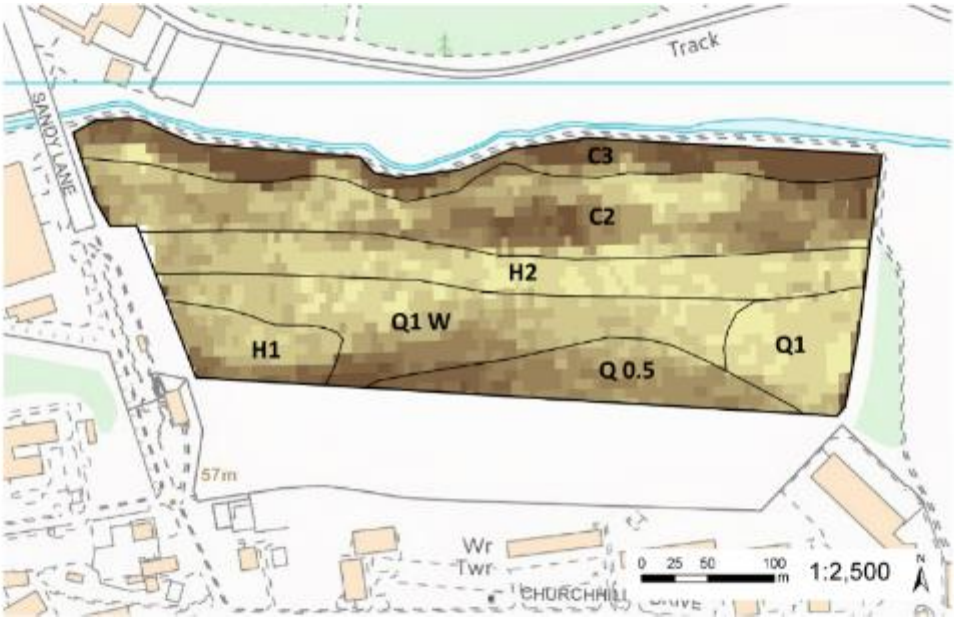


Figure 7. Avenue Field soil zones based on soil survey (shown on soil brightness map)

The following description of the soil zones (as indicated in Figure 7) were provided by IPF:

- H1 is deep stoneless sandy loam; H2 is deep stoneless medium clay loam. H1/H2 soils are developed from Lower Greensand.
- C2 is medium clay loam with few stones; C3 is heavy clay loam over mottled clay with few stones. C2/C3 soils are developed from Head (clay, silt, sand and gravel). C3 is prone to seasonal drainage impedance due to low-lying position and clayey subsoil.
- Q 0.5 is loamy sand over stony sandy loam and loamy sand. Q1 is sandy loam over stony loamy sand. Q0.5/Q1 soils are developed from glaciofluvial deposits and are prone to drought due to light textures and light, stony subsoil.

ii. Spatial grouping analysis.

Soil management zones were created for Avenue Field by ADAS using spatial grouping analysis combining soil EC data, soil brightness values and three years of historic winter wheat spatial yield data to define spatially similar areas. Yields maps were available for winter wheat crops grown in 2010, 2013 and 2015. A normalised (averaged) yield map was created for Avenue Field by Farmplan using GateKeeper software (Figure 8). The spatial grouping analysis identified four spatially distinct zones (Figure 9).

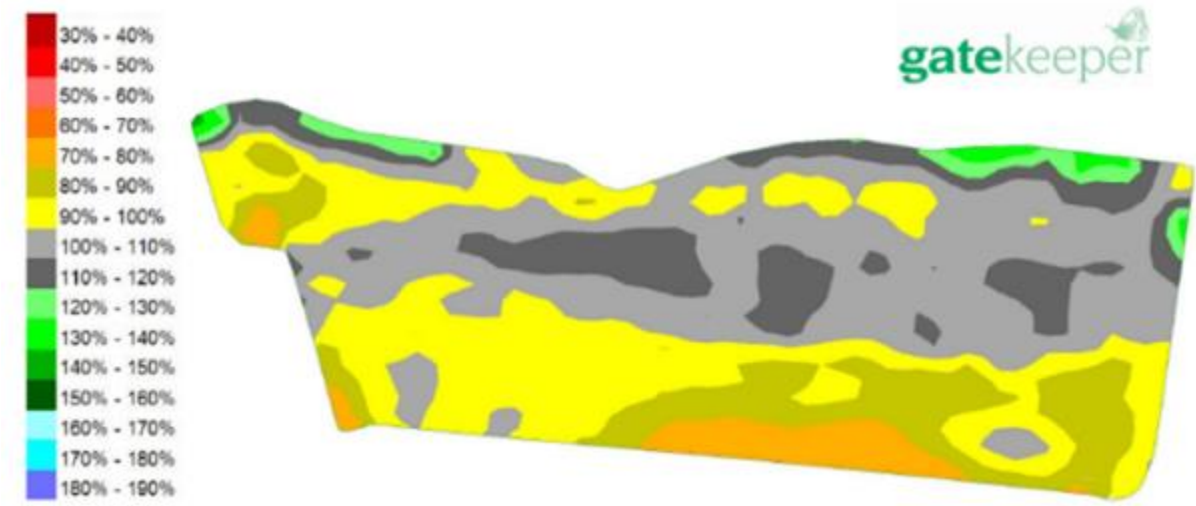


Figure 8. Avenue Field normalised yield map for winter wheat in 2010, 2013 and 2015

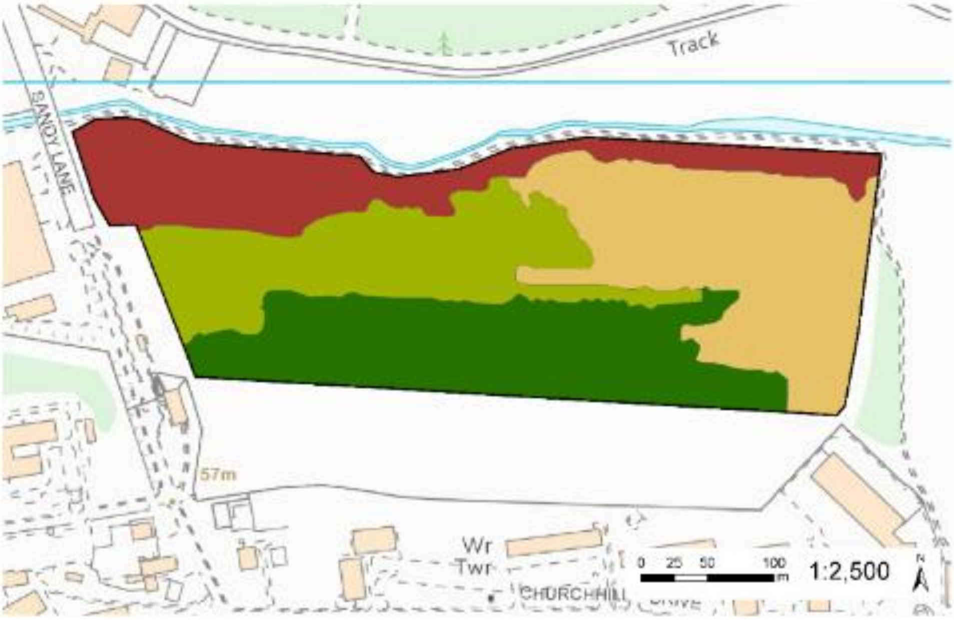


Figure 9. Avenue Field soil zones based on spatial grouping analysis

Both approaches to soil management zoning are valid and both have been included here to illustrate the range of factors that may be taken into consideration when defining soil management zones. Importantly, once the soil management zones are defined, each is sampled separately and the soil pH and nutrient maps produced will reflect the boundaries between the soil management zones. Both approaches to zoning Avenue Field identified a similar pattern of mainly linear zones and both identified the thinner band of heavier textured soil on the north side of the field; although this band is wider in the north-eastern side of the field in the zones defined by spatial grouping analysis than in the IPF-defined zones.

Soil pH and nutrient maps were created based on the two zoning approaches by taking the average soil analysis result from all of the soil samples taken within each zone.

Results and discussion

Soil sensing

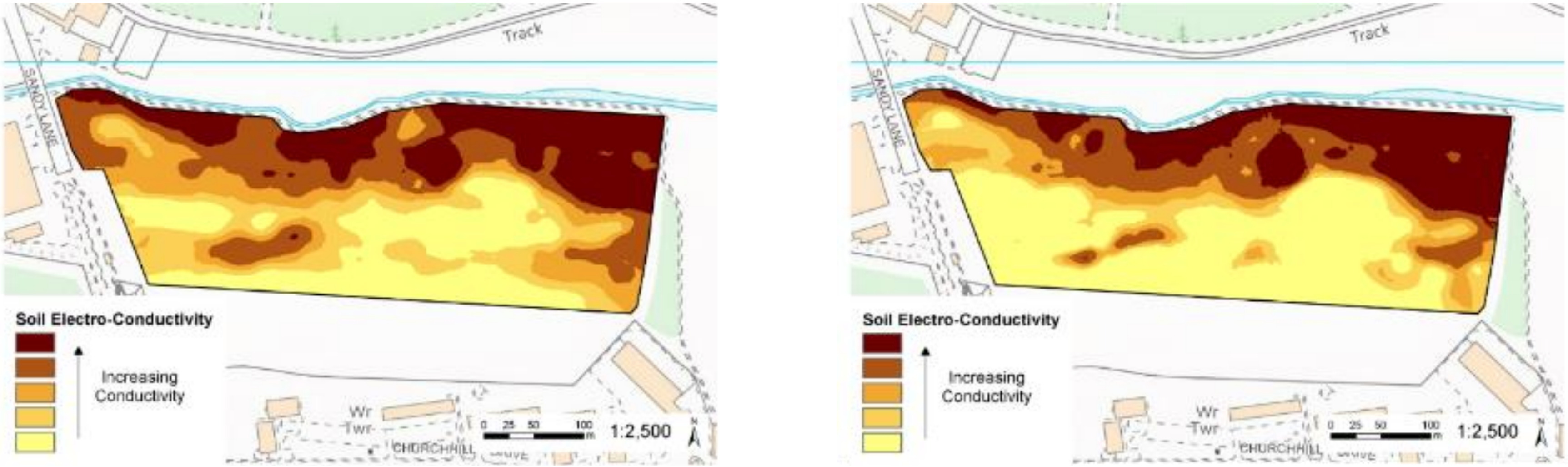
Figure 10 shows soil EC maps for Avenue Field produced from the SOYL non-contact EMI scanner and Agrovista's contact Veris MSP3 EC scanner. Both machines measure EC/EMI at two depths; SOYL's EMI sensor measures shallow EC to 40 cm depth and deep EC to 120 cm, whilst the Veris MSP3 sensor measures shallow EC to 30 cm and deep EC to 50 cm depth.

Both the EC and EMI maps of Avenue Field identified lighter textured areas on the south side of the field (on a slight ridge) and heavier textured areas on the north and north west side of the field. This pattern of EC corresponds well with the farms existing understanding of soil texture variability within the field. Both EC and EMI scanners provide information on soil variability that is broadly comparable. Any apparent differences between EC/EMI maps may reflect:

- Differences in scan points between mapping (i.e. machines not driving in exactly the same place).
- Data interpolation between measurements.
- Scale used for the map.
- Depth of measurement (the Veris MSP3 scanner provides readings from a shallower soil depth).

EMI scan – shallow 0-40 cm

EMI scan – deep 0-120 cm



EC scan – shallow 0-30 cm

EC scan – deep 0-50 cm

Figure 10. Avenue Field soil electrical conductivity surveys

Soil brightness maps are derived from optical satellite imagery and describe how intensively the surface layer of bare soil reflects incoming sunlight. Figure 7 shows a soil brightness map of Avenue Field. Soil brightness maps can be provided at a resolution of up to 5 m and are usually cheaper than soil EC/EMI surveys as the satellite data are collected remotely. Soil brightness provides an integrated measure of the combined effects of soil texture, organic matter, surface crop residues and moisture content at the time the image was taken.

A soil brightness classification is performed on a farm-by-farm basis from imagery captured on a particular date. The resulting bandings are standardised across a farm for a given date. It is not appropriate to compare brightness between farms or dates since soil moisture and other temporally- and spatially-variable conditions will affect the reflectance.

In order to assess soil brightness, the satellite image has to be of bare soil, consequently measurements are typically taken before crop establishment. Each image will show a slightly different colour range based on the method of cultivation, time of data acquisition, soil moisture and stubble interference. Soil brightness maps can be used to help identify spatial variation, but they don’t provide absolute values.

The soil brightness map for Avenue Field has identified a darker thin band on the north side of the field which corresponds to an area of heavier textured soil and is consistent with the pattern identified in the EC maps. The image also identifies a darker area on the south side of the field, which we know to be a distinct area of lighter textured soil on a slight ridge. Although the soil brightness map may be considered to have correctly identified these different zones on the north and south sides of the field, this highlights the importance of ground-truthing because these two areas have different soil textures.

Soil sampling

Table 1 compares soil analysis results from the single whole field sample with the mean and range of soil analysis results from the 143 grid soil samples for pH, P, K and Mg. The whole field soil sample provided a good measure of the mean field value for pH and P Index, but underestimated soil K and Mg Indices. The 25 m grid soil samples indicated significant within-field variability in soil pH and nutrients; soil pH varied from 5.3 to 7.1, P Index from 2 to 4, K index from 1 to 4 and Mg Index from 2 to 4.

Table 1. Avenue Field soil analysis for pH, P, K and Mg – comparison between the whole field soil sample and range and mean values from intensive grid sampling (143 samples)

	pH	**P**		**K**		**Mg**	
		mg/l	Index	mg/l	Index	mg/l	Index
Mean	6.1	35	3	217	2+	110	3
Min	5.3	16	2	92	1	53	2
Max	7.1	55	4	428	4	215	4
Whole field	6.1	33	3	171	2-	77	2

Table 2 compares soil analysis results from the single whole field sample with the mean and range of soil analysis results from the ten 1 ha area samples for organic matter and % sand, silt and clay.

Appendix 2 includes all soil analysis results and GPS co-ordinates for each sampling position.

Table 2. Avenue Field soil analysis for organic matter and % sand, silt and clay – comparison between the whole field soil sample and range and mean values from the 1 ha area soil sampling (representative sample taken from each 1 ha area – total of 10 samples)

	Organic matter	**% Sand**	**% Silt**	**% Clay**
Mean	3.1	63	22	15
Min	2.1	54	16	10
Max	4.1	73	26	20
Whole field	2.6	67	20	13

Soil mapping

1. Soil texture

Soil texture was measured on the representative samples taken from each of the 1 ha blocks (Figure 4) and varies from lighter textured sandy loam in the southern half of the field to heavier textured sandy clay loam in the northern half of the field (Figure 11) and this corresponds to the EC maps which show higher conductivity (indicating heavier soils) in the north and lower EC (indicating lighter soils) in the south (Figure 10).

Soil texture was also measured on the point samples closest to the centre point of each 1 ha area (10 samples) (Figure 6). Regression analysis was used to evaluate the relationship between soil texture (% sand, silt and clay) and shallow soil EC at each of the 10 points.

There was a significant ($P<0.10$) negative relationship between shallow soil EC and sand content ($R^2=0.34$) and significant ($P<0.10$) positive relationship between shallow soil EC and clay content ($R^2=0.37$) (Figure 12). The relationship between shallow soil EC and silt content was not significant ($P=0.16$; $R^2=0.23$).

Figure 11. Avenue Field soil texture (analysis of a representative sample from each 1 ha area)

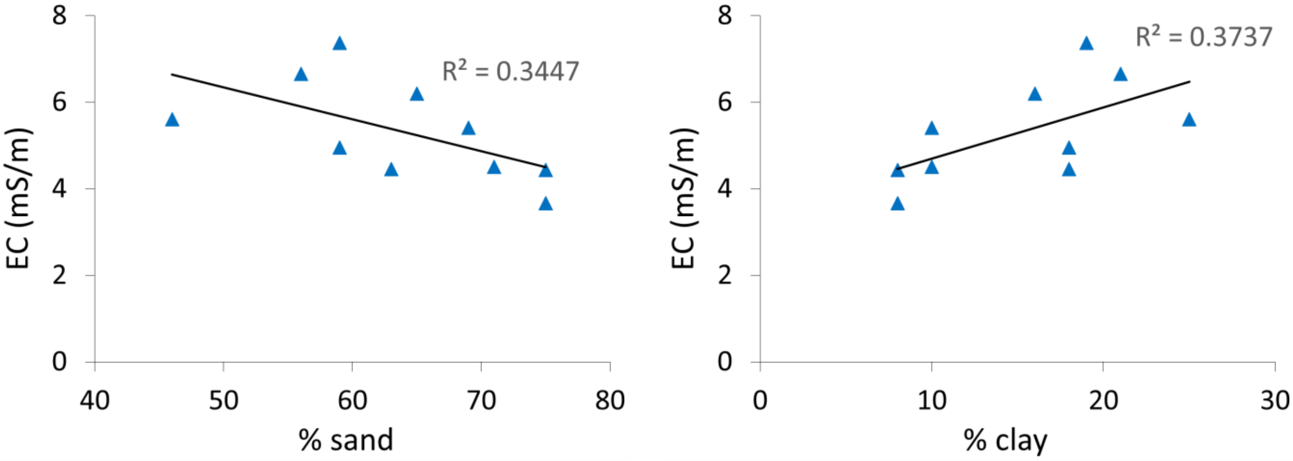


Figure 12. Relationship between shallow soil EC and % sand (left) and % clay (right)

2. *Soil organic matter*

Soil organic matter was measured on the same samples as soil texture, and was greater in the northern than southern half of the field, corresponding to the soil texture (Figure 11) and EC maps (Figure 10) which show heavier textured soil and higher EC in the northern part.

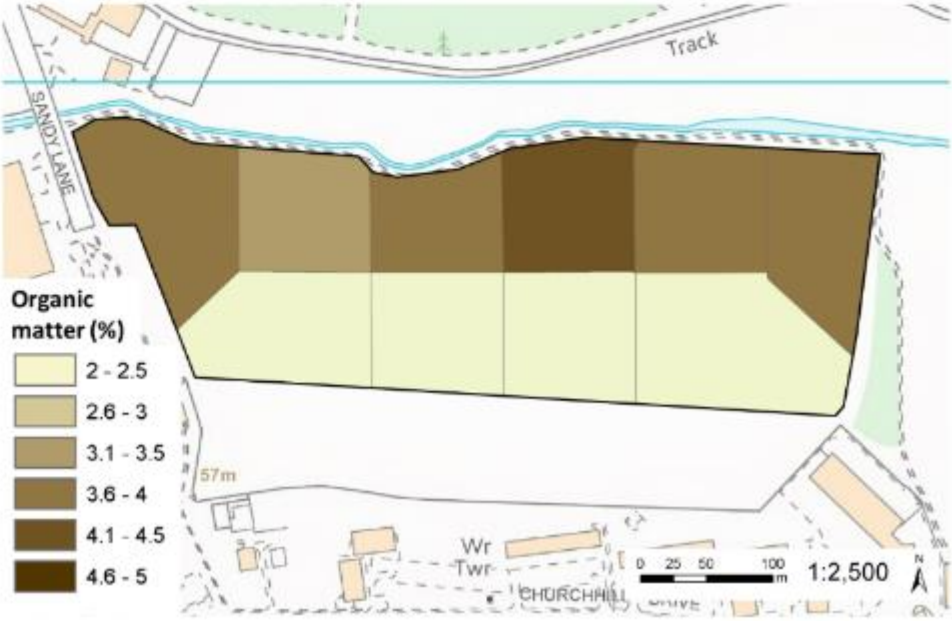


Figure 13. Avenue Field soil organic matter (from a representative sample from each 1 ha)

There was a strong positive relationship (*P*<0.05) between soil organic matter and clay (R^2=0.97) and silt (R^2=0.58) content, and negative relationship (*P*<0.05) between soil organic matter and sand content (R^2=0.88) (Table 3), which is as expected and reflects the greater ability of heavier textured clay and silt soils to retain soil organic matter. There was also a strong positive relationship between soil organic matter and extractable Mg (*P*<0.05; R^2=0.93), but not pH, extractable P or K (Table 3). There was a weaker positive relationship between soil organic matter and shallow soil EC (*P*<0.10; R^2=0.31).

Table 3. Relationship between soil organic matter and measured soil parameters (n=10)

Soil analysis	**R^2**	***P*-value**
Soil EC (shallow)	0.31	0.09
Sand	0.88	<0.01
Silt	0.58	0.01
Clay	0.97	<0.01
pH	0.01	0.79
P	0.05	0.52
K	<0.01	0.90
Mg	0.93	<0.01

3. Soil pH

Figure 14 shows Avenue Field soil pH maps created by grid- and zone-based sampling. The 25 m grid showed soil pH to vary from 5.3 to 7.1 (mean 6.1) and Figure 14b shows significant small-scale variability in soil pH, with patches of lower pH on both sides of the field. As the level of sampling intensity reduces from 16 samples per hectare to 1 sample per hectare, the level of detail in the map also reduces and some of the patches of lower pH are missed in the maps produced from the lower sampling intensities (1 and 2 samples per hectare; Figure 14d,e,f) and in the zone-based maps (Figure 14g,h). There was no relationship between soil pH and organic matter (Table 3) or soil EC (Table 4). There was a significant ($P<0.05$) but weak positive relationship between soil pH and extractable P and K and a significant ($P<0.05$) but weak negative relationship between soil pH and extractable Mg; R^2 <0.10 for all three (Table 4).

Table 4. Relationship between measured soil parameters (n=143)

	Soil EC		**pH**		**P**		**K**	
	R^2	***P*-value**	**R^2**	***P*-value**	**R^2**	***P*-value**	**R^2**	***P*-value**
pH	<0.01	0.81						
P	0.35	<0.01	0.09	<0.01				
K	<0.01	0.50	0.06	<0.01	0.07	<0.01		
Mg	0.62	<0.01	0.03	0.04	0.47	<0.01	0.02	0.14

4. Soil extractable P

Figure 15 shows Avenue Field soil extractable P maps created by grid- and zone-based sampling. Soil extractable P varied between 16 and 55 mg/l (index 2-4) and had a mean of 35 mg/l (Index 3). There was a general north to south gradient in soil extractable P, with lowest levels in the north/north east section of the field and highest levels in the south/south west section of the field. This pattern of variability in soil extractable P shows similarity with the general north to south gradient in clay content and soil EC (Figure 10); with higher EC levels tending to correspond to areas of lower extractable P and this is most apparent in the north east section of the field where there is an area of low soil P and high EC. Regression analysis showed a significant ($P<0.05$) negative relationship between soil P and EC ($R^2=0.35$) (Table 4). There was no relationship between soil pH and organic matter (Table 3).

The soil extractable P maps (Figure 15) show a similar pattern of variability to soil extractable Mg maps (Figure 17), with the areas of lower soil P tending to correspond with areas of higher soil Mg (discussed further below). There was a significant negative relationship ($P<0.05$)

between soil extractable P and Mg (R^2=0.47) (Table 4). Although there was a significant relationship between soil P and K (P<0.05) the level of variability accounted for was low (R^2=0.06) and the soil P and K maps showed different patterns of spatial variability (Figure 15 and Figure 16).

5. *Soil extractable K*

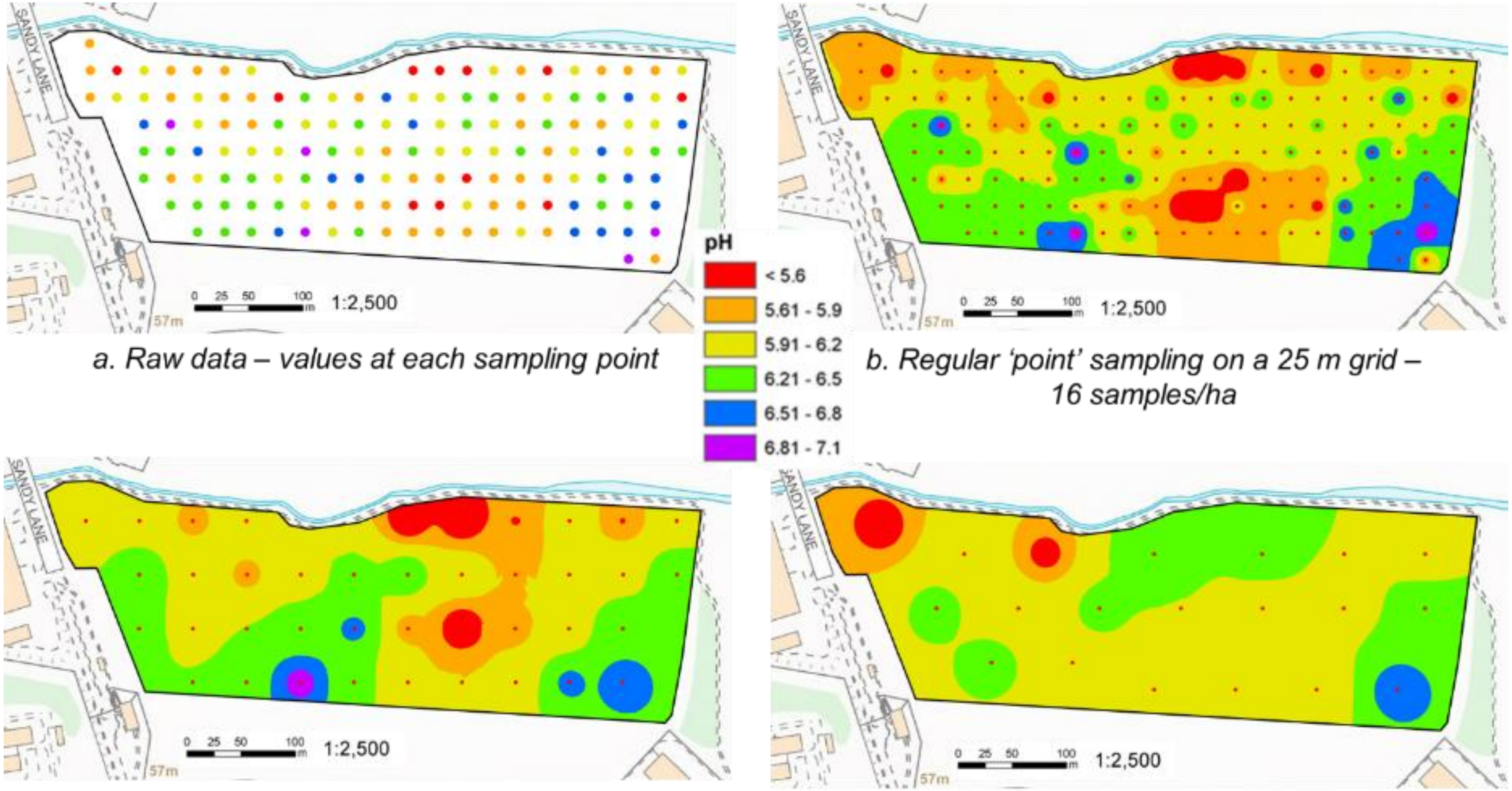
Figure 16 shows Avenue Field soil extractable K maps created by grid- and zone-based sampling. Soil extractable K varied significantly between 92 and 428 mg/l (Index 1-4) and had a mean of 217 mg/l (Index 2). Unlike soil extractable P and Mg, extractable K concentrations showed significant small-scale variability rather than general gradients or trends across the field. Because of this small-scale variability, as the level of sampling intensity reduces from 16 samples per hectare to 1 sample per hectare, the level of detail in the map also reduces and some of the patches of lower/higher extractable K are missed in the maps produced from the lower sampling intensities and also in the zone-based maps.

Regression analysis showed no relationship (P>0.05) between extractable K and organic matter (Table 3) or soil EC (Table 4). There was a significant (P<0.05) positive relationship between extractable K and soil pH (R^2=0.06) and between K and P (R^2=0.07), but the percentage of variance accounted for was very low. There was no relationship between extractable K and Mg (Table 4).

6. *Soil extractable Mg*

Figure 17 shows Avenue Field soil extractable Mg maps created by grid- and zone-based sampling. Soil extractable Mg varied between 53 and 215 mg/l (Index 2-4) and had a mean of 110 mg/l (Index 3). There was a north to south gradient in soil extractable Mg, with lowest levels in the south section of the field and highest levels in the north section of the field. This pattern of variability in soil extractable Mg is similar to the general north to south gradient in soil EC (Figure 10), with higher EC levels tending to correspond to areas of higher extractable Mg. Regression analysis showed a significant (P<0.05) and strong positive relationship between soil Mg and organic matter (R^2=0.93; Table 3) and EC (R^2=0.62; Table 4). The north to south gradient in extractable Mg shows a similar pattern of spatial variability to extractable P with higher extractable Mg concentrations corresponding to lower extractable P concentrations (R^2=0.47; Table 4).

Both approaches identified mainly horizontal soil zones, and comparison of Figure 17b (25 m grid soil sampling) and Figure 17g (IPF defined zones) and Figure 17h (spatial grouping analysis defined zones) show that soil Mg maps produced by zoning give a good representation of variation in soil Mg shown by the more intensive 25 m grid soil sampling.

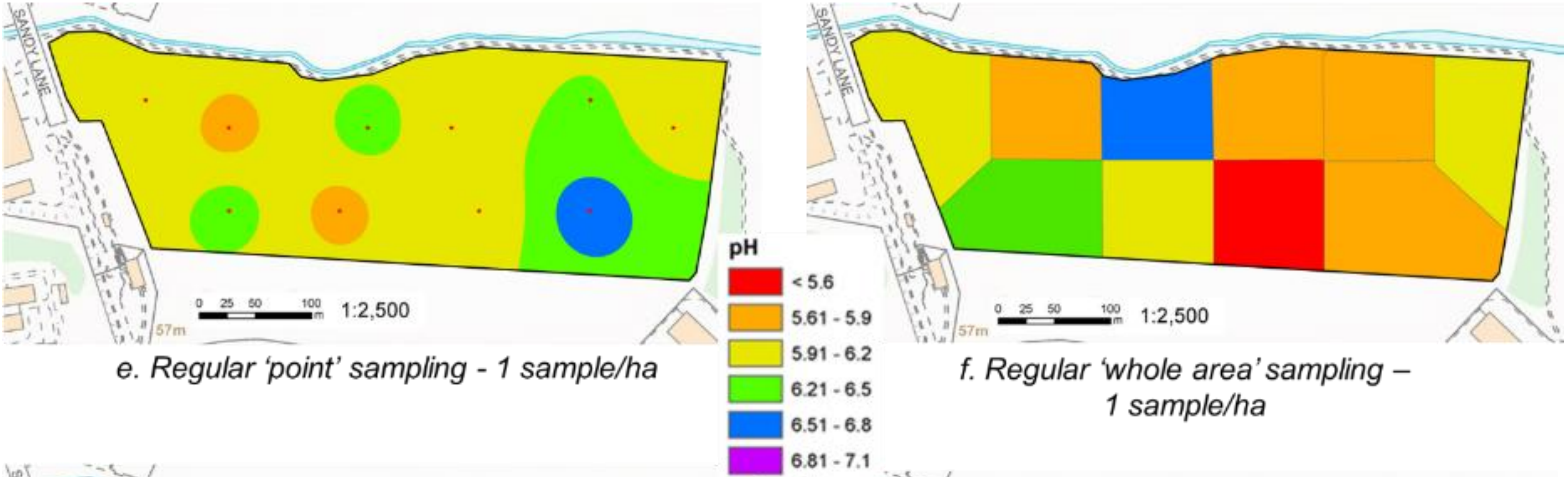


a. Raw data – values at each sampling point

b. Regular 'point' sampling on a 25 m grid – 16 samples/ha

c. Regular 'point' sampling on a 50 m grid – 4 samples/ha

d. Regular 'point' sampling - 2 samples/ha



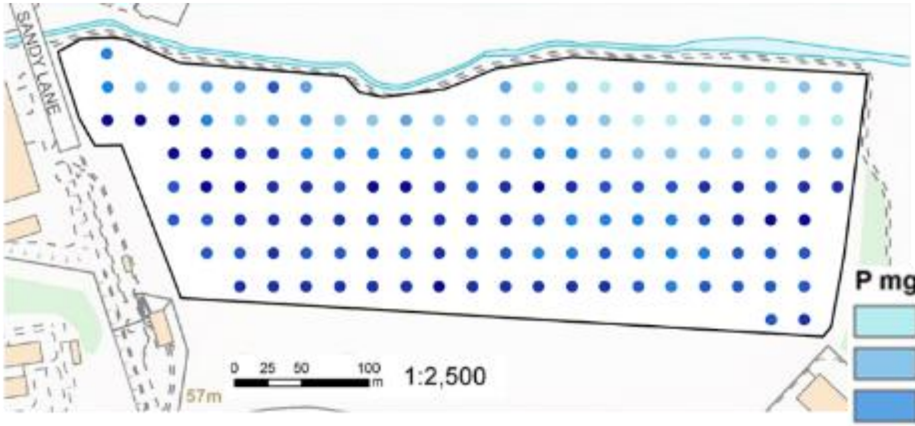
e. Regular ‘point’ sampling - 1 sample/ha

f. Regular ‘whole area’ sampling – 1 sample/ha

g. Zone based sampling (IPF defined zones)

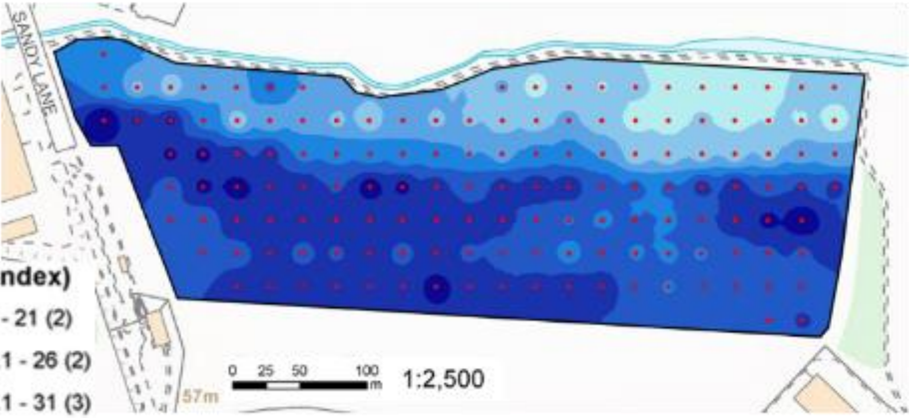
h. Zone based sampling (zones defined using spatial grouping analysis)

Figure 14. Avenue Field soil pH maps

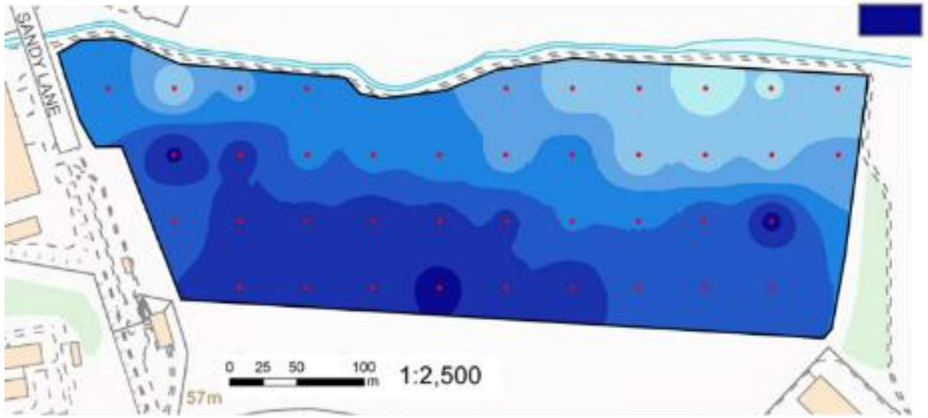


a. Raw data – values at each sampling point

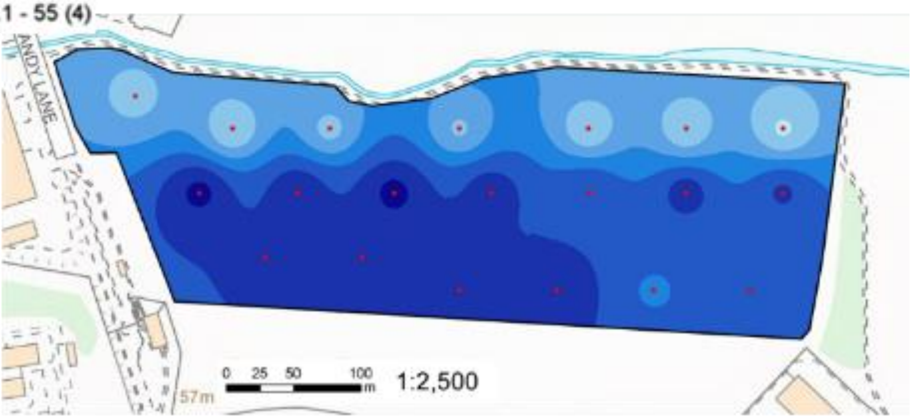
P mg/l (Index)	
🟦	16 - 21 (2)
🟦	21.1 - 26 (2)
🟦	26.1 - 31 (3)
🟦	31.1 - 36 (3)
🟦	36.1 - 41 (3)
🟦	41.1 - 46 (4)
🟦	46.1 - 55 (4)



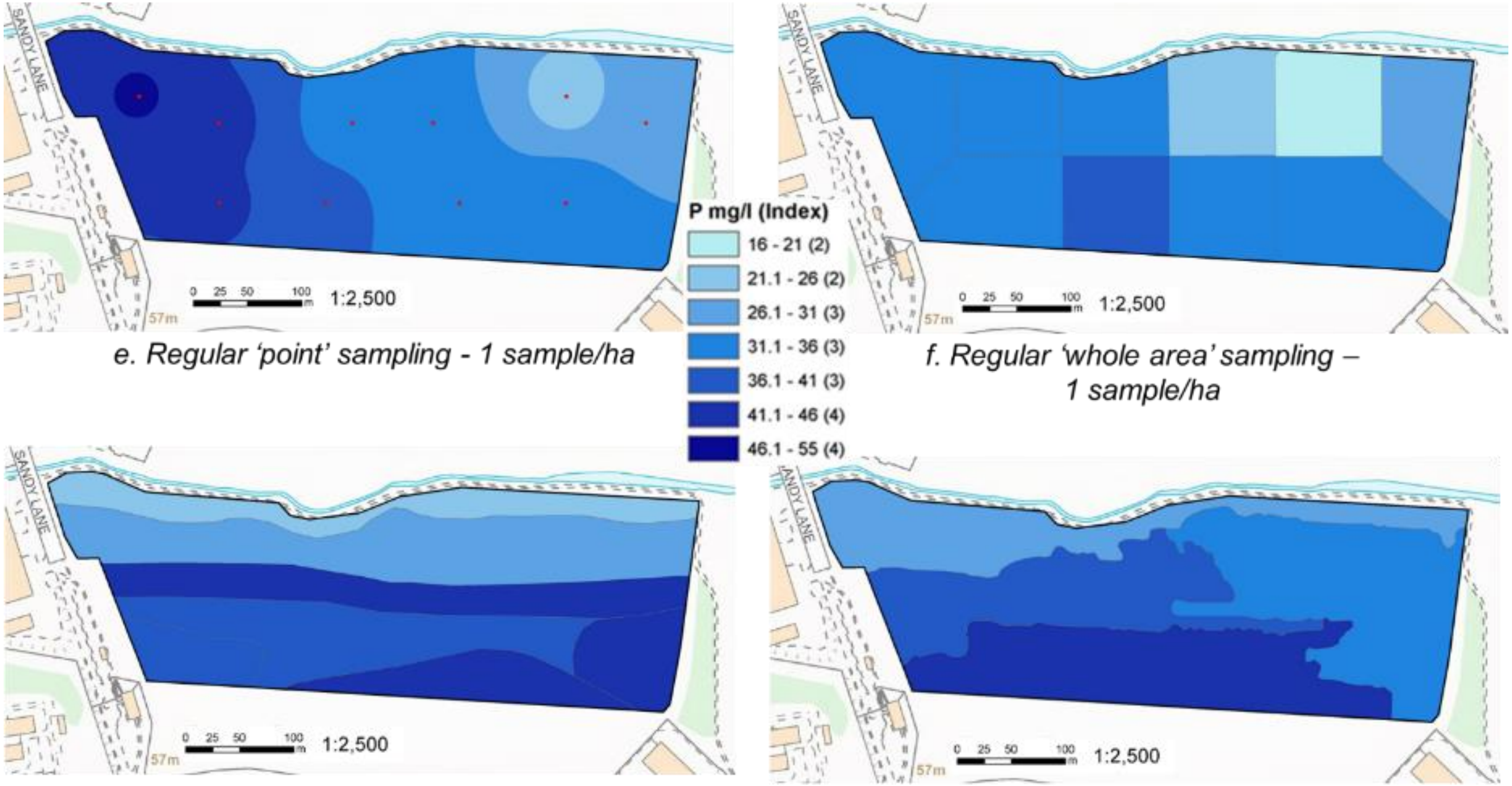
b. Regular 'point' sampling on a 25 m grid – 16 samples/ha



c. Regular 'point' sampling on a 50 m grid – 4 samples/ha



d. Regular 'point' sampling - 2 samples/ha



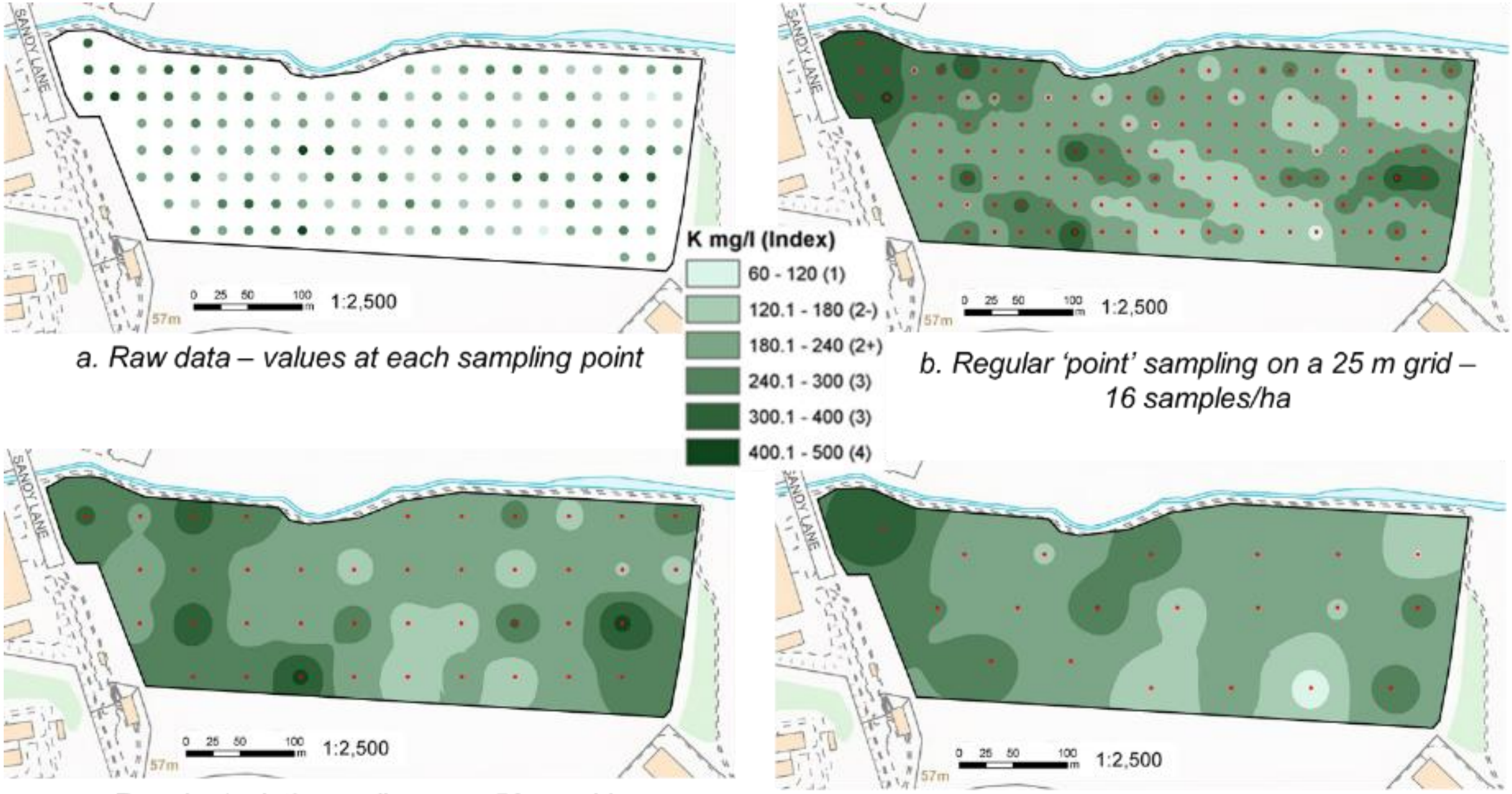
e. Regular 'point' sampling - 1 sample/ha

f. Regular 'whole area' sampling – 1 sample/ha

g. Zone based sampling (IPF defined zones)

h. Zone based sampling (zones defined using spatial grouping analysis)

Figure 15. Avenue Field soil extractable P maps

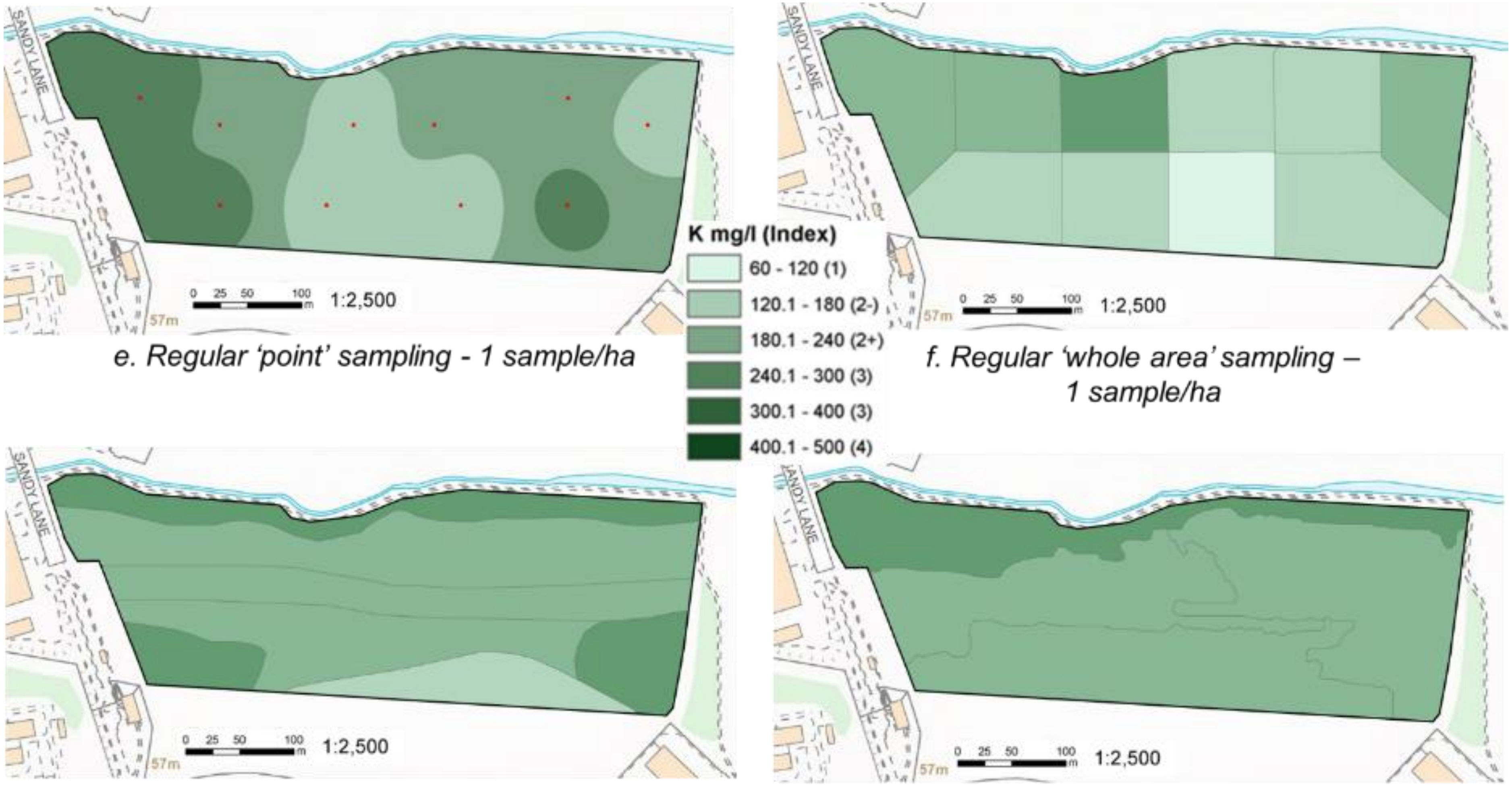


a. Raw data – values at each sampling point

b. Regular 'point' sampling on a 25 m grid – 16 samples/ha

c. Regular 'point' sampling on a 50 m grid – 4 samples/ha

d. Regular 'point' sampling - 2 samples/ha



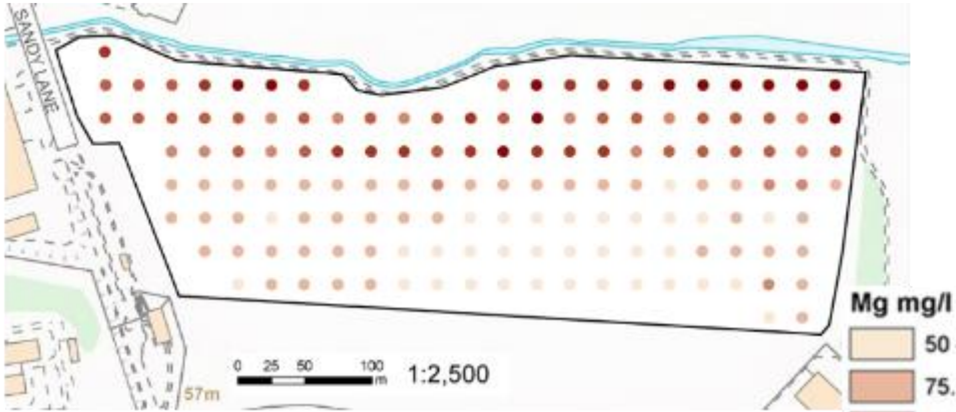
e. Regular ‘point’ sampling - 1 sample/ha

f. Regular ‘whole area’ sampling – 1 sample/ha

g. Zone based sampling (IPF defined zones)

h. Zone based sampling (zones defined using spatial grouping analysis)

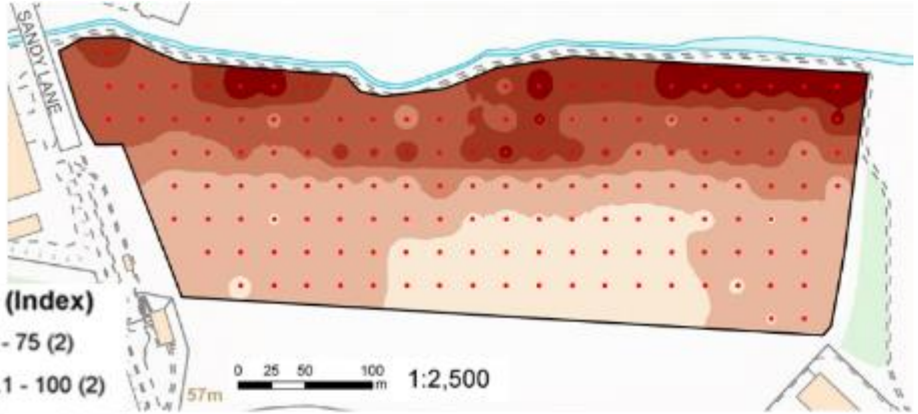
Figure 16. Avenue Field soil extractable K maps



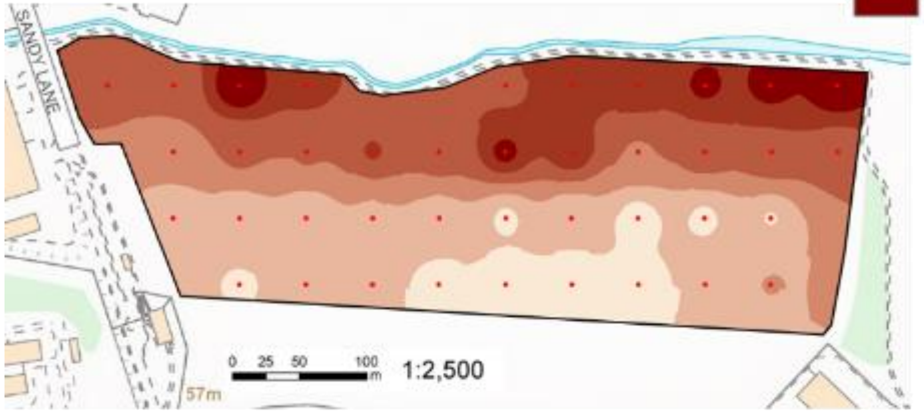
a. Raw data – values at each sampling point

Mg mg/l (Index)

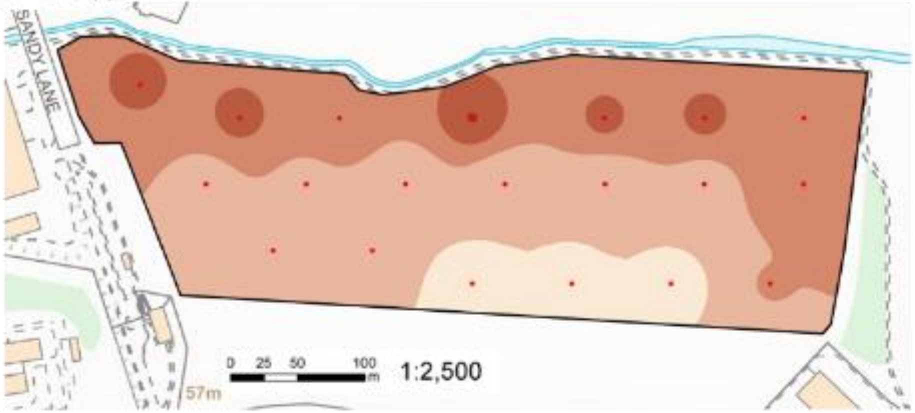
- 50 - 75 (2)
- 75.1 - 100 (2)
- 100.1 - 125 (3)
- 125.1 - 150 (3)
- 150.1 - 175 (3)
- 175.1 - 225 (4)



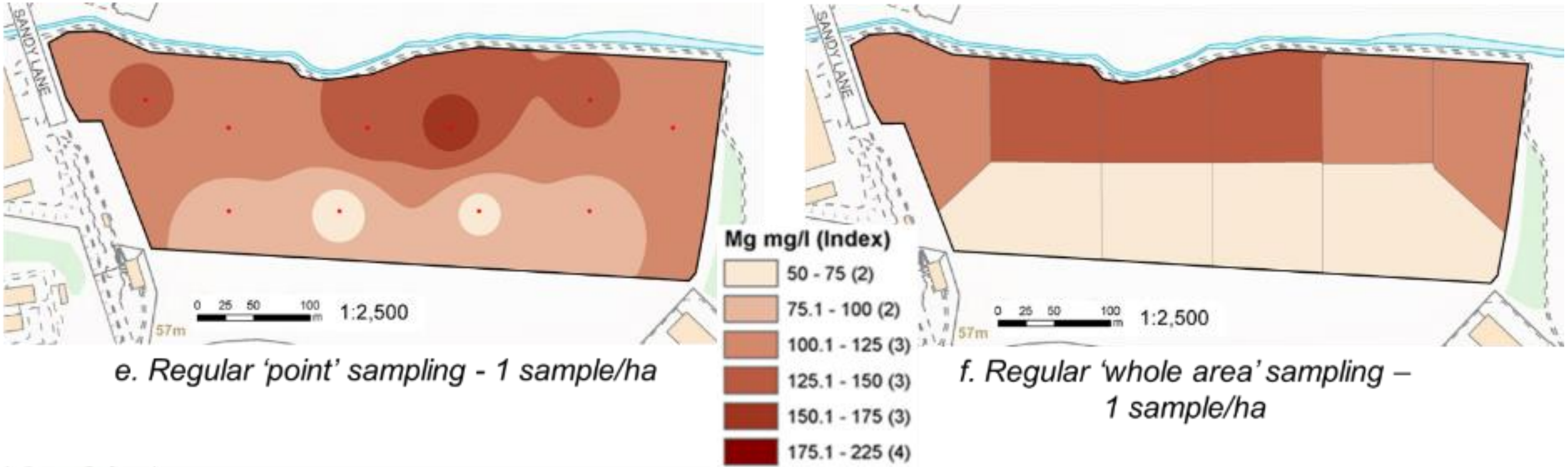
b. Regular 'point' sampling on a 25 m grid – 16 samples/ha



c. Regular 'point' sampling on a 50 m grid – 4 samples/ha

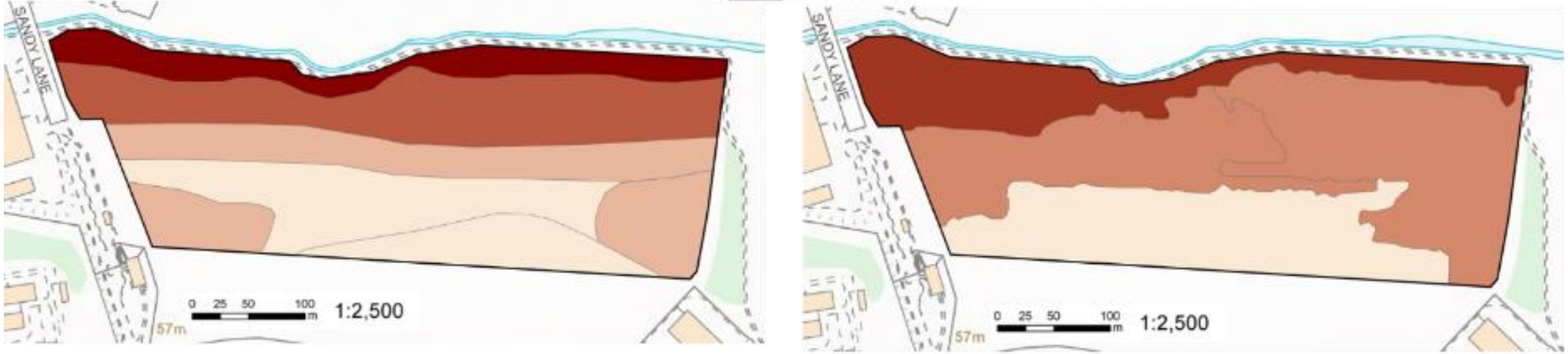


d. Regular 'point' sampling - 2 samples/ha



e. Regular 'point' sampling - 1 sample/ha

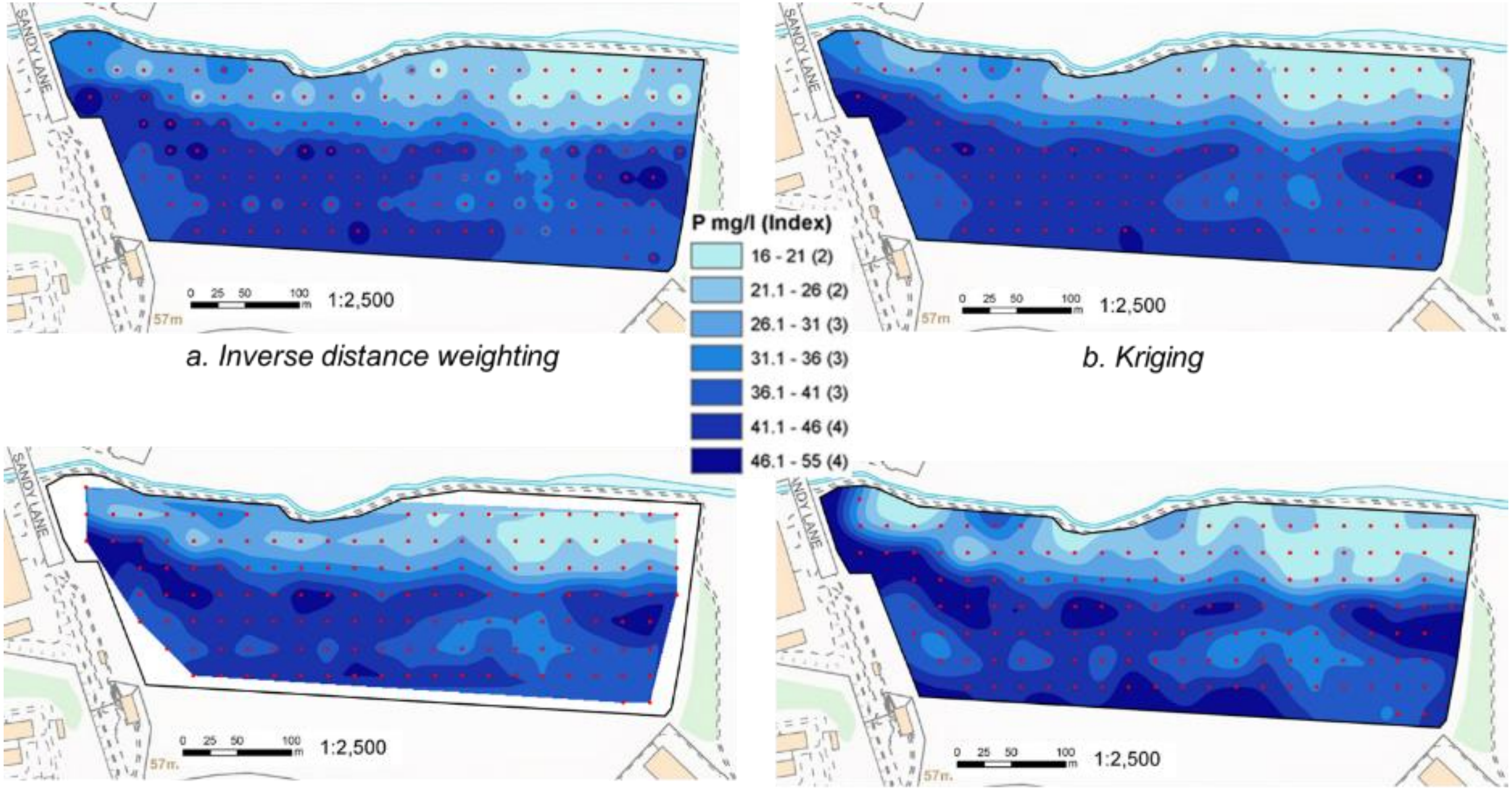
f. Regular 'whole area' sampling – 1 sample/ha



g. Zone based sampling (IPF defined zones)

h. Zone based sampling (zones defined using spatial grouping analysis)

Figure 17. Avenue Field soil extractable Mg maps



a. Inverse distance weighting

b. Kriging

c. Natural neighbour

d. Spline

Figure 18. Comparison of spatial data interpolation methods: Avenue Field soil extractable P maps produced using four methods of spatial data interpolation

Comparison of spatial interpolation methods

Figure 18 shows soil extractable P maps produced from the 25 m grid samples using four different methods of spatial interpolation: inverse distance weighting, kriging, natural neighbour and spline. Each data interpolation method produced a slightly different map. However, these small differences should be viewed in the context of how the maps will be used; it is generally not possible to variably apply fertiliser or lime at a resolution of less than one tramline width (typically 24 m) and therefore small differences in maps are unlikely to be of practical significance.

This case study did not attempt to statistically evaluate which method of data interpolation was better. Review of the literature shows that there isn’t necessarily a consensus view of the best data interpolation method for this type of soils data. Precision farming companies interviewed for the Precision Farming Review reported using inverse distance weighting and nearest neighbour methods of data interpolation for soil pH and nutrient mapping. Visual examination of all the maps produced for Avenue Field using the four methods of data interpolation for all data showed inverse distance weighting to produce reasonable maps at all the sampling intensities. In some cases kriging appeared to over smooth the data particularly at lower sampling intensities and spline sometimes produced anomalous patterns at the edge of the field. Within ArcGIS it isn’t possible to extend the mapped area to the edge of the field for the natural neighbour technique, which made this method less useful particularly at the lower sampling intensities.

Conclusions

Both grid- and zone-based soil sampling are valid options for assessing within-field soil variability and both have advantages and disadvantages. Zone sampling focuses on managing areas by soil type, which forms the basis of good nutrient management. It uses patterns and boundaries evident from looking at soil surveys or yield maps to form the basis of management zones. However, grid sampling may identify hot spots of soil fertility or pH (often related to field management history) that cannot be achieved using zone sampling; and grid sampling (because of the smaller point area sampled) is better at detecting change over time. Grid sampling is typically more expensive than zone sampling as a greater number of samples are usually taken.

For Avenue Field soil zoning identified mainly horizontal (i.e. east to west orientated) soil zones, which corresponded well to the spatial variability in extractable P and Mg, and the soil zone P and Mg maps gave a good representation of the variation shown by the more intensive 25m grid sampling from a much smaller number of samples. However, there may be patterns in soil fertility, which could be identified using grid sampling that may not be detected using zone sampling. Soil pH and K showed significant small scale spatial variability which was only apparent at the more intensive grid sample (>2 samples/ha).

Typically, when taking grid-based soil samples, most precision farming companies will take one soil sample per hectare (on a 100 m grid). The maps produced for Avenue Field highlight the impact of soil sampling intensity on the soil pH and nutrient maps produced. Where there is significant small-scale variability, for example soil pH/extractable K in Avenue Field:

i. This variability can be concealed when only taking one sample per hectare.

ii. Taking point soil samples within a confined area (e.g. within a 3 m radius of a sampling point) may give undue weight to the soil property value at that single point, particularly at lower sampling intensities.

Once created, soil pH and nutrient maps can be converted into prescription maps for variable rate fertiliser or lime application. A prescription map is an electronic data file that is used to control the variable rate fertiliser spreader. Variable rate fertiliser application maps are typically based on RB209 fertiliser recommendations at different soil indices and lime recommendations for different soil pH values.

Potential advantages of variable rate fertiliser or lime include:

- Cost savings in fertiliser or lime through not over applying to areas of higher soil nutrient Index or soil pH.
- Potential for increased yields where lower index areas of a field would otherwise have been under-fertilised/limed.
- The longer term levelling of within-field soil pH and nutrient variability

This type of more detailed soil sampling, either grid- or zone-based, is of most value in variable fields where it identifies lower soil index areas which would otherwise have been under-fertilised or under-limed. For field vegetables the target soil Indices are pH 6.5, P Index 3, K Index 2+ and Mg Index 2. Where soil pH or nutrient levels vary above these target levels, this variation should not be expected to affect crop yields, however variable rate fertiliser application may still offer cost savings through not over applying nutrients to higher Index areas.

Controlled traffic farming – Barfoot Farms Ltd.

Background

Barfoot Farms Ltd. is a horticultural business based in southern England (Hampshire and West Sussex) with farms at Trotton, Chichester and Little Abshot in Hampshire. The company is developing a long term soil management strategy including the use of cover crops, controlled traffic farming (CTF) and reduced tillage. The main drivers for this strategy were reducing costs (reduced fuel consumption – minimal cultivation, fewer machinery passes, reduced depth of cultivation where possible); soil quality benefits; and associated increases in crop yield.

Annual crops grown were sweetcorn, tenderstem broccoli (TSB), courgettes, pumpkins, dwarf beans and broad beans; with no fewer than 4 years between courgette and pumpkin; 3 years for TSB; and 2 years for sweetcorn. There was therefore scope to work all the crops within a rotation with sweetcorn being the most frequently grown crop. In Hampshire organic sweetcorn, TSB and courgettes were also grown.

The main perennial crops were rhubarb and asparagus. The system for these crops could potentially be converted to complete CTF (within ten years or so) with spray and harvest operations on 25 m widths.

The Chichester farm began CTF in 2012, making progressive changes to machinery and operations. In 2016, the Little Abshot farm made significant investment in CTF equipment, including satellite guidance systems, autosteer and a standard track gauge for all machinery.

Barfoot staff had not received formal advice on CTF, but attended workshops and open days, and read about potential benefits. They became aware of the importance of tyre pressure and noted that 75% of compaction can be created in the first machinery pass. The other key principle that Barfoots follow is “never put a wheel where a seed would ever go”.

Although, at the time of the demonstration (2016), a complete CTF system had not been attained, the approach was based on all machines operating a working width of 5 m and a track gauge for all tractors of 1.67 m as standard. A sprayer had been adapted to work across 25 m with the standard 1.67 m track gauge.

Within the CTF system, power harrows, two cultivators and the maize drills all had a working width of 5 m. The track gauge was wider (1.8 m) on maize harvesters and trailers, but the harvester header was fitted the 1.67 m track gauge system. The plan was to fit tracks to the most powerful (and heaviest) tractors (>500 horse power).

The demonstration activities provided the opportunity to compare the previous cultivations and tracking system with the recently adopted CTF system. It was also possible to take baseline soil quality measurements within a year of CTF implementation, with a view to repeating the measurements in 4-5 years time.

The CTF field demonstration at Barfoot Farms contained three elements:

i. Capturing detailed technical information on machinery to compare the extent of tracking and fuel consumption under the previous conventional and recently adopted CTF systems.
ii. A short-term field study to investigate within-field soil quality and crop variability under the recently adopted CTF system.
iii. A field study investigating the longer-term effects of introducing CTF on soil quality and health and implications for cropping productivity, versatility and profitability.

CTF tracking study

As CTF had been recently introduce at Little Abshot Farm, Barfoots were keen to establish a baseline from which they could measure the percentage reduction in tracking that could be achieved within different rotations.

The field demonstration tracking study was based on a rotation of sweetcorn, pumpkins, TSB and beans with cover crops used whenever possible. Detailed technical information was collated for all the machinery before and after CTF adoption, including track widths and implement working widths. This data was then used to establish an operational sequence of field operations for conventional and CTF systems, as indicated in Table 5.

Results

Before introducing CTF

Figure 19 shows the tracking overlay for all the operations involved in the four-year rotation prior to CTF, including the preparatory operations for all crops each season. This only provides an image of the last series of tracks whereas Figure 19 quantifies these in terms of intensity of coincident passes.

Table 5. Operations before and after the introduction of CTF in a rotation of sweetcorn, pumpkins, tenderstem broccoli and beans

Crop	**Operations**	**Width, m**		Operating width, m
	Before CTF		*After CTF*	
All	Subsoiler	3	Primary cultivation	5
	Subsoiler	4	Targeted de-compaction	5
	Primary cult	3	Seedbed preparation	5
	Primary cult	3		
	Primary cult	3		
	Seedbed	5		
	Rolling	6		
	Spraying	24	Spraying	25
	Fertiliser	24	Fertiliser	25
	Irrigation	72	Irrigation	70
	Topping	6	Topping	5
	Topping post harvest	6	Topping post harvest	5
Sweetcorn	Drilling	4.5	Drilling	5
	Plastic laying	4.5	Poly removal	5
	Poly removal	4.5	Hoeing	5
	Hoeing	4.5	Harvesting	5
	Harvesting	4.5	Harvesting	5
	Harvesting	4	Harvesting	5
	Harvesting	10	Harvesting	4
	Harvesting	10	Harvesting	10
Pumpkins	Drilling	4.5	Drilling	5
	Hoeing	4.5	Hoeing	5
	Harvesting		Harvesting	
Tenderstem broccoli	Planting	5	Planting	5
	Fleece removal	5	Fleece removal	5
	Hoeing	1.67	Hoeing	5
	Harvesting	20	Harvesting	20
Beans	Drilling	5	Drilling	5
	Hoeing	1.67	Hoeing	5
	Harvesting	1.67	Harvesting	1.67
Cover crops			Drilled with Topdown	5
			Rolling	5

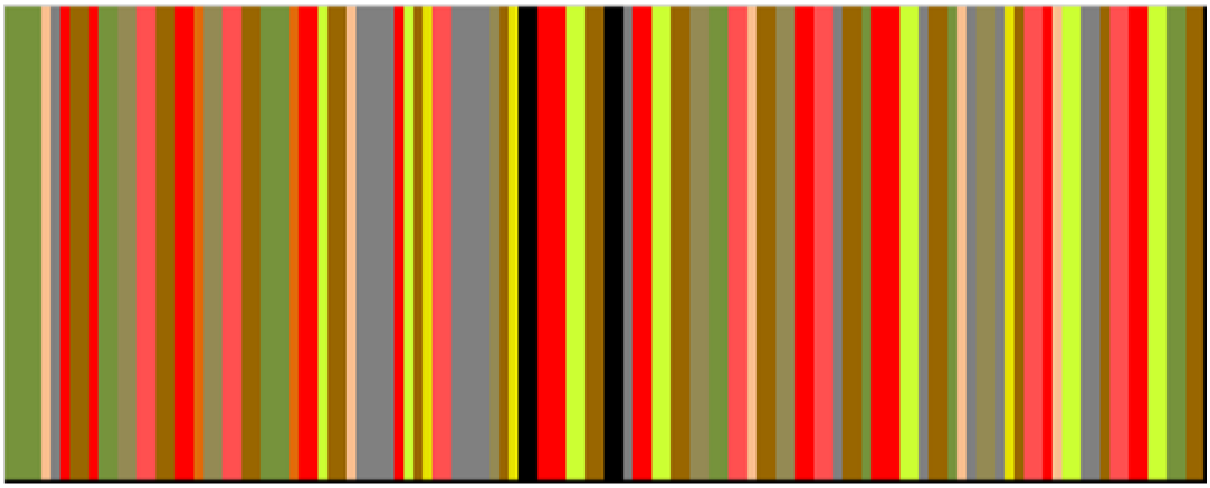


Figure 19. Overlays of tracking for all crops prior to CTF. 100% of the growing area was tracked at least once – see Figure 24 for more detail.

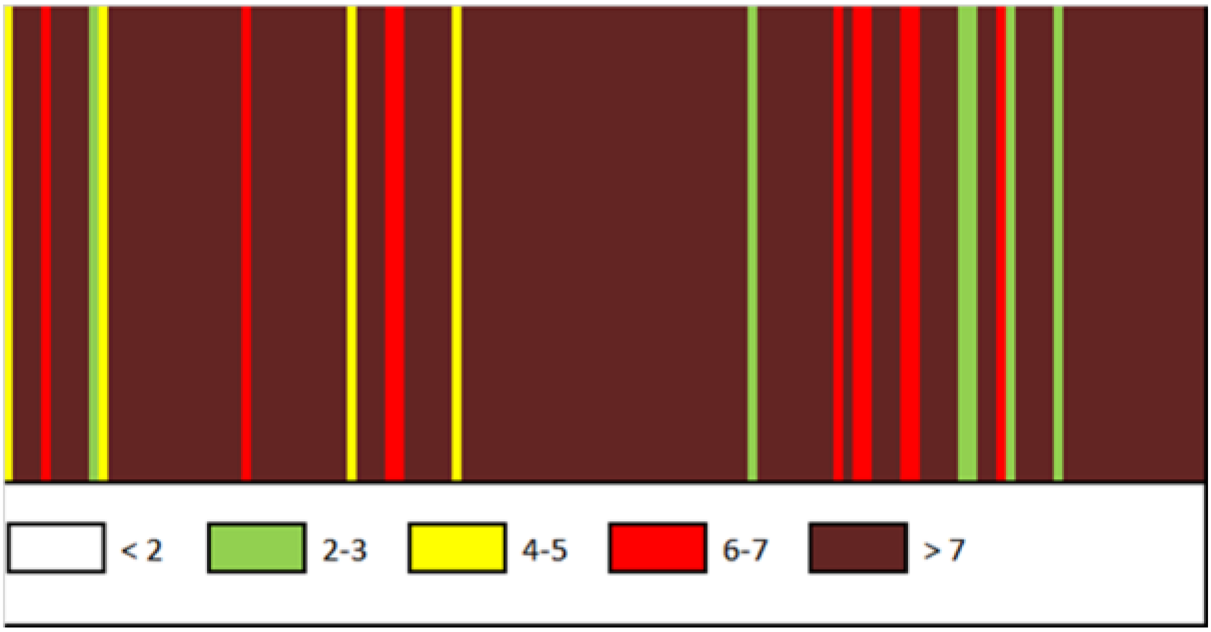


Figure 20. Intensity of tracking – number of coincident passes for all crops prior to CTF.

After introducing CTF

Figure 21 shows tracking for the CTF system, which indicates a 30% reduction (70% versus 100%) compared with the previous operations. However, most of this tracking is created by just two machines, the 4 m bunker harvester and the 1.67 m bean harvester, which only operate on a small proportion of the harvested area. If the tracks of these two harvesters could be aligned with CTF tracking widths, the wheeled area would fall to just below 37% (Figure 23), i.e. a 63% reduction compared with the conventional system in all areas. Figure 24 presents the tracking for each individual machine in the sweetcorn crop, indicating the degree of tracking overlap for each system.

Figure 21. Overlays of tracking for all crops with CTF. 70% of the area is tracked.

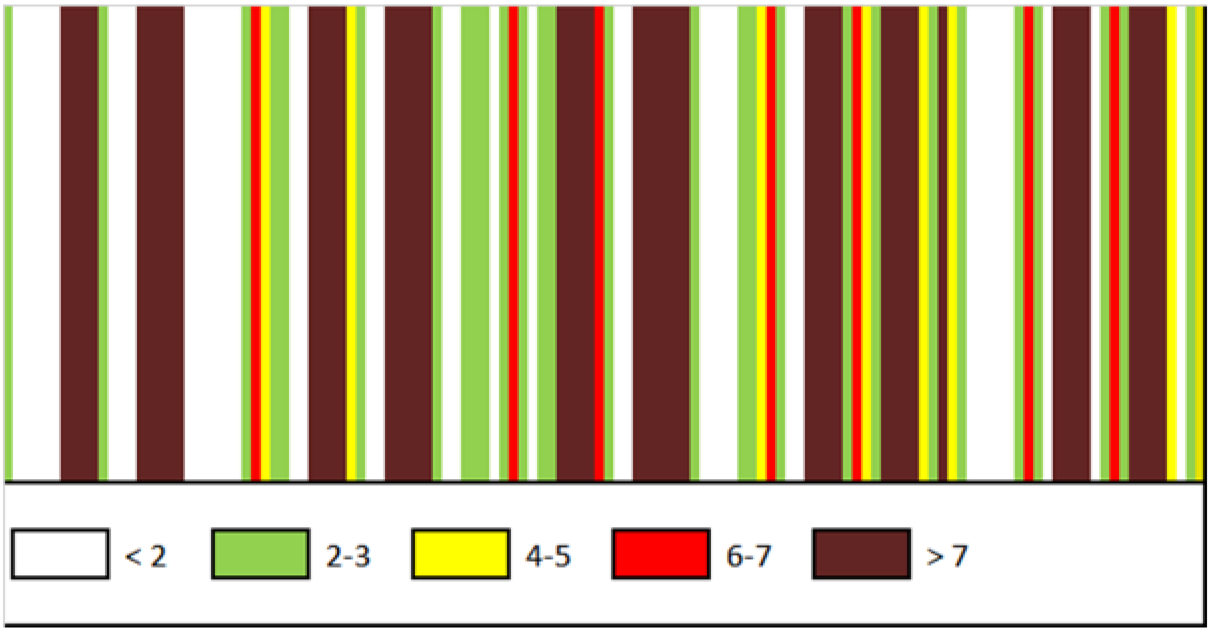


Figure 22. Intensity of tracking - number of coincident passes associated with CTF shown in Figure 23.

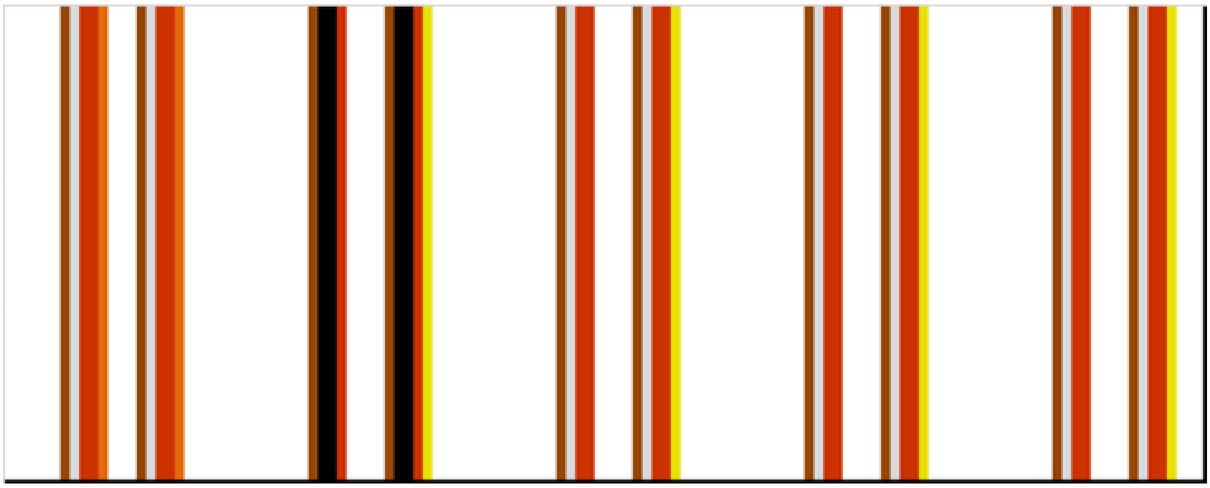


Figure 23. Tracking for all crops without the 4 m bunker harvester or trailed Oxbo harvester. Tracked area is just under 37%.

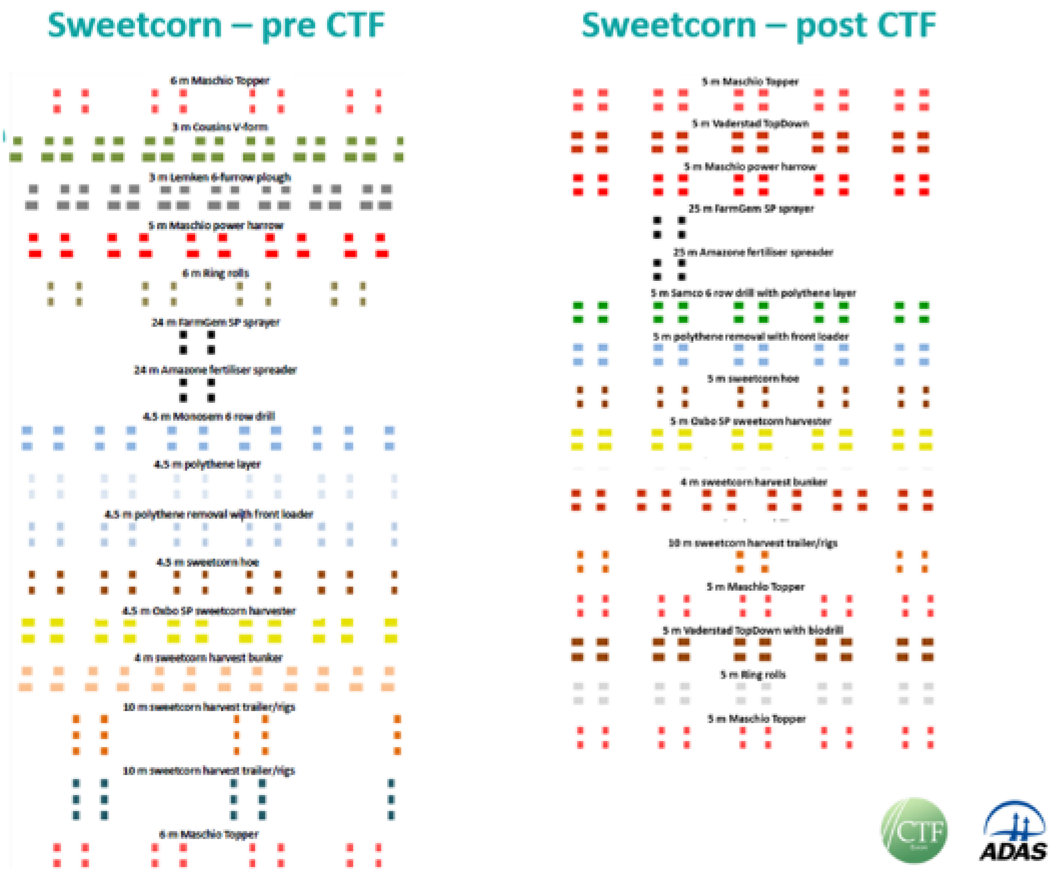


Figure 24. Comparison of tracking in sweetcorn before and after introducing CTF.

Short-term field study - 2017

The main aim of the short-term (1 year) field study was to investigate the effect of CTF and intermediate wheelings, and wheelings from non-CTF traffic on soil quality and crop yield in two sweetcorn fields:

- Yards Field at Easton Farm with sweetcorn at 1.67 m wheelings in 2017, following courgettes on 2 m wheelings in 2016.
- Parrett 1 Field at Little Abshot Farm, managed under CTF in 2016 and 2017

Soil quality and crop growth/yield was assessed in rows:

i. Adjacent to the drilling wheelings
ii. Where the non-CTF wheelings were in the previous courgette crop
iii. In the non-traffic area (i.e. in the bed).

Both fields were scanned using electro-magnetic induction (EMI) in September 2016 to establish homogeneous soil zones for the field demonstrations.

At each site, topsoil (0-15 cm) soil samples were taken for analysis of soil pH; extractable P, K and Mg; soil organic matter content and textural analysis (% sand, silt and clay).

In spring 2017, sweetcorn was planted in both demonstration fields and plots (1 row by 20 m) marked out in the following locations/treatments, with 4 replicate blocks per treatment:

- TRT 1 row between intermediate wheelings (least traffic)
- TRT 2 row next to intermediate CTF wheeling
- TRT 3 row next to main wheeling/tramline
- TRT 4 row away from wheelings but near main tramline (in Parrett 1);
    - row in previous courgette wheeling (In Yards Field)

In May 2017, the following soil physical measurements were made:

- Penetrometer measurements to 50 cm depth - maximum resistance and depth of maximum resistance (x 5)
- Dry bulk density (BD) at 10-15 cm depth (x 3)
- Visual Evaluation of Soil Structure (VESS assessment; Guimaraes *et al*., 2011) (x 1)
- Assess presence of a tillage pan (x 1)

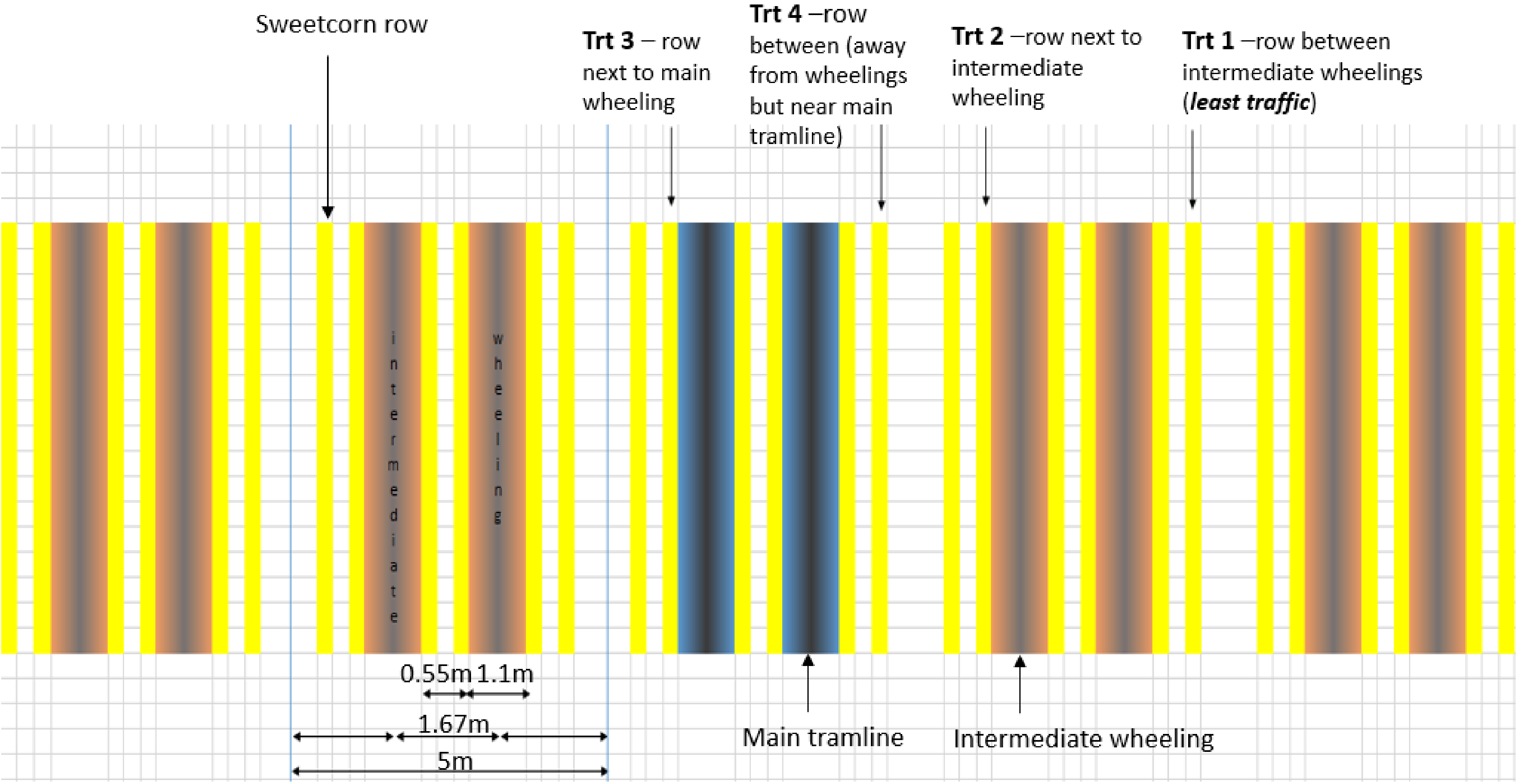


Figure 25. Examples of treatment locations for one replicate block in Parrett 1 Field.

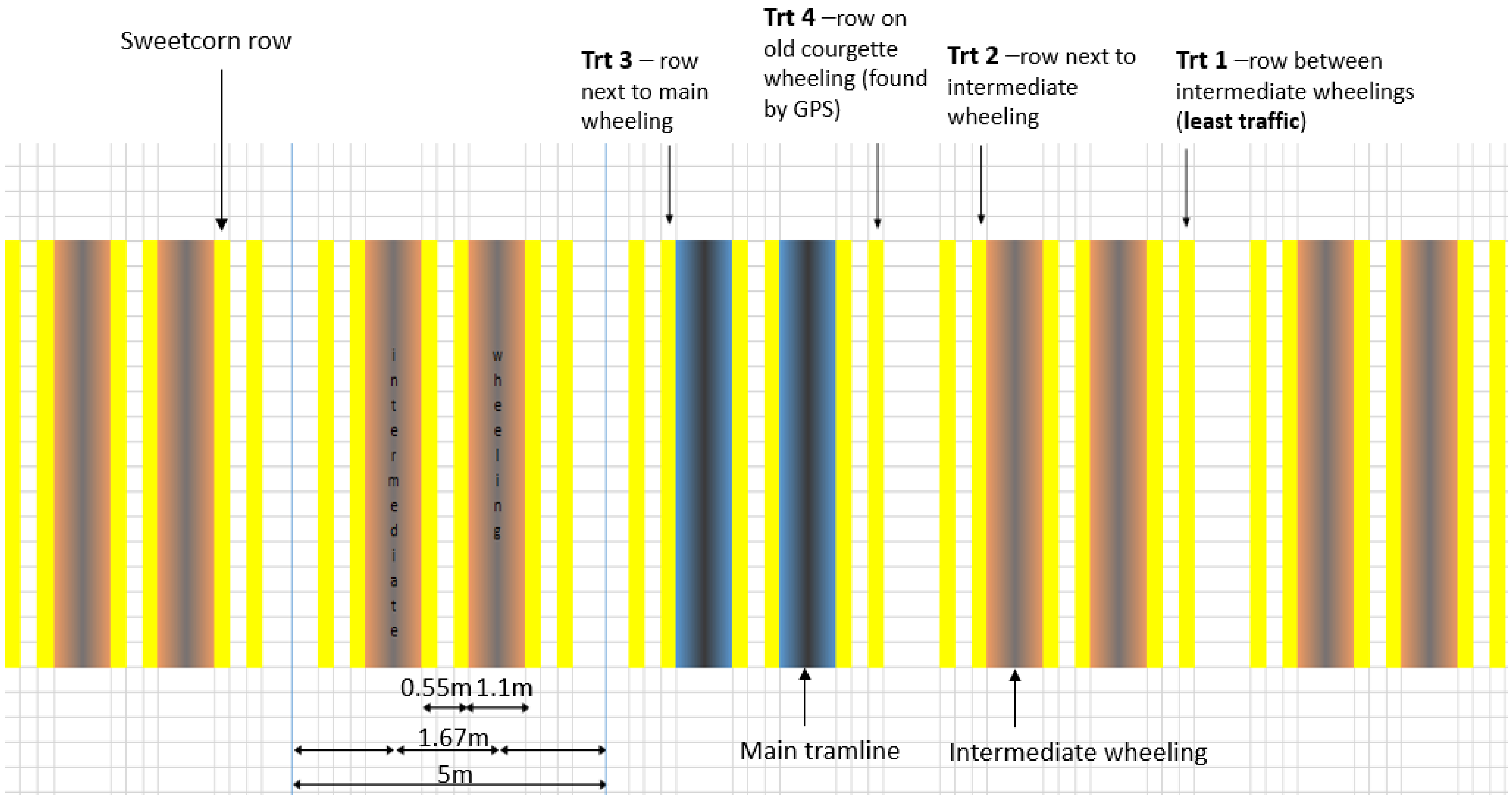


Figure 26. Examples of treatment locations for one replicate block in Yards Field.

Soil bulk density measurements were assessed relative to the topsoil BD 'trigger' levels (i.e. the level at which soil physical conditions may reduce crop yields and further investigation is recommended; Table 6) and subsoil BD 'concern' levels in

Table *7* (Merrington, 2006).

Table 6. Topsoil bulk density (g/cm^3) trigger values for mineral and organic soils in the UK (source: Merrington, 2006).

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

Table 7. Bulk density (g/cm^3) trigger values for mineral and peat subsoils in the UK (source: Merrington, 2006).

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

- * For sandy textures, the levels may be up to 0.05 g/cm^3 higher.

Sweetcorn establishment was assessed within each field:

- Number of plants per metre at 5 points per plot
- The height of plants at 10 points per plot

In summer 2017, plant biomass was measured and crop yield and quality assessed. In each plot, a sub-sample of 3 sweetcorn cobs was taken for determination of dry matter and quality:

- Plant biomass was harvested to ground level from the first 3 m of each row and the number of plants recorded and weighed.
- The primary cobs were picked from the remaining 7 m of row from the yield assessment area in each row/plot.
- Number of cobs and total fresh weight was recorded.

- Barfoots staff assessed cobs for marketable yield counts, weight and sweetness by Brix scores, using a refractometer to measure dissolved solids in the liquid fraction from marketable cobs (i.e. levels of sugar, minerals and protein). Higher Brix levels (above 12) indicate higher nutritional value, and lower nitrate and water levels.

Results

Topsoil analysis results

Soil pH was optimum in Parrett 1 Field, but sub-optimal in Yards Field (Table 8). Extractable nutrients (phosphorus, potassium and magnesium) were at maintenance levels or above. The topsoil texture was sandy silt loam in both fields with an organic matter content of between 2-3%.

Table 8. Topsoil (0-15cm) analysis from Parrett 1 and Yards Fields (sampled Nov 2016).

Determinand	Units	Parrett 1 (CTF)	Yards (CTF)
pH		6.4	5.9
Extractable Phosphorus	mg/l (Index)	41.8 (3)	45.2 (3)
Extractable Potassium	mg/l (Index)	159 (2-)	230 (2+)
Extractable Magnesium	mg/l (index)	83.7 (2)	93.3 (2)
Textural Class		Sandy Silt Loam	Sandy Silt Loam
Sand	%	48	39
Silt	%	38	44
Clay	%	14	17
Organic Matter (LOI)	%	2.0	3.3
Organic Matter (modified Walkley Black)	%	2.6	2.6

Soil physical measurements and visual evaluation scores

In Parrett 1 Field, post-establishment in May 2017, the poorest topsoil layer was firm to compact according to the VESS scoring system (Table 9; Figure 29). This firmer layer was encountered at 13-29 cm depth, which was below cultivation depth within the newly adopted reduced tillage system. As expected, the soil was most firm (scoring 3.7 on average) in the rows next to the main wheeling (Trt 3).

The highest penetrometer resistance was encountered in the rows next to the main wheeling (Trt 3) and the rows next to the intermediate wheeling (Table 9; Trt 2; *P*<0.05). The depth of maximum resistance was shallowest, at 24 cm depth, in the rows next to the main wheeling (Table 9; Figure 28). Notably, in the rows next to the main wheeling, the maximum resistance was within the poorest VESS layer (13-29 cm depth), whereas in the other rows/treatments the maximum resistance was below this depth; in the transition layer or upper subsoil, at around 29-33 cm depth (P<0.05; *Figure 28*).

There was no difference in mid-topsoil (10-15 cm depth) BD between rows/treatments (Table 9). The topsoil in all the rows was at or above UK Soil Quality Indicator Consortium (UKSIC; Merrington, 2006) BD trigger value of 1.50 g/cm^3 (for a soil with 2.0-2.9% organic matter content), indicating that further investigation and a possible change in management was required.

Table 9. Post establishment soil structural assessments Parrett 1

Assessment	Treatment			
	Trt 1 (row between intermediate wheeling, least traffic)	Trt 2 (row next to intermediate wheeling)	Trt 3 (row next to main wheeling)	Trt 4 (row away from wheeling but near main tramline)
VESS score of poorest layer (mean of 5 replicates) (1-Friable,2-Intact, 3-Firm,4-Compact, 5-Very Compact)	3.3 (ns)	2.9 (ns)	3.7 (ns)	3.1 (ns)
VESS worst layer depth (cm)^1	16-29	15-27	14-29	13-29
Tillage pan score (0- well developed, 1-moderately developed, 2-no pan)	0.8	0.9	0.6	1.0
Topsoil penetrometer max resistance (kPa) (mean of 5)	550 (ab)	598 (b)	597 (b)	495 (a)
Depth of max resistance (cm) (mean of 5)	33 (b)	29 (ab)	24 (a)	33 (b)
Mid topsoil bulk density (g/cm^3)	1.50 (ns)	1.55 (ns)	1.55 (ns)	1.54 (ns)

Note – values followed by different letters in brackets indicate significant differences between treatments (P<0.05); ns – not significantly different.

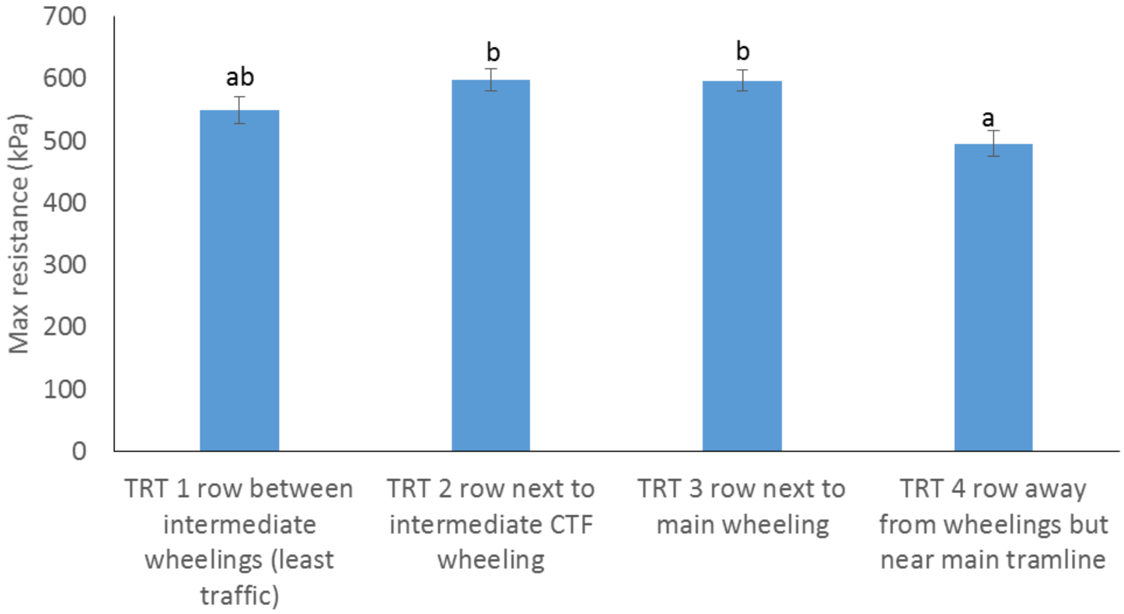
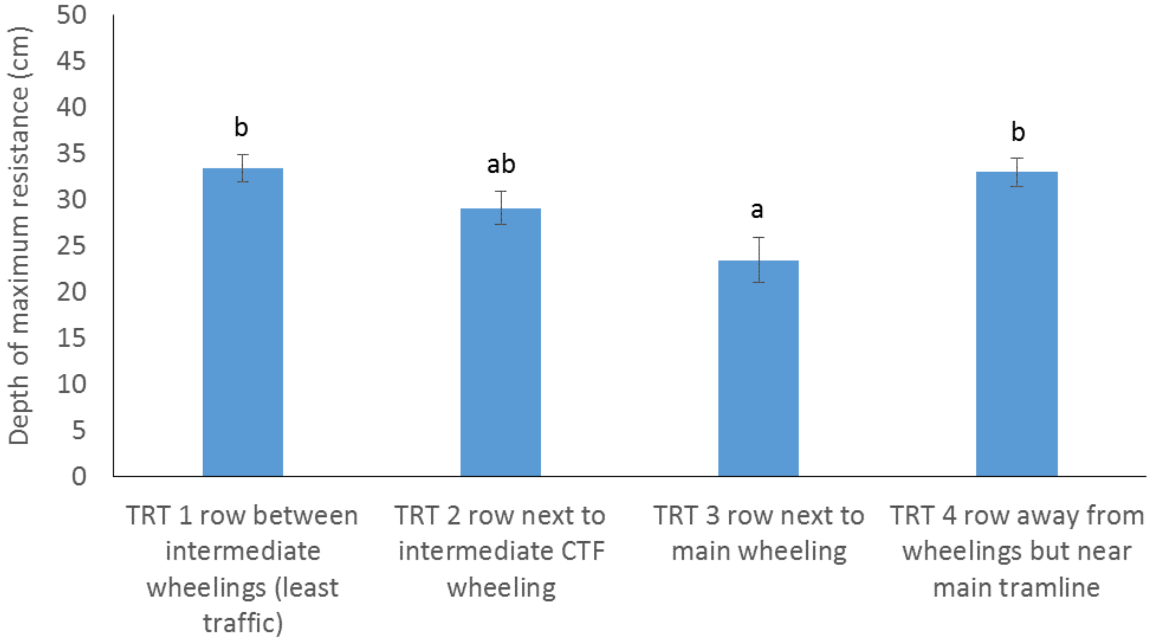


Figure 27. Penetrometer maximum resistance values in Parrett 1 Field.

Figure 28. Penetrometer depth of maximum resistance measurements in Parrett 1 Field.



Trt 1

Trt 2

Trt 3

Trt 4

Figure 29. VESS photos from field areas post establishment Parrett 1

In Yards Field, post-establishment in May 2017, the poorest topsoil layer was firm to compact according to the VESS scoring system (

Table *10*; Figure 30), as was the case in Parrett 1 Field. The firmer layer was encountered at 15-30 cm depth, which was below cultivation depth within the reduced tillage system. The worst scoring soil (although not statistically significant) was in the rows next to the intermediate wheelings.

There were no differences in maximum penetrometer resistance, depth of maximum resistance or mid-topsoil (10-15 cm depth) BD between the rows/treatments. At 26-33 cm depth, the depth of maximum resistance was towards the base of or just below the lower topsoil layer, which was the poorest layer in the VESS assessments. At 1.35-1.45 g/cm^3, the mid-topsoil BD was below UKSIC (Merrington, 2006) BD trigger value of 1.50 g/cm^3 (for a soil with 2.0-2.9% organic matter content).

Table 10. Post establishment soil structural assessments Yards

Assessment	**Treatment**			
	Trt 1 **(row between intermediate wheeling, least traffic)**	**Trt 2** **(row next to intermediate wheeling)**	**Trt 3** **(row next to main wheeling)**	**Trt 4** **(row on previous courgette wheeling)**
VESS Overall block score (mean of 5) (1-Friable,2-Intact, 3-Firm,4-Compact, 5-Very Compact)	2.5 (ns)	2.7 (ns)	2.2 (ns)	2.2 (ns)
VESS worst layer score (mean of 5) (1-Friable,2-Intact, 3-Firm,4-Compact, 5-Very Compact)	3.3 (ab)	3.7 (b)	3.1 (ab)	2.7 (a)
VESS worst layer depth (cm)[1]	14-30	15-30	17-30	20-30
Tillage pan score (0- well developed, 1- moderately developed, 2-no pan)	0.8	0.6	0.9	1.3
Topsoil penetrometer max resistance (kPa) (mean of 5)	393 (ns)	452 (ns)	471 (ns)	404 (ns)
Depth of max resistance (cm) (mean of 5)	33 (ns)	26 (ns)	31 (ns)	32 (ns)
Mid topsoil bulk density (g/cm3)	1.40 (ns)	1.45 (ns)	1.42 (ns)	1.35 (ns)

Note – values followed by different letters in brackets indicate significant differences between treatments ($P<0.05$); ns – not significantly different.

Trt 1

Trt 2

Trt 3

Trt 4

Figure 30. VESS photos from field areas post establishment Yards

In Parrett 1, crop assessments carried out one month following planting (May 2017) and at harvest (August 2017) indicated no significant differences between treatments (*P*>0.05; Table 11). The row treatments had no significant effect on total cob yield (t/ha), the number of cobs per ha, the number of marketable cobs per hectare or the average cob weight.

Table 11. Post establishment and harvest assessments Parrett 1

Assessment	**Treatment**			
	Trt 1 **(row between intermediate wheeling, least traffic)**	**Trt 2** **(row next to intermediate wheeling)**	**Trt 3** **(row next to main wheeling)**	**Trt 4** **(row away from wheeling but near main tramline)**
One month following planting 23/05/2017				
Plant counts (1m length of row)	5 (ns)	5 (ns)	5 (ns)	5 (ns)
Crop height (cm)	21.8 (ns)	22.0 (ns)	22.8 (ns)	21.1 (ns)
Harvest 01/08/2017 (Variety Early Bird)				
Total cob yield (t/ha)	12.5 (ns)	12.7 (ns)	13.6 (ns)	12.8 (ns)
Marketable Yield (t/ha)	9.4 (ns)	10.1 (ns)	10.7 (ns)	9.5 (ns)
Total number of cobs (per ha)	52641 (ns)	51602 (ns)	56450 (ns)	53333 (ns)
Total number of marketable cobs (per ha)	39481 (ns)	40866 (ns)	44329 (ns)	39134 (ns)
Average cob weight (g)	238.3 (ns)	246.7(ns)	240.8(ns)	242.0 (ns)
Brix level	16.7 (ns)	18.0 (ns)	17.7 (ns)	18.2 (ns)
Cob dry matter (%)	23.16 (ns)	23.55 (ns)	23.80 (ns)	23.47 (ns)

In Yards Field, there were no statistically significant differences between treatments in the crop assessments carried out approximately one month following planting (May 2017) or the harvest assessments carried out in August 2017 (Table 12). Treatment 2 (the rows next to the intermediate wheeling) had numerically lower values for crop height (initial assessments), crop yield (t/ha), average cob weight and number of marketable cobs per hectare, although differences were not significant.

Table 12. Post establishment and harvest assessments Yards

Assessment	**Treatment**			
	Trt 1 **(row between intermediate wheeling, least traffic)**	**Trt 2** **(row next to intermediate wheeling)**	**Trt 3** **(row next to main wheeling)**	**Trt 4** **(row on previous courgette wheeling)**
One month following planting 31/05/2017				
Plant counts (1m length of row)	5 (ns)	5 (ns)	5 (ns)	4 (ns)
Crop height (cm)	20.4 (ns)	18.1 (ns)	20.1 (ns)	20.4 (ns)
Harvest 07/08/2017 (Variety unknown)				
Total cob yield (t/ha)	7.3 (ns)	6.4 (ns)	7.8 (ns)	8.0 (ns)
Marketable yield (t/ha)	6.2 (ns)	5.4 (ns)	6.7 (ns)	6.6 (ns)
Total number of cobs (per ha)	39134 (ns)	38442 (ns)	42944 (ns)	43290 (ns)
Total number of marketable cobs (per ha)	33247 (ns)	32554 (ns)	36710 (ns)	35671 (ns)
Average cob weight (g)	185.1 (ns)	161.6 (ns)	181.8 (ns)	183.0 (ns)
Brix level	13.2 (ns)	13.8 (ns)	16.3 (ns)	9.9 (ns)
Cob dry matter (%)	21.9 (ns)	21.7 (ns)	21.7 (ns)	22.2 (ns)

Note – values followed by different letters in brackets indicate significant differences between treatments (P<0.05) ns = not significantly different

Discussion and conclusions

One of the principal objectives CTF is to improve soil conditions and hence crop yield within the growing beds. Over time, soil structure in the non-trafficked area is likely to improve, with crop size, height and yield potentially increasing with distance from a main or intermediate wheeling. Within this study, the soil was firm to compact in a distinct layer between around 15 cm and 30 cm depth in both the fields; and in all the rows between wheelings.

In the field where a CTF and reduced tillage system had recently been introduced there was a difference in soil resistance and the depth of that resistance between rows next to the main wheeling and other rows further from it. The soil had higher resistance with the resistant layer at shallower depth in the row next to the wheeling. The mid-topsoil BD also indicated that the soil was compacted, although there were no differences between rows. It is most likely that there has not been sufficient time to resolve soil structural problems inherited from the previous cultivation system. The use of targeted subsoiling, where appropriate; natural restructuring (primarily through shrink-swell and biological processes); and cover cropping could help to improve soil structure and drainage over time. This process of soil structural regeneration should be accelerated within a CTF system since the growing bed will not be compacted by machinery.

In the field where a CTF system had been in place for 4 years there were still signs of firmness in the topsoil. However, the soil BD values indicated that the soil was not generally compacted and, although not statistically significant, crop heights and yields were numerically lower in the rows next to the intermediate wheeling, which is to be expected under a CTF system using large machinery.

The soil and crop yield data from both fields indicated that it can take more than 5-10 years for soils to recover from a system of random traffic and deep cultivation in which crops are often harvested in unfavourable (i.e. wet) field conditions. It would be of great interest to repeat the measurements after 5-10 years to investigate how soil structure, organic matter content and differential crop yields have developed in the two fields. The measurements should also be carried out in more than one year to take account of weather (e.g. timing and amount of rainfall; sunshine hours, temperature) factors, which can vary significantly from year to year.

Little Abshot long term study

The main aim of the long-term study was to establish baseline measurements in three fields at Little Abshot with contrasting management/land use (CTF, inversion tillage and permanent grassland) with a view to resampling in 4-5 years. The treatments were the contrasting management/land use in each field:

- Parrett 1 – CTF
- Chilling 3 – Conventional (random traffic) inversion tillage
- Meon – Permanent grass

The three fields were EMI scanned in September 2016 to establish homogeneous soil zones for sampling. Following EMI scanning, the following baseline soil measurements were taken in November 2016:

- 20 penetrometer measurements to 50 cm depth. Penetrometer measurements provided points of maximum, median and minimum resistance. At these three points the following assessments were then made:
    - Visual Soil Assessment (VSA) topsoil assessment (Shepherd, 2009)

  - VESS topsoil assessment (Guimaraes *et al*.,, 2011)
  - Mid topsoil (10-15cm) BD
  - Upper subsoil (30-35 cm) BD
  - Mid subsoil (40-45 cm) BD
  - 40-60 cm penetrometer resistance (maximum resistance and depth of maximum resistance x 3)
  - SubVESS subsoil assessment (30-60 cm depth; Ball *et al*., 2015)

These measurements were also carried out to characterise Yards Field (see short-term study).

At the three long-term CTF sites (Parrett 1, Chilling 3, Meon) nine additional BD measurements were taken from a 10 m x 10 m grid at 15-20 cm depth using the core cutter method and earthworm counts were carried out to further characterise baseline soil physical and biological properties (both methods carried out according to ADAS Standard Operating Procedures). The location of the BD samples and earthworm assessments were GPS logged.

Earthworms were sampled using the following method:

- Three blocks of soil (30 x 30cm x 25 cm deep) per field were extracted and hand searched for a total of 5 minutes
- The base of each hole was then irrigated with two 1.5 litre applications of 100 mg/l allyl isothiocyanate (AITC) at ten minute intervals to bring deep burrowing earthworms to the soil surface for counting
- Earthworms were collected for 10 minutes after each application, washed with water and placed in a labelled sample container
- The adult earthworms were split into three ecotypes (anecic, epigeic and endogeic) counted and weighed for biomass (g)

Future field operations will be recorded in each field and, after 4-5 years, sampling areas will be relocated to carry out the same measurements and assess any changes in soil physical, chemical and biological properties, and associated implications for the production system.

Results

Topsoil results

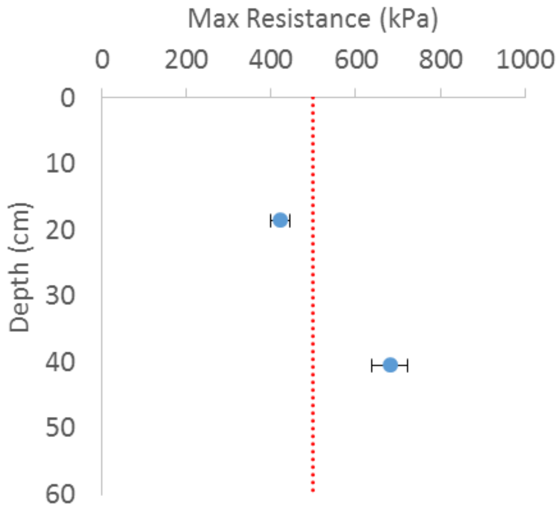
Soil pH was at or above optimum levels of 6.5 recommended in the Nutrient Management Guide (RB209) - Section 6 p.5 - Vegetables and bulbs (AHDB, 2017; Table 13). Soil nutrient levels (extractable phosphorus, potassium and magnesium) were at or above target levels. Clay content ranged from 14% (sandy silt loam) in Parrett 1 to 20% (clay loam) in Chilling 3 and Meon. Soil organic matter content reflected land use with levels of 2.6% and 2.9% in Parrett 1 and Chilling 3 respectively (annual horticultural crops) and 3.6% in Meon (grass ley).

Table 13. Topsoil (0-15cm) results from Barfoots case study fields (Sampled Nov 2016)

Determinand	**Units**	**Parrett 1 (CTF)**	**Meon (Grass ley)**	**Chilling 3 (Conventional)**
pH		6.4	6.9	7.0
Extractable Phosphorus	mg/l (Index)	41.8 (3)	23.2 (2)	43.8 (3)
Extractable Potassium	mg/l (Index)	159 (2-)	125 (2-)	156 (2-)
Extractable Magnesium	mg/l (index)	83.7 (2)	74 (2)	130 (3)
Textural Class		Sandy Silt Loam	Clay Loam	Clay Loam
Sand	%	48	30	27
Silt	%	38	51	53
Clay	%	14	19	20
Organic Matter (LOI)	%	2.0	2.8	2.5
Organic Matter (modified Walkley Black)	%	2.6	3.6	2.9

Penetrometer resistance

The depth of maximum resistance within the top 50 cm of the soil varied between the fields and was closest to the soil surface in Parrett 1 (around 19 cm depth), and lowest in Chilling 3 (around 40 cm depth; Figure 31 + Figure 33). Within Parrett 1 and Chilling 3 fields the penetrometer resistance was highest within the 40-60 cm depth layer; the penetrometer did not go far into the subsoil before meeting maximum resistance at around 40 cm depth (Figure 31 + Figure 33).



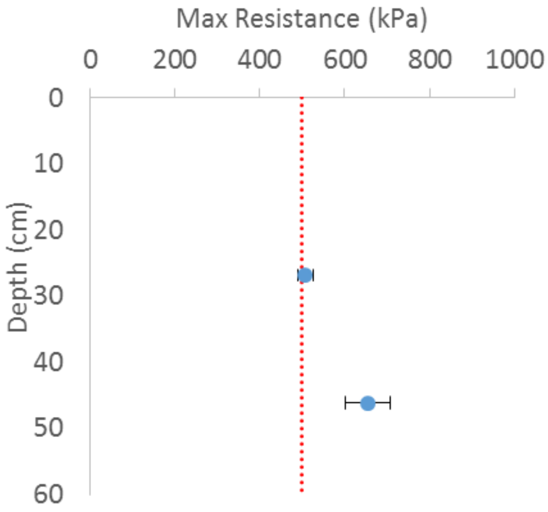


Figure 31. Penetrometer resistance profile Parrett 1 field

Figure 32. Penetrometer resistance profile Meon field

The 500 kPa (red dotted) line represents the boundary between Loose and Medium resistance (MAFF, 1982).

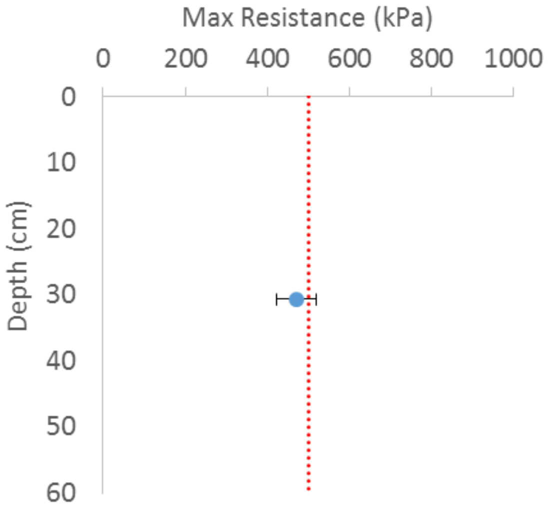


Figure 33. Penetrometer resistance profile Chilling 3 field.

The 500 kPa (red dotted) line represents the boundary between Loose and Medium resistance (MAFF, 1982).

Visual Soil Assessment (VSA)

Two of the fields (Meon and Chilling 3) were in good condition, while Parrett 1 Field was in moderate condition (

Table 14). In Meon and Chilling 3, the topsoil was in the most part friable, with occasional man-made clods that were small to moderate in size (Figure 34). In Parrett 1, there was evidence of very poor soil structure and porosity; and a well-developed tillage pan in the lower topsoil. Earthworm numbers were poor to moderate in all the fields.

Table 14. Background visual soil evaluation results from Barfoots

[1] These results were mean results taken from blocks which had more than one layer.

Assessment	**Parrett 1 (CTF)**	**Meon (Grass Ley)**	**Chilling 3 (Conventional)**
Average VSA (mean of 3) (Good <25, Moderate 10-25, Poor >10)	21	26	27
VESS Overall block score (mean of 3)[1] (1-Friable,2-Intact,3-Firm,4-Compact, 5-Very Compact)	2.7	1.8	1.7
VESS worst layer score (mean of 3) (1-Friable,2-Intact,3-Firm,4-Compact, 5-Very Compact)	4.2	2.7	2.2
VESS worst layer depth (cm)[1]	13-25	12-25	12-23
SubVESS Overall block score (mean of 3) (1-Friable,2-Firm,3-Some compaction, 4-Compact,5-Structureless)	2.3	2.5	2.7
Average worm numbers in extracted block of soil (mean of 3) (Good <8, Moderate 4-8, Poor >4)	4	8	3

Parrett 1 Meon

Chilling 3

Figure 34. VSA structure and consistence photos from field areas at Little Abshot

VESS and subVESS

Using the VESS overall score (average score for all topsoil layers weighted by depth of each distinct layer within the topsoil) the topsoil in Parrett 1 was intact (Sq2) and friable (Sq1; highly porous) in Chilling 3 and Meon. However, in Parrett 1 the poorest topsoil layer, at 13-25 cm depth was compact with large, sub-angular aggregates and few macropores and cracks (Figure 35). The poorest layers in Chilling 3 and Meon, at 12-24 cm depth, were intact (Sq2), although the layer in Meon was approaching firm (Sq3). In all three fields the topsoil near the soil surface was relatively friable, with abundant plant roots present.

Parrett 1

Meon

Chilling 3

Figure 35. VESS photos from field areas at Little Abshot

The upper subsoil in all three fields was firm according to SubVESS assessments, with a dense transition layer in which aggregates were harder to obtain and slightly more angular and of lower porosity. This hardened layer was particularly evident in Parrett 1 where considerable force was required to insert a knife into the lower topsoil/upper subsoil. There was evidence of mottling in the subsoil in Meon, an indication of poor drainage (Figure 36).

Parrett 1

Meon

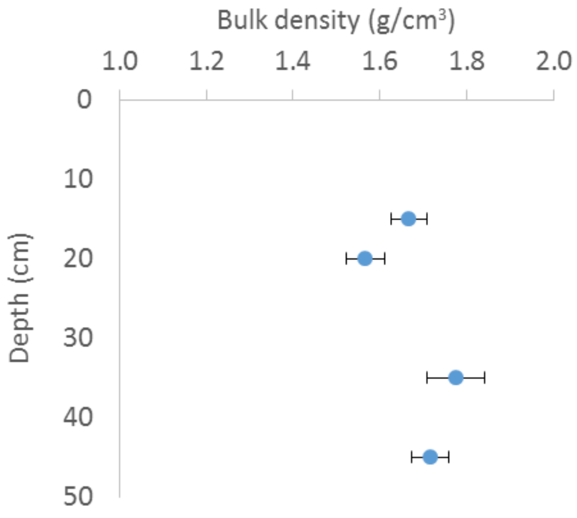
Chilling 3

Figure 36. SubVESS photos from field areas at Little Abshot

Bulk Density (BD)

The mean BD values in Parrett 1 (horticultural cropping) and Meon (grass ley) were above UKSIC (Merrington, 2006) trigger values in all topsoil and subsoil layers (Figure 38 and Figure 40). The lower topsoil in Chilling 3 was the only soil layer in the three fields in which soil BD was below the trigger value (Figure 42). Where soil BD is above trigger values it is an indication that some action may be required to remediate the issue, or plant growth could be impaired.

Notably, BD in the topsoil layer (at 13-25 cm depth in Parrett 1 and 12-23 cm depth in Chilling 3), which scored most poorly using the VESS method, was lower than in the upper topsoil layer that scored friable. This demonstrates that while soil BD is generally a good proxy for soil porosity, it is not always a reliable indicator of good or poor soil structure in terms of the size and shape of soil aggregates and the size and continuity of pores.



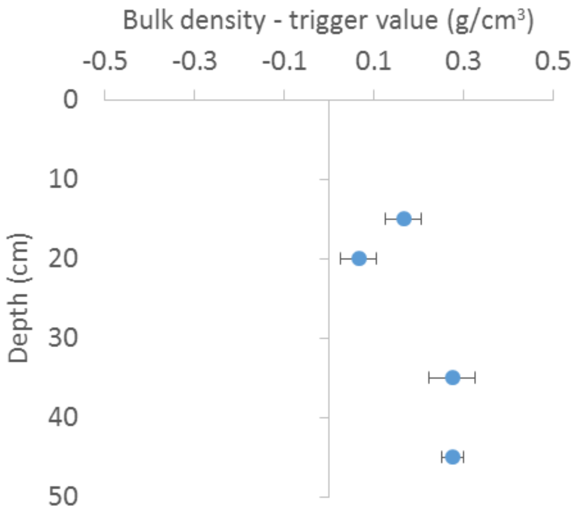
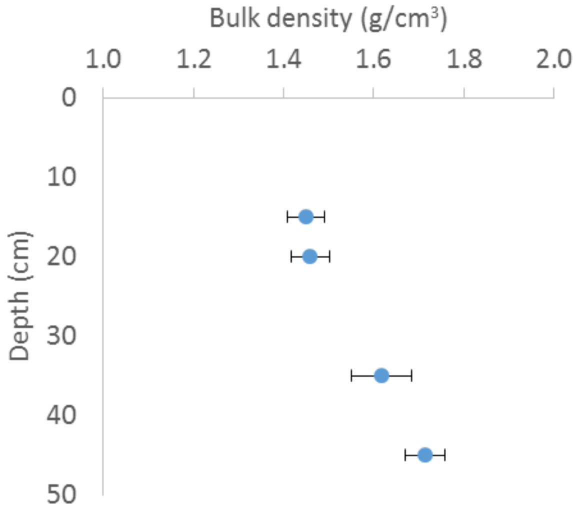


Figure 37. Bulk density profile Parrett 1

Figure 38. BD profile in relation to trigger values in Parrett 1.



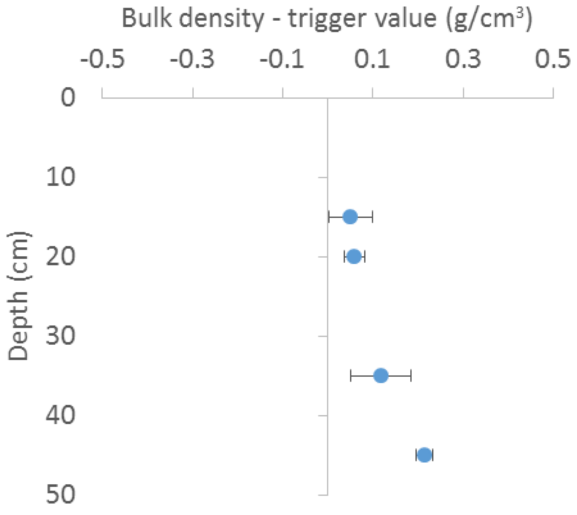


Figure 39. BD profile in Meon.

Figure 40. BD profile in relation to trigger values in Meon.

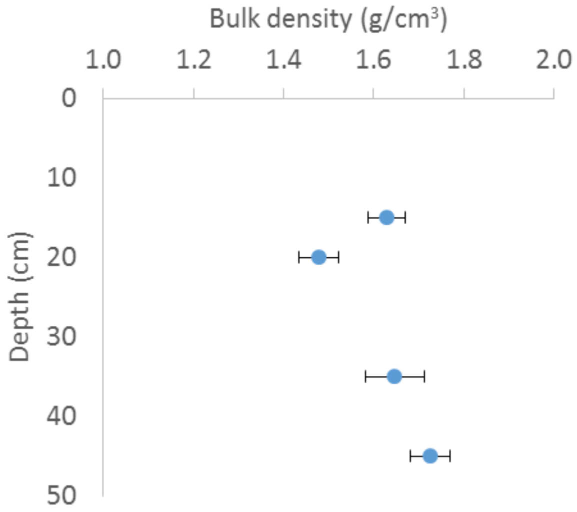


Figure 41. BD profile in Chilling 3.

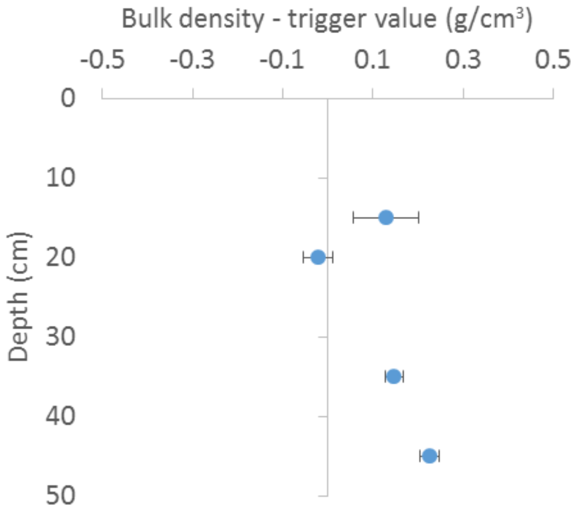


Figure 42. BD profile in relation to trigger values in Chilling 3.

The range of soil physical measurements and visual evaluations provide a robust baseline from which to monitor changes in soil structure over time. Re-sampling the fields in 4-5 years' time, will identify whether there has been any noticeable or significant change in soil physical properties under the contrasting soil cultivation and land management systems.

Barfoot Farms conclusions

- The introduction of CTF at Little Abshot Farm has resulted in a 63% decrease in tracked area across the rotation (i.e. from >100% to 37%), which, over the years, in combination with reduced tillage and the use of cover crops, is likely to result in improvements in soil structure and crop yield in the non-trafficked area and reduced fuel consumption.
- In the years following conversion to CTF at Little Abshot and Easton farms there were clear signs of compaction below cultivation depth (i.e. below 13-15 cm depth), indicating that it could take 5-10 years for soil structure to improve under the new CTF system.

Soil management strategies – Wyevale Transplants (Forestry) Ltd.

Background

Wyevale Nurseries' Transplant Division is a horticultural company based in Herefordshire who specialise in raising hedges and tree transplants, which are typically established in outdoor seedbeds until they are around 30 cm tall.

One of the greatest challenges for soil management is that plants are harvested in the autumn-winter period when soils are moist to wet; and in the absence of mulch, soils are left bare over winter. Young plants are lifted between October and February and cold stored prior to being transplanted into beds in the spring (March-May). The plants are then grown on for 1 to 2 years before autumn-winter harvesting and selling on into various markets.

The main production site is 90 ha; soils are sandy (Bromsgrove Association) and many of the fields are sloping. Soil erosion is therefore a significant issue at the site, resulting in loss of soil organic matter and topsoil nutrients, and a major pollution risk for watercourses. Slumping, resulting in soil compaction, and capping also reduce production at the nursery. Wyevale have explored several erosion mitigation options (e.g. grassed headlands, sedimentation ponds and sediment traps) with the aim of protecting sensitive receptors (neighbours and local watercourses) from surface runoff. Additional methods such as the use of grass leys in the rotation target the source of the sediment by improving topsoil structure and increasing soil organic matter content.

Objectives

The specific objectives of the Wyevale Transplants demonstration were to:

- Establish baseline soil structural conditions in three fields at Wyevale Transplants
- Consider methods for addressing soil erosion and compaction whilst maintaining or improving profitability of the business

Methods

Baseline soil structure assessments

Three fields were selected for assessment to represent the range of tree and hedge species grown at Wyevale Nurseries' Transplants site:

No.	Field name	Species	Crop duration
1	Northbank	*Crataegus monogyna*	1 year
2	Vinnings	*Crataegus monogyna*	2 years
3	Upper Foxbury	*Viburnum opulus*	2 years

To characterise each field, topsoils were sampled to 0-15 cm depth) and analysed for:

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

A cone penetrometer was used to quantify the range and depth of (maximum) penetration resistance values at twenty randomly selected points across the main body of each field to a depth of 50 cm.

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

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

Soil management practices review

Wyevale transplants were visited in April 2016 and January 2018 to identify current practice and evaluate the potential for adopting soil erosion and compaction mitigation options, including the use of grass leys and applying bulky organic manures; and the potential for adopting CTF. Information was gathered on the technical specifications of the machinery used on the nursery, including track gauges, working widths and tyre sizes. Based on the collated information it was possible to calculate the percentage of land that was tracked before bed forming, and following bed forming; and assess the potential for introducing CTF at Wyevale.

Results

Topsoil analysis results

Soil pH was slightly acidic and satisfactory in all three fields sampled, ranging from 6.2 to 6.5 (Table 15). Extractable nutrients (phosphorus, potassium and magnesium) were at maintenance levels or above. The topsoil texture was sandy loam or loamy sand with organic matter content (Dumas) ranging from 0.9% to 1.3%, which is low.

Table 15. Topsoil (0-15 cm depth) results from Wyevale transplants

Determinand	**Units**	**Northbank** *Crataegus monogyna* 1 year	**Vinnings** *Crataegus monogyna* 2 years	**Upper Foxbury** *Viburnum opulus* 2 years
pH		6.2	6.7	6.5
Extractable Phosphorus	mg/l (Index)	42.2 (3)	40.8 (3)	72.8 (5)
Extractable Potassium	mg/l (Index)	237 (2+)	266 (3)	249 (3)
Extractable Magnesium	mg/l (index)	69.9 (2)	37.7 (1)	66.2 (2)
Textural Class		Sandy Loam	Loamy Sand	Loamy Sand
Sand	%	75	82	84
Silt	%	16	11	9
Clay	%	9	7	7
Organic Matter (LOI)	%	1.7	1.7	2.1
Organic Matter (Dumas)	%	1.1	0.9	1.3

Penetrometer resistance

In Vinnings and Upper Foxbury fields, soil penetrometer resistance levels were relatively firm (600-650 kPa). Resistance in the topsoil was higher than in the subsoil (Figure 43) and the depth of maximum resistance in the topsoil was similar in both fields at around 23-24 cm depth (Figure 43). It was not possible to obtain accurate penetrometer resistance results from Northbank due to the stony topsoil. A penetrometer pushing against a stone results in resistance values significantly higher than in the surrounding soil.

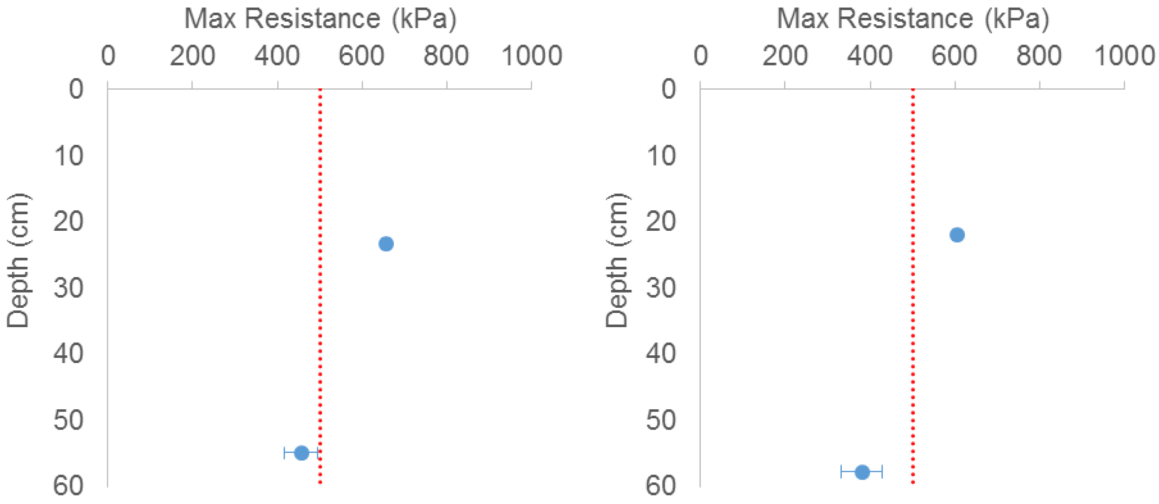


Figure 43. Pentrometer resistance profile for Vinnings (left) and Upper Foxbury (right)

The 500 kPa (red dotted) line represents the boundary between Loose and Medium resistance (MAFF, 1982).

Visual Soil Assessment

Visual Soil Assessment (VSA; Shepherd, 2000) indicated that two of the fields (Northbank and Vinnings) were in moderate condition, with one field (Upper Foxbury) in good condition. Topsoil was mainly friable with occasional manmade clods small to moderate in size (Figure 44). There was evidence of a tillage pan in the lower topsoil in all three fields, and very clear signs of surface runoff and soil erosion (Figure 44), which is an indicator of unstable soil aggregates. No earthworms were found in any of soils sampled, which may have been due to the time of year (January) and lack of crop residues in the topsoil (Table 16).

Table 16. Visual soil evaluation results from Wyevale Transplants

Assessment	Northbank *Crataegus monogyna* 1 year	Vinnings *Crataegus monogyna* 2 years	Upper Foxbury *Viburnum opulus* 2 years
Average VSA (mean of 3) (Good <25, Moderate 10-25, Poor >10)	24	23	25
Average number of earthworms in extracted block of soil (mean of 3) (Good <8, Moderate 4-8, Poor >4)	0	0	0
VESS Overall block score[1] (mean of 3) (1-Friable,2-Intact,3-Firm,4-Compact, 5-Very Compact)	2.0	1.4	1.2
VESS worst layer score (mean of 3) (1-Friable,2-Intact,3-Firm,4-Compact, 5-Very Compact)	2.1	2.3	2.3
VESS worst layer depth (cm)[1]	10-25	10-25	10-25
SubVESS Overall block score[1] (mean of 3) (1-Friable,2-Firm,3-Some compaction,4-Compact, 5-Structureless)	2.0	2.2	2.5

[1] mean results taken from soil blocks with more than one layer

Northbank Vinnings

Upper Foxbury

Surface runoff in Northbank

Figure 44. VSA photos from field areas at Wyevale Transplants

VESS and subVESS

In Vinnings and Upper Foxbury, the topsoils scored friable (Sq1) for the overall VESS scores, and in Northbank the overall VESS score was intact (Sq2). The topsoil generally broke up relatively easily, and was friable (due to its light texture) with mainly fine aggregates and occasional larger, sub-angular aggregates (Figure 45). The mean VESS score for the poorest layer was intact (Sq 2). Topsoil aggregates were particularly fine and rounded (scoring as friable) where plant roots were present. In all fields there was however a moderately-developed tillage pan in the mid to lower topsoil at 10-25 cm depth (Figure 45); the base of the tillage pan corresponded with the depth of maximum penetrometer resistance.

Northbank Vinnings

Upper Foxbury

Figure 45. VESS photos from field areas at Wyevale Transplants

According to the SubVESS assessments the subsoil in all three fields was firm (Ssq2), with Upper Foxbury having a slightly worse (higher) score than the other two fields. In all of the fields sampled there was a layer at around 30-45cm depth that was firmer than the lower subsoil (45-60 cm depth). Within this firmer layer, aggregates were harder to obtain, more angular and of lower porosity. The firmer layer was particularly evident in Upper Foxbury, where inserting a knife into the subsoil required considerable force and there was evidence of water ponding above the layer (Figure 46). When obtaining subsoil fragments in Upper Foxbury there was also a clear difference in size, strength and shape between the upper subsoil and lower subsoil (Figure 46).

Northbank

Vinnings

Upper Foxbury

Soil water seeping in to pit in Upper Foxbury

Figure 46. SubVESS photos from field areas at Wyevale Transplants

Bulk Density

BD values were relatively high (at or above BD trigger values) at all the depths sampled; mid-topsoil, upper subsoil and mid subsoil (Figures Figure 47 to Figure *52*). BD was highest in numerical terms (and relative to BD trigger values) in the upper subsoil (30-35cm), and lowest at mid-topsoil depth. This is an indication that cultivations had created porosity in the topsoil that was relatively high compared with the firmer layers below. BD values above trigger values generally indicate that further investigation is required to determine whether or not a change in management is needed to improve soil structure and the plant growth medium.

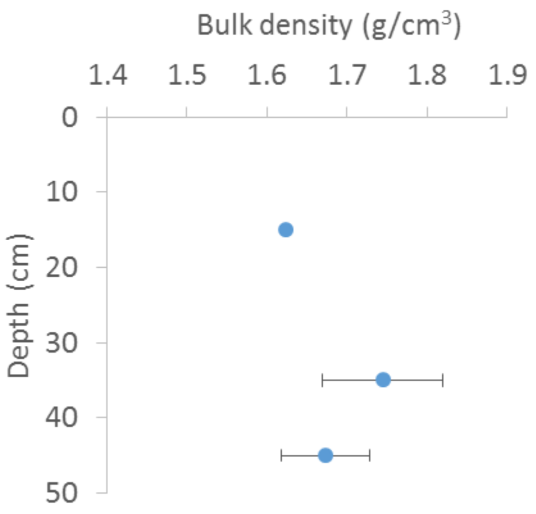


Figure 47. BD profile in Northbank.

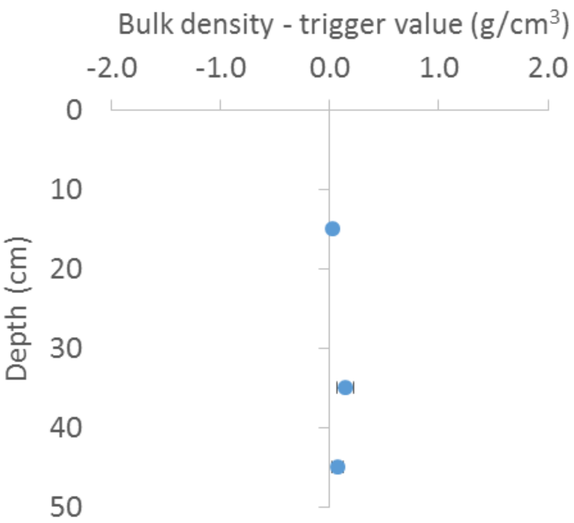


Figure 48. BD profile in relation to BD trigger values in Northbank

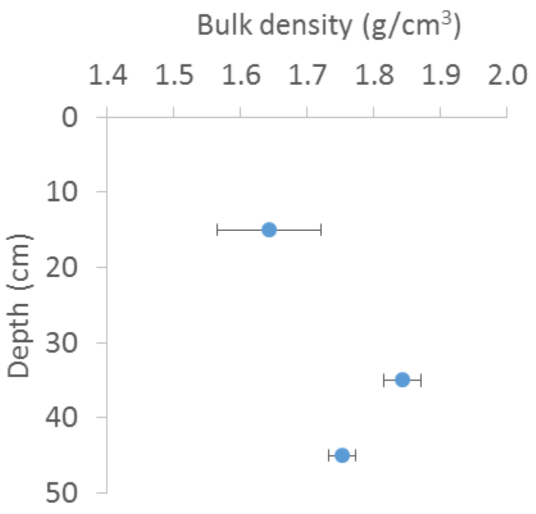


Figure 49. BD profile Vinnings.

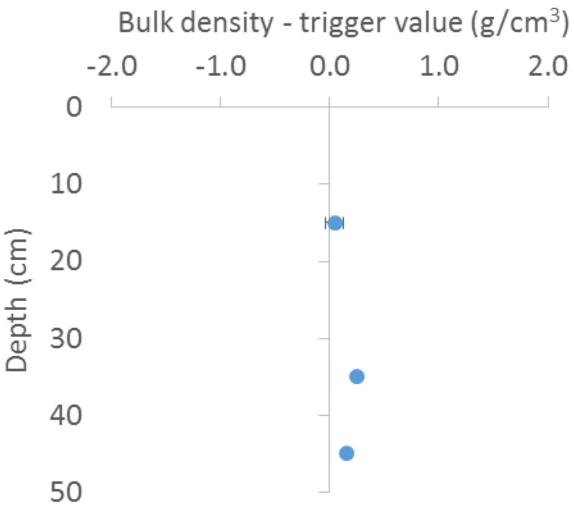


Figure 50. BD profile in relation to BD trigger values in Vinnings.

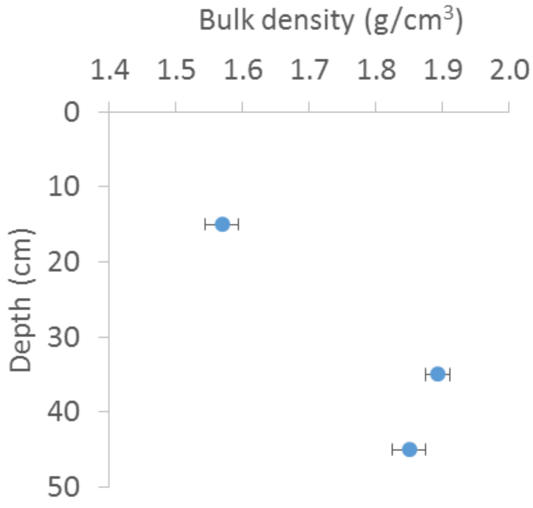


Figure 51. BD profile in Upper Foxbury.

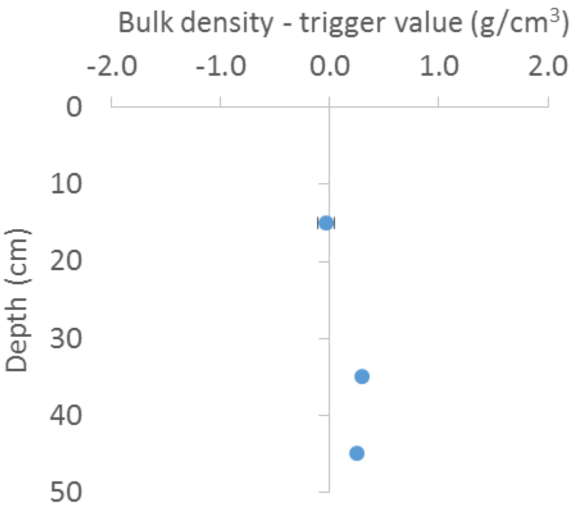


Figure 52. BD profile in relation to BD trigger values in Upper Foxbury.

Discussion

Soil assessments and measurements carried out at Wyevale Transplants indicated that the upper topsoil was generally well structured, with a firmer layer at 10-25 cm depth and a moderately-developed tillage pan. The upper subsoil at around 30-45 cm depth was the firmest layer as indicated by high BD values, SubVESS assessments and soil saturation above this layer in one of the fields. Soil compaction generally extended to below the effective working depth of most agricultural subsoilers (c. 45 cm depth).

The lack of earthworms was a further indication of soils with low organic matter. When left bare, these soils are particularly prone to erosion from raindrop impact and surface runoff.

Soil erosion has significant implications for horticultural production systems since losing topsoil reduces soil organic matter and nutrient content and presents a serious pollution risk. In the three fields sampled there were clear signs of poor soil structure, which would exacerbate erosion problems.

Machinery, controlled traffic and other mitigation options

At Wyevale, seedbed preparation began with two subsoiling operations; the second loosening operation carried out at right angles to the first. The fields were then ploughed and power harrowed prior to bed forming. Beds were formed with wheel tracks at 1.65 m centres and all subsequent operations carried out on the same traffic lanes.

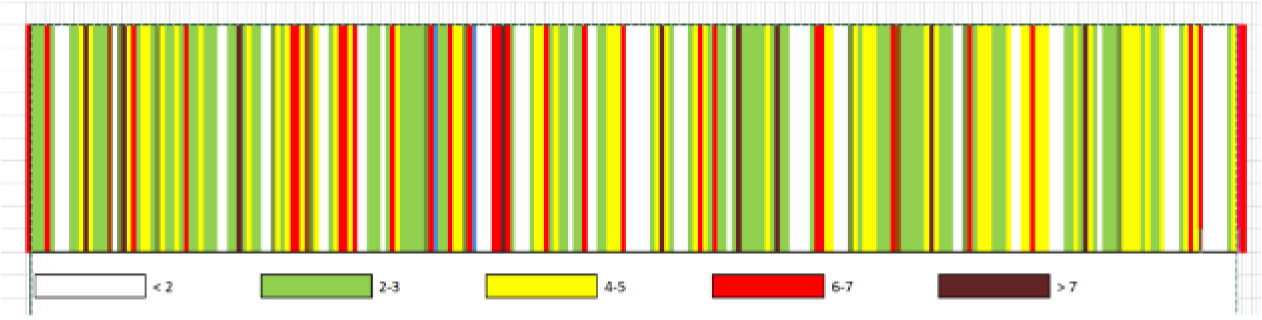


Figure 53. Tracking at Wyevale Transplants (based on grass ley topped, manure spreading, and seedbed preparation before bed forming). Colours denote the number of coincident passes with white in this case representing areas of no tracking.

Total field tracking prior to bed-forming, from topping of an 18-month grass ley to power harrowing resulted in around 78% of the field being tracked (Figure 53). This assumes all operations are parallel to each other but that some are coincident. An additional subsoiling operation at right angles to the other operations added another 39% tracked area, but some of this was coincident with the previous tracking. Once beds were formed, all further operations were carried out with machine tyres of 390 mm in width, equating to a tracked area of around 24%.

Following harvest of transplants, the established traffic lanes on the 1.65m centres were effectively obscured due to soil “spillage” during the harvesting operation and the difficulty of keeping within the lanes during wet field conditions. When pronounced traffic lanes are obscured by harvest, re-establishment in the same location (i.e. maintaining the same growing beds) is difficult. As a result, the whole field is subsoiled and ploughed, even though there was no traffic on the beds during the growing period. There is some potential for established wheel tracks to be located and used again. This could be achieved through the use of a global navigation satellite system and auto-steer (particularly those based on real-time kinematic - RTK - correction) or the use of markers in hedge/fence lines to establish A-B lines. However, the cost of establishing a global navigation system and autosteer has been considered to be too high to implement.

Further tracking reduction could be achieved by adopting ultra-flex (VF) tyres and reducing the tyre pressure by around 40%, and maximum tyre width to around 300 mm. This would reduce tracking to 18% post seedbed preparation.

The principal mitigation methods used by Wyevale Transplants to increase soil organic matter content, improve soil structure and reduce erosion risk were the establishment of grass leys (typically for 18 months) within the rotation and the use of PAS100 certified green compost; applied at 500 kg total N/ha every two years as permitted under Nitrate Vulnerable Zone

(NVZ) Action Programme Rules (Defra, 2015). This change in practice should be effective in increasing topsoil organic matter content, which has potential to improve topsoil structure and aggregate stability within 10-15 years (Bhogal *et al*., 2009; see also the AHDB *Soil management for horticulture* guide). The main methods used to mitigate the effects of surface runoff and erosion were wide grass margins at the base of fields, sediment traps and sedimentation ponds.

Other mitigation options considered by the nursery included the use of straw, compost mulch or grass strips to protect the soil surface within wheelings.

Wyevale Transplants conclusions

- The nature of the production and (winter) harvesting operations at Wyevale Transplants mean that soil erosion and compaction are significant issues that could compromise business viability
- The nursery has reduced off-site impacts of soil erosion by establishing wide grass margins, sediment ponds and filter barriers
- Within-field soil erosion is being tackled by growing 18-month grass leys and applying green compost to increase soil organic matter content. Use of mulches to protect the soil surface and grass strips in wheelings is also being considered.
- The nursery is investigating ways to reduce cultivation and the degree of soil disturbance to alleviate compaction and increase soil aggregate stability. A small trial is being carried out to assess the need for subsoiling.
- There may be some potential to reduce the extent of compaction using controlled traffic, but establishing permanent trackways is challenging with machinery harvesting on sloping land in wet conditions over winter. The first effective action to reduce compaction could be to upgrade tyres to one of the latest designs to reduce tracking and ground contact pressure.

Canopy sensing for variable rate nitrogen applications to Savoy cabbage – Glassford Hammond Farming LLP

Background

Canopy sensing measures reflectance from the crop surface. This information is presented in the form of a vegetation index, which can relate to crop biomass and crop nitrogen (N) uptake. Canopy sensing can give us useful information on spatial and temporal variability in crop growth and can be used as the basis for variable rate N management.

A crop with a well-developed thick canopy will typically have a different N requirement to one with a weaker canopy. Information on canopy variation across a field can be used to vary N application; usually by applying more to thinner areas and less to thicker areas.

Canopy sensors are increasingly being used to variably apply N fertiliser to combinable arable crops. This technology may have the potential to improve nitrogen use efficiency in horticultural crops. The overall aim of this field experiment was to demonstrate the potential for canopy sensing for variable rate N management on Savoy Cabbage. This project included two demonstrations focussing on variable rate N management for brassica vegetables; this demonstration on Savoy Cabbage (2016) and a second on Brussels sprouts in 2017, which is presented later in this report.

Methods

Experimental site

This demonstration was hosted by Glassford Hammond Farming in Peters House Field near Worksop, Notts. The field was planted with a number of Savoy cabbage varieties on 30th June at 38,140 plants/ha. The experimental area was planted with the variety Tourmaline.

Approach

The demonstration included N response experiments and tramline comparisons of uniform and variable rate N application which were set up to address the following questions:

- Does the optimum N rate for the crop vary across the field?
- Can we relate canopy sensing information to crop biomass and N uptake during the growing season?
- Can we demonstrate a benefit from variable rate N application?

Nitrogen response experiments

Nitrogen response experiments were replicated in three different areas of the field to see if there was any evidence of within field variation in optimum N rate (Figure 54) – variable rate N management will only be beneficial where there is variability in the crop N requirement.

Each experiment included seven N application rates (0, 60, 120, 180, 240, 300 and 360 kg N/ha) replicated four times and arranged in a randomised block design. Each plot was 6 x 5 m and included 10 cabbage rows. All other fertilisers (apart from N) were applied by the farm at recommended rates to the whole field (including N response experiments and tramline treatments).

Table 17. Nitrogen response treatments fertiliser application rates and timings

Treatment number	**N fertiliser applied (kg N/ha)**			
	4th July	**4th August**	**24th August**	**Total**
1	0	0	0	0
2	30	30	0	60
3	40	80	0	120
4	70	80	30	180
5	80	100	60	240
6	100	120	80	300
7	120	140	100	360

Topsoil samples (0-15 cm depth) were taken from each of the three N response experimental areas and analysed for pH, extractable P, K and Mg, organic matter and soil texture. Soil mineral N samples (0-90 cm) were also taken prior to planting (one sample from each area) and after harvest (from the 0, 120, 240 and 360 kg N/ha treatments).

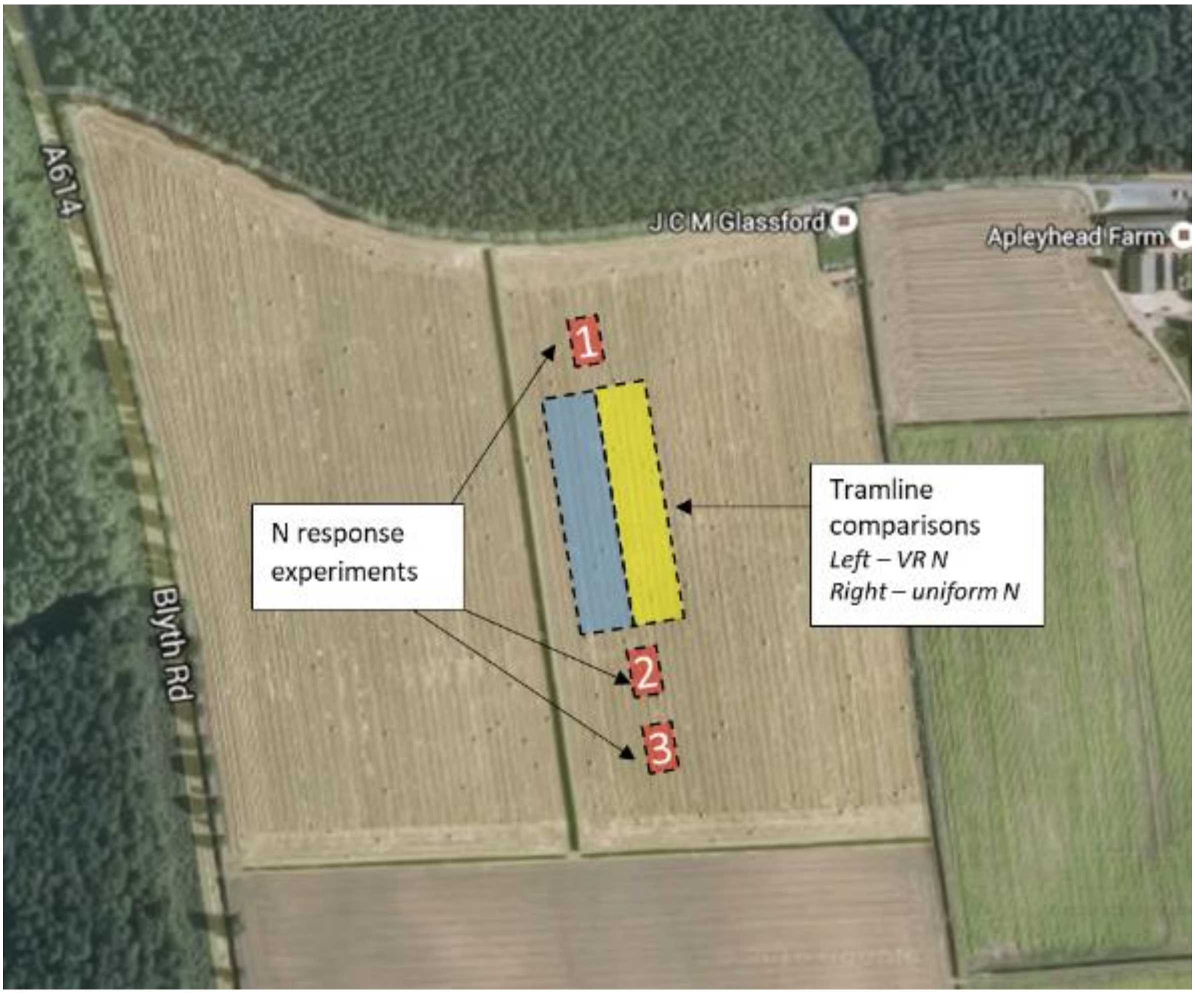


Figure 54. Field demonstration layout

A handheld CropScan sensor (Figure 55) was used to measure reflectance from the crop canopy from each of the N response plots (7 N rates x 4 replicates x 3 N experiments = 84 plots) four times during the growing season: 3rd August, 24th August, 18th September and 19th October. At the same time, crop samples were taken from the same area as the CropScan measurement from each N treatment from one replicate block from each N experiment (7 N rates x 1 replicate x 3 N experiments = 21 crop samples); six cabbages were cut at ground level and weighed to determine total biomass, and a subsample taken for dry matter and total N analysis in order to calculate total N uptake.

Figure 55. Use of handheld CropScan sensor to measure reflectance from the crop canopy

The N response plots were harvested between 7th and 11th November. Thirty cabbages were cut and weighed from each of the plots. The total weight was recorded to calculate total yield and a subsample taken for dry matter and total N analysis in order to determine total N uptake at harvest. The cabbages were then trimmed and weighed again individually to give marketable yield. Damaged or diseases cabbages and cabbages <500 g were classed as unmarketable.

Tramline comparisons

In addition, the farm standard uniform N application rate was compared to variable N management in tramline comparisons – each N treatment was applied to an area 36 m x 125 m (Figure 56). The farm standard N application rate was 240 kg N/ha and was applied in three splits:

- 80 kg N/ha on 04/07/16 just after planting
- 100 kg N/ha on 04/08/16
- 60 kg N/ha on 24/08/16

For the variable rate N treatment, the second N application was varied between 60 and 140 kg N/ha (i.e. +/- 40 kg N/ha from the 100 kg N/ha farm standard) using crop canopy information. The first and third N applications were applied at the farm standard uniform rate to the whole field using the farm spinning disc fertiliser spreader. The total N application (from all three N applications) therefore varied between 200 and 280 kg N/ha

The precision farming company SOYL collected crop canopy information from the field using a UAV on 27th July (the week before the second N application). SOYL used their ADC camera to collect canopy information from the whole field and their MCA camera to collect canopy information at a higher resolution from the tramline comparison area (Figure 56).

SOYL used the NDVI vegetation index to create a variable rate N prescription map for the trial area (a 96 x 150 m area including both tramline treatments and 12 m buffer around the edge of the trial) (Figure 57). Nitrogen was variably applied to the 36 x 125 m variable rate N tramline treatment only – the rest of the area received a uniform 100 kg/ha N application. Glassford Hammond Farming did not have the facility to variably apply N fertiliser using the farm fertiliser spreader, therefore the N fertiliser was applied by hand to the variable rate treatment at different application rates on a 6 x 5 m grid. The N prescription map for the tramline area was produced on a 6 x 5 m grid – N application rates were calculated based on a liner relationship between NDVI and N application rate with the highest N application rate to areas of lowest NDVI and vice versa.

The uniform 100 kg N/ha treatment was applied using the farms modified seed drill, which places the N fertiliser between the cabbages. The fertiliser spreader was calibrated prior to use to check the application rate.

The prescription N map was used to identify three 6 x 5 m areas of crop with a lower NDVI and three 6 x 5m areas of crop with a higher NDVI from both the uniform and variable rate N treatment areas. Leaf samples[2] were taken from each of these areas on 4th August prior to the second N fertiliser application and analysed for total N, P, K, Mg, S, Ca, Mn, B, Cu, Zn and Fe to see whether there was any indication that the differences in crop canopy were attributable to differences in any other plant nutrients. In addition, the handheld CropScan sensor was used to measure reflectance from the crop canopy from each of the N response plots four times during the growing season: 3rd August, 24th August, 18th September and 19th October, to see if there was any evidence that the higher/lower variable N rate applications changed crop canopy growth compared to the uniform N application.

A topsoil sample (0-15 cm depth) was taken from the tramline treatment area (single sample from the area covered by both the uniform and variable rate treatments) and analysed for pH, extractable P, K and Mg, organic matter and soil texture. A soil mineral N sample (0-90 cm) was also taken immediately prior to planting.

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[2] Each sample was a composite of the youngest fully expanded leaves from at least 20 plants in each area.

At harvest, marketable yield was measured from the uniform and variable N rate treatments; each 36 x 125 m treatment area was harvested by hand on a 6 x 5 m grid (the same as used for the variable rate N application); 30 cabbages were harvested and weighed from each of the grid plots[3]. The effect of variable rate N application on total marketable yield and crop uniformity was assessed.

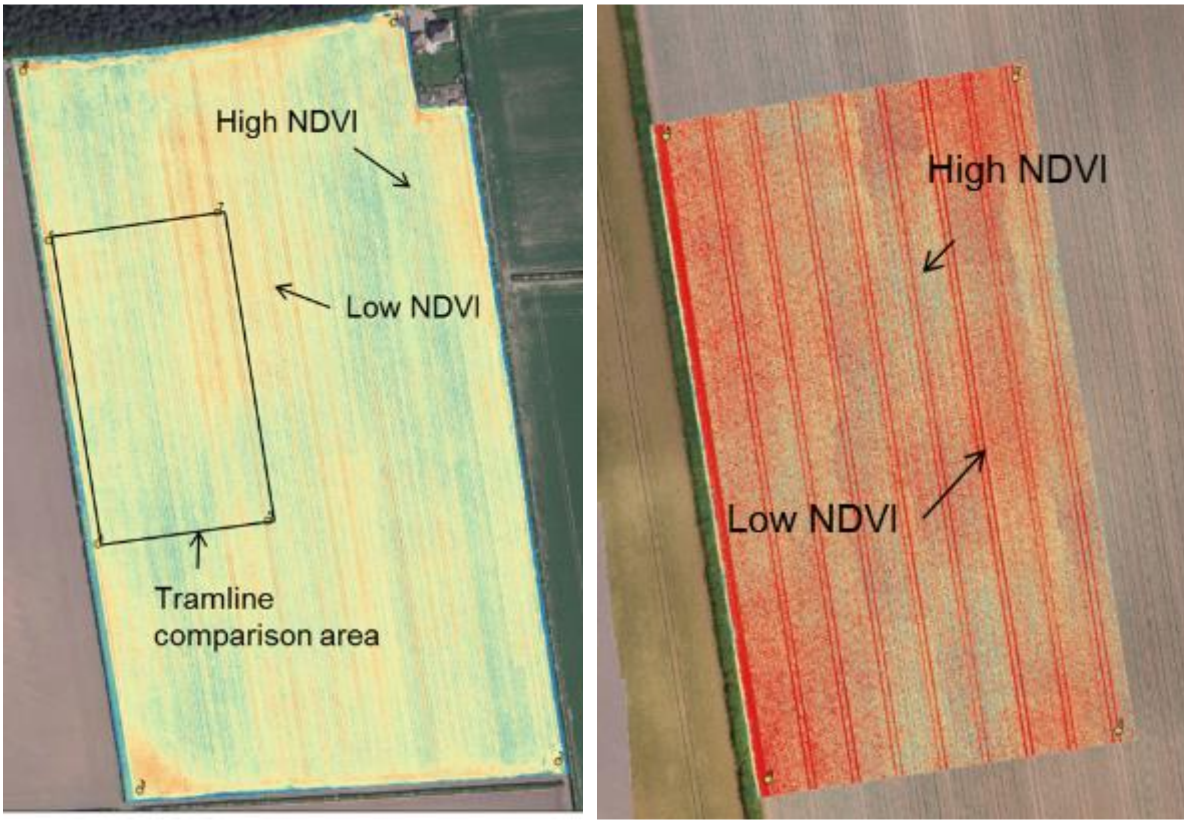

Figure 56. NDVI (26th July) from the whole field using ADC camera (left) and from the tramline area using MCA camera (right)

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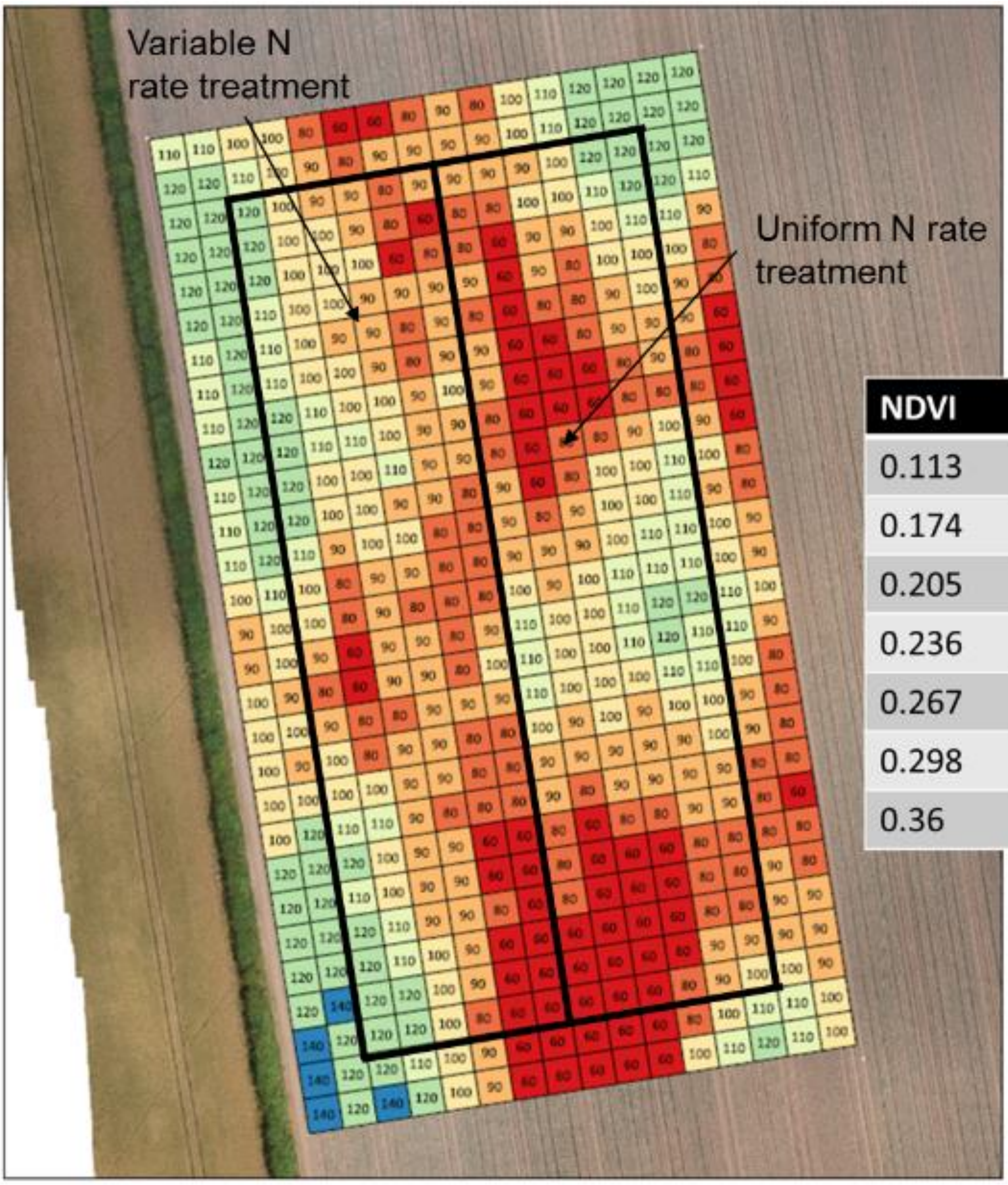
[3] An area of each of the tramline treatments was mistakenly harvested by the farm. The actual number of 6 x 5m plots harvested and weighed for the trial (out of a total of 150 in each treatment area) was 105 for the uniform nitrogen rate and 121 for the variable nitrogen rate treatment.



NDVI	N Rate
0.113	140
0.174	120
0.205	110
0.236	100
0.267	90
0.298	80
0.36	60

Figure 57. Variable rate N application map for the second N application to the tramline treatment areas. Nitrogen was variably applied to the variable N rate treatment according to this plan; the uniform N rate treatment received a uniform 100 kg/ha N application.

Results and discussion

Initial soil analysis

Soil mineral N samples (0-90 cm) were taken mid-June prior to planting. The three N response experiments had SMN levels of 69, 64 and 82 kg N/ha respectively, and the tramline experimental area had 78 kg N/ha – giving an average site SNS index of 1. The soil was a sandy loam textured soil with P Index 2, K Index 2- and Mg Index 2 (Table 18).

Table 18. Soil analysis from N response and tramline experimental areas

	Unit	**N response experiments**			**Tramline area**[1]
		Exp 1	**Exp 2**	**Exp 3**	
pH	-	7	6.7	6.7	7.3
Extractable P	mg/l (index)	22 (2)	22 (2)	31 (3)	25 (2)
Extractable K	mg/l (index)	137 (2-)	170 (2-)	165 (2-)	155 (2-)
Extractable Mg	mg/l (index)	72 (2)	104 (3)	90 (2)	76 (2)
Organic matter	%	72	68	77	66
Sand	%	20	24	16	24
Silt	%	8	8	7	10
Clay	%	2	2.2	2	2.4
Textural class[2]	-	SL	SL	SL/LS	SL
SMN (0-90cm)	kg/ha	69	64	82	78

1. A single representative soil sample was taken from the uniform and variable N rate treatment areas.
2. SL = sandy loam; LS = loamy sand.

Nitrogen response experiments

Crop reflectance data from the N response plots showed a strong relationship between NDVI and total biomass (Figure 58) and between NDVI and crop N uptake (Figure 59)[4]. An exponential model fitted to the total biomass data accounted for 95% of the variation in NDVI, and an exponential model fitted to the crop N uptake data accounted for 88% of the variation in NDVI. This indicates the canopy sensing can be used to provide a good proxy measure of variation in Savoy cabbage biomass and N uptake during the growing season.

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[4] Data presented here excludes the final measurements on 19th Oct. The relationship between NDVI and biomass (but not NDVI and N uptake) is altered when including the 19th Oct measurements; this is possibly due to a combination of senescence of older leaves and the large number of overlapping leaves at the latest sampling date. The relationship between NDVI and biomass/N uptake is most relevant when it can be used to inform N fertiliser applications; the 19th Oct measurements are beyond this time.

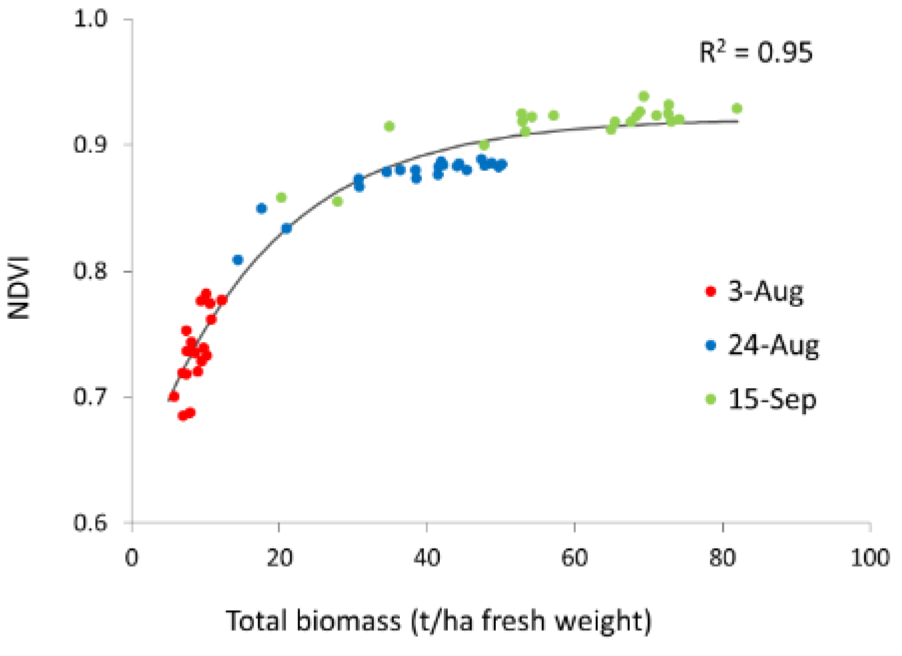

Figure 58. Relationship between NDVI and total biomass

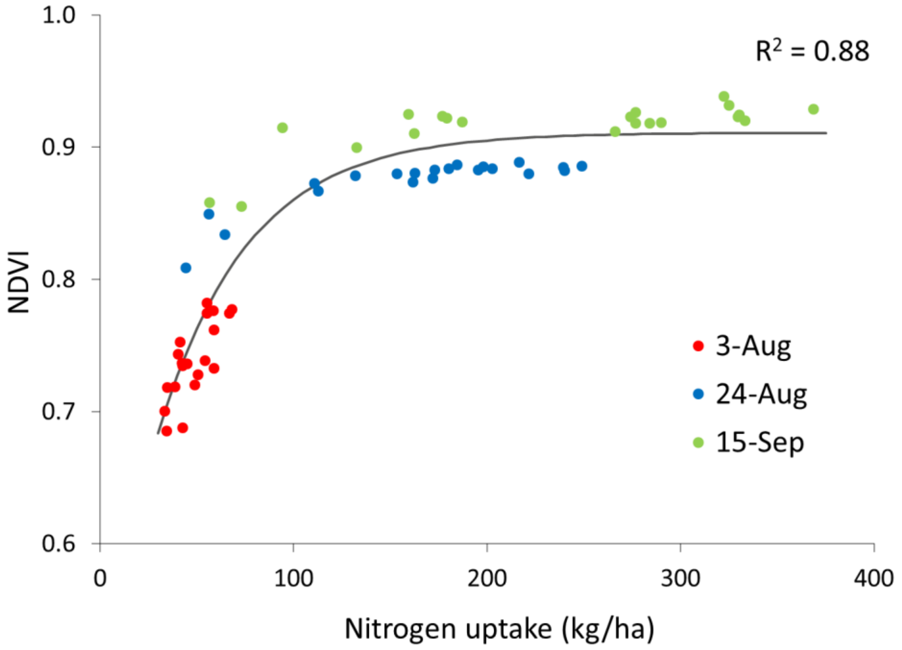

Figure 59. Relationship between NDVI and crop N uptake

The CropScan sensor measures reflectance at 17 wavelengths which can be used to calculate a number of different vegetation indices. In addition to NDVI, nine other vegetation indices were calculated from the CropScan crop reflectance data. The relationship between each of these vegetation indices and total biomass and crop N uptake has been calculated to compare the relative performance of each of the vegetation indices and this analysis is included in Appendix 3.

There was a significant yield response to N fertiliser (Table 19). The percentage of marketable heads (undamaged heads >500 g) increased from a mean of 39% on the zero N treatment, to 90% at 60 kg N/ha and to >97% at rates >180 kg N/ha. Fresh weight marketable yield increased from 10 t/ha (mean marketable head weight of 603 g) on the zero N treatment to 40 t/ha (mean marketable head weight of 1061 g) at the farm standard N rate of 240 kg N/ha and to a maximum of 44 t/ha (mean marketable head weight of 1174 g) at the highest N rate of 360 kg N/ha (Figure 60 and Figure 61).

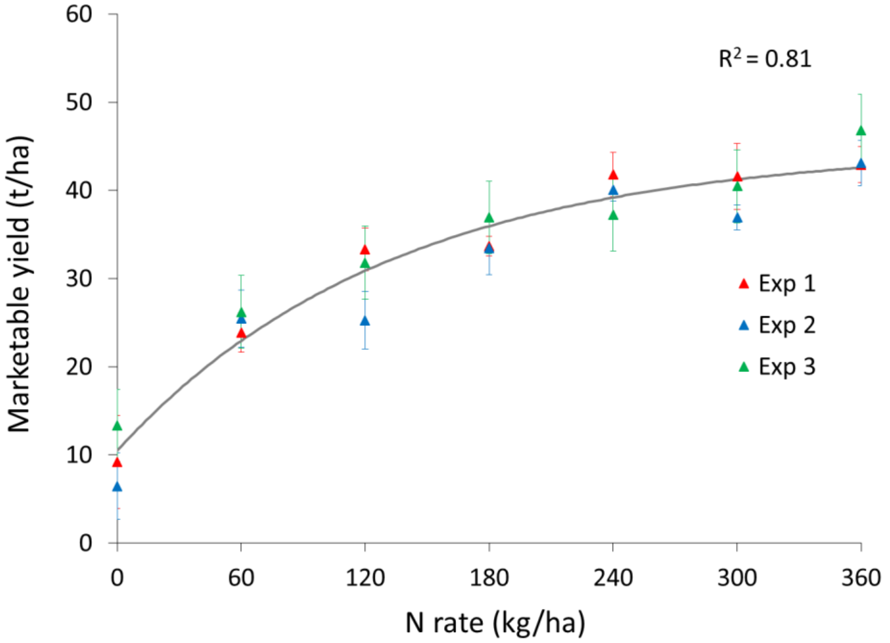

Figure 60. Marketable yield - response to N fertiliser

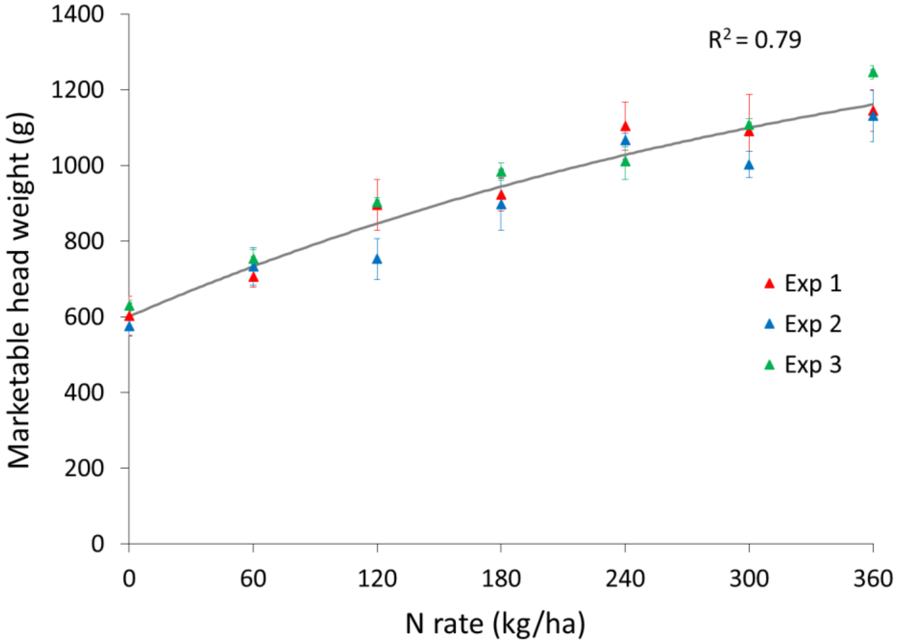

Figure 61. Mean marketable head weight – response to N fertiliser

The savoy cabbage crop was sold at 12 p/head for 500-600g heads (as whole fresh produce for retailers) and at 14 p/kg for heads >600g (for processing). The value of the crop at the different N fertiliser rates was calculated after taking into account the price of N fertiliser (assuming £240/tonne for ammonium nitrate, equivalent to 70 p/kg N). The majority of the crop was sold for processing; at the farm standard N rate of 240 kg N/ha only 2% of heads were in the 500-600g range. Crop value increased from £1650/ha at the zero N treatment, to £5450 at the farm standard N rate of 240 kg N/ha and to a maximum of £5979 at the 360 kg N/ha treatment (Figure 62). The value of the crop after taking into account the cost of the N fertiliser continued to increase with N rate up to the maximum N rate tested of 360 kg N/ha indicating that the economic optimum N rate at this site was >360 kg N/ha.

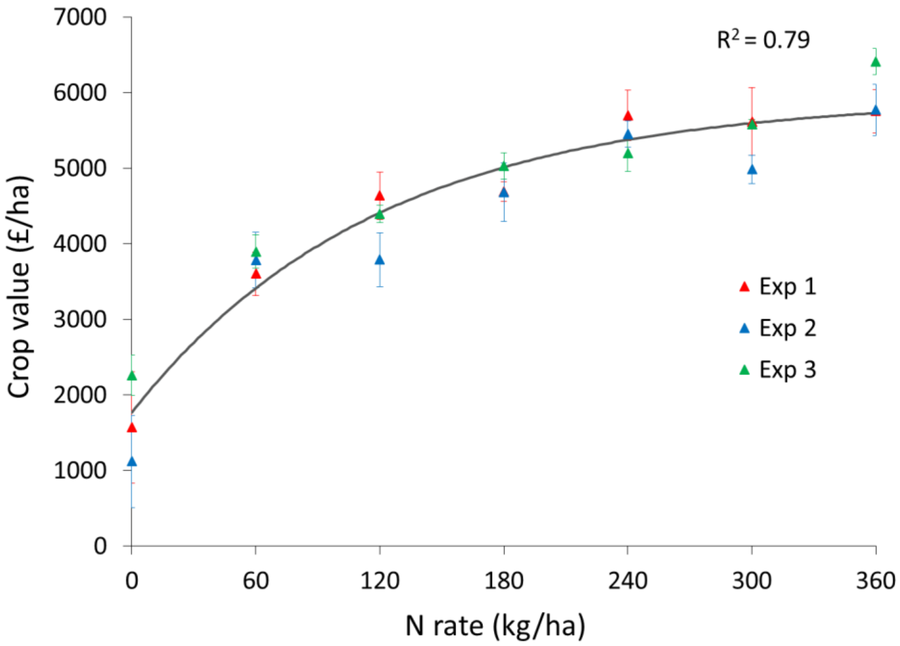

Figure 62. Increase in crop value with N fertiliser (after taking into account N fertiliser cost)

Genstat was used to fit curves to the marketable yield, marketable head weight and crop value data from the N response experiments. Regression analysis showed that fitting separate curves for marketable yield, marketable head weight and crop value data for each of the three N response experiments was not statistically justified, i.e. the crop response to N did not vary between the three N response experiments. An exponential model was fitted to marketable yield data, marketable head weight data and crop value data from all three N response experiments and explained 81%, 79% and 79% of variation in the marketable yield, marketable head weight and crop value data, respectively.

The total above ground crop N uptake at harvest increased from a mean of 59 kg N/ha on the zero N treatment to 281 kg N/ha at the farm standard N rate of 240 kg N/ha and to a maximum of 326 kg N/ha at the 300 kg N/ha fertiliser rate (Table 20). Fertiliser N use efficiency[5] decreased from a maximum of 113% at the 60 kg N/ha fertiliser rate to a minimum of 68% at the 360 kg N/ha fertiliser rate (Table 20). Fertiliser N use efficiency at the farm standard N rate of 240 kg N/ha was relatively high at 92% (RB209 assumes a typical fertiliser N recovery of 60%) indicating that the crop had effectively taken up the applied N fertiliser.

The cabbages were trimmed in the fields and the crop residue (i.e. trimmed leaves) left on the soil surface. The quantity of crop residue increased from 29 t/ha (fresh weight) on the zero N treatment to 47 t/ha at the farm standard N rate of 240 kg N/ha and to a maximum of 49 t/ha fresh weight at the 360 kg N/ha fertiliser rate (Table 20). The N in crop residue increased from 44 kg N/ha on the zero N treatment to 151 kg N/ha at the farm standard N rate of 240 kg N/ha and to a maximum of 179 kg N/ha at the 300 kg N/ha N fertiliser rate (Table 20).

Soil mineral N (0-90cm) measured after harvest in November from the 0, 120, 240 and 360 kg N/ha fertiliser treatments was 7, 10, 13 and 39 kg/ha N, respectively. Although SMN concentrations increased with increasing N fertiliser rate, these autumn SMN concentrations are comparatively low and represent a low risk of overwinter nitrate leaching losses from the farm standard N rate of 240 kg N/ha. However, N return in crop residue is relatively high (151 kg N/ha in crop residue at the farm standard N rate of 240 kg N/ha) and mineralisation of crop residue N will contribute to SMN.

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[5] Fertiliser N use efficiency = [(Crop N uptake – crop N uptake on zero N control)/Fertiliser N applied] x 100

Table 19. Effect of N fertiliser rate on percentage of marketable cabbage heads, total fresh weight yield, marketable fresh weight yield and average marketable head weight

N rate **kg N/ha**	**% cabbage heads marketable**				**Total yield (t/ha fresh weight)**			
	Exp. 1	**Exp. 2**	**Exp. 3**	**Mean**	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Mean**
0	36	28	55	**39**	38	34	44	**38**
60	88	90	91	**90**	56	57	62	**59**
120	98	87	93	**92**	67	60	76	**68**
180	96	98	98	**97**	75	72	85	**77**
240	99	98	97	**98**	86	86	86	**86**
300	100	97	96	**98**	89	81	94	**88**
360	98	100	98	**99**	91	92	98	**93**

N rate **kg N/ha**	**Marketable yield (t/ha fresh weight)**				**Mean marketable head weight (g fresh weight)**			
	Exp. 1	**Exp. 2**	**Exp. 3**	**Mean**	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Mean**
0	9	6	13	**10**	603	575	630	**603**
60	24	25	26	**25**	705	733	754	**731**
120	33	25	32	**30**	895	753	902	**850**
180	34	33	37	**35**	923	898	984	**935**
240	42	40	37	**40**	1105	1067	1010	**1061**
300	42	37	40	**40**	1091	1002	1107	**1067**
360	43	43	47	**44**	1144	1131	1247	**1174**

Note – marketable heads are >500g not damaged or diseased.

Table 20. Effect of N fertiliser rate on total N uptake, fertiliser N use efficiency and crop residues

N rate kg N/ha	**Total N uptake (above ground at harvest)**				**N use efficiency (%)**			
	Exp. 1	**Exp. 2**	**Exp. 3**	**Mean**	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Mean**
0	58	52	68	59	*	*	*	*
60	122	124	135	127	106	120	111	113
120	159	141	179	159	84	74	92	83
180	207	198	234	213	83	81	92	85
240	280	281	280	281	93	95	88	92
300	332	300	347	326	91	82	93	89
360	295	296	316	303	66	68	69	68

N rate kg N/ha	**Crop residues (t/ha fresh weight)**				**Crop residues (kg N/ha)**			
	Exp. 1	**Exp. 2**	**Exp. 3**	**Mean**	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Mean**
0	29	27	31	29	44	42	47	44
60	32	32	36	33	70	69	78	72
120	34	34	44	37	81	81	104	88
180	41	38	48	42	114	106	132	117
240	44	46	49	47	144	151	159	151
300	48	44	53	48	178	163	197	179
360	48	48	51	49	156	157	165	159

Tramline comparisons

Comparison of marketable head weights and total marketable yields from the uniform and variable rate N tramline comparisons showed that marketable yield was an average of 2 t/ha lower ($P<0.05$), and mean marketable head weight was an average of 45 g lower ($P<0.05$) from the variable compared to uniform N rate treatments, respectively. The crop value[6] was equivalent to £4858/ha from the uniform N rate tramline and £4615/ha from the variable N rate tramline.

Lower yields from the variable N rate compared to uniform N rate treatments may indicate that the lower N rate in some areas reduced yields. The N rates for the variable rate treatment were allocated based on measured NDVI and the total quantity of N fertiliser applied to the entire variable rate N treatment area was 92 kg/ha N – slightly lower than the 100 kg/ha N applied to the uniform N treatment.

However, comparison of yields from 6 x 5 m sub-plots with comparable initial NDVI values from the variable and uniform rate treatments indicates that the lower overall yield from the variable N rate treatment was unlikely to be due to N; Table 21 shows that marketable yields and mean marketable head weights were consistently lower from the variable N rate compared to uniform N rate treatment across the range of NDVI values measured prior to the second N application; the grid-plots from the variable rate treatment which received 100 kg N/ha for the second N application (i.e. the same as the flat rate treatment) yielded a mean of 33 t/ha compared to 36 t/ha from uniform N rate treatment. There was no evidence that higher N application at the second N timing (110 and 120 kg N/ha) to thinner areas of crop increased crop yields compared to the standard uniform N rate (100 kg N/ha). These results indicate that the initial variation in crop canopy assessed as NDVI four weeks after planting and just prior to the second N application was not a result of differences in N availability or crop N demand.

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[6] Crop value (after taking into account cost of nitrogen fertiliser) based on 12 p/head for heads 500-600 g (as whole fresh produce for retailers) and at 14 p/kg for heads >600g (for processing).

Table 21. Marketable yields and mean marketable head weights from the variable and uniform N tramline comparisons

NDVI	**N fertiliser rate (kg N/ha)**		**Marketable yield (t/ha fresh weight)**		**Mean marketable head weight (g)**	
	VR N	**Uniform N**	**VR N**	**Uniform N**	**VR N**	**Uniform N**
0.36	60	100	34	37	899	979
0.298	80	100	36	36	943	950
0.267	90	100	34	35	893	932
0.236	100	100	33	36	878	938
0.205	110	100	33	35	883	914
0.174	120	100	34	35	897	907
Overall mean			***34***	***36***	***898***	***943***

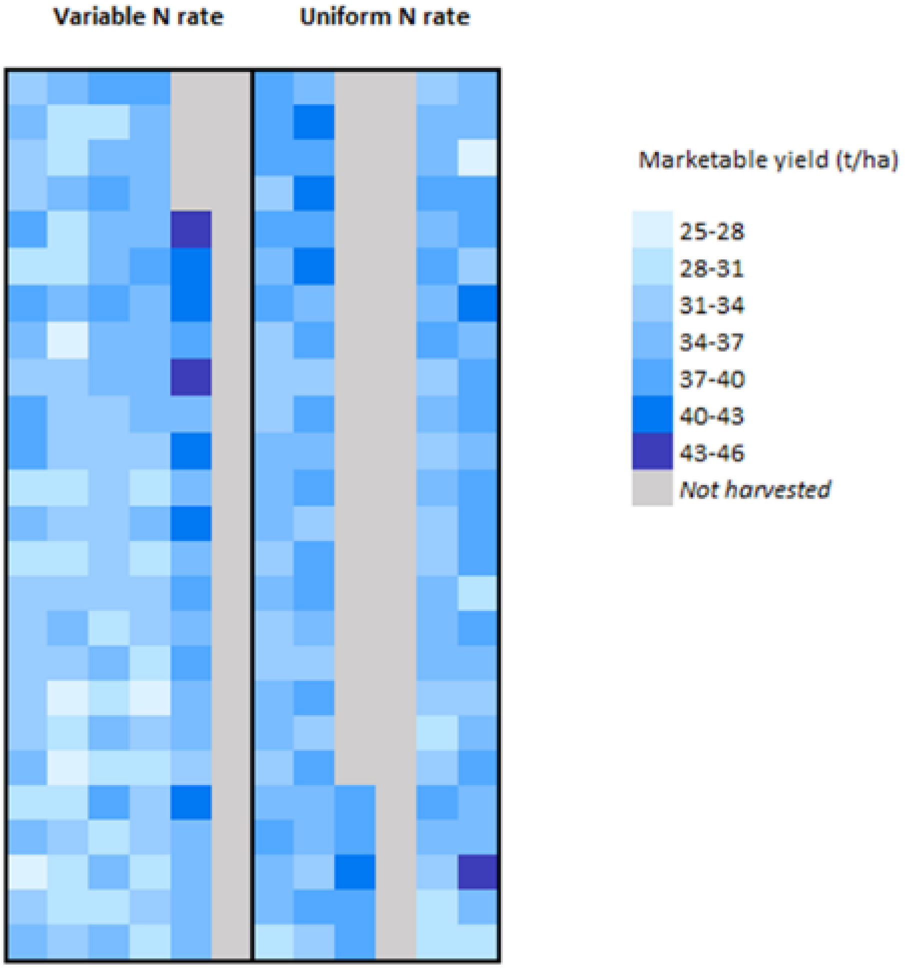

Figure 63. Yield map of tramline comparisons

However, comparison of leaf tissue analysis (sampled at the second N application four weeks post planting) from areas of cabbage which were identified as having low and high NDVI values (i.e. thinner and thicker crop canopy) did not provide any evidence that the differences in crop canopy could be attributed to differences in the availability and uptake of other plant nutrients (Table 22). There were no significant difference in leaf tissue analysis between lower and higher NDVI areas with the exception of Zn ($P<0.05$) and Fe ($P=0.05$). Leaf tissue Zn concentrations in the low NDVI areas were lower (31 mg/kg Zn) than in the high NDVI areas (33 mg/kg Zn). However Zn deficiency is very rare in the UK and Zn tissue analysis from the low NDVI areas was still above the threshold of 15-20 mg/kg Zn for indicating Zn deficiency[7]. Leaf tissue Fe concentrations were actually slightly lower in the high NDVI areas.

Table 22. Leaf tissue analysis from area of lower and higher NDVI

	N	**P**	**K**	**Mg**	**Ca**	**S**	**Mn**	**Cu**	**Fe**	**Zn**	**B**
	%					**mg/kg**					
Low NDVI	5.30	0.60	4.09	0.34	1.96	1.11	198	5.9	93	31	23
High NDVI	5.25	0.64	3.99	0.33	1.84	1.16	207	6.0	88	33	24
P-value	*0.71*	*0.16*	*0.28*	*0.36*	*0.25*	*0.34*	*0.39*	*0.56*	*0.05*	*0.03*	*0.35*

The CropScan crop reflectance measurements during the season from the lower and higher NDVI areas in the variable and uniform N treatments did not provide any evidence that the higher/lower variable N rate applications changed crop canopy growth compared to the uniform N application.

Figure 64 shows the frequency distribution of marketable head weights from the variable and uniform rate N treatments. There was no evidence that varying the N rate improved uniformity of cabbage head weights; the standard error of marketable height weights was similar between treatments (3.1 g and 3.2 g from the variable and uniform rate N treatments, respectively).

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[7] AHDB Nutrient Management Guide (RB209) Section 6 Vegetables and bulbs

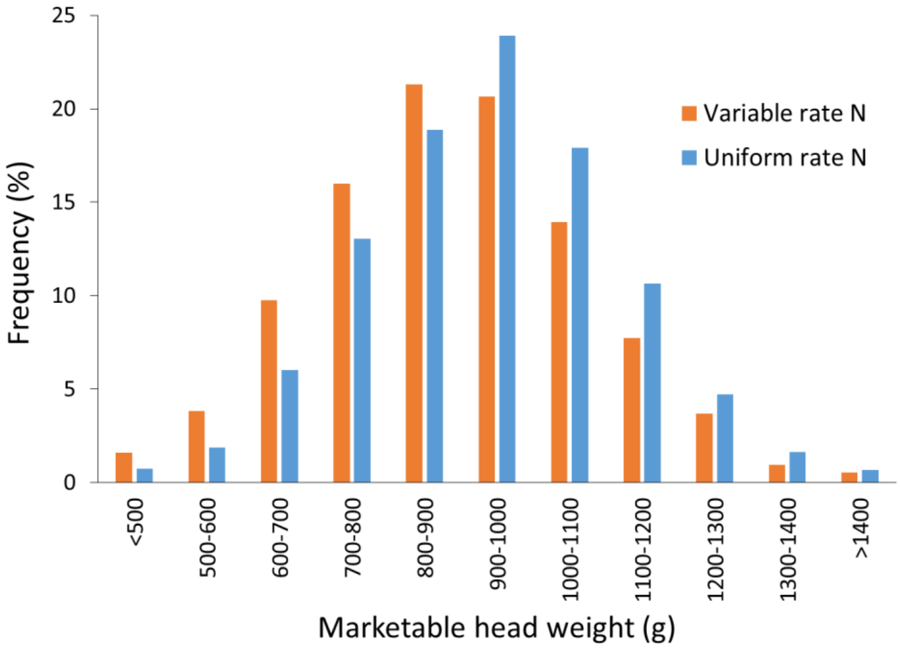

Figure 64. Frequency distribution of marketable head weights

Conclusions

The large yield response to N fertiliser and the strong relationship between crop reflectance measurements (NDVI) and above ground crop biomass and N uptake indicate that canopy sensing can be used as a basis to vary N applications and where N availability varies across the field and N is the main factor determining yield variability, we could potentially see the crop becoming more uniform and/or an overall yield increase. However, statistical analysis of N response data from the three experiments showed that, in this case, N response was similar across the length of the field.

Comparison of marketable head weights and total marketable yields from the uniform and variable rate N tramline comparisons indicated that varying the N rate did not increase total marketable yield or produce a more consistent sized crop in this demonstration field.

Variable rate N management will only be of benefit if N is the main cause of variability in the crop canopy. At this site, the N response experiments showed that the crop response to N was similar across the length of the field, and it is therefore likely that the variability in crop reflectance measured by the UAV was due to other soil or crop factors.

Canopy sensing for variable rate nitrogen applications to Brussels sprouts – W Clappison Ltd., Park Farm, Risby

Background

Canopy sensors are increasingly being used to variably apply N fertiliser to combinable arable crops. This technology may have the potential to improve N use efficiency in horticultural crops and this project has included two demonstrations of variable rate N management to brassica vegetable; the first in 2016 on Savoy cabbage and the second in 2017 on Brussels Sprouts (this demonstration). This demonstration used a similar approach to that sed on Savoy cabbage demonstration, but on a longer-season brassica crop.

Methods

Experimental site

The demonstration was hosted by W Clappison Ltd. at Park Farm, Risby, Yorkshire. The field was planted with Brussels sprouts (variety Petrus) at about 34,700 transplants/ha between late April and early May and harvested in January. The area of the field used for the demonstration was planted on 3rd May and harvested between 9th and 12th January.

Approach

The demonstration used the same approach as the demonstration on Savoy cabbage in 2016 and included N response experiments and tramline comparisons of uniform and variable rate N application set up to address the following questions:

- Does the optimum N rate for the crop vary across the field?
- Can we relate canopy sensing information to crop biomass and N uptake during the growing season?
- Can we demonstrate a benefit from variable rate N application?

Nitrogen response experiments

Nitrogen response experiments were replicated in two different areas of the field to see if there was any evidence of within field variation in optimum N rate. The field was EC scanned by Agrovista in mid-April prior to planting, and the EC map used as a guide to position the two N response experiment in areas of contrasting soil EC (Figure 65). Variable rate N management will only be of benefit where there is variability in the crop N requirement and this is more likely in areas of contrasting soil types/textures.

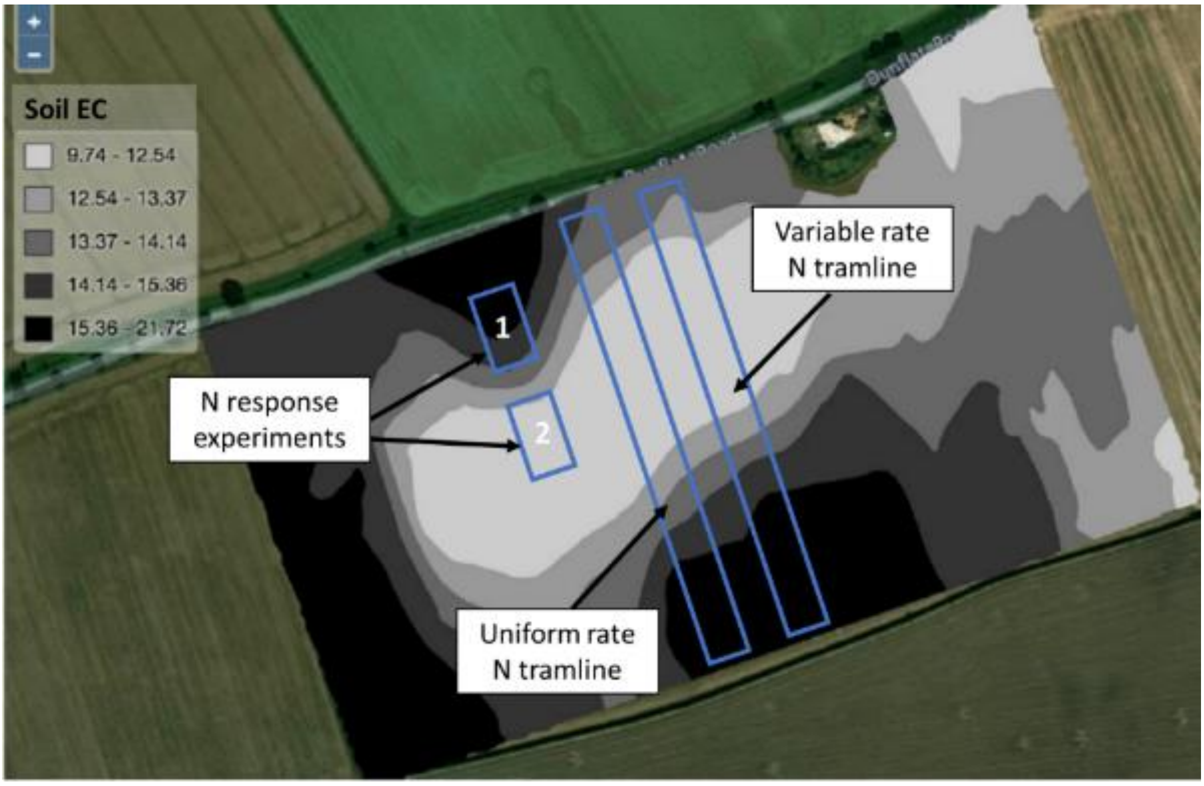

Figure 65. Field demonstration layout

Each experiment included seven N application rates (0, 80, 160, 200, 280, 340 and 400 kg N/ha; Table 23) replicated four times and arranged in a randomised block design. Each plot was 6 x 5 m and included ten rows of sprouts. All other fertilisers (apart from N) were applied by the farm at recommended rates to the whole field (including N response experiments and tramline treatments).

Table 23. Nitrogen response treatments fertiliser application rates and timings

Treatment number	**N fertiliser applied (kg N/ha)**			
	5th May	**14th June**	**27th June**	**Total**
1	0	0	0	0
2	50	30	0	80
3	80	60	20	160
4	100	80	40	220
5	120	100	60	280
6	150	120	70	340
7	180	140	80	400

Topsoil samples (0-15 cm depth) were taken from each of the N response experiment areas and analysed for pH, extractable P, K and Mg, organic matter and soil texture. Soil mineral N samples (0-90 cm) were also taken immediately prior to planting at the beginning of May (one sample from each area) and after harvest in January 2018 (from the 0, 280, 340 and 400 kg N/ha treatments).

A handheld CropScan sensor was used to measure reflectance from the crop canopy from each of the N response plots (7 N rates x 4 replicates x 2 N experiments = 56 plots) four times during the growing season: 14th June, 1st July, 27th July and 15th August. At the same time, crop samples were taken from the same area as the CropScan measurements from each N treatment in two replicate blocks of each experiment (7 N rates x 2 replicates x 2 N experiments = 28 crop samples): six Brussels sprout plants were cut at ground level and weighed to determine total biomass, and a subsample taken for dry matter and total N analysis in order to calculate total N uptake.

The N response plots were harvested between 10th and 12th January 2018 (Figure 66). Twenty sprout plants from each plot were cut at 5cm above ground and the total fresh weight recorded. The farms sprout harvester was used to strip the sprouts from the stalks and the total fresh weight of all sprouts was recorded. The farms grading machine was used to sort and grade the sprouts; this machine discards any discoloured or diseased sprouts and grades the marketable sprouts according to size (small 23-28 mm, medium 28-33 mm and large 33-38 mm). The 20 sprout plants from each plot were processed through the harvest and grading machines separately. The total fresh weight of all marketable sprouts in each size category was recorded. Separate representative sub-samples of crop residue and sprouts were taken from each plot for dry matter determination. The dried samples from each N treatment from each experiment for blocks 1 and 2, and from blocks 3 and 4 were combined (to give 2 samples for each N treatment from each experiment – 4 replicate samples from each N treatment in total) and sent to NRM laboratory for analysis of total N (7 N rates x 2 replicate samples x 2 N experiments = 28 samples in total).

Sprout plants at harvest *Plants were cut at ground level*

Harvest machine strips sprouts from stalk *Collecting sprouts from under harvester*

Sampling crop residue (leaves & stem) *Grading sprouts*

Figure 66. Harvesting sprouts from the N response plots (January 2018)

Sulphur response experiments

Sulphur fertiliser was applied to all of the N response plots at the farm standard rate of 175 kg SO_3/ha. An additional two S treatments were included within N response experiment 1 (0 and 100 kg SO_3/ha). The additional S treatments were included to quantify the yield response from the two S application rates (100 and 175 kg SO_3/ha) and were funded by Yara UK as an extension to the AHDB Horticulture project demonstration at this site. For detailed methodology and results see Appendix 4.

Tramline comparison

In addition, the farm standard uniform N application rate was compared to variable N management in tramline comparisons. The farm standard N rate was 305 kg N/ha and was applied in three splits –

- 135 kg N/ha on 3rd May at planting
- 100 kg N/ha on 14th June
- 70 kg N/ha on 27th June

For the variable rate N treatment, the third N application was varied between 30 and 110 kg N/ha (i.e. +/- 40 kg N/ha from the 70 kg N/ha farm standard) using crop canopy information. All fertiliser applications to the tramline comparisons were applied by the farm; the first N application was placed at planting and the second and third applications were applied using the farms spinning disc fertiliser spreader. Nitrogen was spread at a variable rate along two tramlines and at a uniform N rate along two tramlines and the areas between each set of two tramlines (24 x 306 m) were allocated as the treatment areas (Figure 67).

The precision farming company Precision Decisions provided a Yara N sensor which was mounted to the farm tractor and used to collect crop reflectance data. The whole field was scanned on 27th June and a variable rate N map created for the two variable rate N tramlines with minimum (30 kg N/ha) and maximum (110 kg N/ha) application rates set (Figure 67). The N application rate was higher to the thinner crop at the south of the field although a larger area of both tramlines received the lowest 30 kg N/ha application rate. The overall mean application rate across both the variable rate N tramlines was 45 kg N/ha, which is lower than applied to the uniform N tramlines (70 kg N/ha).

Topsoil samples (0-15 cm depth) were taken from each of the tramline treatment areas and analysed for pH, extractable P, K and Mg, organic matter and soil texture. Soil mineral N samples (0-90 cm) were also taken immediately prior to planting at the beginning of May (one sample from each tramline area).

The crop reflectance data from the Yara N sensor was used to identify three points within the tramlines comparison area where the crop was thicker, thinner and average compared to the rest of the field. Leaf samples[8] were taken from each of these areas on 27th June and analysed for total N, P, K, Mg, S, Mn, B, Cu, Zn and Fe to see whether there was any indication that the differences in crop canopy were attributable to differences in any other plant nutrients.

At harvest, marketable yields were measured by the farm from an area of each of the tramline treatments. The farm used their harvest equipment to harvest all the sprouts from a single strip (4 sprout rows) along the length of the field (306 m); the sprouts were collected and weighed and then graded and the weight of each grade recorded.

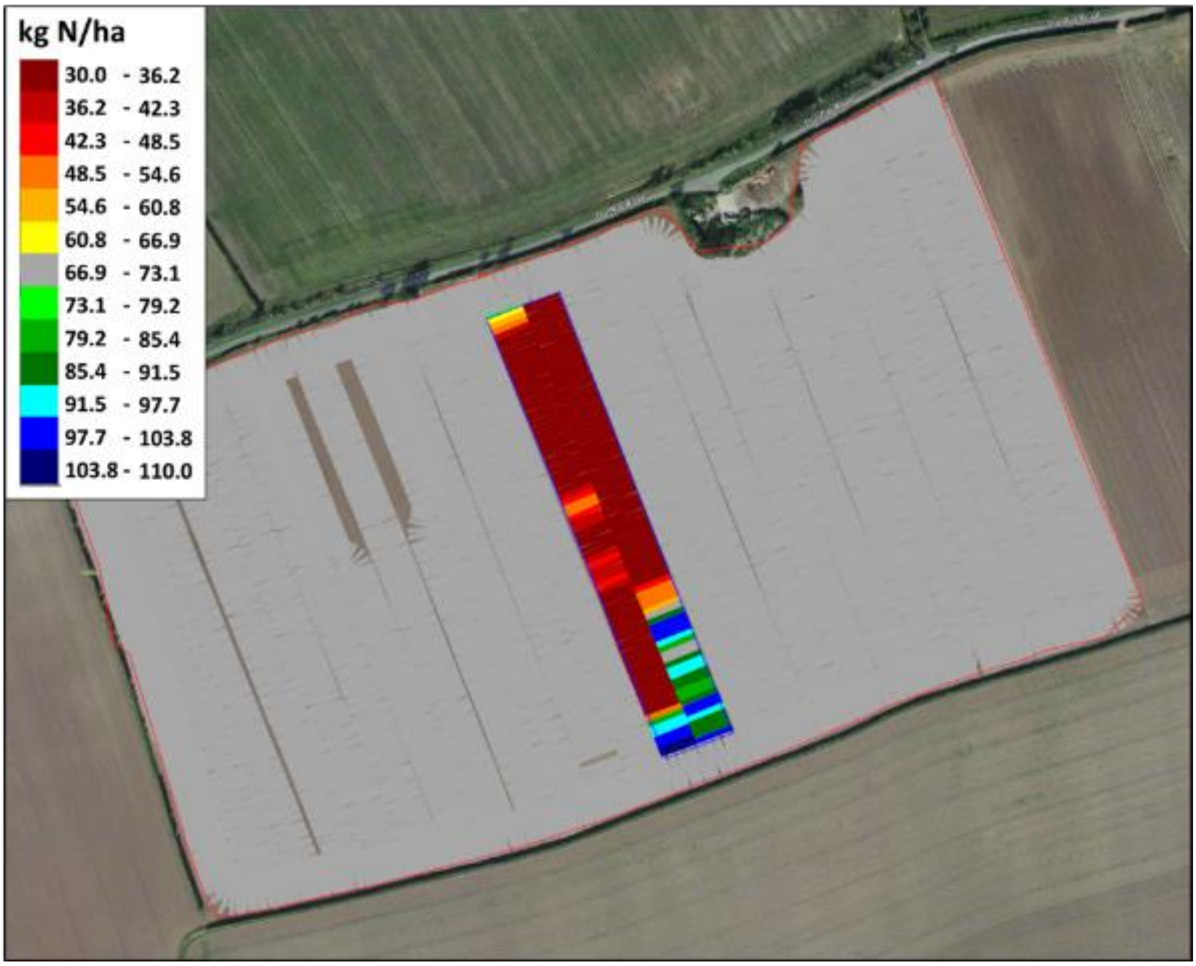

Figure 67. Variable rate N application map for the third N application to the two variable rate N tramlines

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[8] Each sample was a composite of the youngest fully expanded leaves from at least 20 plants in each area.

Results and discussion

Initial soil analysis

Soil mineral N samples (0-90 cm) were taken early May prior to planting, and showed higher SMN from N response experiment 1 (89 kg/ha; SNS Index 2) than experiment 2 (134 kg/ha; SNS Index 4). The two tramline comparison areas had very similar SMN levels at 121 and 124 kg/ha (SNS Index 3) from the uniform and variable treatments, respectively. The soil was a heavy/medium clay loam with an average P Index of 3, K Index +- and Mg Index 2 (Table 24). Although the two N response experiments were positioned in areas of different soil EC, soil analysis showed that soil texture and organic matter content were very similar between the two experimental areas (Table 24).

Table 24. Soil analysis from N response and tramline experimental areas

	Unit	**N response experiments**		**Tramline comparisons**	
		Exp 1	**Exp 2**	**Uniform N**	**Variable N**
pH	-	7.8	7.5	7.9	7.6
Extractable P	mg/l (index)	24 (2)	33 (3)	33 (3)	29 (3)
Extractable K	mg/l (index)	217 (2+)	223 (2+)	261 (2+)	213 (2+)
Extractable Mg	mg/l (index)	66 (2)	95 (2)	68 (2)	91 (2
Organic matter	%	4.6	4.4	4.2	4.2
Sand	%	29	32	34	32
Silt	%	42	40	41	43
Clay	%	29	28	25	25
Textural class[1]	-	HCL	HCL	MCL	MCL
SMN (0-90cm)	kg/ha	134	89	121	124

1. HCL = heavy clay loam; MCL = medium clay loam

Nitrogen response experiments

Crop reflectance data from the N response plots showed a strong relationship between NDVI and total biomass (Figure 68) and between NDVI and crop N uptake (Figure 69). An exponential model fitted to the total biomass data accounted for 93% of the variation in NDVI, and an exponential model fitted to the crop N uptake data accounted for 81% of the variation in NDVI. However, closer examination of the data shows that at the later sampling dates the exponential relationship has flattened off indicating that the NDVI vegetation index has saturated and is no longer sensitive to variation in biomass/crop N uptake. This indicates that canopy sensing can be used to provide a good proxy measure of variation in Brussels sprouts biomass and N uptake early in the season, but that later in the season as the crop develops a larger number of overlapping leaves the NDVI index saturates and no longer provides a good measure of variation in biomass or crop N uptake. Appendix 3 includes a more detailed analysis of the performance of ten different vegetation indices calculated from the CropScan data (including NDVI) in predicting crop biomass and N uptake during the season.

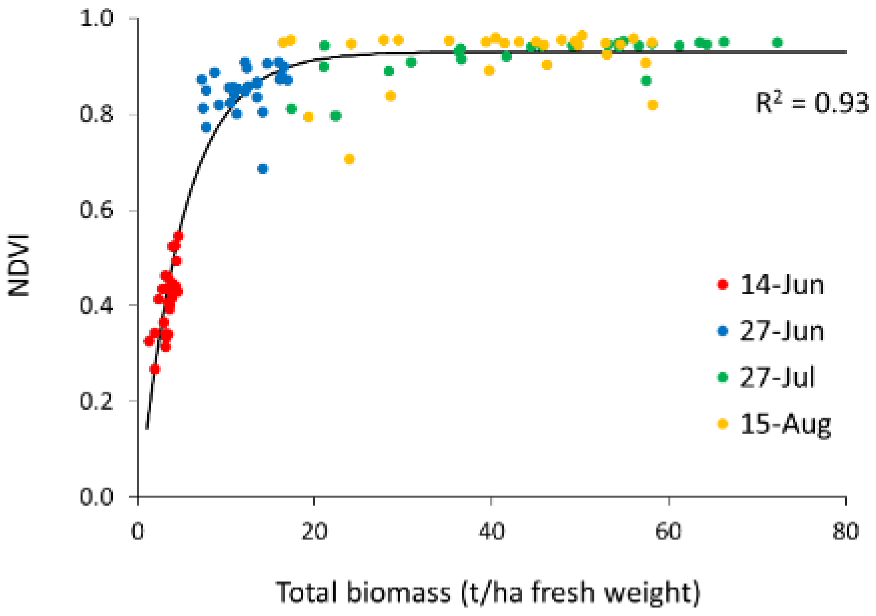

Figure 68. Relationship between NDVI and total biomass

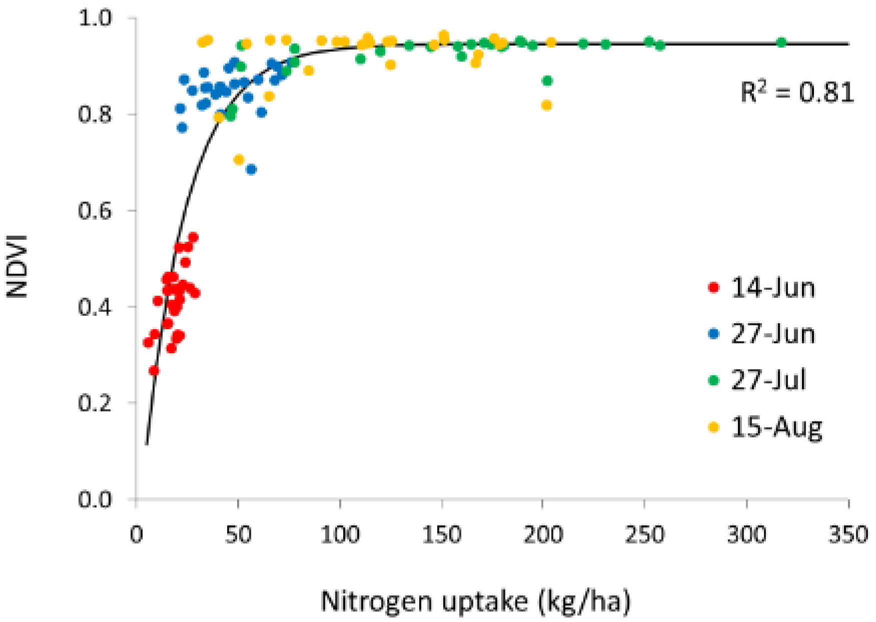

Figure 69.Relationship between NDVI and crop N uptake

There was a significant yield response to N fertiliser (Table 25 and Figure 70). The percentage of marketable sprouts (assessed using the farms grading machine) increased from a mean of 37% on the zero N treatment, to >70% at N rates greater than 280 kg N/ha. Fresh weight marketable yield increased from 5 t/ha on the zero N treatment to 25 t/ha at 280 kg N/ha and a maximum of 26 t/ha at the highest N rate of 400 kg N/ha. The marketable sprouts were graded into small, medium and large size categories; increasing the N fertiliser rate reduced the proportion of small sprouts and increased the proportion of medium and large sprouts (Table 25). Although in the past smaller sprouts were sold for a higher value, the farm now sell the three size grades for the same value (£600 per tonne fresh weight for all marketable grades).

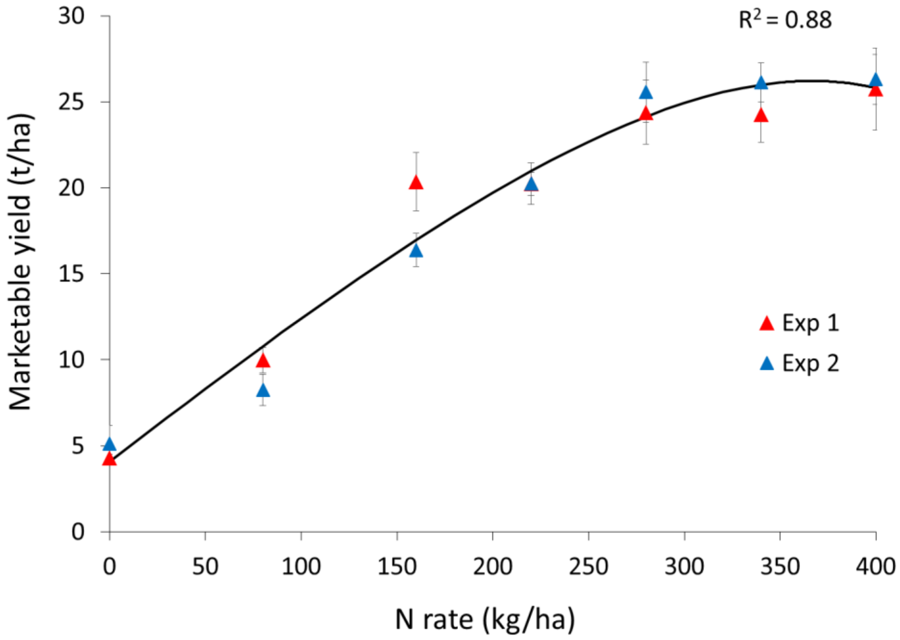

Figure 70. Marketable yield - response to N fertiliser

The value of the crop at the different fertiliser N rates was calculated after taking into account the price of N fertiliser (assuming £240/tonne for ammonium nitrate, equivalent to 70 p/kg N) (Figure 71). Genstat was used to fit curves to the marketable yield and crop value data from the N response experiments. Regression analysis showed that fitting separate curves for each of the N response experiments was not statistically justified, i.e. the crop response to N was not significantly different between the two N response experiments. A linear plus exponential model fitted to the marketable yield and crop value data from both N response experiments explained 88.1% and 87.7% of variation in marketable yield and crop value data respectively. The economic optimum N rate (based on £600/t for the crop and £0.70 p/kg N) was 365 kg N/ha giving a predicted yield of 26.2 t/ha and crop value £15,468/ha.

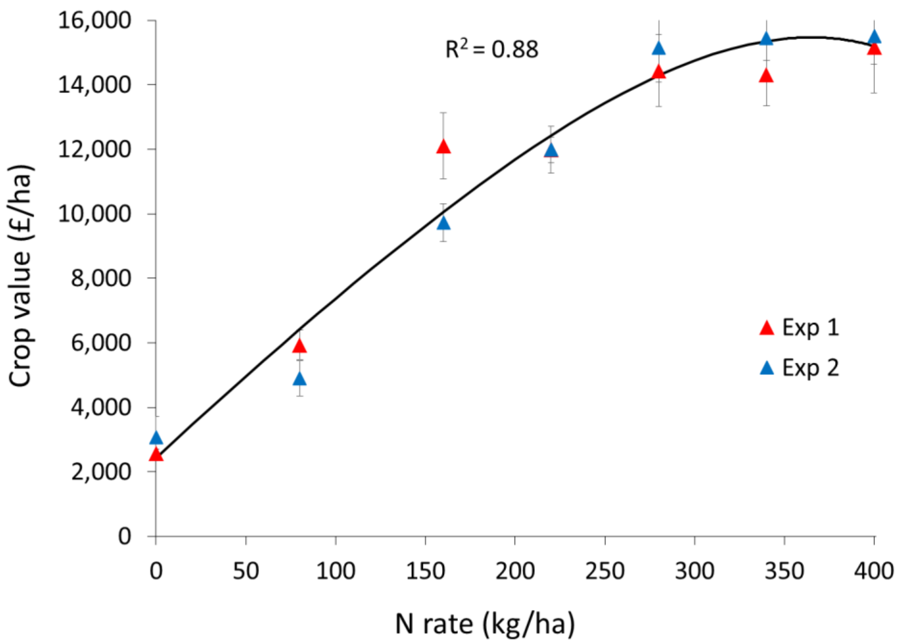

Figure 71. Increase in crop value with N fertiliser (taking into account cost of N fertiliser)

The total above ground crop N uptake increased from 68 kg N/ha on the zero N treatment to 190 kg N/ha at the 280 kg N/ha fertiliser N rate and a maximum of 227 kg N/ha at the highest N rate of 400 kg N/ha. Fertiliser N use efficiency[9] was a mean of 60% and did not vary much with fertiliser N rate (Table 26).

The sprouts were stripped from the stalks using the farm's harvester and the crop residue (stems and leaves) was left on the soil surface (Figure 66). The quantity of crop residue increased from 14 t/ha (fresh weight) on the zero N treatment to 35 t/ha at the 280 kg N/ha fertiliser N rate and a maximum of 45 t/ha at the highest N rate of 400 kg N/ha. The N in crop residue increased from 39 kg N/ha on the zero N treatment to 101 kg N/ha at the 280 kg N/ha fertiliser N rate and a maximum of 132 kg N/ha at the highest fertiliser N rate of 400 kg N/ha (Table 26).

Soil mineral N (0-90cm) measured after harvest in January 2018 from the 0, 280, 340 and 400 kg N/ha fertiliser treatments was low at 11, 13, 15 and 15 kg/ha N, respectively. Although mineralisation of crop residue N will contribute to SMN, the sprouts were harvested in January when the soil was cold and there is unlikely to be significant mineralisation of crop residue N until the soil temperature increases in the spring.

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[9] Fertiliser N use efficiency = [(Crop N uptake – crop N uptake on zero N control)/Fertiliser N applied] x 100

Table 25. Effect of N fertiliser rate on total sprout yields, marketable yields and percentage of marketable sprouts in each size category

N rate kg N/ha	**Total sprout yield (t/ha fresh weight)**			**% sprouts marketable**			**Marketable yield (t/ha fresh weight)**		
	Exp. 1	**Exp. 2**	**Mean**	**Exp. 1**	**Exp. 2**	**Mean**	**Exp. 1**	**Exp. 2**	**Mean**
0	13	13	13	32	41	37	4	5	5
80	21	19	20	48	42	45	10	8	9
160	31	26	28	65	62	64	20	16	18
220	31	31	31	65	66	65	20	20	20
280	34	35	35	71	72	72	24	26	25
340	35	36	36	68	72	70	24	26	25
400	37	37	37	69	71	70	26	26	26

	Percentage of marketable yield in each size category								
	Experiment 1			**Experiment 2**			**Mean (Exp. 1 and Exp. 2)**		
N rate kg N/ha	**% Small (22-28 mm)**	**% Medium (28-33 mm)**	**% Large (33-38 mm)**	**% Small (22-28 mm)**	**% Medium (28-33 mm)**	**% Large (33-38 mm)**	**% Small (22-28 mm)**	**% Medium (28-33 mm)**	**% Large (33-38 mm)**
0	62	26	12	62	28	10	62	27	11
80	52	34	14	52	30	18	52	32	16
160	37	43	20	45	41	14	41	42	17
220	37	48	14	35	50	15	36	49	15
280	32	52	16	28	48	25	30	50	20
340	31	50	20	28	50	22	29	50	21
400	27	51	22	27	52	21	27	52	21

Table 26. Effect of N fertiliser rate on total N uptake, fertiliser N use efficiency and crop residues

N rate **kg N/ha**	**Total N uptake (above ground at harvest)**			**N use efficiency (%)**		
	Exp. 1	**Exp. 2**	**Mean**	**Exp. 1**	**Exp. 2**	**Mean**
0	70	66	68	*	*	*
80	104	91	98	54	40	47
160	165	128	146	82	53	67
220	162	160	161	57	60	59
280	184	195	190	59	68	63
340	204	207	205	62	62	62
400	233	222	227	62	59	61

N rate **kg N/ha**	**Crop residues (t/ha fresh weight)[1]**			**Crop residues (kg N/ha)**		
	Exp. 1	**Exp. 2**	**Mean**	**Exp. 1**	**Exp. 2**	**Mean**
0	16	13	14	44	35	39
80	20	17	19	54	42	48
160	31	24	27	83	60	72
220	30	29	29	82	76	79
280	35	36	35	99	102	101
340	43	38	41	129	112	121
400	45	44	45	141	123	132

Leaf samples

Comparison of leaf tissue analysis (sampled immediately prior to the third N application) from areas which were identified as having high, moderate and low crop reflectance (compared to the rest of the field) showed an increasing trend in % N content from low (6.1% N) to high (7.3% % N) crop reflectance (Table 27). This indicates that the thicker crop (as indicated by higher crop reflectance) had higher N status and may therefore also indicate that differences in N availability/crop N uptake contributed to crop variability. There was no evidence that the differences in crop canopy could be attributed to differences in the availability of any of the other measured plant nutrients (Table 27).

Table 27. Leaf tissue analysis from area of high, moderate and low crop reflectance

Crop reflectance	**N**	**P**	**K**	**Mg**	**Ca**	**S**	**Mn**	**Cu**	**Fe**	**Zn**	**B**
	%					**mg/kg**					
High	7.3	0.80	3.25	0.22	0.77	1.04	44	6.1	201	62	27
Moderate	7.0	0.83	3.25	0.20	0.86	1.05	50	6.2	216	65	27
Low	6.1	0.67	3.21	0.20	0.90	1.09	45	6.3	149	65	25

Tramline comparisons

Marketable yield was 1.4 t/ha greater from the variable rate than uniform N rate tramline, despite the overall lower N application rate to the variable rate tramline; the average N application to the variable rate tramline was 45 kg N/ha at the third N application (total N application 280 kg N/ha) compared to 70 kg N/ha at the third N application (total N application 305 kg N/ha) to the uniform N rate tramline. The proportion of sprouts in the small size category is notably lower and the proportion of sprouts in the large size category is notably higher from the variable rate compared to the uniform N rate treatments (Table 28).

However the yield difference is small (*c*.3%) and it is not possible to assess whether the yields from the two tramlines are statistically significantly different without replicate measurements.

Table 28. Total sprout yields, marketable yields and percentage of marketable sprouts in each size category from the variable and uniform N tramline comparisons

	Variable rate N	Uniform N rate
Total sprout yield (t/ha fresh weight)	30.8	32.1
% sprouts marketable	78.8	78.0
Marketable yield (t/ha fresh weight)	24.3	25.1
% small (23-28 mm) marketable sprouts	11.2	30.5
% medium (28-33 mm) marketable sprouts	57.7	58.3
% large (33-28 mm)marketable sprouts	31.2	11.3

Conclusions

There was a good relationship between crop reflectance measurements (NDVI) and above ground biomass and N uptake early in the season 6 weeks post planting, however later in the season the NDVI index appeared to saturate and no longer provided a good measure of variation in crop biomass/N uptake. The results indicate that canopy sensing can be used to provide a good proxy measure of variation in Brussels sprouts biomass and N uptake and may be used as the basis to vary N applications early in the season, but may not be as effective in identifying biomass/N uptake differences later in the season as the crop develops a larger number of overlapping leaves.

Soil mineral N sampling prior to planting from the two N response experiment areas showed higher background SMN levels from N response experiment 1 (89 kg N/ha) than experiment 2 (134 kg N/ha). However, despite the difference in background SMN levels, statistical analysis of N response marketable yield data showed that N response was similar from the two experimental areas.

Leaf tissue analysis showed lower N content in areas of thinner than thicker crop. Comparison of marketable yields from the uniform and variable rate N tramline comparisons showed slighter higher yields and a greater proportion of large sprouts from the variable rate N treatment. However, the yield difference (1.4 t/ha) was small and it was not possible to assess whether the yields from the two tramlines were statistically significantly different without replicate measurements. Field scale tramline or split field comparisons are increasingly being used to assess variable rate N applications to combinable arable crops where combine yield maps can be used to quantify any yield benefit. The uniform and variable N rate tramline comparisons in this project (on both Savoy cabbage and Brussels sprouts) have highlighted the difficulties in assessing any yield benefit without field scale yield monitoring equipment.

Focus on variability – G's growers, Cambridgeshire (lettuce)

Background

Consistency of crop size and quality are key issues for growers. However, within-field variability in crop growth is usually apparent in most crops and fields. Soil variability is one of the main factors determining differences in crop growth within and between fields. Variations in soil texture, moisture holding capacity, organic matter content, nutrient content, drainage, compaction and soil depth are reflected in crop growth differences. Precision farming tools such as soil mapping, canopy sensing and yield mapping can provide growers with valuable information about the variability of their soils and crops. Growers need to be able to understand their soil and crop variability before they can attempt to manage it. The challenge for growers, agronomists and researchers is to try and disentangle the various soil and other yield-limiting factors to understand which are most important in driving crop variability.

The overall aim of this field demonstration was to use a case study field to demonstrate to growers the various precision farming tools available to them to measure variation in their soils and crops and to consider how best to use these tools to help quantify, understand and manage within field soil/crop variability.

Methods

Experimental site

The demonstration was hosted by G's Growers in P16 field at Redmere Farm near Littleport, Ely, Cambs. (Figure 72). P16 is approximately 30 ha and national soil survey maps show three soil series within the field: Adventures (peat soil), Willingham (carbonic loam) and Downholland (humic-alluvial gley soil). The field was planted with iceberg lettuce transplants (nine different varieties) between 20th and 27th April 2017. The lettuce transplants were grown for 7.5 weeks and harvested between 11th and 17th June.

Figure 72. P16 field at Redmere Farm

Measuring soil variability

Soil electrical conductivity (EC) information for P16 was provided by G’s Growers. The field was EC scanned the precision farming company Fresh Produce Consultancy in August 2016 using a Veris 3100 EC scanner which measures EC at two depths (0-30 cm and 0-60 cm). Satellite soil brightness imagery for the field was provided by Intelligent Precision Farming (IPF – owned by The Courtyard Partnership).

Soil management zones were created for P16 field by IPF based on a field survey and satellite soil brightness maps. Available geological data, Google satellite images, previous national soil survey data and satellite soil brightness maps were collected and used to guide the field survey, which was carried out in March 2017. The field survey used standard soil survey techniques and one observation point per hectare (using a soil auger up to 1 m depth). This information was combined to delineate ten soil management zones in P16 field (Figure 73).

Soil zones 9 and 10 (Figure 73) were selected for more detailed soil physical measurements to assess whether the soil structural condition varied between these two zones. In May 2017 the following soil physical measurements were made in each zone:

- Penetrometer measurements to 50 cm depth – maximum resistance and depth of maximum resistance (20 per zone).
- Dry bulk density (BD) at 10-15 cm depth (3 assessments per zone at the points of minimum, mean and maximum penetration resistance).

- Visual Evaluation of Soil Structure (VESS assessment; Guimaraes *et al*., 2011) (3 assessments per zone at the points of minimum, mean and maximum penetration resistance).

In addition three soil moisture sensors (Sentek EasyAG capacitance probes) were installed by G's Growers in zones 9 and 10 to record variation in soil moisture during the growing season. The sensors measure moisture content at 10 cm, 20 cm, 30 cm, 40 cm and 50 cm and were installed on 16th May and removed at harvest in mid-June.

Figure 73. P16 field soil zones based on soil survey (defined by IPF)

Topsoil samples (0-15 cm) were taken from P16 field in February 2017 by Fresh Produce consultancy. The field was divided into approximately 30 1 ha area and a single composite sample (of 25 soil cores) was taken from each 1 ha block by walking a 'W' in each block. All soil samples were analysed by NRM Ltd. for pH, extractable P (Olsen's extraction), K and Mg (ammonium nitrate extract), organic matter (loss on ignition method) and particle size distribution (soil texture).

Soil EC data from the Veris EC 3100 scanner was used to provide an mean shallow (0-30 cm) EC value for each of sampled 1 ha areas. Regression analysis was used to assess the relationship between EC and each of the measured soil parameters (pH, P, K, Mg, organic matter, % sand, % silt and % clay).

Measuring crop variability

Crop canopy sensing was used to provide a measure of crop variability across the field. Crop reflectance data was collected using three different methods to provide examples of some of the different platforms available for collecting this type of crop information. Data was collected between 18th and 23rd May approximately 4 week after planting using:

- Light manned aircraft (18th May): G's Growers provided high resolution (*c*.5 cm) NDVI imagery from Spectrum Aviation collected using light manned aircraft.
- Tractor mounted Isaria sensor (23rd May): provided by Phieldtek Precision Agronomy.
- Satellite crop sensing (22nd May): IPF provided NDVI satellite imagery for the field.

Targeted soil and crop sampling

Crop reflectance data from the Isaria sensor was used to identify contrasting areas of thinner and thicker crops within five blocks of different lettuce varieties in P16 (10 points in total). Topsoil (0-15 cm) and leaf samples were taken from each of these areas on 13th June. Samples were taken from a 5m radius area of the central GPS located point; each topsoil samples was a composite sample of 25 soil cores and each leaf sample was a composite sample of 25 youngest fully expanded leaves.

Soil and leaf samples were analysed by NRM Ltd. Topsoil samples were analysed for pH, extractable P (Olsen's extraction), extractable K, Mg and Ca (ammonium nitrate extract), organic matter (loss on ignition method), particle size distribution (soil texture), NH_4-N and NO_3-N, extractable S (phosphate buffer extract), EDTA extractable Cu and Zn, hot water soluble B and DPTA extractable Fe and Mn. Leaf tissue samples were analysed for total N (Dumas method) and total P, K, Mg, Ca, S, Mn, Cu, Zn, Fe and B (nitric/hydrochloric acid digest and analysis by ICP-OES).

Harvest assessments were also carried out at each of the 10 points immediately prior to the commercial harvest (on 13/14th June in zones 1-3 and on 19th June in zones 4 and 5). Ten lettuce heads were harvested from each area (two rows of five lettuces); the lettuce heads were timed as per commercial practice and marketable head weight was recorded.

Results

Measuring soil variability

1. *Soil EC*

Figure 75 shows soil EC maps for P16 field produced from the Veris 3100 EC scanner. The shallow soil EC map identifies three areas of higher EC in north east, central southern, and central western parts of the field, which correspond to areas of higher organic matter (Figure 77). There was a significant relationship between shallow soil EC and organic matter content

(*P*<0.01), but no relationship (*P*>0.05) between shallow soil EC and % sand, silt or clay (Table 29 and Figure 74). This is in contrast to the results from the soil mapping demonstration in Avenue Field where there was a stronger relationship between soil EC and texture than soil EC and organic matter (Table 3), however the variation in soil organic matter in P16 field (7.4 to 44.8% organic matter) is much greater than the variation in Avenue Field (2.1 to 4.1% organic matter, Table 2). There was no relationship between shallow soil EC and soil extractable P, K or Mg (*P*>0.05).

Table 29. Relationship between shallow soil EC (0-30 cm) and other measured soil parameters (n=30)

Soil analysis	**R^2**	***P*-value**
Organic matter	0.30	<0.01
Sand	0.00	0.98
Silt	0.05	0.26
Clay	0.01	0.66
pH	0.11	0.07
P	0.01	0.63
K	0.02	0.42
Mg	0.00	0.99

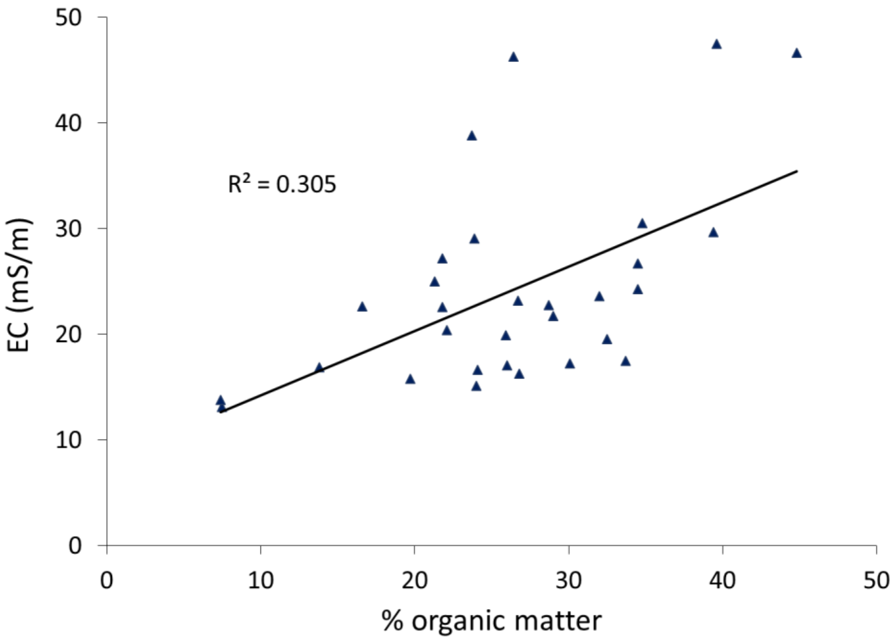

Figure 74. Relationship between shallow soil EC and % organic matter content

Boubou (2018) also looked at the use of soil EC at Redmere Farm as part of an AHDB-funded studentship on understanding the causes of in-field variation in lettuce crop maturity and yield.

In the fields used in this project shallow EC did not correlate with either lettuce yield or any of the measured soil parameters (soil texture, organic matter, soil pH or nutrient content). It was noted that there is very little published scientific information on the use of EC measurements on organic/peat soils.

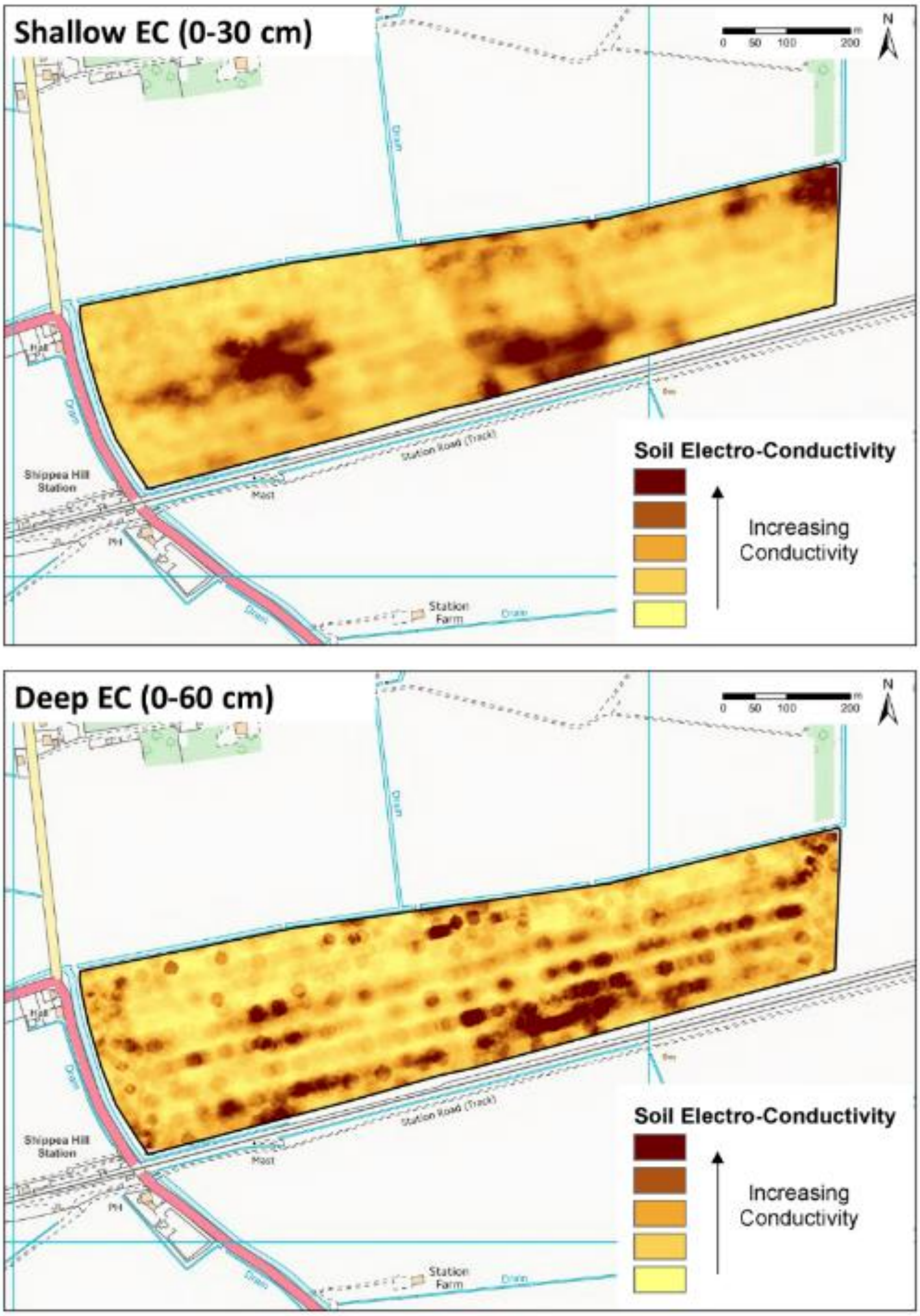

Figure 75. P16 field soil EC maps

2. Soil brightness

Figure 76 shows a soil brightness map for P16 field. This map clearly identifies a lighter area in the south east section of the field, which corresponds to the area of lowest soil organic matter. The darker areas in the north east and south west sections of the field also correspond to the areas of highest soil organic matter (Figure 77).

Figure 76. P16 field satellite soil brightness

3. *Soil sampling*

Topsoil sampling and analysis showed a large variation in soil organic matter content from a minimum of 7% to a maximum of 45% (Table 30 and Figure 77). Soil pH varied slightly from 7.3-8.3 (Figure 78), but all samples were above the target soil pH of 6.5. Soil extractable P varied from 27 mg/l (Index 3) to 42 mg/l (Index 3) (Figure 79), extractable K varied from 126 mg/l (Index 2-) to 255 mg/l (Index 3) (Figure 80) and extractable Mg varied from 41 mg/l (Index 1) to 163 mg/l (Index 3) (Figure 81) (Table 30). The area of lowest soil organic matter in the south east section of the field also corresponded to areas of lower soil extractable P, K and Mg. There was a significant positive relationship between soil organic matter and soil P and Mg (Table 31).

Table 30. P16 field soil topsoil analysis - mean, minimum and maximum values (n=30)

	Organic matter %	Sand (%)	Silt (%)	Clay (%)	pH	P	K	Mg
						mg/l (Index)		
Mean	26.4	18	43	38	7.8	42 (3)	189 (2+)	91 (2)
Min	7.4	9	35	25	7.3	27 (3)	126 (2-)	41 (1)
Max	44.8	40	48	47	8.3	62 (4)	255 (3)	163 (3)

Table 31. Relationship between soil organic matter and other measured soil parameters (n=30)

Soil analysis	R^2	*P*-value
Sand	0.02	0.51
Silt	0.22	0.01
Clay	0.12	0.06
pH	0.60	<0.01
P	0.20	0.01
K	0.07	0.15
Mg	0.29	<0.01

Figure 77. P16 field % soil organic matter

Figure 78. P16 field soil pH

Figure 79. P16 field soil extractable P

Figure 80. P16 field soil extractable K

Figure 81. P16 field soil extractable Mg

4. Soil physical measurements and visual evaluation scores

Soil visual evaluation in May 2017 assessed the soil in the contrasting peaty loam (zone 9) and silty clay loam soil zones as friable. Penetrometer resistance and bulk density measurements were greater ($P<0.05$) in the silty clay loam zone reflecting the lower soil organic matter content, however these values are not of concern and there was no evidence of compaction or soil structural issues which could be limiting to crop growth in either zone (Table 32).

Table 32. Soil structure assessments in P16

Assessment	P16 field zones (Figure 73)	
	Zone 9 (Loamy peat)	Zone 10 (Silty clay loam)
VESS score of (mean of 3 replicates) (1-Friable, 2-Intact, 3-Firm, 4-Compact, 5-Very Compact)	1.7 (ns)	1.8 (ns)
VESS score of poorest layer (mean of 3 replicates) (1-Friable, 2-Intact, 3-Firm, 4-Compact, 5-Very Compact)	1.7 (ns)	1.8 (ns)
Topsoil penetrometer max resistance (kPa) (mean of 20)	410*	459*
Depth of max resistance (cm) (mean of 20)	45 (ns)	42 (ns)
Mid topsoil bulk density (g/cm^3) (mean of 3 replicates)	0.54**	0.93**
Mid subsoil bulk density (g/cm^3) (mean of 3 replicates)	0.64*	0.89*

Note – * indicates significant differences between treatments *P*<0.05; ** indicates significant differences between treatments *P*<0.01; ns – not significantly different.

5. Soil moisture

Soil moisture content was consistently higher in the loamy peat than silty clay loam zone (at all soil depths) (Figure 82), reflecting the greater moisture holding capacity of the higher organic matter soil. Although the lettuce crop was irrigated it is clear that the differences in soil type have an important effect on soil moisture content, which may impact on crop yields.

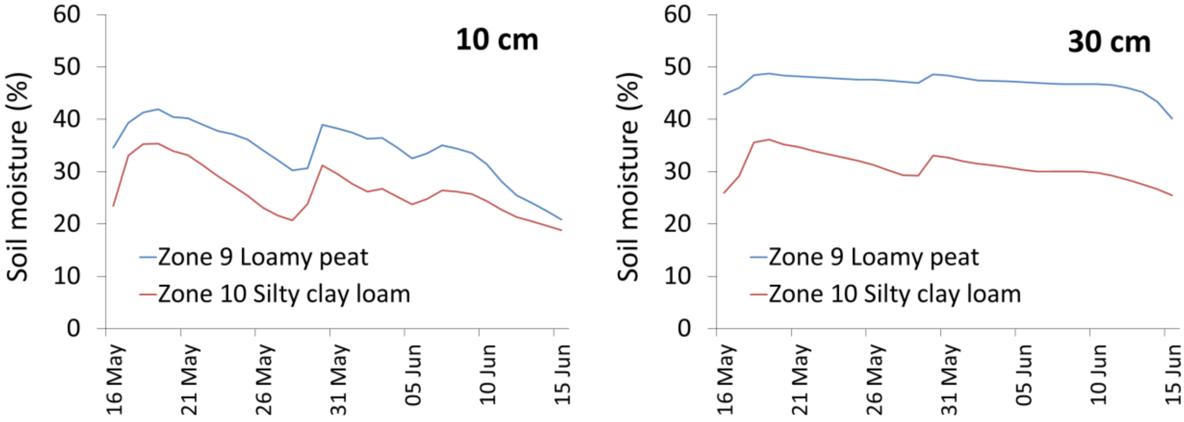

Figure 82. Soil moisture measured at 10 cm (left) and 30 cm (right) in the contrasting loamy peat and silty clay loam soil zones

Measuring crop variability

Figure 83 to Figure 85 show crop canopy reflectance data collected from the three different platforms (satellite, tractor mounted and manned light aircraft) between 18th and 22nd May approximately 4 weeks after planting. The satellite and manned light aircraft platforms provide maps of the NDVI vegetation index. The Isaria tractor mounted sensor provides two vegetation indices; IBI (an indicator of crop biomass) and IRMI (an indicator of crop N content). All three platforms provide crop reflectance data that shows broadly similar patterns, although there are clear differences in the level of resolution in the data.

Satellite imagery is collected remotely and is therefore relatively cheap to source compared to other methods of canopy sensing, however it also tends to provide lower resolution data (typically 10 m resolution) than other platforms. The satellite NDVI map (Figure 83) identifies an area of lower NDVI (thinner crop) in the southeast section of the field, which corresponds to the area of lower soil organic matter (Figure 77). The thinner vertical north-south strip of lower NDVI in the middle of the field corresponds to a wide uncropped trackway, which has been removed from the crop canopy maps produced from the Isaria sensor and manned light aircraft. The satellite image also identifies patches of higher NDVI that correspond to areas of higher soil organic matter, notably in the northeast section of the field (Figure 77). However, the satellite map shows a limited number of NDVI colour bands, especially compared to the canopy maps produced from the Isaria sensor and manned light aircraft.

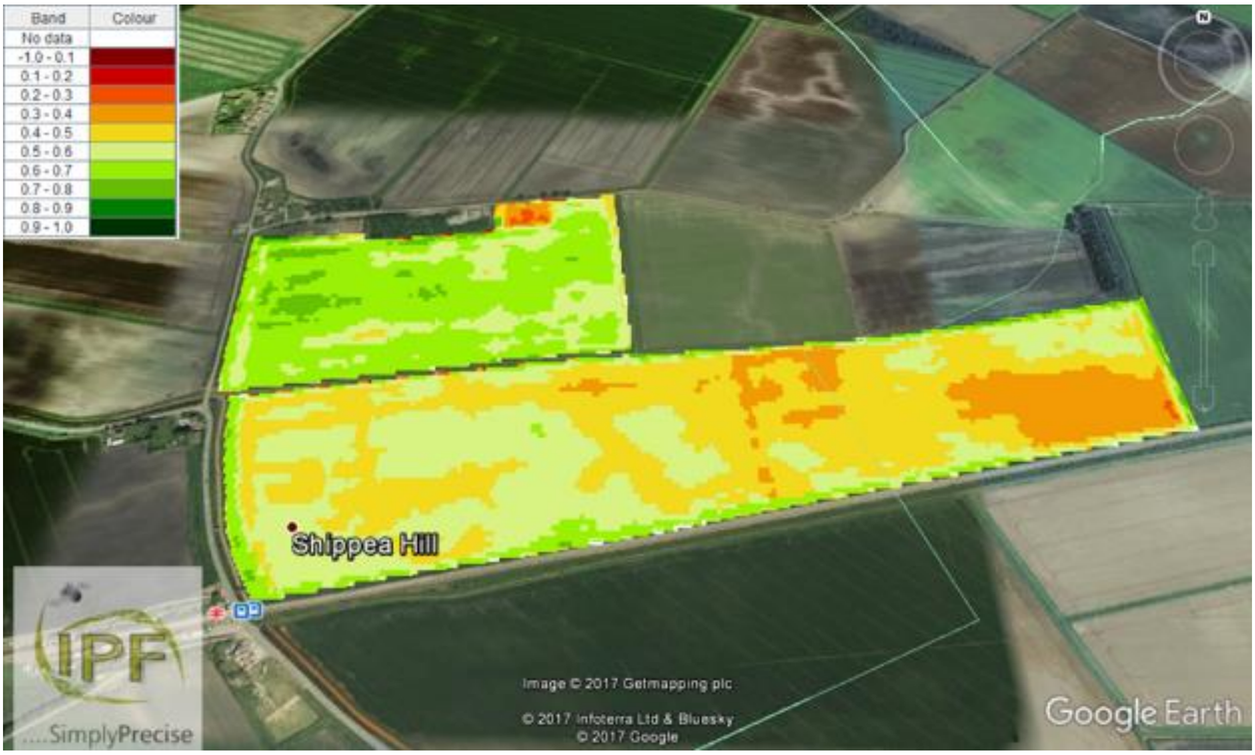

Figure 83. Satellite canopy sensing NDVI (22/05/2017)

The Isaria IBI and IRMI vegetation index maps (Figure 84) show a similar pattern of crop variation, although there are some differences between the two maps as they measure at different wavelengths. Both maps show an area of lower vegetation index in the south east section extending to middle northern section of the field, which includes the area of lower NDVI identified by the satellite image (Figure 83) and corresponds to areas of lower soil organic matter content (Figure 77). Similarly, the areas of higher soil organic matter correspond to areas of higher IBI and IRMI values. Visual comparison of the Isaria IBI and IRMI maps to the NDVI maps from satellite and manned light aircraft indicates that the IBI index, which provides a measure of crop biomass, corresponds better than the IRMI index to the pattern shown in the NDVI maps.

The manned light aircraft provides the highest resolution crop canopy information (*c*. 5 cm resolution). The pattern of variation shown in this map (Figure 85) is similar to that shown in the Isaria and satellite images, although the level of resolution is much greater, and the areas of higher and lower NDVI correspond to areas of lower and higher soil organic matter (Figure 77).

The field was planted with 9 different iceberg lettuce varieties planted and harvested over the course of one week. Differences in varieties and planting date can also be expected to have an impact on crop growth, although differences shown in crop reflectance data from all three platforms were dominated by irregular shaped patterns rather than clear planting blocks.

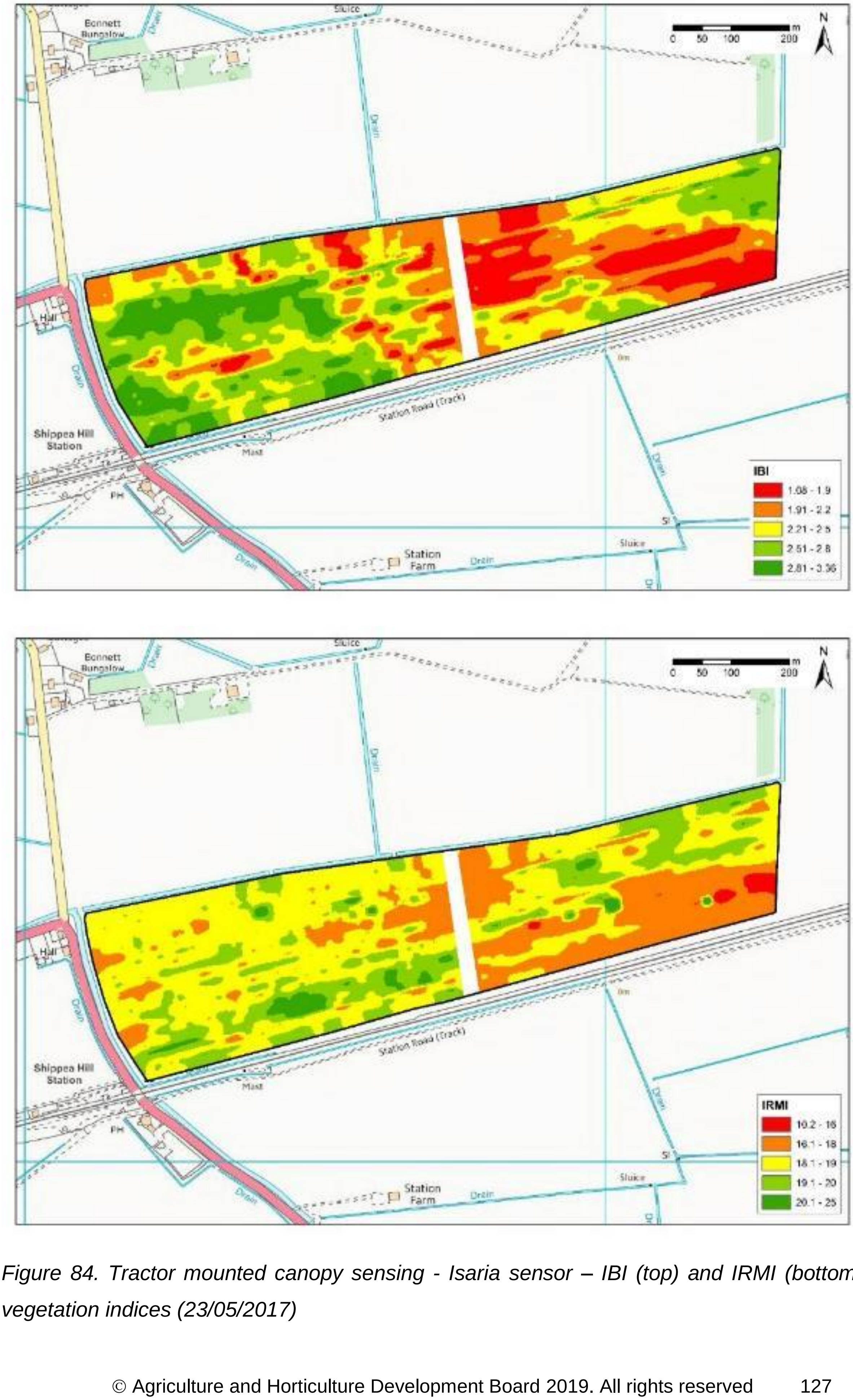

Figure 84. Tractor mounted canopy sensing - Isaria sensor – IBI (top) and IRMI (bottom) vegetation indices (23/05/2017)

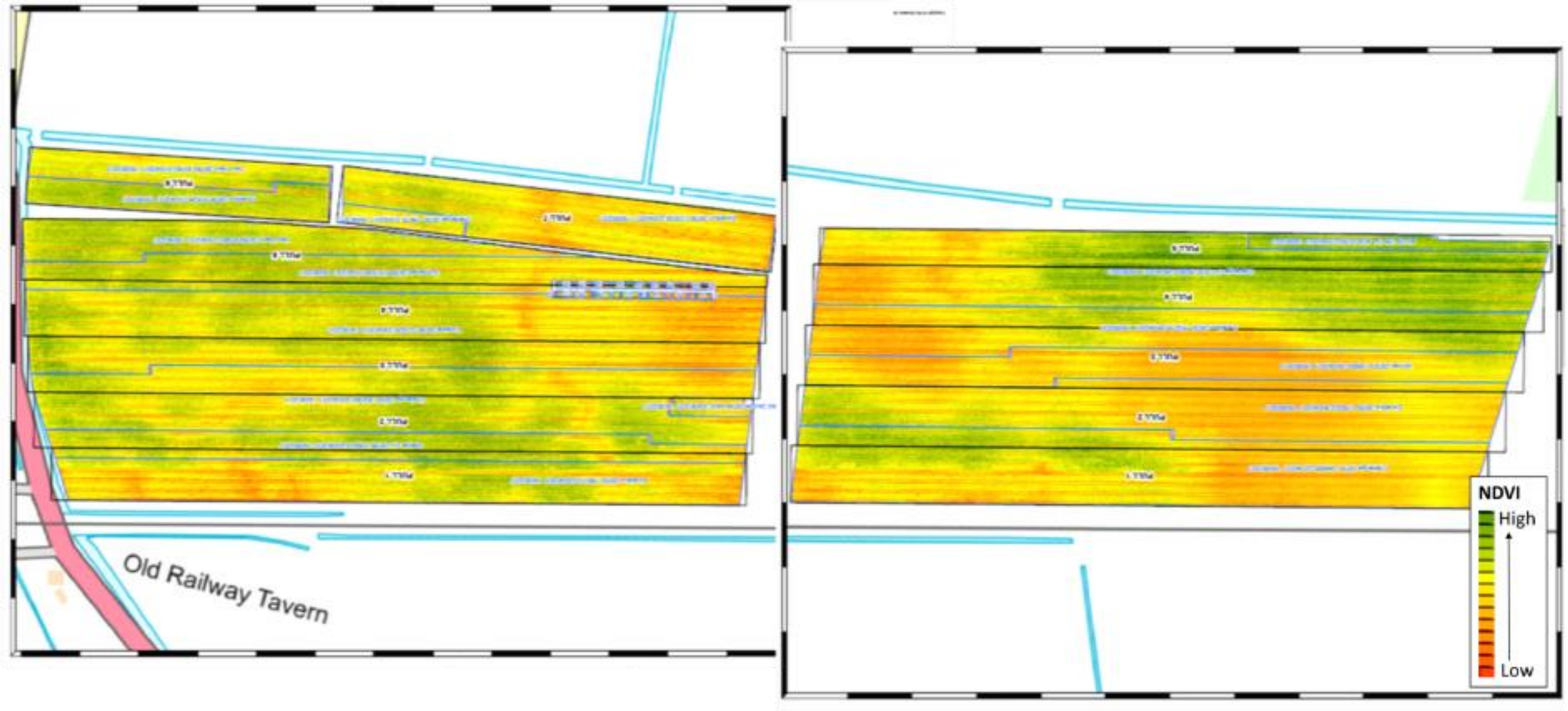

Figure 85. Canopy sensing using manned light aircraft - NDVI vegetation index (18/05/2017)

Targeted soil and crop sampling

Crop reflectance data from the Isaria sensor was used to identify contrasting areas of thin and thick crops within five blocks of different lettuce varieties/planting dates/harvest dates for targeted soil and leaf tissue testing and harvest assessments (10 points in total; Figure 86)

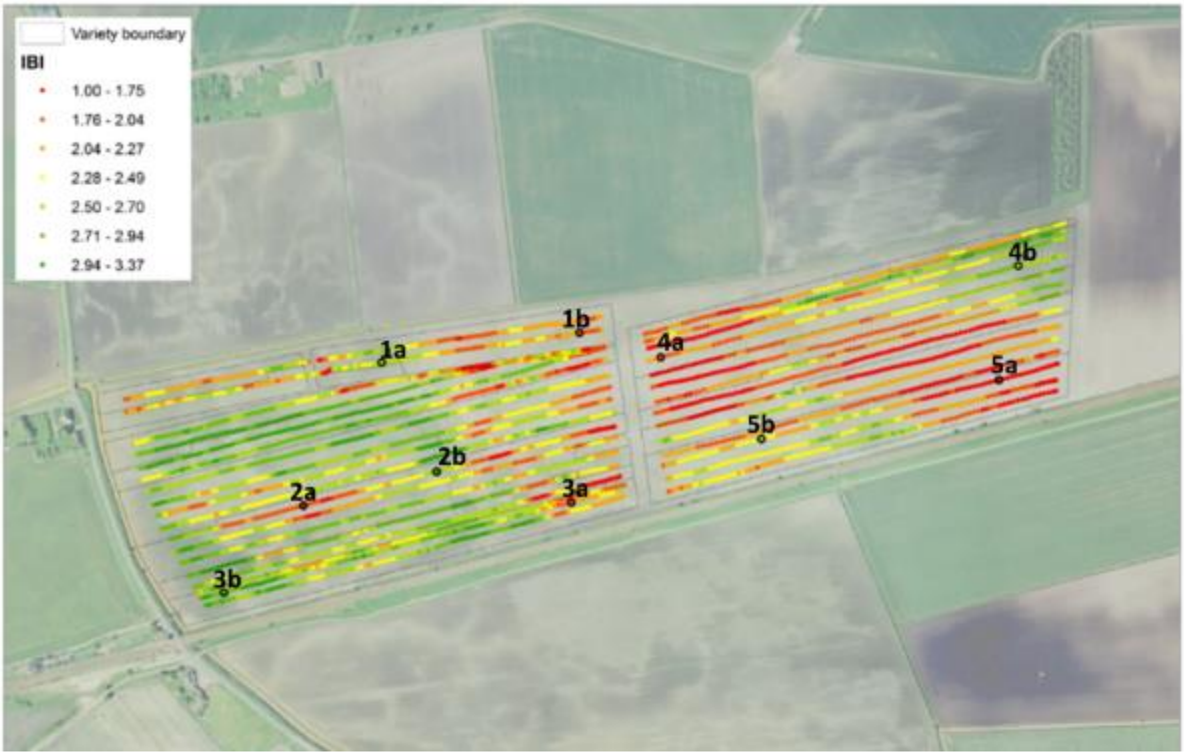

Figure 86. Sampling points identified using the Isaria IBI vegetation index (note: map shows the raw Isaria scan data) – ‘a’ sampling points are in thinner crop and ‘b’ sampling points are in thicker crop

Table 33 shows mean harvested head weight (untrimmed and marketable trimmed) from each of the sampling points[10]. Total untrimmed and marketable trimmed head weight was lower from the points identified as thinner/low IBI value (‘a’ points) than from points identified as thicker/higher IBI value (‘b’ points) in each zone apart from zone 1. Within each of the zones the difference in marketable head weight ranged from 49g (zone 3) to 211g (zone 4), demonstrating significant within field variability in head weight.

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[10] Each of the five sampling zones represents a different combination of variety, planting date and harvest date. Therefore, comparisons of head weight should focus on difference within rather than between zones.

Table 33. Harvested head weight (untrimmed and marketable) from each sampling point

ID	Variety	Planting date	Harvest date	IBI Index	Harvested head weight (g)[1]	
					Untrimmed	Marketable
1a (thin)	Excalibur	22 Apr	13 Jun	2.0	1004	499
1b (thick)				2.7	808	397
2a (thin)	Challenge	20 Apr	14 Jun	1.8	520	239
2b (thick)				2.8	904	416
3a (thin)	Excalibur	20 Apr	14 Jun	1.9	803	454
3b (thick)				2.8	872	504
4a (thin)	Challenge	26 Apr	19 Jun	2.0	682	306
4b (thick)				2.7	1021	516
5a (thin)	Challenge	22 Apr	19 Jun	1.6	760	375
5b (thick)				2.5	956	474

[1] Mean of 10 measurements

Table 34 shows the results of targeted topsoil and plant tissue testing. Comparison of results from thinner (‘a’ samples) and thicker (‘b’ samples) crop sampling points show:

- **Soil organic matter** was lower in the thin compared to thick crop in all five sampling zones. This is consistent with the crop canopy and soil organic matter maps which show that the lettuce crop was thicker in areas of the field with a higher soil organic matter content. Regression analysis showed a significant ($P<0.05$) positive relationship between soil organic matter and soil extractable Ca ($R^2=0.41$), Zn ($R^2=0.53$), B ($R^2=0.43$) and Fe ($R^2=0.58$). There was no significant relationship ($P>0.05$) between soil organic matter and available N, extractable P, K, Mg, S, Cu or Mn.
- **Soil pH –** soil pH varied between 6.5 and 7.9. All samples were at or above the target pH (6.5); although low pH is unlikely to be limiting growth, high pH may be linked to lower trace element availability. Regression analysis showed a significant ($P<0.05$) negative relationship between soil pH and organic matter ($R^2=0.45$); the area of low soil organic matter in the south east section of the field is a high pH calcareous silty clay loam. There was a strong significant ($P<0.01$) negative relationship between soil pH and Cu ($R^2=0.67$), Zn ($R^2=0.85$) and Fe ($R^2=0.87$).
- **Nitrogen –** soil mineral N (SMN) was lower in the thin compared to the thick crop in four of the five sampling zones, and leaf tissue N concentrations were lower in the thin compared to the thick crop in four of five sampling zones. SMN concentrations at all sampling points were relatively high for the top 15cm soil layer – the lowest measured SMN of 53 kg/ha is equivalent to SNS Index 6 assuming an even distribution of SMN

throughout the soil profile. Leaf tissue N concentrations below 2.5-3.5% (depending on maturity stage) indicate deficiency (AHDB, 2010); measured concentrations in this mature crop of between 3.4 and 4.4% in the thin crop and between 4.0 and 4.7% in the thick crop do not indicate deficiency.

- **Phosphorus –** soil extractable P was lower in the thin compared to the thick crop in four of the five sampling zones, although all samples were at or above the target P Index of 3. There was no consistent trend for lower leaf tissue P concentrations in thin compared to thick crop.
- **Potassium –** soil extractable K varied from 98 mg/l (Index 1) to 291 mg/l (Index 3), although there was no consistent trend for lower soil extractable K concentrations in thin compared to thick crop. Leaf tissue K concentrations were lower in the thin compared to the thick crop in four of the five sampling zones, however all samples were within/above the normal leaf tissue K range of 4.0-7.0% (AHDB, 2010).
- **Magnesium –** soil extractable Mg concentrations varied from 36 mg/l (Index 1) to 222 mg/l (Index 4) and were lower in the thin compared to the thick crop in all five sampling zones, and tissue Mg concentrations were lower in the thin compared to the thick crop in four of five sampling zones. Leaf tissue Mg concentrations in the range 0.3-0.5% are considered normal and concentrations below 0.2% are indicative of deficiency (AHDB, 2010). All of the sampling points had tissue concentrations <0.3% and eight of ten sampling points had concentrations less than or equal to 0.2%. This indicates that Mg may be limiting growth and potentially a contributory factor to yield variation.
- **Calcium -** soil extractable Ca concentrations varied from 1508 to 6997 mg/l. Calcium concentrations in soil and plant tissue were lower in the thin compared to the thick crop in four of the five sampling zones, although tissue Ca concentrations are not considered a reliable diagnostic tool for Ca deficiency.
- **Sulphur –** soil extractable S concentrations were lower in the thin compared to the thick crop in four of the five sampling zones, however recent work has shown that soil S analysis is not a good indicator of crop S deficiency (Sagoo *et al.,* 2018). There was no consistent trend for lower leaf tissue S concentrations in thin compared to thick crop.
- **Copper -** There was no consistent trend for lower soil extractable or leaf tissue Cu concentrations in thin compared to thick crop. Six of the eight soil samples were below the critical value for deficiency (2.5 mg Cu/l in high organic matter soils, AHDB 2016), however all leaf tissue samples were above the critical value of 2 mg Cu/kg (AHDB, 2010).

- **Zinc –** soil extractable Zn was lower in the thin compared to the thick crop in all five sampling zones and leaf tissue Zn concentrations were lower in the thin compared to the thick crop in four of the five sampling zones. However all soil samples were above the critical value of 1.5 mg Zn/l (AHDB, 2016) and all leaf tissue samples were above the critical range of 15-20 mg Zn/kg (AHDB, 2010), indicating that variability in Zn availability is unlikely to be a contributory factor to yield variation.
- **Boron** - **–** soil extractable B was lower in the thin compared to the thick crop in all five sampling zones and leaf tissue B concentrations were lower in the thin compared to the thick crop in four of the five sampling zones. However all soil samples were above the critical value of 0.8 mg B/l (AHDB, 2016) and all leaf tissue samples were above the critical range of 20-40 mg Zn/kg (AHDB, 2010), indicating that variability in B availability is unlikely to be a contributory factor to yield variation.
- **Iron** - soil extractable Fe was lower in the thin compared to the thick crop in all five sampling zones and leaf tissue Fe concentrations were lower in the thin compared to the thick crop in four of the five sampling zones. However, Fe deficiency is very rare in the UK and critical limits for soils and plant tissue are not given in the AHDB Nutrient Management Guide (AHDB, 2016) or the AHDB Crop Walkers Guide for outdoor salads (AHDB, 2010).
- **Manganese** - there was no consistent trend for lower soil extractable or leaf tissue Mn concentrations in thin compared to thick crop. However, eight of ten leaf tissue samples were below the critical limit of 20 mg Mn/kg (AHDB, 2010). Soil analysis isn't considered a reliable indicator of crop deficiency.

Targeted soil and crop sampling identified a number of trends for lower soil and tissue nutrient concentrations in areas of thinner crop, however these trends do not necessary mean that these nutrients contribute to crop variability and it is important to also look at critical soil and crop values which indicate deficiency (where available). For example, the trend for lower Fe and Zn soil and tissue concentrations in areas of thinner crop is more likely a reflection of the correction with soil organic matter, than an indication of Fe or Zn deficiency.

Based on the results of soil and crop tissue testing, Mg is the most likely nutrient to be contributing to crop variability. There was a clear trend for lower soil and tissue Mg concentrations in areas of thinner crop and leaf tissue concentrations were generally below the critical value for indicating deficiency. However only one of the sample points had a soil Mg Index below the target of Index 2. Fertiliser Mg response experiments in areas of lower soil Mg index could be used to confirm whether there is a crop response to applied Mg.

Table 34. Soil and plant tissue analysis from sampling points

Topsoil analysis (0-15 cm)													
ID	**Organic matter (%)**	**pH**	**SMN (kg/ha)**[1]	**P**	**K**	**Mg**	**Ca**	**S**	**Cu**	**Zn**	**B**	**Fe**	**Mn**
				(extractable mg/l)									
1a (thin)	25	7.7	97	64 (4)	291 (3)	111 (3)	4568	73	1.8	2.8	5.5	145	2.1
1b (thick)	35	7.3	116	76 (5)	192 (2+)	133 (3)	5362	105	4.0	4.6	7.2	200	2.8
2a (thin)	25	7.4	53	42 (3)	199 (2+)	82 (2)	6997	382	5.2	2.7	4.6	121	2.0
2b (thick)	35	7.5	77	82 (5)	214 (2+)	99 (2)	5023	70	3.4	3.8	6.5	147	1.9
3a (thin)	19	7.7	91	60 (4)	211 (2+)	128 (3)	4850	73	1.9	2.7	4.8	115	1.7
3b (thick)	35	6.5	65	54 (4)	131 (2-)	222 (4)	4957	78	8.4	6.8	5.2	325	4.4
4a (thin)	16	7.6	204	37 (3)	133 (2-)	62 (2)	3158	46	0.8	1.6	3.4	83	2.5
4b (thick)	46	7.2	311	60 (4)	159 (2-)	72 (2)	4977	61	1.2	3.8	4.2	191	3.1
5a (thin)	6	7.9	54	42 (3)	105 (1)	36 (1)	1508	45	1.4	1.5	1.4	30	4.9
5b (thick)	23	7.7	187	47 (4)	98 (1)	84 (2)	3936	88	0.8	2.3	5.1	131	3.0
Plant tissue analysis													
ID			**N**	**P**	**K**	**Mg**	**Ca**	**S**	**Cu**	**Zn**	**B**	**Fe**	**Mn**
			(%)						**(mg/kg)**				
1a (thin)	*	*	4.4	0.4	7.8	0.2	1.1	0.2	4.5	31	37	96	17
1b (thick)	*	*	4.2	0.4	6.4	0.2	1.0	0.2	5.2	39	31	110	14
2a (thin)	*	*	3.8	0.5	6.0	0.2	0.7	0.2	7.8	40	27	114	19
2b (thick)	*	*	4.2	0.4	6.4	0.2	1.4	0.2	4.1	30	36	102	13
3a (thin)	*	*	4.1	0.4	7.1	0.2	0.8	0.2	4.7	38	30	98	18
3b (thick)	*	*	4.7	0.4	8.1	0.3	1.0	0.2	5.3	43	34	152	22
4a (thin)	*	*	4.1	0.4	5.3	0.2	0.7	0.2	3.9	39	25	79	16
4b (thick)	*	*	4.4	0.4	5.4	0.2	0.8	0.2	3.2	42	32	94	17
5a (thin)	*	*	3.4	0.3	5.5	0.1	0.8	0.2	4.6	29	26	65	23
5b (thick)	*	*	4.0	0.3	6.1	0.2	1.0	0.2	2.6	30	32	73	19

[1].Soil mineral nitrogen (SMN) in 15cm sampling depth calculated using mean measured bulk density in 10-15cm layer 0.74 g/cm^3

Conclusions

The case study field at G’s showed significant within field soil and crop variability. Soil sampling and analysis showed that soil organic matter content varied from 7 to 45%. The soil EC and brightness maps both showed patterns of variability that corresponded to variation in soil organic matter. Crop canopy reflectance data was collected using three different platforms (satellite, tractor mounted and manned light aircraft); all showed a similar pattern of crop variability, however there were clear differences in the resolution and level detail in the maps. Harvest assessments showed significant variability in marketable head weight within blocks of the same variety planted and harvested on the same date.

It is likely that the variation in lettuce head weight is driven by factors related to variation in soil organic matter and this may be a combination of differences in soil moisture availability and nutrient availability. Targeted soil and crop sampling identified a number of trends for lower soil and tissue nutrient concentrations in areas of thinner crop, however it was difficult to confidently identify any specific nutrients as likely causes of yield variation.

This case study demonstrated the various options available to growers to monitor variation in their soils and crops; it also showed that it can be difficult to disentangle the various soil and other yield-limiting factors to understand which are most important in driving crop variability.

Focusing on crop variability can help growers identify and address yield-limiting factors. If the causes of yield variation can be identified and eliminated, the yields in the low yielding areas can potentially be increased resulting in quick wins for all crops grown in the rotation. This approach is most effective for yield limiting factors such as localized areas of low pH that can be corrected by variable rate liming and areas of poor soil drainage that can be addressed to some extent by maintaining and repairing field drains. However, it may never be possible to eliminate the effect of soil variability on the crop, particularly in inherently variable fields such as P16 field used in this demonstration.

Knowledge and Technology Transfer

Demonstration open days

Each of the six field experiment/demonstration sites hosted an open day:

- Canopy sensing for variable rate N management: 22nd September 2016 at Glassford Hammond Farming LLP, Notts.
- Controlled traffic farming: 3rd November 2016 at Barfoot Farms Ltd., West Sussex.
- Options for soil mapping: 7th February 2017 at F.B. Parrish & Son Ltd., Beds.
- Focus on variability – precision farming techniques for measuring soil and crop variability: 22nd June at G's Growers Ltd., Cambs (part of the NIAB Lettuce varieties open day).
- Canopy sensing for variable rate N applications: 7th November 2017 at W Clappison Ltd., Park Farm, Risby, East Yorkshire.
- Soil management strategies for Nursery stock: 18th May 2018 at Wyevale Transplants, Herefordshire

The Agendas for the demonstration open days are included in Appendix 1. Each field demonstration open day included:

- Demonstration of the precision/management technique featured at that site. Including machinery and field demonstration plots specific to the site.
- Soil pits for the demonstration of visual soil evaluation and information on approaches to sol management.

Other project meetings and knowledge transfer activities

Project steering group meetings

- Initial project steering group meeting (22/05/15).
- Second project steering group meeting (18/01/16).
- Third project steering group meeting (31/01/17).
- Final project steering group meeting (28/02/18).

Other meetings and events

- Poster outlining the project exhibited at AHDB Smart Agriculture Conference (08/09/15), Elsom's Open day (14-15/10/15) and AgriTech East REAP 2015 Conference (Nov 2015).
- Presentation to Jepco and Anglia Salads agronomy staff (25/02/16).
- AHDB soils workshop, 7th April 2016. Presentation:

    - *The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems:* PF-*Hort*
- Elsoms open day, 12-13th October 2016. Mini presentations:
    - *Soil structural condition in horticultural systems*
    - *How can we use precision faming tools to improve soil and nutrient management in horticulture?*
- International Fertiliser Society Technical Conference, Cambridge, 7th December 2017. Presentation:
    - *Review of current use of precision farming techniques in the UK*
- Brassica and leafy salads conference, 25th January 2017. Presentation:
    - *State of our soils and potential for precision farming to improve soil and nutrient management*
- GREAT soils workshop, 10th May 2017. Presentation:
    - *Using Organic Manures to Manage Soil Health and Supply Nutrients*
- ECPA 2017 - 11th European Conference on Precision Agriculture, 16th to 20th July 2017. Poster:
    - *Using canopy sensing to improve nitrogen management of brassica vegetable*s
- International Soil Tillage Research Organization (ISTRO) Grassland and Tillage Visual Soil Evaluation Workshop, 30th and 31st August 2017, Co Carlow, Republic of Ireland. Presentation:
    - *Soil structural condition in horticulture systems*
- GREAT soils event, 21st September 2017 at Riviera Produce Cornwall. Presentation:
    - *Taking the compact out of compaction*
- GREAT soils workshop, 30th November 2017. Presentation:
    - *How can we use precision faming tools to improve soil and nutrient management in horticulture?*
- British Society of Soils Science Annual Conference, 4th-5th September 2018. Presentation:
    - *Soil structural conditions and soil management guidelines for horticultural cropping systems*
- 21st ISTRO Conference, 24th to 27th September 2018, Paris. Presentation:
    - *Survey of Soil Structure and Soil Management in UK Horticulture*

Press articles

- ADAS Technical Update, July 2015
    - *Mapping soil variability*
- AHDB Grower magazine, June 2016

    - *AHDB demonstrates soils research results* (in news section)
- AHDB Grower magazine, June 2016
    - *Breaking new ground* (feature article including results from soil structure survey and precision farming review).
- Vegetable Farmer magazine, August 2016
    - *Increased awareness of soil health does not make management easier* (feature article)
- AHDB Grower Field Vegetables Review 2016
    - *Cross-sector programme generates soil management guidance*
- AHDB Grower magazine, December 2016/January 2017
    - *Take the pressure off* (feature article from CTF demonstration day at Barfoots).
- AHDB Grower magazine, March 2017
    - *Cover crops and precision farming feature in soils events* (in news section)
- Vegetable Farmer magazine, March 2017
    - *Precision farming project demonstrates savings* (in news section based on CTF demonstration at Barfoots)
- AHDB Grower magazine, April 2017
    - *Does it pay to be precise?* (feature article on variable rate N demonstration at Glassford Hammond Farming).
- Vegetable Farmer magazine, April 2017
    - *Profitable soil Management*
- Vegetable Farmer magazine, May 2017
    - *Soil focus at NIAB Leafy Salads Open Day*
- Elsoms vegetable open day article, 11th and 12th October 2017:
    - *Crop variability – is the answer in the soil?*
- AHDB Grower magazine, February - March 2018
    - *Are you in the zone?* (feature article on soil and nutrient mapping at Parrish Farms in Bedfordshire).
- AHDB Grower magazine, April, May 2018
    - *Crop variability – Is the answer in the soil?* (feature article on understanding soil and crop variability at G's Growers in Cambridgeshire).
- Vegetable Farmer magazine, May 2018
    - *Variable rate N has potential but think carefully with veg crops* (article on Brassica nutrition based on work at Glassford Hammond Farming and Park Farm, Risby, near Beverley).

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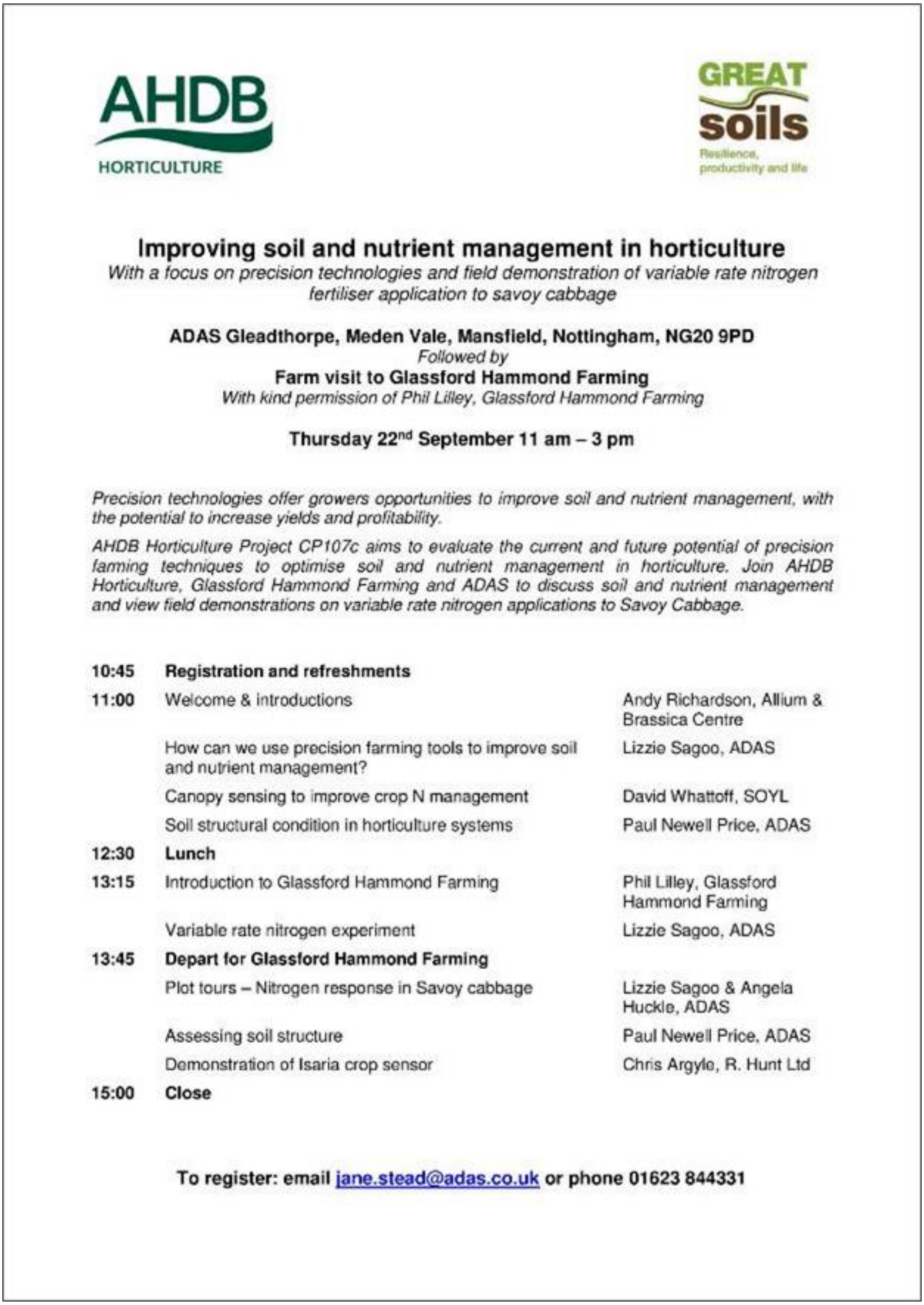
Phil Lilley (Glassford Hammond Farming LLP); Neil Cairns and James Rome (Barfoot Farms Ltd.); Emma Garfield, Elzbieta Witkowska and Rob Parker (G’s Growers Ltd.); John Clappison (W Clappison Ltd., Park Farm, Risby); Adrian Baker and Nick Parrish (F.B. Parrish & Son Ltd.); and Ray Jenkins (Wyevale Transplants (Forestry) Ltd.).

The following have provided input to the project steering group: Andy Richardson (Allium & Brassica Centre & Industry representative), Jim Dimmock & Grace Choto (AHDB Horticulture), Clive Rahn (Plant Nutrition Consulting), Philip Effingham (Greentech Consultancy), Tim Chamen (CTF Europe), Ian Beecher-Jones, John Sedgwick (Produce World), Emma Garfield & Elzbieta Witkowska (G’s Growers), Dermott Tobin & Lizzie Pritchard (PDM Produce), Richard Fitzpatrick (HMC Peas), Jonathan Blackman & Nigel Kitney (Hutchinson’s) and Mark Holden (Adrians Cripps).

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

The following have provide input to the precision farming review: Paul Rose (AgLeader Technology), Jack Harris (Agrovista), Stuart Alexander & John Lord (Agrii), Vince Gilliingham (AgSpace/IPF/Courtyard), Simon Redhill (Airinov), Alli Grundy (CF Fertilisers), Rhun Jones (Cultivation Solutions), David Norman (Fresh Produce Consultancy), Oliver Wood (Hutchinson’s), Clive Blacker & Charley White (Precision Decision), Simon Griffin & David Whatton (SOYL), David Wright (Spectrum Aviation), Alex Dinsdale (Ursula), Chris Harry Thomas, Will Munford & Mick Whitely (AS Communications), Jim Thompson (Allpress Farm), Neil Cairns (Barfoots), Paul Cripsey (FB Parrish & Son), Emma Garfield & Elzbieta Witkowska (G’s Growers), Philip Lilley (Glassford Hammond Farming), Nick Sheppard (Jepco), Jake Freestone (Overbury Farms), Dermott Tobin & Lizzie Pritchard (PDM Produce), Mark Lyon (T.H. Clements), Andy Elworthy & Nataschia Schneider (Vitacress).

Appendix 1: Demonstration open day invites



AHDB HORTICULTURE

GREAT soils Resilience, productivity and life

Improving soil and nutrient management in horticulture

With a focus on precision technologies and field demonstration of variable rate nitrogen fertiliser application to savoy cabbage

ADAS Gleadthorpe, Meden Vale, Mansfield, Nottingham, NG20 9PD
Followed by
Farm visit to Glassford Hammond Farming
With kind permission of Phil Lilley, Glassford Hammond Farming

Thursday 22nd September 11 am – 3 pm

Precision technologies offer growers opportunities to improve soil and nutrient management, with the potential to increase yields and profitability.

AHDB Horticulture Project CP107c aims to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management in horticulture. Join AHDB Horticulture, Glassford Hammond Farming and ADAS to discuss soil and nutrient management and view field demonstrations on variable rate nitrogen applications to Savoy Cabbage.

10:45	**Registration and refreshments**	
11:00	Welcome & introductions	Andy Richardson, Allium & Brassica Centre
	How can we use precision farming tools to improve soil and nutrient management?	Lizzie Sagoo, ADAS
	Canopy sensing to improve crop N management	David Whattoff, SOYL
	Soil structural condition in horticulture systems	Paul Newell Price, ADAS
12:30	**Lunch**	
13:15	Introduction to Glassford Hammond Farming	Phil Lilley, Glassford Hammond Farming
	Variable rate nitrogen experiment	Lizzie Sagoo, ADAS
13:45	**Depart for Glassford Hammond Farming**	
	Plot tours – Nitrogen response in Savoy cabbage	Lizzie Sagoo & Angela Huckle, ADAS
	Assessing soil structure	Paul Newell Price, ADAS
	Demonstration of Isaria crop sensor	Chris Argyle, R. Hunt Ltd
15:00	**Close**	

To register: email jane.stead@adas.co.uk or phone 01623 844331

AHDB
HORTICULTURE

GREAT
soils
Resilience, productivity and life

Controlling traffic for profitable and resilient soils

With a focus on the new soil management and precision technology strategy at Barfoots

Queens Head, High Street, Titchfield, PO14 4AQ
Followed by
Field visit to Abshot Farm, Barfoots
With kind permission of Neil Cairns, Barfoots

Thursday 3rd November 11 am – 3 pm

Controlled traffic farming and other precision technologies offer growers opportunities to improve soil and nutrient management, with the potential to increase yields and profitability.

AHDB Horticulture Project CP107c aims to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management in horticulture. Join AHDB Horticulture, Barfoots and ADAS to discuss soil and nutrient management and view controlled traffic and cover crop strategies in the field.

10:45	**Registration and refreshments**	
11:00	Welcome & introductions	
	Introduction to Barfoots and the Hampshire farms	James Rome, Barfoots
	Soil structural condition in horticulture systems	Paul Newell Price, ADAS
	How can we use precision farming tools to improve soil and nutrient management?	Lizzie Sagoo, ADAS
	Principles of Controlled Traffic Farming	Tim Chamen, CTF Europe
12:30	**Lunch**	
	Soil management and CTF strategy at Barfoots	James Rome, Tim Chamen, and Paul Newell Price
13:45	**Depart for Posbrook Lane, Abshot Farm, Barfoots**	
	CTF approach and machinery modifications at Barfoots	James Rome, Barfoots & Tim Chamen, CTF Europe
	Cover crop trials and assessing soil structure	Neil Cairns, Barfoots & Paul Newell Price, ADAS
15:00	**Close**	

Includes BASIS points

Places will be limited so please register via:
email jane.stead@adas.co.uk or phone 01623 844331

AHDB
HORTICULTURE

GREAT soils
Resilience, productivity and life

Smart soil mapping for improved soil and nutrient management in horticulture

With a focus on options for soil mapping and precision technologies

Millennium Barn, F.B. Parrish & Son, Lodge Farm,
Chicksands, Shefford, Beds, SG17 5QB
With kind permission of F.B. Parrish & Son

Tuesday 7th February 11 am – 3 pm

Precision technologies offer growers opportunities to improve soil and nutrient management, with the potential to increase yields and profitability.

AHDB Horticulture Project CP107c aims to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management in horticulture. Join AHDB Horticulture, F.B. Parrish & Son and ADAS to discuss soil and nutrient management and options for soil mapping.

10:45	**Registration and refreshments**	
11:00	Welcome & introductions	Andy Richardson, Allium & Brassica Centre
	Introduction to Parrish Farm	Adrian Baker/Nick Parrish, F.B. Parrish & Son
	Soil structural condition in horticulture systems	Paul Newell Price, ADAS
	How can we use precision farming tools to improve soil and nutrient management?	Lizzie Sagoo, ADAS
12:30	**Lunch**	
13:15	Options for soil mapping – Parrish Farm Avenue field case study	Lizzie Sagoo, ADAS
14:00	**Avenue field visit**	
	Demonstration of Veris MSP3 scanner	Graeme Barrett, Mount Liming
	In field variation in soil – Avenue field case study	Dan Munro, ADAS
	Assessing and managing soil structure	Paul Newell Price, ADAS
15:00	**Close**	

Includes BASIS and NRoSO points

Places will be limited so please register via:
email jane.stead@adas.co.uk or phone 01623 844331

NIAB Leafy salads open day

Including soils and growing media themed morning seminar sessions

G's Fresh, Ely, Cambs

Thursday 22nd June 2017 10:00 am – 4:00 pm

This year's leafy salad varieties open day will be held at G's Fresh on 22nd June. The event will include four interactive soils and growing media themed workshops in the morning. In the afternoon delegates will have the opportunity to visit over 90 variety plots demonstrated by Bruce Napier and representatives from the seed houses and a chance to quiz them about their extended catalogues. In addition, there will be a soil pit and the opportunity to look at how to assess soil structure in the field.

Programme

10:00	**Registration and refreshments**	
10:30	**Soils and growing media themed workshops** *Attendees will be split into 4 groups and take it in turns to visit each workshop.*	
	1. How can we use precision farming tools to measure and manage variability in our soils and crops	Lizzie Sagoo, ADAS
	2. Soil health indicators to inform land management decisions and increase crop yield and quality	Stefan De Cristoforo, Waitrose
	3. Responsibly sourced growing media	Chloe Whiteside & Sonia Newman, ADAS
	4. When lettuce transplants meet the soil – a love affair with a happy ending	Jim Monaghan, Harper Adams University
12:30	**Lunch**	
13:30	**Depart for field visit**	
	Variety plots	Bruce Napier, NIAB Seed companies
	Assessing and managing soil structure	Paul Newell Price, ADAS
16:00	**Close**	

Includes BASIS points

To register: email brooke.lovelock@britishgrowers.org or phone 01507 353792

AHDB
HORTICULTURE

GREATSOILS

Improving soil and nutrient management in horticulture

With a focus on precision technologies and field demonstration of variable rate nitrogen fertiliser application to Brussels sprouts

Bishop Burton College, York Road, Bishop Burton, East Yorkshire, HU17 8QG
(Seminar Room 3)
Followed by
Farm visit to Park Farm, Risby
With kind permission of John Clappison

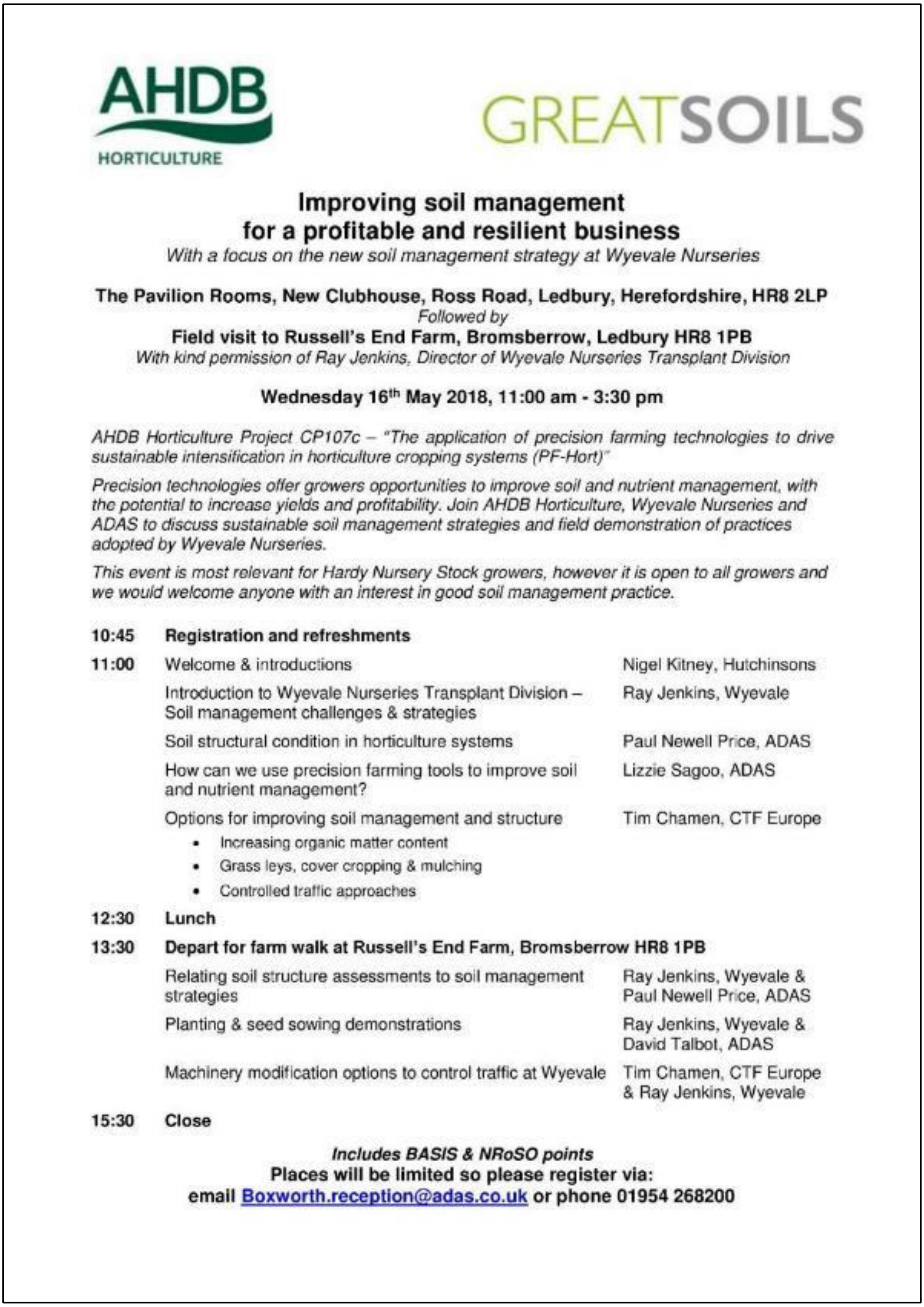
Tuesday 7th November 11 am – 3 pm

Precision technologies offer growers opportunities to improve soil and nutrient management, with the potential to increase yields and profitability.

AHDB Horticulture Project CP107c aims to evaluate the current and future potential of precision farming techniques to optimise soil and nutrient management in horticulture. Join AHDB Horticulture and ADAS to discuss soil and nutrient management and view field demonstrations including nitrogen and sulphur response and variable rate nitrogen applications to Brussels sprouts.

10:45	**Registration and refreshments**	
11:00	Welcome & introductions	Andy Richardson, Allium & Brassica Centre
	How can we use precision farming tools to improve soil and nutrient management?	Lizzie Sagoo, ADAS
	Using canopy sensing to improve N management	Clive Blacker, Precision Decisions
	Soil structural condition in horticulture systems	Paul Newell Price, ADAS
12:30	**Lunch**	
13:15	Introduction to Park Farm, Risby	John Clappison, Park Farm
	Variable rate nitrogen experiment	Lizzie Sagoo, ADAS
13:45	**Depart for Park Farm**	
	Brussels sprouts plot tours • Nitrogen response plots • Sulphur response plots	Lizzie Sagoo & John Clappison
	Assessing and managing soil structure	Paul Newell Price, ADAS
	Demonstration of Yara N Sensor	Clive Blacker, Precision Decisions
15:00	**Close**	

To register: email jane.stead@adas.co.uk or phone 01623 844331



AHDB
HORTICULTURE

GREATSOILS

Improving soil management for a profitable and resilient business

With a focus on the new soil management strategy at Wyevale Nurseries

The Pavilion Rooms, New Clubhouse, Ross Road, Ledbury, Herefordshire, HR8 2LP
Followed by
Field visit to Russell's End Farm, Bromsberrow, Ledbury HR8 1PB
With kind permission of Ray Jenkins, Director of Wyevale Nurseries Transplant Division

Wednesday 16th May 2018, 11:00 am - 3:30 pm

AHDB Horticulture Project CP107c – "The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems (PF-Hort)"

Precision technologies offer growers opportunities to improve soil and nutrient management, with the potential to increase yields and profitability. Join AHDB Horticulture, Wyevale Nurseries and ADAS to discuss sustainable soil management strategies and field demonstration of practices adopted by Wyevale Nurseries.

This event is most relevant for Hardy Nursery Stock growers, however it is open to all growers and we would welcome anyone with an interest in good soil management practice.

10:45	**Registration and refreshments**	
11:00	Welcome & introductions	Nigel Kitney, Hutchinsons
	Introduction to Wyevale Nurseries Transplant Division – Soil management challenges & strategies	Ray Jenkins, Wyevale
	Soil structural condition in horticulture systems	Paul Newell Price, ADAS
	How can we use precision farming tools to improve soil and nutrient management?	Lizzie Sagoo, ADAS
	Options for improving soil management and structure • Increasing organic matter content • Grass leys, cover cropping & mulching • Controlled traffic approaches	Tim Chamen, CTF Europe
12:30	**Lunch**	
13:30	**Depart for farm walk at Russell's End Farm, Bromsberrow HR8 1PB**	
	Relating soil structure assessments to soil management strategies	Ray Jenkins, Wyevale & Paul Newell Price, ADAS
	Planting & seed sowing demonstrations	Ray Jenkins, Wyevale & David Talbot, ADAS
	Machinery modification options to control traffic at Wyevale	Tim Chamen, CTF Europe & Ray Jenkins, Wyevale
15:30	**Close**	

Includes BASIS & NRoSO points
Places will be limited so please register via:
email Boxworth.reception@adas.co.uk or phone 01954 268200

Appendix 2. Avenue Field soil analysis results

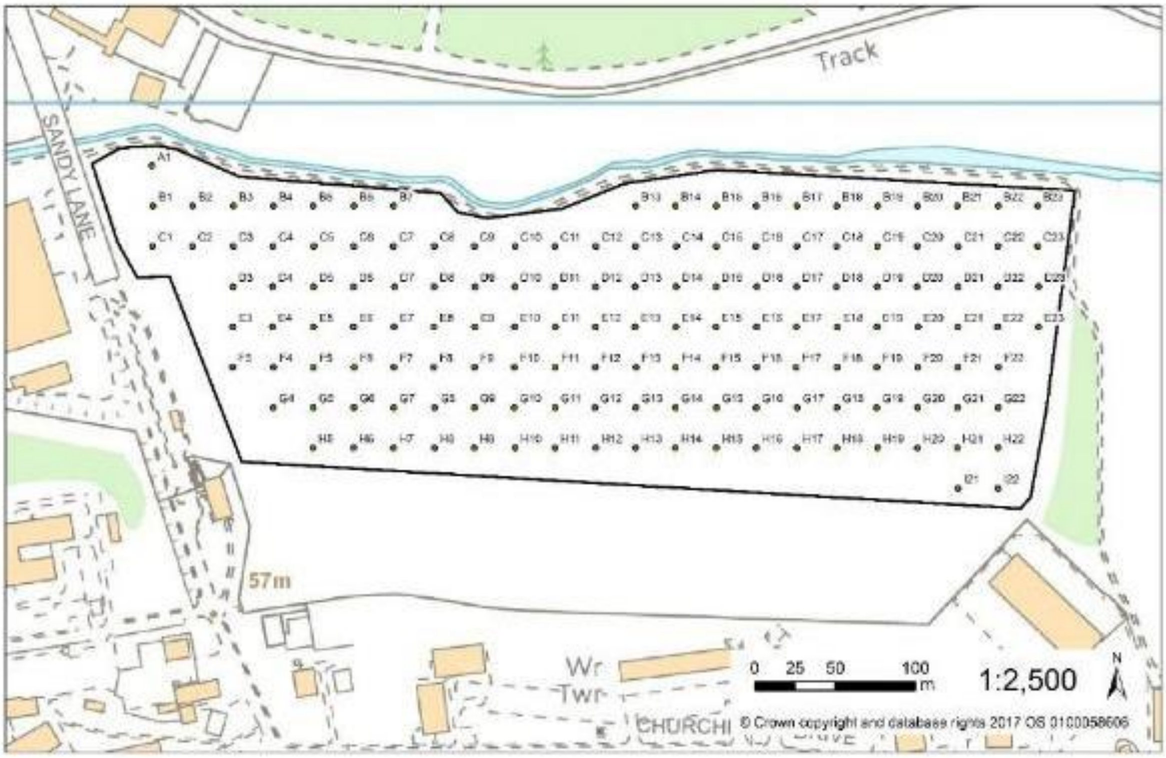


Figure A2-1. Map showing location of 25 m grid sampling points and sample point identifiers

Table A2-1. Soil analysis – 25 m grid samples (143 samples) for pH, extractable P, K and Mg

Point ID	Location of sampling point		pH	Extractable P (mg/l)	Extractable K (mg/l)	Extractable Mg (mg/l)
	Latitude	Longitude				
A1	52.04667647	-0.36368	5.8	31.2	328	168
B1	52.04645179	-0.36368	5.9	31.8	305	135
B2	52.04644673	-0.36332	5.6	24.4	361	129
B3	52.04644167	-0.36295	6.1	21.2	232	132
B4	52.04643660	-0.36259	5.8	26.2	306	173
B5	52.04643154	-0.36223	5.8	29.8	344	213
B6	52.04642647	-0.36186	5.9	36.8	297	196
B7	52.04642141	-0.36150	6.1	31.0	261	164
B13	52.04639098	-0.35931	5.5	26.4	199	147
B14	52.04638590	-0.35895	5.4	18.4	153	193
B15	52.04638082	-0.35858	5.5	22.6	201	169
B16	52.04637575	-0.35822	6.1	20.8	245	163

Point ID	Location of sampling point		pH	Extractable P (mg/l)	Extractable K (mg/l)	Extractable Mg (mg/l)
	Latitude	Longitude				
B17	52.04637067	-0.35785	5.7	21.8	259	166
B18	52.04636559	-0.35749	5.6	20.8	238	215
B19	52.04636051	-0.35712	6.1	15.6	165	182
B20	52.04635543	-0.35676	5.7	18.0	150	199
B21	52.04635034	-0.35640	5.7	20.4	207	188
B22	52.04634526	-0.35603	5.9	21.4	230	195
B23	52.04634017	-0.35567	6.0	21.8	273	208
C1	52.04622711	-0.36369	5.8	54.6	338	126
C2	52.04622205	-0.36333	6.1	46.4	428	147
C3	52.04621699	-0.36296	6.1	46.8	276	128
C4	52.04621193	-0.36260	5.8	34.6	254	133
C5	52.04620686	-0.36223	6.1	21.4	210	134
C6	52.04620179	-0.36187	5.8	27.0	234	118
C7	52.04619673	-0.36151	5.9	26.8	295	141
C8	52.04619166	-0.36114	5.6	24.6	174	125
C9	52.04618659	-0.36078	6.2	21.2	188	130
C10	52.04618152	-0.36041	6.1	26.4	155	114
C11	52.04617645	-0.36005	5.9	24.8	187	132
C12	52.04617137	-0.35968	6.5	25.4	288	151
C13	52.04616630	-0.35932	6.0	22.4	180	136
C14	52.04616122	-0.35895	6.1	23.0	204	178
C15	52.04615615	-0.35859	6.3	27.4	164	123
C16	52.04615107	-0.35823	6.4	22.0	186	132
C17	52.04614599	-0.35786	5.9	18.6	147	135
C18	52.04614091	-0.35750	6.0	17.8	182	120
C19	52.04613583	-0.35713	6.2	22.0	237	132
C20	52.04613075	-0.35677	6.2	18.8	144	128
C21	52.04612566	-0.35640	6.7	20.8	140	141
C22	52.04612058	-0.35604	6.1	20.4	119	125
C23	52.04611549	-0.35568	5.6	17.6	164	180
D3	52.04599231	-0.36297	6.5	46.8	182	105
D4	52.04598725	-0.36261	6.9	47.6	235	121
D5	52.04598218	-0.36224	6.1	42.8	265	132

Point ID	Location of sampling point		pH	Extractable P (mg/l)	Extractable K (mg/l)	Extractable Mg (mg/l)
	Latitude	Longitude				
D6	52.04597712	-0.36188	5.8	43.0	237	125
D7	52.04597205	-0.36151	5.8	34.6	224	127
D8	52.04596698	-0.36115	6.4	34.4	214	162
D9	52.04596191	-0.36078	6.0	34.0	197	153
D10	52.04595684	-0.36042	6.1	32.2	218	172
D11	52.04595177	-0.36006	6.3	31.6	156	144
D12	52.04594669	-0.35969	6.0	30.8	176	171
D13	52.04594162	-0.35933	6.5	28.2	216	185
D14	52.04593654	-0.35896	6.1	31.6	196	167
D15	52.04593147	-0.35860	6.2	34.0	238	171
D16	52.04592639	-0.35823	6.1	30.8	190	153
D17	52.04592131	-0.35787	5.9	21.6	133	122
D18	52.04591623	-0.35751	6.3	22.0	130	126
D19	52.04591115	-0.35714	5.9	23.4	181	142
D20	52.04590607	-0.35678	5.9	22.4	183	143
D21	52.04590099	-0.35641	6.1	23.8	174	145
D22	52.04589590	-0.35605	6.1	29.2	144	109
D23	52.04589082	-0.35568	6.5	26.2	161	133
E3	52.04576763	-0.36298	6.3	38.6	189	88
E4	52.04576257	-0.36262	6.3	47.2	241	87
E5	52.04575750	-0.36225	6.5	48.4	179	89
E6	52.04575244	-0.36189	6.1	45.4	198	86
E7	52.04574737	-0.36152	6.0	45.4	186	93
E8	52.04574230	-0.36116	6.1	40.6	213	88
E9	52.04573723	-0.36079	7.0	49.8	409	85
E10	52.04573216	-0.36043	6.3	47.4	301	81
E11	52.04572709	-0.36006	6.0	43.8	237	109
E12	52.04572202	-0.35970	5.8	39.6	156	82
E13	52.04571694	-0.35934	6.2	43.8	151	77
E14	52.04571187	-0.35897	6.0	46.4	197	89
E15	52.04570679	-0.35861	6.0	46.0	194	76
E16	52.04570171	-0.35824	6.0	41.0	209	81
E17	52.04569663	-0.35788	6.3	37.6	189	82

Point ID	Location of sampling point		pH	Extractable P (mg/l)	Extractable K (mg/l)	Extractable Mg (mg/l)
	Latitude	Longitude				
E18	52.04569155	-0.35751	5.9	37.0	175	74
E19	52.04568647	-0.35715	6.1	43.4	177	89
E20	52.04568139	-0.35678	6.7	45.6	209	92
E21	52.04567631	-0.35642	6.1	40.2	239	114
E22	52.04567122	-0.35606	6.3	41.6	258	115
E23	52.04566614	-0.35569	6.2	42.6	238	89
F3	52.04554295	-0.36299	6.4	36.8	224	77
F4	52.04553789	-0.36262	5.8	36.6	225	79
F5	52.04553283	-0.36226	6.0	44.4	364	78
F6	52.04552776	-0.36189	6.3	45.2	176	73
F7	52.04552269	-0.36153	6.2	42.0	188	77
F8	52.04551762	-0.36117	6.1	44.4	180	96
F9	52.04551255	-0.36080	6.3	44.8	180	94
F10	52.04550748	-0.36044	6.5	43.8	254	90
F11	52.04550241	-0.36007	6.6	43.0	283	84
F12	52.04549734	-0.35971	6.1	44.0	255	72
F13	52.04549226	-0.35934	5.8	42.0	153	69
F14	52.04548719	-0.35898	5.8	39.2	141	74
F15	52.04548211	-0.35862	5.4	35.6	148	75
F16	52.04547703	-0.35825	5.9	34.8	186	64
F17	52.04547196	-0.35789	5.8	36.0	306	61
F18	52.04546688	-0.35752	5.7	35.0	286	71
F19	52.04546180	-0.35716	6.0	39.8	226	68
F20	52.04545671	-0.35679	6.2	45.2	257	88
F21	52.04545163	-0.35643	6.5	47.6	426	73
F22	52.04544655	-0.35606	6.6	53.2	378	79
G4	52.04531321	-0.36263	6.4	36.2	204	92
G5	52.04530815	-0.36227	6.3	38.8	172	91
G6	52.04530308	-0.36190	6.3	42.2	271	86.2
G7	52.04529801	-0.36154	6.3	39.4	338	91
G8	52.04529294	-0.36117	6.4	40.2	242	88
G9	52.04528788	-0.36081	6.1	43.8	187	77
G10	52.04528280	-0.36045	5.8	38.6	127	62.2

Point ID	Location of sampling point		pH	Extractable P (mg/l)	Extractable K (mg/l)	Extractable Mg (mg/l)
	Latitude	Longitude				
G11	52.04527773	-0.36008	5.7	43.4	143	70
G12	52.04527266	-0.35972	5.8	39.8	185	67
G13	52.04526759	-0.35935	5.3	39.2	244	75
G14	52.04526251	-0.35899	5.4	35.8	185	65
G15	52.04525743	-0.35862	6.0	32.4	132	66.2
G16	52.04525236	-0.35826	5.7	40.2	170	67
G17	52.04524728	-0.35789	5.8	35.4	143	70
G18	52.04524220	-0.35753	5.6	35.4	163	69
G19	52.04523712	-0.35717	6.7	35.4	274	89.9
G20	52.04523204	-0.35680	6.2	36.8	231	96
G21	52.04522695	-0.35644	6.2	40.4	191	80
G22	52.04522187	-0.35607	6.7	40.2	234	96
H5	52.04508347	-0.36228	6.2	44.4	273	70
H6	52.04507840	-0.36191	6.3	41.4	183	80
H7	52.04507333	-0.36155	6.4	44.2	263	82
H8	52.04506827	-0.36118	6.7	45.2	292	82
H9	52.04506320	-0.36082	7.0	44.2	421	78
H10	52.04505813	-0.36045	6.0	42.2	197	68
H11	52.04505305	-0.36009	6.3	49.2	186	61
H12	52.04504798	-0.35972	5.9	46.0	131	57
H13	52.04504291	-0.35936	5.9	41.4	125	54
H14	52.04503783	-0.35900	5.8	44.4	192	53
H15	52.04503276	-0.35863	5.9	46.0	195	61
H16	52.04502768	-0.35827	5.7	44.8	145	54
H17	52.04502260	-0.35790	6.1	39.8	130	64
H18	52.04501752	-0.35754	5.9	35.6	92	55
H19	52.04501244	-0.35717	6.6	40.0	199	75
H20	52.04500736	-0.35681	6.5	37.6	220	72
H21	52.04500227	-0.35645	6.7	38.0	263	101
H22	52.04499719	-0.35608	7.1	38.6	199	77
I21	52.04477760	-0.35645	6.8	36.4	186	74
I22	52.04477251	-0.35609	5.8	41.4	182	85

Table A2-2. Soil analysis – 25m grid points closest to the centre point of each 1 ha area (10 samples; Figure 6) analysis for organic matter and soil texture

Point ID	Location of sampling point		Organic matter %	Soil texture			
	Latitude	Longitude		% sand	% silt	% clay	Class
C3	52.04621699	-0.36296	4.3	63	19	18	SCL/SL
C19	52.04613583	-0.35713	4.1	65	19	16	SL
D6	52.04597712	-0.36188	4.1	59	23	18	SCL/SL
D11	52.04595177	-0.36006	4.6	56	23	21	SCL
D14	52.04593654	-0.35896	5.4	46	29	25	MCL
D22	52.04589590	-0.35605	4.1	59	22	19	SCL
G6	52.04530308	-0.36190	2.3	69	21	10	SL
G10	52.04528280	-0.36045	2.2	75	17	8	SL
G15	52.04525743	-0.35862	2.3	75	17	8	SL
G19	52.04523712	-0.35717	2.5	71	19	10	SL

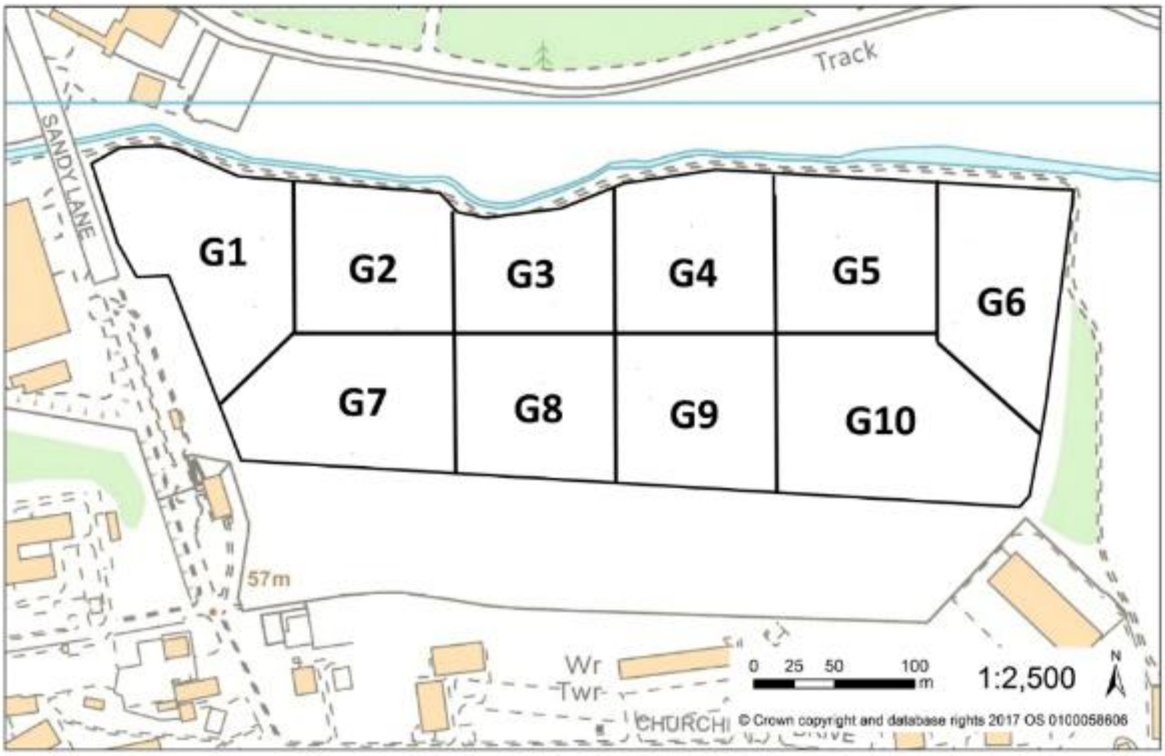


Figure A2. Map showing 1 ha grids and grid identifiers

Table A2-3. Soil analysis – 1 ha grid samples for pH, extractable P, K and Mg, organic matter and soil texture

Grid ID	pH	Ext P (mg/l)	Ext K (mg/l)	Ext Mg (mg/l)	Organic matter %	Soil texture			
						%sand	%silt	%clay	Class
G1	6.0	35.0	237	116	3.7	68	18	14	SL
G2	5.8	33.8	238	130	3.5	58	25	17	SL
G3	6.6	34.2	255	142	3.6	54	26	20	SCL
G4	5.7	25.4	169	131	4.1	56	24	20	SCL
G5	5.7	22.8	143	107	3.6	57	25	18	SCL/SL
G6	6.0	30.6	199	117	3.8	56	25	19	SCL
G7	6.3	33.4	154	67	2.2	66	22	12	SL
G8	6.1	37.8	158	58	2.3	73	16	11	SL
G9	5.6	34.6	118	51	2.1	72	18	10	SL
G10	5.9	35.4	171	58	2.3	69	20	11	SL

Appendix 3. Comparison of different vegetation indices to predict crop biomass and N uptake

Introduction

Ten different vegetation indices were calculated from the CropScan crop reflectance data (Table A3-1) collected from the N response experiments on Savoy Cabbage (2016) and Brussels sprouts.

Table A3-1. Vegetation indices calculated from the crop reflectance data

Vegetation index abbreviation	Vegetation Index	Formula	Reference
NDVI 1	Normalised Vegetation Index	$(\lambda_{810}-\lambda_{640})/(\lambda_{810}+\lambda_{640})$	Rouse *et al*., 1973; Tucker, 1979; Sellers, 1985
NDVI 2		$(\lambda_{780}-\lambda_{670})/(\lambda_{780}+\lambda_{670})$	
GDVI	Green normalised vegetation index	$(\lambda_{780}-\lambda_{670})/\lambda_{670}$	
EVI_2	Enhanced vegetation index two bands	$(2.5*((\lambda_{780}-\lambda_{670})/(\lambda_{780}+(6*\lambda_{670})-(7.5*\lambda_{460})+1))$	Huete *et al.,* 1997
NDRE 1	Normalised difference vegetation index	$(\lambda_{780}-\lambda_{720})/(\lambda_{780}+\lambda_{720})$	Barnes *et al*., 2000
NDRE 2		$(\lambda_{780}-\lambda_{740})/(\lambda_{780}+\lambda_{740})$	
OSAVI	Optimised soil adjusted vegetation index	$((\lambda_{810}-\lambda_{670})/((\lambda_{810}+\lambda_{670}+0.16)*(1+0.16))$	Rondeaux, G., *et al*., (1996)
REIP	Red edge inflection point	$\lambda_{700}+40*((((\lambda_{670}+\lambda_{780})/2)-\lambda_{700})/(\lambda_{740}-\lambda_{700}))$	Guyot and Baret 1988
DCNI	Double canopy nitrogen index	$(\lambda_{720}-\lambda_{700})/(\lambda_{700}-\lambda_{670})/(\lambda_{720}-\lambda_{670}+0.03)$	Chen *et al*., 2010
NDNI	Normalised difference canopy index	$[\log(1/\lambda_{1510})-\log(1/\lambda_{1680}]/[\log(1/\lambda_{1510})+\log(1/\lambda_{1680})])$	Serrano *et al*., 2002

The data from each sample date was grouped and analysed together. Genstat was used to assess linear, exponential and linear plus exponential models to describe the relationship between the vegetation indices and crop biomass and crop N uptake during the growing season, and the percentage variance accounted for by each model recorded (Table A3-2 and Table A3-3).

Savoy cabbage

Table A3-2. Percentage of variance in Savoy cabbage crop biomass and crop N uptake data accounted for by the different vegetation indices

	Crop biomass			**Crop N uptake**		
	Linear	**Exponential**	**Linear plus exponential**	**Linear**	**Exponential**	**Linear plus exponential**
NDVI 1	87.8	96.6	97	74.6	90.4	90.9
NDVI 2	83.6	95.4	96.3	69.3	87.6	88
GDVI	91.8	91.7	91.7	78.2	79.9	81
EVI	75.9	91.4	92.3	58.6	80.6	80.6
NDRE 1	94.2	97.7	97.8	85.4	95.1	95.1
NDRE 2	86.6	92.2	92.2	83.4	94.4	94.3
OSAVI	83.6	95.6	96.4	69.4	87.8	88.1
REIP	83.6	86.3	86.4	82.5	89.4	89.5
DCNI	41.7	41.5	40.6	52.5	54.4	53.8
NDNI	3.5	21.3	35.8	5.5	18.7	24.8

Brussels sprouts

Table A3-3. Percentage of variance in Brussels sprouts crop biomass and crop N uptake data accounted for by the different vegetation indices

	Crop biomass			**Crop N uptake**		
	Linear	**Exponential**	**Linear plus exponential**	**Linear**	**Exponential**	**Linear plus exponential**
NDVI 1	55.0	94.0	94.1	43.2	83.8	83.7
NDVI 2	81.1	86.3	86.2	69.1	84.3	84.4
GDVI	80.4	84.9	86.2	64.6	79.7	80.6
EVI	44.4	91.5	91.5	34.9	78.8	79.1
NDRE 1	74.3	89.1	90.4	62.3	86.6	86.5
NDRE 2	81.1	86.3	86.2	69.1	84.3	84.4
OSAVI	52.9	94.2	94.3	41.2	83	83.1
REIP	16.2	21.5	65.5	16.9	16.8	39.1
DCNI	14.5	17.1	21.7	19.2	18.5	22.3
NDNI	*	2.9	8.1	*	4.4	10

* Residual variance exceeds variance of response variate

Conclusions

An exponential model provided a good fit to the crop biomass and N uptake data for the NDVI 1, NDVI 2, EVI, NDRE1, NDRE 2, OSAVI, REIP vegetation indices. There was a marginal increase in the percentage variance accounted for by fitting a linear plus exponential model for some indices. The DCNI and NDNI vegetation indices did not provide a good fit to the crop biomass or N uptake data from either the Savoy Cabbage or Brussels sprouts.

NDRE 1 provided the best fit to the crop biomass and N uptake data from the cabbages (97.7 and 95.1% variance accounted for using an exponential model respectively). OSAVI provided the best fit to the crop biomass data from the sprouts (94.2% variance accounted for using an exponential model) and NDRE 1 provided the best fit to the crop N uptake data from the sprouts (86.6% variance accounted for using an exponential model).

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Appendix 4. Sulphur response experiment on Brussels sprouts

Background

Sulphur is an essential plant nutrient and as such has an important influence on the yield and quality of crops. The risk of S deficiency and likely yield responsiveness to S will depend on the crop requirement for S (i.e. crop S uptake) and the S supply from the environment from both the mineralisation of soil organic S and the input of S from atmospheric deposition. Sulphur deficiency in crops has become more widespread since the 1990's due to the substantial decrease in atmospheric S deposition.

Although there has been recent research on the S response of cereals and oilseed rape on which to base S recommendations (25-50 kg SO_3/ha for cereals and 50-75 kg SO_3/ha for oilseed rape), there has been very limited work on the S response of field vegetable crops and the current S recommendations for vegetable brassica crops in the AHDB Nutrient Management Guide (AHDB, 2017) of 50-75 kg SO_3/ha are based on the recommendations for oilseed rape.

Sulphur fertiliser was applied to all of the Brussels sprouts N response plots at Park Farm, Risby at the farm standard rate of 175 kg SO_3/ha. An additional two S treatments of 0 and 100 kg SO_3/ha were included within N response experiment 1. The additional S treatments were included to quantify the yield response from the two S application rates (100 and 175 kg SO_3/ha) and were funded by Yara UK as an extension to the AHDB Horticulture project demonstration at this site.

Methodology

There were three S application rates (0, 100 and 175 kg SO_3/ha) replicated four times and arranged in a randomised block design with the other N response treatments as part of N response experiment 1. Sulphur was applied as ammonium sulphate fertiliser split in two applications (Table A4-1). Each plot was 6 x 5 m and included ten rows of sprouts. The three S treatments received 340 kg N/ha.

Table A4-1. Sulphur fertiliser application rates and timings

Treatment number	S fertiliser applied (kg SO_3/ha)		
	5th May	14th June	Total
1	0	0	0
2	50	50	100
3	85	90	175

Leaf samples[11] were taken from each treatment four times during the growing season and analysed for malate: sulphate ratio. Where present, visual symptoms of S deficiency were recorded.

The plots were harvested between 10th and 12th January 2018. Twenty sprout plants from each plot were cut at 5cm above ground and the total fresh weight recorded. The farms sprout harvester was used to strip the sprouts from the stalks and the total fresh weight of all sprouts was recorded. The farms grading machine was used to sort and grade the sprouts; this machine discards any discoloured or diseased sprouts and grades the marketable sprouts according to size (small 23-28 mm, medium 28-33 mm and large 33-38 mm). The 20 sprout plants from each plot were processed through the harvest and grading machines separately. The total fresh weight of all marketable sprouts in each size category was recorded. Separate representative sub-samples of crop residue and sprouts were taken from each plot for dry matter determination and analysis for total S (by NRM laboratory) and glucosinolates (by Sciantec laboratory).

Results and discussion

Table A4-2 showed leaf malate: sulphate analysis results. The malate: sulphate ratio in the youngest leaves of plants can be used as an indicator of crop S deficiency. A ratio greater than 1.5 is used to indicate that the plant is deficient at the time of sampling (Blake-Kalff *et al*. 2000). The malate: sulphate ratio is used most commonly for oilseed rape and cereals, although it is believed to be applicable to other crop types (Blake-Kalff, pers. Comm. June 2017). Although, leaf tissue malate: sulphate ratios were highest from the zero S control treatment on all sampling dates, the relatively low ratios (all less than the critical value of 1.5) indicate the crop was not deficient in S.

Table A4-2. Leaf malate: sulphate ratio

Sulphur rate (kg SO_3/ha)	**Malate: sulphate ratio measured on each sampling date**			
	14 Jun	**27 Jun**	**27 Jul**	**15 Aug**
0	0.52	0.12	0.22	0.16
100	0.13	0.07	0.16	0.08
175	0.19	0.08	0.13	0.09

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[11] Each sample was a composite of the youngest fully expanded leaves from at least 20 plants from each treatment (giving a single sample from each S rate treatment)

Visual symptoms of S deficiency were observed in mid- October (Figure A4-1), but were not apparent earlier in the season. The plants on the zero S control treatments showed a general yellowing of the leaves compared to the plots which had received S.

Figure A4-1. Visual symptoms of S deficiency – yellowing of the crop in the zero S control treatment (left) compared to 175 kg SO_3/ha treatment (right) (19/10/17)

Table A4-3 show the results from the sprout harvest. Although there was a trend for increasing above ground biomass production and total sprout yields with increasing S application rate, these differences were not statistically significant ($P>0.05$) and marketable yields from the higher S rate (175 kg SO_3/ha) were the same as from the zero S control (both 24.3 t/ha). Sulphur fertiliser significantly increased ($P<0.05$) the S content of the sprouts (from 5770 mg S/kg on the zero S control to 7376 mg S/kg on the 175 kg SO_3/ha treatment) and increased the crop S offtake (both in total biomass and harvested sprouts). There was no effect of S application rate on glucosinolate concentrations in the sprouts ($P>0.05$).

Table A4-3. Effect of S fertiliser rate on total and marketable yields, S offtake and glucosinolates in sprouts

	Sulphur rate (kg SO_3/ha)			***P*-value**
	0	**100**	**175**	
Total above ground biomass (t/ha FW)	74.0	75.0	78.4	0.58
Total sprout yields (t/ha FW)	34.1	34.8	35.3	0.78
Marketable sprout yields (t/ha FW)	24.3	24.0	24.3	0.98
% sprouts marketable	71.2	68.4	68.5	0.56
% small (23-28 mm) marketable sprouts	31.1	31.7	30.6	0.94
% medium (28-33 mm) marketable sprouts	49.1	49.9	49.6	0.95
% large (33-28 mm)marketable sprouts	19.8	18.4	19.7	0.87
Total above ground biomass S offtake (kg S/ha)	62.5 (a)	73.8 (ab)	86.4 (b)	0.01
Sprout S offtake (in marketable sprouts) (kg S/ha)	28.9 (a)	35.8 (b)	38.9 (b)	<0.01
S in sprouts (mg S/kg)	5770 (a)	6928 (b)	7376 (b)	<0.01
Gluconsiolates in sprouts (µmol/g)	0.29	0.20	0.30	0.43

FW = fresh weight. Sulphur offtake reported as kg S/ha – to convert to kg SO_3/ha multiply by 2.5. Letters in brackets indicate significant differences between treatments (P<0.05).

Conclusions

Although S fertiliser increased the S content of the Brussels sprout crop, there was no significant effect on marketable yields. The site was a heavy clay loam soil which is at lower risk of S deficiency. This is consistent with the results from recent S response experiments on oilseed rape which showed that soil texture is a key factor controlling the risk of S deficiency and that heavier textured soils are at low risk of deficiency (Sagoo *et al.,* 2018), however the total crop S uptake of Brussels sprouts is likely to be greater than oilseed rape (Zhao *et al*., 2002).

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