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The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems: A *review of precision farming techniques for improved soil and nutrient management*

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Research Review

The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems:
A review of precision farming techniques for improved soil and nutrient management

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1. Introduction

1.1. Introduction to AHDB Project CP107c

AHDB Horticulture project CP107c '*The application of precision farming technologies to drive sustainable intensification in horticulture cropping systems (PF-Hort)*' was a three year project which started in March 2015. The overall aim of the 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 any commercially available techniques that have potential to increase yields and profitability in horticultural systems. This review was produced as part of the first phase of this project, which also includes a field survey of soil structural condition under horticultural crop production (autumn 2015 to spring 2016) and field demonstrations of the use of specific precision farming techniques in horticulture on six commercial farms (harvest years 2016 and 2017).

1.2. Background

Precision technology can help to improve the efficiency of farm operations, including cultivation and better-targeted fertiliser and agrochemical applications. Improvements in farm efficiency increase farm profitability by reducing labour, fuel and input costs and improvements in soil structural condition and nutrient use efficiency can lead to increased yields and crop quality and reductions in soil, nutrient and pesticide losses to the environment. Data from the Defra Farm Practice Survey (2012) showed a notable increase in the number of holdings using precision farming techniques between 2009 and 2012. In 2012, 22% of holdings reported using GPS, 20% used soil mapping, 16% used variable rate fertiliser application and 11% used yield mapping. The two most common reasons for using precision farming techniques were to improve accuracy (indicated by 76% of farms using precision farming techniques) and to reduce input costs (indicated by 63% of farms). The Farm Practice Survey (2012) did not distinguish between the types of holdings using this technology, although anecdotal evidence suggests uptake is greatest in the arable sector.

Precision farming involves measuring and responding to variability in soils and crops to optimise returns on inputs (i.e. fertiliser applications, soil cultivations etc.). Potential increases in marketable yield of high value crops makes precision farming 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 N sensing and yield mapping has largely been focussed in broad-acre crops. Some of these precision farming techniques have direct relevance to horticulture and there is now interest from growers in their potential to increase yields and improve profitability and sustainability.

1.3. Objective

To review the current commercially available precision farming techniques for improved soil and nutrient management and their potential application to horticulture cropping systems.

2. Methodology

A comprehensive literature review, a survey of precision farming companies and machinery manufacturers and a targeted survey of horticulture growers who have experience using precision farming techniques were carried out.

2.1. Literature review

The literature review investigated relevant published scientific and 'grey' literature to gather information on each technique and provide evidence of the benefits, likely costs, trade-offs, limitations and applicability of the techniques for horticulture crops. Sources for the literature review included:

- Web of Science search (for published scientific papers)
- Relevant AHDB published research reports.
- On-going (unpublished) relevant AHDB research projects.

2.2. Survey – precision farming companies

Structured surveys of open and closed questions were produced (and agreed by the steering group) as a framework to engage with the precision farming companies and machinery manufacturers (Appendix 1). The aim of the survey of precision farming companies was to establish:

- Current uptake of precision farming techniques for improved soil and nutrient management in the horticulture sector, and
- Perceived benefits, opportunities and challenges of expanding the use of these precision farming techniques in horticulture.

Interviews were carried out with the following precision farming companies – AgLeader, Agrii, AgSpace, Agrovista, Airinov, CF Fertilisers, Fresh Produce Consultancy, Hutchinson's, Precision Decisions, SOYL, Soil Essentials, Spectrum Aviation and Project Ursula.

2.3. Survey – machine manufacturers

The aim of the machinery manufacturer's survey was to identify:

- Novel soil compaction detection and alleviation techniques.
- Potential to adapt machinery for use of CTF in horticulture.
- Potential for yield mapping of horticulture crops.

Machine manufacturers contacted as part of the review include AS Communications, Claydon, Cultivating Solutions, Great Plains, Grimme, Manterra and Sumo, although some commented that they were primarily focussed on the broad-acre arable market.

2.4. Survey – horticultural growers

The grower's survey was targeted at producers that have experience of using precision farming techniques. The aim of the grower's survey was to collect information on the benefits, challenges and limitations of the various precision farming techniques under different cropping conditions. Grower interviews have been carried out with Allpress Farm (Jim Thompson), Barfoots (Neil Cairns), FB Parrish & Son (Paul Cripsey), G's (Emma Garfield), Glassford Hammond Farming (Philip Lilley), Jepco (Nick Sheppard), Overbury Farms (Jake Freestone), PDM Produce (Dermott Tobin), T.H. Clements (Mark Lyon), Vitacress (Andy Elworthy/Nataschia Schneider) and two Scottish growers (one arable and potatoes, and another arable, potatoes and daffodil bulbs).

3. Review

3.1. Guidance systems

3.1.1. Principles – How does it work?

Guidance systems are based on positioning technology such as vision guidance, ultrasonic sensor systems and satellite-based navigation systems, generically referred to as the Global Navigation Satellite System (GNSS). The market is now dominated by GNSS –based equipment, which uses several satellite networks to calculate position through a three-dimensional version of triangulation using the signal from three or more satellites (Knight et al., 2009). Contributors to the GNSS include the USA's's Global Positioning System (GPS), the Russian 'GLONASS', China's 'Beidou' and the EU-owned 'GALILEO'. The degree of positioning accuracy increases with the number of satellite signals that are available to the receiver and the use of a correction signal that can be provided by an orbiting satellite (lower accuracy) or a static terrestrial reference point, e.g. a local base station (greater accuracy). Some receivers have the ability to receive signals from two or more satellite systems (Bramley, 2009).

Accuracy from one machinery pass to another (short-term, relative or dynamic accuracy) or from day-to-day (long-term, static accuracy – enabling vehicles to return to the same position after a number of weeks) increases with the level of technology and the overall cost of the system. Unenhanced GNSS locates the user to within around 1 m, and is not sufficiently accurate for most agricultural operations. Differential GNSS (DGNSS) uses a minimum of five satellites and the position of a fixed object to correct for GNSS drift (change in the calculated position by up to 1.5 m per hour due to satellite orbit errors and fluctuating weather conditions) and can achieve sub 1 m pass-to-pass accuracy (up to within +/- 10 cm for receivers able to receive positioning data from satellites in two wavelength bands, i.e. dual frequency receivers). Real Time Kinematic (RTK) systems use a local base station, comprising a DGNSS receiver and a radio transmitter, to provide a correction signal; and can achieve pass-to-pass and static accuracies of +/- 1-2 cm. Companies in the UK are now setting up networks of radio transmitters to provide a secure RTK service to customers in some areas. RTK systems can also be supported using a mobile phone signal or a virtual reference station, i.e. using a network of reference stations, which does not require a change of channel from one radio transmitter to another.

Guidance systems using positional technology range from entry level manual steering systems (using a light bar or graphic display to help the driver make steering corrections) to assisted and automatic steering systems. Assisted steering is delivered through the vehicle steering wheel, while for greatest accuracy auto-steering uses communication between the positioning system and wheel angle sensors to activate the steering valves. Auto-steering can be combined with a ‘headland management system’ to provide automatic ‘total implement control’, from pass-to-pass accuracy to all operations required to turn at headlands.

3.1.2. Uptake

Improved performance and reduced cost of satellite-based positioning systems have increased uptake of guidance systems in recent decades. The development and standardisation of Controller Area Networks (CAN, also known as CAN bus networks), which allow microcontrollers and devices to communicate with each other in applications without a host computer, has improved data transfer within vehicles and between tractors and implements, and has had important implications for simplifying the wiring in large vehicles. Growth in the extent of the RTK transmitter network is also increasing uptake. Additionally, a number of growers in our survey reported that guidance systems were awkward to use at first, but that providers had adapted software over the past 8-10 years, based on grower feedback, to make it more user friendly.

The Farm Practices Survey (Defra, 2013) indicated that 46% of cereal farms and 40% of general cropping farms (including horticulture growers) were using GNSS-based guidance systems in 2012. Since then, the number of growers using guidance systems has increased, as indicated by an increase in the percentage of general cropping farms using *“soil mapping and the use of satellite technology to guide fertiliser applications”* from 25% in 2012/13 to 44% in 2014/15 (Defra, 2016b). In both surveys uptake increased with farm size.

In our grower survey, farm size ranged from 250 ha to 3,250 ha (mean = 1,370 ha). All farms had GNSS-based guidance, with the majority using an RTK system. The grower survey was biased towards larger farms (> 3 full time equivalent workers – FTE; Defra, 2016). However, the current trend in many sectors (e.g. vegetable growers) is towards larger farms with many smaller producers going out of production (Phil Effingham, pers comm). A recent surge in the uptake of guidance systems reported by some commercial providers (e.g. Manterra Ltd.) has been mainly restricted to farms greater than 100-250 ha.

Costs associated with implementing GNSS systems will depend on farm size. In the Netherlands, innovation grant subsidies were made available for growers to invest in new technology such as satellite guidance systems (2010-14), which enabled smaller farms (50-60 ha) to gain access to this technology. In England, as part of the Rural Development Programme for England (RDPE; 2010-14), capital grants were paid at a rate of up to 40% in lowland areas and up to 50% in upland areas under the Farming and Forestry Improvement Scheme (FFIS) with grants of £2,500 to £35,000 available for farm businesses to invest in capital items such as soil mapping software and satellite guidance systems for tractors and associated base stations. More recently, as part of the new RDPE (2015-20) a 40% grant was available to arable and horticulture growers to pay for remote crop sensors under the Countryside Productivity Scheme (https://www.gov.uk/government/collections/countryside-productivity-scheme).

3.1.3. Benefits and Costs

Benefits

The economic and operational benefits from guidance systems include reducing overlaps and underlaps, increased "field-fill" (resulting in more plants/yield per hectare), a potential small increase in machine value at replacement due to fewer hours worked and possibly increased work rates. Other benefits that are more difficult to assess in economic terms are reduced operator fatigue (which can translate into sustained operations while conditions are suitable and improved quality of life) and the ability to focus on the efficiency of the field operation rather than steering.

Reductions in overlaps between passes during cultivation, planting/seeding, spraying, fertilising and harvesting can result in direct operational savings in fuel, time and wear and tear on the vehicle and implement. In addition, there can be indirect savings in input costs (seed, spray, fertilisers) resulting from a reduction in double-dosed areas. However, the greatest gains (of potentially over £10 per hectare; Knight et al., 2009) are only achievable where existing accuracy is poor (i.e. initial overlaps of 0.75 m for cultivations, 0.3 m for drilling, 1.2 m for spraying/fertilising and 0.9 m for harvesting). On farms with average accuracy, Knight et al. (2009) predicted that typical gains were £1-2/ha, and on farms where the existing accuracy was better than average there was no economic gain from reduced overlaps. However, it was acknowledged that sustaining high levels of accuracy over an extended period using manual steering/guidance may be unrealistic.

It is important to note that the economic analysis carried out by Knight et al. (2009) used field operations and typical inputs on cereal farms. On some horticulture farms (e.g. vegetable and fruit growers) there are many more operations that could be carried out using guidance systems, which (depending on the number of vehicles equipped with guidance and autosteer) could improve the cost:benefit ratio from reduced overlaps.

One of the key potential benefits of satellite guidance in horticulture systems (particularly field vegetables) is increasing the number of viable plants per hectare through improved "field-fill". There is also potential to improve overall crop quality at harvest by reducing the risk of crop damage during the growing season, through double-dosing or under-dosing of fertilisers and sprays, and physical damage from poor steering.

Guidance systems form the basis for other precision farming techniques such as yield mapping, soil mapping, canopy sensing, variable rate nutrient applications and controlled traffic farming (CTF). Indeed, the ability to re-position equipment in a field with +/- 1-2 cm accuracy after an interval of days or weeks, which only RTK-based systems can provide, may be essential for farms wishing to adopt CTF systems in which seeds/plants are placed in beds that have not been wheeled (within the growing season). Even if growers do not intend to adopt a full CTF system the use of guidance systems can help reduce the amount of random traffic within a field, thereby improving soil structural condition and yield potential (e.g. Chamen et al., 2015).

Additional savings and benefits include faster forward speeds without loss of accuracy and/or extending the working day thereby allowing fieldwork to be completed in optimal conditions (Knight et al., 2009; Herman Schlepers, pers comm, 2016). However, increased work rates from satellite guidance may be overestimated as they do not account for 'down-time' due to set up or signal problems (Knight et al., 2009).

Costs

The main cost of satellite-based guidance systems is associated with the purchase of the receiver, display unit and, for RTK systems, the base station or virtual reference station. Other costs include licences and subscriptions, maintenance/servicing, operator training, set-up time and upgrading, which may occur every 3-5 years. The costs vary considerably between systems and according to the number of vehicles equipped with receivers and assisted steering.

Fully-integrated auto-steer systems cost around £6,000-7,000, based on July 2016 prices. However, many larger tractors and combines have the capability integrated as standard in their specification, requiring activation at around half the cost. Some CTF farmers, however, seek this capability on smaller tractors as they have found that larger tractors cause unacceptable levels of compaction, even within a CTF system (Duco Vebrugge; Andre Jurrius, pers comm). The combined cost of a receiver/display unit and steering for a vehicle is likely to be from around £10,000. Total implement control adds around £2,000 to this cost; and an RTK base station a further £15,000. However, there is the potential for base stations to be shared depending on the size of farms and local obstructions due to landscape, etc. RTK transmitter networks are also available in some areas (e.g. central and eastern England and eastern Scotland) at an annual cost. Overall, the cost of an RTK base station (single farm), receiver/display unit, auto-steering and total implement control would typically cost around £25,000-£30,000 for a single tractor; £40,000-£45,000 for two vehicles and £50,000-£55,000 for three vehicles (e.g. tractor, harvester and sprayer). Costs per hectare and per year will vary according to farm size; depreciation rate; replacement rate and value; capital interest rate; and costs for operator training, set-up, calibration, annual servicing and maintenance checks.

Based on likely costs per hectare (using typical depreciation and capital interest rates etc.) and potential savings per hectare (based on lower operational costs, fewer inputs and improved machine replacement value) Knight et al. (2009) calculated that an RTK-based system was unlikely to be cost-effective on combinable crop farms of less than 400-500 ha, and that within the 400-800 ha range, the most profitable system (low/DGNSS, medium/DGNSS or high/RTK accuracy) depends on the number of receiver/display units required. The threshold farm size at which satellite guidance becomes cost-effective will reduce with the overall cost of systems and with the number of operations that can be carried out using guidance. The threshold farm size for some horticulture systems may be significantly lower than for combinable crop farms, although as stated above, this will depend on the initial level of accuracy prior to the adoption of satellite guidance.

3.1.4. Challenges / Barriers

In the 2012 Defra Farm Practices Survey (Defra, 2013) 47% of respondents not using PF techniques stated that the technologies were not cost effective and/or initial setup costs were too high; 28% that they were not suitable or appropriate for their farm; 27% that they were too complicated to use; and 2% that they were not accurate enough. The results by farm size were very similar, while ‘General Cropping’ farms gave the highest response (62%) for “not cost effective and/or initial setup costs too high”. Cost has therefore been a significant barrier to adoption of guidance systems and other PF techniques. Many growers perceive that the cost associated with equipment purchase, management time and the non-financial cost of introducing a seemingly complex system, outweigh any potential benefits. This is despite a substantial body of literature suggesting that guidance systems can yield financial benefits (e.g. Bramley, 2009; Freeland et al., 2012; Zier et al., 2008).

3.1.5. Trade-offs

The advantages of GNSS-based guidance systems are clear for most farms greater than 400-500 ha; and as investment costs decline over time, due to new RTK signal availability options and reduced cost of equipment, the technology is likely to become increasingly viable on smaller farms. Each farm needs to weigh up the cost of the most appropriate system (in terms of accuracy and the time needed to set-up, calibrate and familiarise oneself with a new system) against the potential financial benefits from reduced overlap and increased machine replacement value; the benefits in terms of increased “field-fill”, reduced operator fatigue and increased operator flexibility; and the benefits derived from access to other PF techniques.

3.1.6. Limitations

Benefits are greatest for farms on which the initial level of accuracy is lowest (i.e. overlaps and underlaps are greatest). Financial gain is not immediate on farms that are able to sustain a high level of manual machine control and accuracy. Limitations to the adoption of guidance systems will decrease as technologies improve. Radio transmitter and mobile phone network coverage still limit the extent of RTK in some areas, but the use of mobile base stations, the expansion of RTK transmitter networks, sharing of base stations and the use of virtual reference stations will increase the uptake of RTK-based guidance systems.

3.1.7. Opportunities / Applicability

The main opportunities associated with satellite guidance systems are access to other PF techniques such as yield mapping, soil mapping, canopy sensing and the variable rate application of nutrients (and sprays). The potential benefits of CTF systems are also greater under a GNSS-based guidance system, and these techniques are applicable to all horticulture sectors on annual and perennial crops. Indeed, there is interest in all sectors including top fruit, Narcissus and asparagus growers (Nigel Kitney, pers comm; Phil Effingham, pers comm).

3.2. Controlled traffic farming

3.2.1. Principles – How does it work?

Controlled traffic farming (CTF) aims to reduce the proportion of each field area that is wheeled by machinery to avoid widespread soil compaction. CTF has been defined as “confining compaction to the least possible area of permanent traffic lanes” (Chamen *et al*., 2015) and involves greater discipline in use of routeways and tramlines. Maximising the area that is not wheeled retains good soil structural condition in the crop growth zone or growing bed, with the aim of improving crop yield and soil drainage. With CTF only 30-40% of the field is trafficked rather than an estimated 80-110% with conventional practice (Godwin *et al*., 2015; Kumala *et al*., 2009).

Increases in the size of agricultural machinery (e.g. the weight of harvesters has increased by 300-400% since the 1960s with axle loads increasing from 3-4 tonnes to 13-14 tonnes (Pedersen, 2015; Schäfer-Landefeld *et al*., 2004) running on different track gauges and tyre widths, and without satellite guidance to help reduce the area wheeled has resulted in increasing levels of soil compaction (Arvidsson and Keller, 2004; Batey, 2009; Hamza and Anderson, 2005). The increase in axle loads has also raised concerns that subsoil compaction is a significant issue that is particularly difficult to alleviate (Håkansson, 2005; Håkansson and Reeder, 1994; Schjønning *et al*., 2010). When harvest traffic is random and carried out when soils are at or close to field capacity (i.e. the amount of soil water held against gravity) soil compaction can be widespread and extend into the subsoil. Subsoiling can alleviate compaction to around 45 cm depth, but is not always effective (Chamen *et al*., 2015; Marks and Soane, 1987).

Avoiding soil compaction is particularly challenging in some horticultural systems (e.g. vegetable production and tree nurseries) as crops are often harvested late in the season (late autumn/early winter) or in wet conditions. Soil compaction can cause a number of challenges for the profitability of a horticultural business by reducing crop yield (e.g. Vrindts *et al*., 2005), increasing draught forces for cultivation (e.g. Mouazen and Ramon, 2009) and reducing water infiltration rates (e.g. Li *et al*., 2009). It is therefore important to alleviate compaction in the early stages of CTF adoption.

In its purest form CTF involves adapting machinery so that all vehicles are on the same track gauge (axle width) and tyre/track width and machinery working widths operate in multiples of the narrowest machine (e.g. the planting or drilling bout width). Within such a system all plants are established in either non-wheeled areas (the majority of the area between the wider tramlines) or intermediate wheeled areas (where the tractor pulling the drill runs). For CTF to be effective, machinery needs to run on the same wheelings/tramlines throughout the season and from year to year. The development of RTK-enhanced satellite guidance systems has therefore facilitated the adoption of CTF (section 3.1 Guidance systems).

A variety of CTF systems have been adopted, from tractors on wide track gauges to gantry systems developed for both experimental and commercial systems. Some growers are now interested in developing CTF systems based on lighter tractors to reduce the compaction caused from wheelings in the autumn and winter (when the soil is at field capacity), thereby reducing impacts on the crop adjacent to wheelings. Provided that the number of passes is not increased the use of lighter tractors should reduce the degree and extent (width and depth) of compaction around wheelings (Horn *et al*. 2003; Peth *et al*., 2006).

Seasonal CTF (SCTF) runs the majority of equipment on common track and working widths up to harvest. Random traffic at harvest is accepted due to the common difficulty of incorporating harvesters into the system, especially where contractors are used. Within SCTF systems, the compaction effects of harvest traffic have to be managed with tillage in the crop growth zone (McPhee et al., 2011). Nevertheless, SCTF can still benefit from many of the advantages of a CTF system.

3.2.2. Uptake

No Farm Practices Survey data exists for uptake of CTF in the UK; most probably because the adoption of the approach is at very low levels, i.e. less than 0.1% in all sectors. Nevertheless, there is increasing interest in broadacre and horticulture crops; and with the adaptation of harvest machinery with wider headers and an increasing number of tractor manufacturers able to change track gauges, as well as bespoke machinery produced for CTF systems (e.g. MultitoolTrac: http://www.multitooltrac.com/construction/), the options for CTF adoption are increasing. Indeed, the potential for uptake is relatively high. For example, Tullberg *et al*. (2007) reported that adoption in Australia increased from around 6 growers in 1993 to 100,000 ha by 1997, through federal support and promotion at national conferences. With the advent of RTK/GNSS, uptake increased to 2 million ha by 2007. Adoption occurred first on cereal farms, but has now increased in many other farming systems, deploying a greater range of compatible equipment. In some of the major cereal growing areas in Australia, around 80% of the cropped area uses some form of CTF, and 'true' CTF, including standard working widths at harvesting, covers around 18% of broadacre cropping in Australia (Chapman, 2015).

In Alberta, Canada, there were only one or two farmers using full permanent CTF systems before 2011. By 2015 around fifteen farmers were using CTF systems in Canada and less than 50 in North America (Gamache; 2015).

In Europe, adoption was minimal until around the turn of the century (Chamen, 2015). The catalyst for adoption was a 5-year Unilever-funded field trial and promotion programme started in 2004, including contact with major machinery manufacturers to adapt machinery. This was followed by charitable funding to promote CTF with growers, and by 2014 there were around 50,000 ha in CTF and a further 15,000 ha in conversion; mostly combinable crops on heavy soils (Chamen, 2015). In the Netherlands, around half of organic vegetable growers use seasonal CTF, and a few are on a near full CTF system (Bernaerts pers comm, 2015).

In the UK, progress has been made with the development of CTF systems in rotations driven by onion and sweetcorn production Of the few horticulture growers adopting CTF, some have adopted a gradual approach, changing track gauges and adapting machinery when it is due to be replaced. Others prefer to make a single large investment where this is possible.

3.2.3. Benefits

The key benefits from CTF include better soil structure; leading to fewer and less energy-intensive cultivations (Chamen *et al*., 1992a; McPhee *et al*., 2015); reduced fuel use (Chamen *et al*., 1992b; Mouazen and Palmqvist, 2015); improved seedbeds; increased water infiltration rates/better drainage (Chyba, 2012; McPhee *et al*., 2015); more machinery work days; improved water and nutrient use efficiency; and increased yields in some years (Chamen *et al*., 2015; McPhee et al., 2015).

Improvements in soil structure and porosity lead to other benefits; including improved workability, infiltration and aeration, which in turn influence drainage, the degree and duration of waterlogging, timeliness of field operations, droughtiness and crop yield. Improved drainage and shorter periods of standing water reduce disease risk. For example, in asparagus good soil and water management can help maintain a healthy stand, and significantly reduce the risk of crown and root rot (Falloon et al., 1986; Hamel et al., 2005; Nigh, 1990; Niziolomski, 2014; Snowdon, 1991)

McPhee *et al*., (2015) reported significant differences in soil bulk density, air-filled porosity and penetrometer resistance under CTF in onions, broccoli, beans and carrots. The depths at which differences in soil physical properties occurred varied between sites and crops, but ranged from 50 to 500 mm depth. Differences in soil physical properties were detected for most crops and sites for at least one depth (25, 150 and 300 mm depth). McPhee (2015) also reported improvements in visual evaluation score after only one season of CTF (Figure 1).

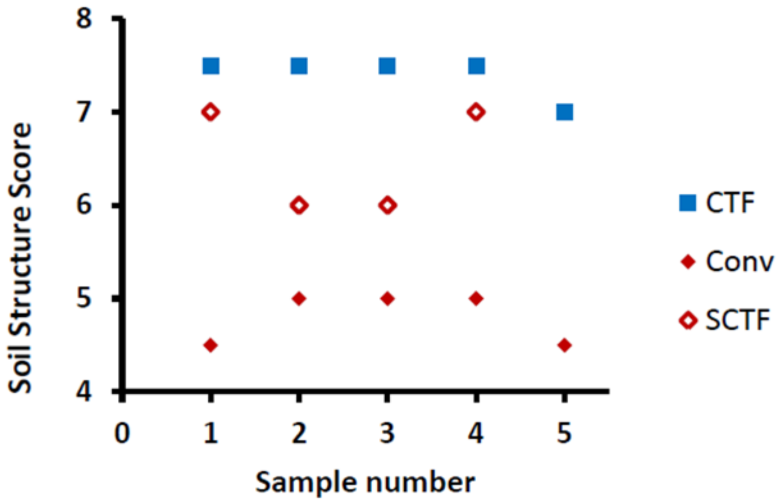

Figure 1. Soil structure score for controlled traffic (CTF), seasonal controlled traffic (SCTF) and conventional (Conv) traffic systems in vegetable production. Score: 10 = excellent, 1 = very poor.

Using a Cornell sprinkle infiltrometer (Ogden et al., 1997) with a single 241mm diameter infiltration ring, McPhee *et al*. (2015) also measured significantly greater water infiltration rates under CTF systems in brocollli, particularly during winter months. For example, in 2010, the average infiltration rate in the CTF treatment was >180 mm/h, compared to 3mm/h in the conventional treatment, which exhibited runoff after only 2.2 minutes. This confirmed improvements in soil structure and water infiltration rate, and reductions in surface runoff measured by other researchers under CTF in arable crops (e.g. Li *et al*., 2007; McHugh *et al*., 2009; Tullberg, 2010; Unger, 1996).

Chamen (2011) collected mean values of data from around the world and concluded that compared with conventional traffic, CTF on average increased yields by 19% on clay, 22% on loam, 8% on silt and 20% for root crops across a range of soil textures (Figure 2). The results indicate that yield increases are possible across a range of crops and situations. However, not all of the results were from replicated experiments with a number of studies conducted in either adjacent or split fields with one in random traffic and the other in controlled traffic management.

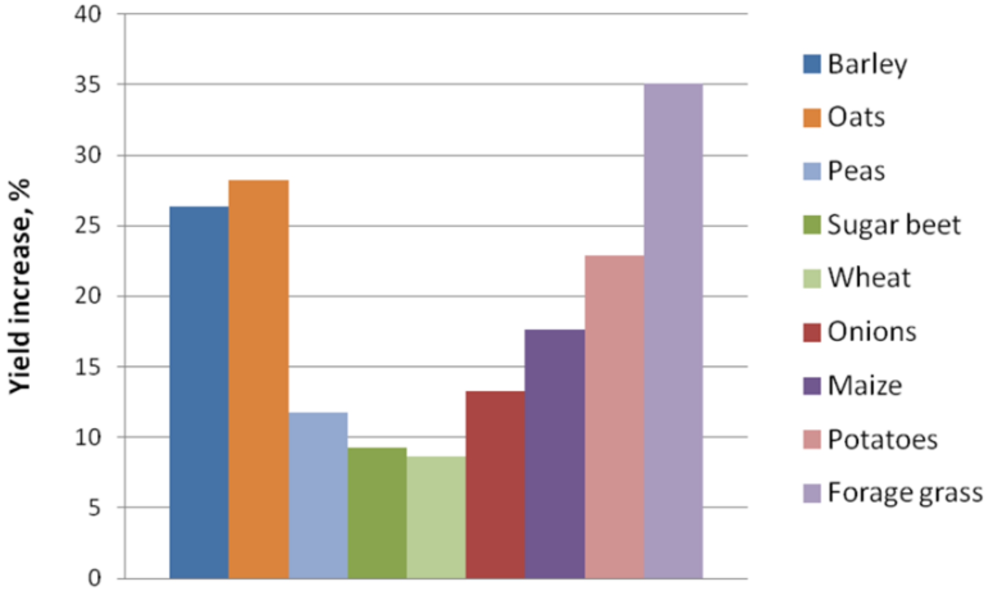

Figure 2. Percentage increase in crop yield of different crops grown on non-trafficked compared with randomly trafficked soil (Chamen, 2011).

Nevertheless, yield increases have been detected from replicated randomised-block experiments investigating the effects of CTF. For example, Godwin et al. (2015) reported a 15-16% improvement in winter wheat yield for 'zero traffic' over 'random traffic' at Morley, in Norfolk in 2008 (cv =7.8%, P = 0.07, lsd = 1.52 t/ha). Similarly, in a study on a sandy loam soil at Harper Adams University, Shropshire, Smith et al. (2013) reported that winter wheat yields were higher on the CTF/shallow tillage (15%; 1.1 t/ha; P<0.10) and Low Ground Pressure/ shallow tillage (9%; 0.64 t/ha; P<0.10) treatments than on the 'random traffic'/deep tillage (effectively conventional farm practice) treatments.

By contrast, in three replicated field experiments on oilseed rape, wheat and maize in Alberta, Canada, where 'simulated random traffic' estimated to track 35-50% of the soil surface was compared with CTF tracking 15-20% of the surface, Gamache (2015) reported no statistically significant increase in crop yields in the first year of a three year project (2014-17). However, based on early improvements in soil physical properties (e.g. water infiltration rate) yield increases were anticipated. Other crops grown in the rotation included barley, sunflowers, peas and field beans.

In potatoes, Dickson et al. (1992) reported increases in total (14%) and marketable (18%) yield under CTF in Scotland, while Lamers et al. (1986) measured increases for ware (3%) and seed (7%) potatoes in The Netherlands. However, comparatively few investigations have been carried out on yield responses to CTF in horticulture crops. In The Netherlands, Vermeulen and Mosquera (2009) reported a variety of responses to CTF ranging from no change to statistically significant increases such as 10% in onions and 35% in spinach. McPhee et al. (2015) reported limited response to CTF in onions, broccoli, beans, processing carrots poppies and leeks in Tasmania, with only onions showing a statistically significant yield increase (14%; P<0.05). However, it is perhaps not surprising that the reported yield responses were variable as it can take several seasons for soil improvements from CTF to be reflected in crop quality and yield (McPhee et al., 2015).

Some studies have investigated the overall benefits associated with CTF adoption. Based on a comprehensive literature review and data on soil properties, topography, machinery, and weather from three farms in England, Scotland and Australia, Mouazen and Palmqvist (2015) estimated that adoption of CTF reduced soil compaction by 24% and tillage energy requirement by 10%; and improved fertiliser use efficiency by 3%. In addition, CTF was estimated to enhance soil biodiversity (7%), erosion control (6%) and soil organic matter (6%); and reduce greenhouse gas (GHG) emissions by 3%.

Using an economic modelling approach, McPhee et al (2011) found that farm-based greenhouse gas emissions could be reduce by 26% under SCTF, and by 60% under a CTF system. The benefits were attributed to a combination of reduced fuel use (reduced tractor power and working time) and lower nitrous oxide emissions. McPhee et al (2011) acknowledged that there were many unknowns in the study, and that the results indicate the potential of CTF, rather than a definitive assessment of actual emissions reductions.

3.3. Yield mapping

3.3.1. Principles – How does it work?

Yield monitors are used to collect information on the harvested crop, and this can be combined with positional data to produce a spatial yield map. Yield mapping is most commonly used in combinable cropping systems. Combine yield monitors have been available since the early 1990s and yield monitors and GPS are now routinely fitted on many combine harvesters.

Most combine yield monitors measure harvested grain/seed mass flow or volume, moisture content and speed to determine total grain harvested, and in this way can be used to record yield of any combinable crop. Typically, the grain/seed is fed into the harvester elevator where a sensor records the moisture content, and as the grain is delivered to the holding tank a mass flow/volume sensor monitors yield.

Yield monitoring of non-combinable crops is less common. Such systems are usually based on measurement of weight of harvested crop combined with positional data. A system for monitoring yields from root crops is now commercially available in the UK. Soil Essentials supply a yield monitor produced by Grimme for root crops; load cells under the web or conveyor belt are used to weigh the crop. The system is available on new machines and can be retrofitted to most harvesters. Soil Essentials have supplied root yield monitoring equipment in the UK for potatoes and onions, although the equipment can be used to monitor yield of any crop that passes over a conveyor.

In top fruit, Hutchinson's now offer the Omnia Fruit Vision system which can be used to count and grade apples on the tree. This system uses optical sensors mounted on a quad bike that takes 20 images per second as it passes through an orchard at about 6 km/hr. The system can be used from about July (i.e. after the June drop) until harvest

Other bespoke systems of yield monitoring may be developed between individual growers and precision farming companies/machine manufacturers. For example, recently HMC peas have worked with Trimble, AS Communications and PMC to develop a yield mapping system for vining peas. HMC have retrofitted load cells in the collection tanks of their vining pea harvesters and linked this to GNSS to produce yield maps.

3.3.2. Benefits/applications

Yield maps are potentially very valuable for growers as they represent the final output of the agronomic process; where crop management across a field is uniform the spatial variation in yield represents spatial variation in profitability across the field. Many farmers with combinable crops are collecting a plethora of data on yield variation across their fields, however anecdotal evidence suggests that many farmers are unclear how best to interpret and utilise the information. Yield maps show the spatial variability in yield, but they don't identify what is causing this variability. The variation in final yield represents the combined effects of spatially variable soil, environmental and crop variables, and the challenge with yield maps is to understand the variation and to try and disentangle the causes of variation. The interpretation of yield maps is a major challenge for their practical use. Whilst yield maps are potentially very valuable, their value is only realised when they are used as part of field management.

For horticultural growers considering the value of yield mapping it is important to consider:

- The costs and practicalities of modifying harvest machinery to record yields.
- Whether yield maps from combinable crops can be used to inform management of horticultural crops grown in the rotation.

Potential applications of yield maps include the following:

i. Targeting low and high yielding areas

Yield maps (single or multiple years) can be used to identify the highest and lowest yielding areas of a field for further investigation. This information can be used to target soil sampling (for pH and nutrients) and soil structural investigations to identify areas of compaction or poor drainage to understand the factors limiting yield. 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 localised areas of low pH that can be corrected by variable rate liming and areas of poor soil drainage that can be addressed by installing or repairing field drains. Griffin (2010) noted that where yield limiting factors were not related to nutrient availability, low yielding areas are often associated with higher soil nutrient concentrations as under conventional uniform fertiliser applications nutrients accumulate in the low yielding areas due to limited nutrient offtake.

ii. Identifying whether variable rate management is likely to be of benefit

Spatial yield variation can also be used to assess the potential benefits in exploring the causes of variation and implementing variable rate management (i.e. variable rate fertiliser application or variable seed/planting rate). Variable rate management is likely to be of greatest benefit in fields which are inherently variable. Where yield variation is relatively low, the cost of detailed sampling and variable rate management is less likely to be justified. In this way growers who are interested in adopting variable rate management can identify which fields are most likely to respond profitably.

Lark *et al*. (2003) describe a methodology for ranking the 'potential for variable rate management' based on yield variation. Similarly, Mohammed *et al*. (2016) reported that yield variation can be used to help determine whether variable rate management is likely to be effective and to rank fields most likely to respond profitability to variable rate management. Although these analysis methodologies are potentially useful, in order for them to be practically adopted by growers they would need to be integrated into data management software packages offered by precision farming companies and/or commercial farm management software.

iii. Creating management zones for variable rate strategies

Yield maps can be used on their own or in combination with other spatial data (i.e. soil EC maps) to define field management zones, which can in turn be used as the basis for variable management. Information from the literature suggest that at least 3-6 years of yield data is necessary to define field management zones. This will allow the identification of spatial yield patterns that are relatively constant over time rather than annual yield variation caused by seasonal factors such as weather or other unpredictable factors such as pest or disease damage.

Multiple years of yield data can be combined in different ways. The most straightforward approach is to create a 'normalised' yield map which combines multiple years of data by calculating the ratio of actual yield to field average in each year and then mapping the average. Another approach identifies areas of the field which show more or less uniform season to season patterns of variation (i.e. consistently above or below average yield) and areas of variable response where the yield is less predictable. A number of the data management software packages offered by precision farming companies as well as commercial farm management software (e.g. GateKeeper) are able to combine yield maps in this way.

Although management zones based on yield map data can be defined using mathematical algorithms, in most cases these zones are drawn by hand by either the farmer or precision farming adviser. Soil electrical conductivity (EC) measurements often closely correlate to yield data and if available, such maps can be used in conjunction with yield maps to help identify field management zones (Lund *et al*., 2000). Once management zones have been identified it is important to understand what factors are contributing to yield differences between the zones, and whether it is possible/economic to manage the zones differently.

Where horticultural crops are grown in rotation with combinable crops it may be possible to use yield maps from combinable crops to create field zones which can be used for all crops in the rotation. Panten *et al*. (2005) found that 49% of the yield variability of the sugar beet crop could be explained by the previous four years of combinable crop yields, and that these yield maps could be used to create zones for variable management of the sugar beet crop.

However, if yield maps from combinable crops are used to inform management of other crops grown in the rotation, it is important to understand which factors are causing the variation in yields and whether these factors vary between crops. For example, yield variation in combinable crops is often attributed to factors affecting water availability (i.e. soil texture and structural condition) and irrigation of horticultural crops may change the pattern of yield variability.

Where yield patterns differ between crops it is important to try and understand the yield limiting factors for the different crops. In research carried out as part of AHDB Horticulture studentship project CP 121, lettuce yields were measured from two successive crops (harvested 8th June and 10th September 2015) in two fields at G's Growers in Cambridgeshire. Although the yield patterns were consistent for the two lettuce crops, they did not correspond with the pattern of yield variation measured in the previous wheat crop. The authors suggested that biological differences between wheat (a non-irrigated long season crop) and lettuce (a short season irrigated crop with high input levels) may not support comparison of yield patterns measured in different crops in the rotation (Monaghan, 2016). This suggests there is limited benefit from combining yield patterns from multiple crops in the rotation unless the crops have similar management and growth characteristics. Where multiple crops are grown in the rotation it will take longer to generate sufficient data to confidently identify stable yield patterns that are not controlled by seasonal and crop differences.

iv. Defining a yield potential map

Yield maps sufficiently robust to identify areas of constant yield response can be used to define maps of yield potential which in turn can be used as a basis for variable rate nitrogen application. This approach is best suited for crops where the nitrogen recommendation depends on expected/target crop yield. The revised Nutrient Management Guide (RB209) (AHDB, 2017) includes a yield adjustment for wheat, barley and oilseed rape nitrogen applications to account for higher and lower than average yields. The Isaria tractor mounted crop sensor is able to integrate a yield potential map and canopy sensing information to vary the nitrogen rate. For wheat, this requires an absolute calibration whilst for oilseed rape and barley the grower must calibrate specific areas of the field against a given N rate and define how the N rate should be altered for a 10% change in yield. AHDB (2017) also provide guidance on adjusting nitrogen fertiliser rate according to expected yields for most field vegetable crops, however there is no evidence of any growers currently varying nitrogen rates for field vegetable crops within a field.

Furthermore, Lund *et al.* (2000) noted that many growers are hesitant to establish site specific yield goals using yield data alone, even with multiple years of data, because of a concern that historical yields aren't strong enough evidence of yield potential. Because of the severe economic penalty for under-applying inputs such as nitrogen, growers are often unwilling to reduce inputs in low yielding areas until they have some confirmation that the low yielding areas truly have lower yield potential, and are not being limited by some other factor which could be easily remedied.

v. Calculating nutrient removal

Yield maps can be used to calculate spatial variation in crop nutrient (phosphate and potash) removal. RB 209 phosphate and potash recommendations (AHDB, 2017) are based on the principle of maintaining soils at target P and K indices. Fertiliser P and K recommendations aim to replace crop P and K offtake at the target index and include an 'index adjustment' where the soil is below target index in order to raise the soil P and K Index to target over a number of years.

For arable crops the target P Index is 2 and K Index is 2-. Fertiliser recommendations are equivalent to crop offtake at the target Index and crop offtake + 60 kg/ha P_2O_5 or K_2O at Index 0 and + 30 kg/ha

P_2O_5 or K_2O and Index 1. In this way fertiliser P and K rates can be calculated based on measured yield:

Example: Winter wheat, straw removed. Field average yield of 8 t/ha, but an area of the field consistently yields 12 t/ha.

- Crop phosphate and potash content 8.4 kg P_2O_5/t and 10.4 kg K_2O/t (AHDB, 2017).
- Crop phosphate and potash offtake from 8 t/ha crop is 67 kg P_2O_5/ha and 83 kg K_2O/ha.
- Crop phosphate and potash offtake from 12 t/ha crop is 101 kg P_2O_5/ha and 125 kg K_2O/ha.
- If phosphate and potash is applied to the whole field based on 8 t/ha field average yield, the high yielding area will receive 34 kg P_2O_5/ha and 42 kg K_2O/ha less than crop offtake. Over a number of years this can be expected to result in a decline in soil P and K levels in the higher yielding areas.

It is possible to combine maps of crop nutrient removal with maps of soil P and K Index to calculate P and K recommendations which take into account both variability in soil index and crop nutrient removal. Such a service is offered by some precision farming companies e.g. SOYL. Where horticultural crops are grown in rotation with arable crops, more accurate management of P and K to the arable crops (where information on yield is available) should be of benefit to all crops in the rotation.

The principles of P and K recommendations are the same for horticultural crops. For field vegetable crops the target P Index is 3 and K Index is 2+. Fertiliser recommendations are sufficient to replace crop offtake at the target index and include the following index adjustments:

- + 50 kg/ha at P Index 2 and K Index 2-
- + 100 kg/ha at P/K Index 1
- + 150 kg/ha at P/K Index 0

The method of adjusting P and K applications based on spatial variation in crop nutrient offtake could also be applied to horticultural crops. However, there is no evidence of any growers or precision farming companies who have used this approach for horticultural crops. This probably reflects the lack of yield variation measurements carried out in horticultural crops and the limited number of horticultural crops for which the AHDB Nutrient Management Guide provides typical crop P and K content values.

vi. On farm experiments

Yield mapping is a potentially very useful tool to evaluate on-farm experiments (Griffin 2009, Sagoo *et al*., 2017). Crop varieties or any aspect of crop management (i.e. fertiliser rates, seed rates, cultivations, agrochemical inputs etc.) can be compared on farm in strip or tramline comparisons allowing the effectiveness of contrasting practices to be assessed using yield maps. This approach is now being used in a number of ongoing arable research projects.

The Innovate UK funded ‘PrecisoN-AG’ project (‘Development of automated systems for precision application of nitrogen fertiliser and plant growth regulators’) (REF) is working on developing automated systems to measure N fertiliser requirements for cereals and oilseed rape and PGR requirements of oilseed rape (Kindred *et al*. 2017; Kendall *et al.* 2017). The validation phase of the project includes tramline treatment comparisons with yield maps used to assess the efficacy of the treatments. The PrecisoN-AG project is utilising statistical methods developed in the Innovate UK funded ‘Agronomics’ project for analysing yield data from tramline trials. These statistical methods have been specially developed to allow spatial analysis of yield data from on-farm tramline trials.

There is no evidence of any growers, researchers or precision farming companies currently using this approach for on-farm trials in horticultural crops. One of the precision farming companies interviewed as part of the review noted that one of the key challenges with precision farming in the horticulture sector is the difficultly of quantifying yield – if growers are unable to quantify yield they can’t quantify the benefit or value of what they can achieve with precision farming.

3.3.3. Limitations

The two main challenges in the use of yield monitor data are (i) effective data management to remove erroneous yield measurements and extract underlying patterns of yield variation, and (ii) understanding the cause of the measured variability. These are discussed further below.

i. Yield monitor data processing

The variability in yield monitor data is a result of naturally occurring yield variation due to soil and weather factors, management induced yield variation, and measurement errors caused by the yield monitoring process. The robustness of the technique relies on accurate measurements and it is important to remove measurement errors caused by the yield monitoring process. This will ensure that the yield map represents in-field yield variation as accurately as possible.

Errors in the yield monitoring process of combinable crops are generally well understood (Blackmore and Marshall, 1996; Blackmore and Moorse, 1999; Grisso *et* al., 2009a) and include: •

- Unknown crop width entering the header during harvest.
- Start and end pass delays: start pass delays occur when the combine starts harvesting the crop, but the grain flow has not stabilised because the elevator gradually fills up; end pass delays occur when the combine moves out of the crop and grain flow reduces to zero as the grain elevator is emptied.
- Grain flow delays representing the time lag for grain to move through the threshing mechanism, which offsets the yield position along the route of the combine.
- Surging grain through the combine transport system.

- Grain losses from the combine.
- The inherent ‘wandering’ error of GNSS (depending on the accuracy of the farm GNSS installation).

Some yield monitors are able to correct for some known sources of error. For example cutting width can be set by the operator or measured with a sensor. Similarly, some yield monitors include a positional offset to ‘shift’ the data to correct for grain flow delays. However, additional post processing of yield data is still required to remove other measurement errors. There has been considerable research effort in devising post-processing routines to integrate yield map data and deal with data errors, including programmes available from Sudduth and Drummond (2007) (Yield Editor), Sun *et al*. (2013), Kindred *et al.*, (2015) (Auto-N) and most recently Muhammed *et al*. (in press) (Roth-YE). Both the Auto-N and Roth-YE routines were developed as part of AHDB Cereals & Oilseeds funded research projects. As most growers are very unlikely to source stand-alone yield data editing routines but may be more likely to utilise one available in precision farming or agronomy software there would be benefit in making routines developed in these research projects available to commercial precision farming and software companies for integration into their products.

Some (but not all) of the precision farming companies and commercial software systems include the ability to remove measurement errors from yield map data. However, a consistent system for post-processing yield data has not been agreed and is not generally used by growers (Kindred *et al.* 2016). SOYL were part of the project consortium developing the Roth-YE routine and have integrated this into their software. Other precision farming companies/software providers may include their own data processing routines. Griffin (2010) noted that users should be cautious when accepting default post-processing parameters imposed by farm level mapping software by understanding the parameters and how the default settings affect the quality of the data.

The GateKeeper software from Farmplan, which is widely used by growers, includes post processing of yield data. The programme allows users to either accept the software’s default data filtering parameters or set their own template for filtering by setting the minimum and maximum amounts above/below which to remove data, setting the maximum machine overlap and identifying harvester speeds above/below which to remove data. This functionality is useful for growers who understand yield maps and are able to differentiate between measurement errors and seasonal yield variation. However, there is a risk that processing of yield data can ‘over-smooth’ the final outputs by editing out the extremes of genuine yield variation.

Yield monitor data from horticultural crops is also likely to contain measurement errors, although these are likely to be different to measurement errors made for combinable crops and depending which yield monitoring system is used may include:

- Zero yield measurements where the harvester stops to change trailers, or where the collection tank is emptied.

- Stones or mud going over the conveyor with the harvesting of root crops. A visual assessment tool is not available on the harvester and adjustment for % stones and mud requires visual assessment by the operator.

Yield data from horticultural crops will also need processing to remove measurement errors. It should be possible to use the same yield processing routines developed for arable crops and provided by precision farming and commercial software companies. However, growers would be advised to work with suppliers of yield monitoring equipment to understand the likely sources of measurement error and then to review and if necessary edit the default post-processing parameters.

The general consensus is that spatial yield patterns should become more stable over time. Blackmore *et al*. (2003) tested this theory by analysing yield data from 4 fields over 6 years and found that in all fields the yield trend maps became more homogenous over time; although single year yield maps often showed significant spatial variability, this appeared to 'cancel out' over time. These findings have potentially significant implications for how yield maps are used as they imply historic yield map trends cannot be used to extrapolate yield patterns into the future. The findings also suggest that the treatment of fields based entirely on historic yield maps can no longer be supported. However, further analysis, including yield data from fields with different levels of inherent soil variably, should be carried out to determine whether 'evening-out' of spatial yield variation over time is typical, before any change can be made to guidance to growers on the use and interpretation of yield maps.

ii. Understanding the cause of variability

Variation in crop yield represents the combined effects of spatially variable soil, environment and crop variables. In order to make most effective use of yield maps the cause of the yield variability needs to be identified. Understanding the cause of yield variability is one of the major challenges to the practical use of yield maps.

Generally yield map patterns with straight lines tend to reflect man-made influences, while irregular patterns reflect naturally occurring factors. Grisso *et al*. (2009a) grouped sources of yield variability into man-made (producer management) and natural sources as follows:

- Variability caused by producer management practices:
  - Field history, i.e. old field boundaries
  - Soil compaction
  - Variability in irrigation
  - Areas of poor drainage
  - Change in planting date or variety
  - Equipment errors, i.e. chemical skips and misapplications
- Variability caused by naturally occurring factors

- Topography
- Changes in soil type
- Soil fertility changes
- Pest/disease damage
- Weed infestations.

In horticulture systems where crop quality is such an important part of the value, the weight of harvested produce (as measured in a yield map) may not be the best indicator of crop value. One of the precision farming companies interviewed for the review noted that it should be possible to develop yield monitoring systems for horticultural crops where the weight of individual crop units was recorded – in this way it should be possible to collect data on crop size, end market and value to process yield data into a 'gross margin' map. However, these sorts of yield monitoring systems would be bespoke systems designed specifically for individual growers.

The Canadian based company Greentronics, who specialise in yield monitoring equipment designed specifically for root and vegetable crops, have developed a yield monitoring system which allows growers to link the quality of stored produce back to harvest location in the field. The RiteTrace system (http://greentronics.com/products/ritetrace/) logs harvest dates, times and locations and where each load is located in storage. This allows problems with a crop in storage to be traced back to harvest location in the field enabling the grower to investigate whether there was an agronomic problem with the crop. However, there is no evidence of any UK growers using this system.

3.3.4. Uptake

Yield mapping is most common for combinable crops reflecting the availability of yield monitors on many combine harvesters and increased uptake of GPS. The 2012 Defra Farm Practice Survey (Defra, 2013) showed that an average of 11% of all farms use yield mapping (an increase from 9% in 2009). Separated by farm type 25% of cereal farms and 18% of 'other crop' farms reported using yield maps (with a lower proportion of mixed and livestock farms using yield maps). However, anecdotal evidence suggests that whilst increasing numbers of growers are collecting yield maps from combinable crops, far fewer are actively using these yield maps in their crop management. It is not clear from the Farm Practice Survey whether the farms that reporting 'using' yield maps were only collecting yield maps, or whether they were actually using these yield maps in their crop management.

Of the twelve growers interviewed as part of the review, four were collecting yield maps from combinable crops grown in the rotation with horticultural crops, however none were using the data to inform management decisions. Two growers noted that they would like to be able to do more with this information. In addition, another three growers discussed yield mapping of horticultural crops:

- In 2016 G's Growers started yield mapping beetroot (using commercial available root crop mapping equipment) and lettuce (using a bespoke system linking GNSS points at harvesting with data taken from weigh cells for the lettuce wrapper).
- Barfoots have plans to start yield mapping machine harvested crops such as sweetcorn.
- F.B. Parrish had previously investigated yield mapping onions, but were not sure how useful the information would be given the inherent variability of much of their land.

PDM Produce noted that yield mapping would be very interesting, but they had no current plans to look at this. In addition, HMC peas (a grower co-operative) started yield mapping vining peas in 2016 (as discussed above).

3.4. Soil mapping – natural soil properties

3.4.1. Principles – How does it work?

Soil variability (i.e. spatial variability 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 (e.g. Bourennane et al., 2003). 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 is used to delineate the boundaries between soil types and to define or characterise the soil types themselves. In the past, this has been achieved using soil survey techniques and a knowledge of how soil types vary within the landscape.

Soil survey maps and local farmer knowledge can provide a good overview of soil variability. However, although the National Soils Resources Institute (formally the Soil Survey and Land Research Centre, and previous to that the Soil Survey of England and Wales) has surveyed all of the country, only 25% of the nation's soils have been mapped at 1:25,000 or 1:63,000 scales (King et al., 2003). Since the intensity of field soil surveying for these maps is commonly 1 core to 3 to 4 ha, the locations of some important within-field soil boundaries have not been captured. Soil electrical conductivity scanning and satellite soil brightness imagery can be used to help better identify soil variability within a field.

Soil electrical conductivity

Soil electrical conductivity (EC) is a measure of the soils ability to conduct an electric current and reflects differences in soil texture. There are currently two main types of commercially available EC sensors:

- Soil EC scanners make contact with the soil when scanning and measure variation in electrical conductivity of the soil (Figure 3). In this method typically two or three pairs of coulters are mounted on a toolbar; one pair provides an electric current into the soil (transmitting electrodes) and the other coulters (receiving electrodes) measure the voltage drop between them. Veris Technologies produce a range of EC scanners (www.veristech.com), which are currently used in the UK by a number of precision farming companies including Agrii, Agrovista and Fresh Produce Consultancy.
- Non-contact Electro-Magnetic Induction (EMI) sensors are held above the soil when scanning (Figure 4). This method uses the principle of electromagnetic induction to derive the apparent electrical conductivity of the soil (ECa); these sensors have a transmitter and receiver coil at opposite ends of the unit and a sensor in the device measures the resulting electromagnetic field that the current induces. The strength of this secondary electromagnetic field is proportional to the soil EC. The EM38 (Geonics Limited) currently used by SOYL and the GEM-2 (Geophenx) are two commercially available EMI sensors.

Figure 3. Soil EC scanner

Figure 4. Soil EMI scanner

Although EC and EMI scanners use different methods of measuring soil EC, research has shown that both provide information on soil variability which is strongly correlated (King et al., 2003; Sudduth *et al*., 1998, 2003, 2005). According to Heege (2013a), provided EC and EMI scanners are calibrated, properly adjusted and are sensing the same soil depths, the results of both should be very similar and can be used in the same way.

Most EC and EMI scanners will measure conductivity for two depths of soil simultaneously, providing EC maps for a shallow and deep vertical cross section of soil. The Veris 3100 measures EC from the 0-30 cm and 0-90 cm soil profiles and the EM38 measures the 0-40cm and 0-120cm profile. Veris Technologies (www.veristech.com) suggest using the shallow EC measurements for directing soil sampling, and using the deep EC measurements for comparing soil EC and crop yield maps or as a basis for variable rate seeding as crops are affected by soil properties to rooting depth.

EC and EMI surveys are conducted when the soil is bare (typically over the autumn/winter period between crops). The instruments are pulled across the field by a tractor or truck at bouts widths of typically 12-24 m and the information combined with GNSS data to produce a soil EC map. Good soil-to-coulter contact is needed for contact EC sensors and therefore scans are usually carried out following harvest prior to cultivation. Soil EC measurements should not be taken when the soil is frozen as this can affect the measurements.

The main factors affecting soil EC are soil texture, moisture content, organic matter content and soil bulk density. In the majority of fields soil texture is the main cause of soil EC variation. Clay soils with high particle-to-particle contact and high moisture holding capacity are highly conductive, whilst sandy soils with limited particle–to-particle contact and low moisture holding capacity are poor conductors. Soil moisture content may affect the measured EC values, but will not affect the pattern of variability – a soil EC map will consistently identify areas of different soil texture regardless of the soil moisture content at the time of measurement. It has been shown that fields mapped several times during the year at differing soil moisture contents had different EC values but consistently identified the same pattern of variation in soil texture (Grisso et al., 2009b). Because soil texture doesn’t change significantly over time, soil EC mapping only needs to be done once.

Although soil EC measurements are affected by other factors such as soil moisture, organic matter content and bulk density, it is often difficult to identify variation in these factors from soil EC measurements because of the dominating impact of soil texture (which can also be expected to correlate with these parameters). Recent research has demonstrated the potential to use EC measurements to detect soil compaction (Besson et al., 2004, Krajco, 2007), however the effect of other confounding factors mean that it is not currently commercially practical to use soil EC as an indicator of soil compaction. Veris Technologies note that compaction is rarely visible on an EC map because a compacted soil layer represents only a small percentage of the assessed soil volume.

Soil brightness

Soil brightness maps are derived from optical satellite imagery (RapidEye) and describes how intensively the surface layer of bare soil reflects incoming sunlight. Soil brightness provides an integrated measure of the combined effects of soil texture, organic matter content and soil moisture at the time the image was taken.

AgSpace (www.ag-space.com) developed this method of processing high resolution satellite imagery using a soil brightness algorithm to identify soil variability within fields. A soil brightness classification is performed on a farm-by-farm basis from imagery captured on a particular date. The resulting soil brightness bandings are standardised across a farm for a given date, but are not comparable between farms or dates since soil moisture and other temporally and spatially variable conditions will affect the reflectance. Soil brightness maps have been available from AgSpace since 2014 and more recently also via Agrii.

In order to assess soil brightness, the satellite image has to be of bare soil, and so is normally taken in the autumn. Each soil brightness image will show a slightly different colour range based on the method of cultivation, time of data acquisition, soil moisture and stubble interference (Vince Gillingham, AgSpace, Pers. Comm, February 2017). Soil brightness maps can be used to help identify spatial variation, but they can only offer relative values.

The use of soil brightness imagery is relatively new and there isn't any published scientific research confirming the use of soil brightness imagery to identify variation in soil properties. However a current Innovate UK project (including AgSpace and Cranfield University) aims to integrate satellite soil brightness data with existing soil databases to produce a new 'precision soil map' to help growers identify soil management zones.

3.4.2. Benefits/applications

The main advantage of soil EC mapping and soil brightness imagery is that these are rapid, low cost methods of obtaining high resolution information on within field soil variability. Soil EC maps are provided at a resolution equivalent to the bout width – generally 12-24 m – and based on a travel speed on 6 mph at 24 m bout widths, can cover 19 ha/hour. Satellite soil brightness imagery is 5 m resolution and is already available for the whole of the UK.

The main use for this data is for defining soil management zones with similar soil properties which can be combined for soil sampling and management; Adamchuk et al. (2004), Grisso et al. (2009) and Gunzenhauser et al., (2012) describe using soil EC to identify management zones. Several of the precision farming companies will define soil management zones for growers based on soil EC or soil brightness maps.

Intelligent Precision Farming (IPF) currently offer a service to farmers where soil brightness maps are used in combination with soil survey approach to zone fields – the soil brightness maps are used to guide the soil surveyor in the field and help to define the boundaries between the soil zones. However, both IPF and Agrii also offer a cheaper soil zoning service based only on soil brightness maps.

Soil EC maps are frequently correlated with yield maps reflecting the dominating effect of soil water holding capacity on yield. Where both soil EC maps and yield maps are available, this information can be used together to define soil management zones (section # yield mapping). Soil EC and yield measurements can also be combined to help establish yield potential maps (i.e. Lund et al. 2000) and this is discussed further in section ##. However, most of the soil EC and yield map comparisons have looked at long season arable crops such as cereals where soil moisture is known to have a significant effect on yield; the correlation between soil EC and yield may be less for irrigated horticultural crops as the dominating effect of soil texture on moisture availability is reduced by irrigation. For example, Monaghan (2016) measured lettuce yields (two successive harvests) and soil EC from two fields at G's growers in Cambridgeshire and although the yield patterns were consistent for the two lettuce crops, they did not correlate to soil EC.

The soil zones delineated by soil EC or soil brightness maps can be sampled separately (for pH, P, K and Mg) to create soil nutrient/pH maps which can be used to target variable rate application of fertilisers or lime. The soil zones can also be used as a basis for variable seed rate/planting densities, where soil texture within each of the zones is confirmed by sampling and the seed rate/planting density adjusted between the zones based on how differences in soil texture are expected to affect yields/establishment, i.e.

- Areas of different soil textures may be expected to have different plant establishment and therefore to create an even crop the seed rate can be altered to take this into account; for example areas of high clay content or high stone content may be expected to have higher plant losses and therefore a higher seed rate is required to achieve an even crop.
- Inherently higher yielding areas may have the potential to support a higher density of plants and therefore justify a higher seed rate.
- Areas of a field which are known to suffer higher pest (i.e. slugs) or weed (i.e. blackgrass in cereal crops) pressure can have a higher seed rate to compensate for this.

Variable seed rate is predominately used in cereal and oilseed crops. Blake *et al.* (2003) showed that soil texture had a strong influence on percentage establishment in cereal crops, with 60-65%

establishment on clays and loams and 90% on sands, indicating that variable rate seeding may be worthwhile in fields with a high degree of topsoil texture variability. The precision farming company AgSpace report average yield benefits from variable seed rate of 13% for winter wheat and 5% for winter oilseed rape.

However, the methodology may not be directly transferrable to horticultural systems and would require field testing to assess whether it is worthwhile. Furthermore, where field vegetable crops are planted as transplants varying the planting rate may not be justified based on establishment/survival, but it may still be beneficial to vary planting rate to even up the crop, i.e. higher density planting would be carried out in areas of higher yield potential to achieve evenness of crop size and maturity. There are also challenges with adjusting machinery to achieve variable rate seeding/planting (Andrew Richardson, pers comm).

Two of the precision farming companies contacted as part of the review reported that they had worked with growers who had tried variable seed rate in horticultural crops (beetroot and vining peas), however none of the horticultural growers contacted as part of the review had used or were considering using variable rate seeding or planting. However, one of the salad growers reported using soil EC maps as a basis for selecting certain salad crops for areas within a field by allocating crops that needed a small head weight to lighter land within a field, and crops that needed a heavier head weight to heavier land.

3.4.3. Limitations

The main limitation of soil mapping using soil EC or brightness images for horticultural growers is understanding how the soil maps relate to crop yields and then how this information can be used to vary soil/crop management. Comparison of soil maps with crop yields is often not possible as most horticultural growers do not collect spatial yield information (section #). However it may be possible to compare with crop canopy maps (i.e. satellite NDVI maps as an indicator of crop growth) to look for patterns in variability between soil and crop growth. Where patterns are evident, this may support a zoning approach, but the grower then needs to decide whether to vary management between the zones.

Variable seed rate has been shown to be worthwhile for cereal crops where there is within-field variation in soil texture, and this approach to varying the seed rate/planting density may also be beneficial for some horticultural crops. However, research/field demonstrations are required to assess whether this approach is worthwhile for other crops and if so which crops. There may also be challenges for some crops in adjusting machinery to achieve variable rate seeding/planting (Andrew Richardson, pers comm).

Whilst there has been considerable research effort defining how measured soil EC relates to soil properties, there is very limited information on the relationship between soil brightness and soil properties, and therefore soil brightness imagery may be best used in conjunction with other information (i.e. yield maps/crop satellite imagery or field soil surveys) to define soil zones, rather than on its own. Further research to investigate the relationship between soil brightness and soil properties and identify other factors that affect soil brightness maps would support the use of this technique in the future.

3.4.4. Uptake

3.5. Soil mapping – soil nutrients and pH

3.5.1. Principles – How does it work?

Soil EC and brightness maps can provide information about spatial variability in soil properties, however in order to get information about spatial variability in soil nutrients it is necessary to take soil samples from the field for laboratory analysis. There have been some developments in on-the-go measurement of soil properties and these are discussed further in section #.

Traditionally, when sampling a field, multiple soil cores (typically 25) would be taken in a 'W' shape across the field and bulked together for analysis. In this way, a single soil analysis is provided for the whole field, and lime and fertiliser P, K and Mg are applied at a uniform application rate based on this analysis. However, a single soil analysis can potentially conceal significant variability in soil nutrients and pH within a field.

As part of AHDB Horticulture project CP 107c field demonstrations, methods of soil sampling and mapping were compared for a 10 ha field at Chicksands in Bedfordshire. Table 1 compares results for pH, P, K and Mg from a single 'whole' field sample with the mean and range of soil analysis results from 143 soil samples taken on an intensive 25 m grid. 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 143 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. 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	3	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

A number of precision farming companies now offer a soil sampling and mapping service where multiple samples are taken and the results used to create a field map of soil nutrients and pH. Precision farming companies employ two main approaches to soil sampling, detailed below:

Grid or regular sampling

Typically one sample is taken per hectare using a strategy such as sampling on a 100 m grid (regular or staggered grid) or dividing the field into 1 ha polygons and sampling the centre point of each polygon. Each point is GNSS logged and a number of subsamples are taken to form a composite sample from each point – typically 16 in a 3m radius around the GNSS logged point.

Alternatively, some precision farming companies will divide the field into regular (e.g. 1 ha) polygons and sample each polygon by taking subsamples in a 'W' shape across the area.

Soil sample results from GNSS logged point samples can be used to create a contoured map of pH and nutrients using a method of data interpolation such as inverse distance weight, nearest neighbour or kriging to estimate values between the measured points (e.g. Figure 5).

Where the field has been divided into regular 1 ha polygons and a representative sample taken from the whole of each polygon, the nutrient or pH map will be based on the polygons (e.g. Figure 5). Where sampling from the central point of a polygon, some precision farming companies will assign the analysis from the central point to the whole polygon rather than contour mapping.

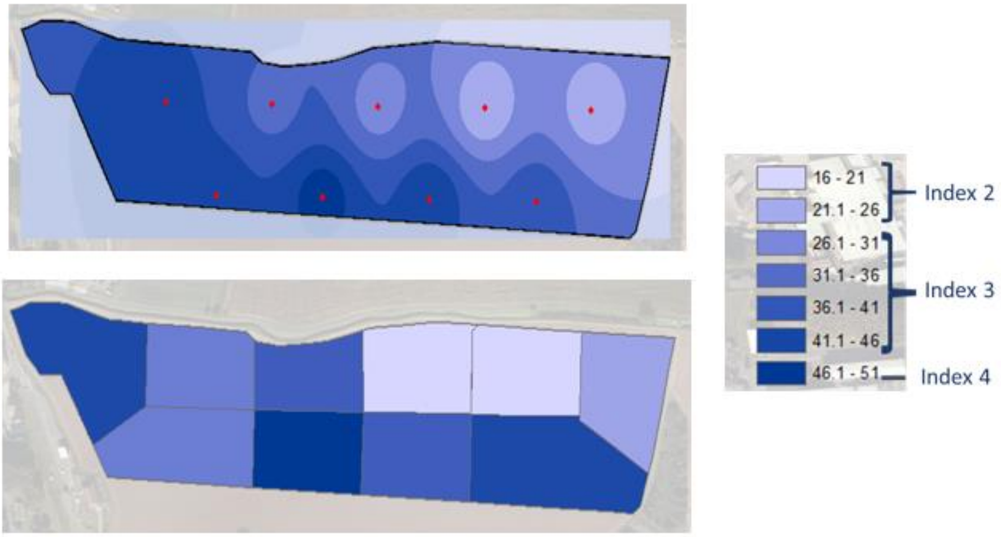

Figure 5. Soil extractable P – contoured map based on 100 m grid soil sampling (top) and mapped for 1 ha polygons based on 'W' sampling within each polygon.

When using a grid or regular basis sampling the number of samples taken will have an important effect on the accuracy of the soil pH or nutrient map produced. The limiting factor is normally cost – the more samples that are taken the more accurate the soil map will be, however the costs of additional samples may not always be justified. The most common commercially used sampling intensity is one sample per hectare. One of the precision farming companies interviewed for the review acknowledged the value of increasing the sampling intensity and noted that a higher degree of accuracy (and cost) was justified for high value crops.

Zone based soil sampling

Zone based or 'targeted' soil sampling uses existing knowledge of within-field soil variability to direct where samples are taken. Soil zones can be based on measured soil and/or crop variability, for example using:

- Soil EC maps
- Soil brightness maps
- Yield maps
- Crop canopy information in the form of mapped vegetation indices (i.e. NDVI)

Once the zones have been defined, each is sampled separately. The soil pH and nutrient maps produced will reflect the boundaries between the soil zones.

Both grid and zone based soil sampling are valid options and both have advantages and disadvantages. Unless the grid is dense enough, grid sampling may miss patterns and boundaries evident from soil surveys or yield maps. Grid sampling is typically more expensive than zone sampling as typically a greater number of soil samples are taken. Zone sampling uses other sources of information to help decide where to target soil sampling. However, there may be patterns in soil fertility, which could be identified using grid sampling that may not be detected using zone sampling.

In a recent AHDB Cereals & Oilseeds project, Muhammed et al. (2016) compared the cost effectiveness of zone based sampling and grid based sampling and found that on average the grid based sampling performed better than the zone based sampling. However, the most appropriate technique is likely to vary from field to field and there is no general consensus which technique gave best results.

3.5.2. Benefits/applications

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 which 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 reduction of within-field soil pH and nutrient variability

3.5.3. Limitations

Perhaps one the main barriers for further uptake of precision soil sampling and variable rate fertiliser (P, K and Mg) and lime applications is the lack of evidence to demonstrate that this approach can increase farm profitability. Although it is reasonable to expect that where more detailed soil sampling identifies areas of low pH or soil nutrient levels, a yield benefit may be seen from increasing fertiliser/lime inputs to these areas, many horticultural fields have soil nutrient indices that are at or above target levels and therefore yield increases from variable rate application would not be expected.

The precision farming review found contrasting views from horticultural growers on the value of variable rate P and K applications; some growers have adopted variable rate applications and were happy with the approach, whilst others were unconvinced of the potential benefits. Both growers and precision farming companies noted that small savings in fertiliser were less important to horticultural growers than to broad-acre arable and grassland farmers. However, a number of growers and precision farming companies highlighted the value of soil nutrient maps in their own right (not necessarily as basis for variable rate fertiliser application), particularly for rented land where the grower may not have the field history and soil nutrient maps enables them to better understand the land they are renting.

3.6. Remote sensing of crop canopies

3.6.1. Principles – How does it work?

Canopy sensing measures light reflectance from the crop canopy. Spectral reflectance of plants in the visible and Near Infra-red (NIR) regions of the electromagnetic spectrum is primarily affected by plant pigments (e.g. chlorophyll and carotenoids) and the cellular structure of the leaves. Large crop canopies absorb more visible light (400 nm to 700 nm) and reflect more NIR radiation (700 nm to 1400 nm). Plant pigments and leaf structures respond to many stresses and this is reflected in the spectral signature measured by remote sensing (Basso et al., 2004).

Figure 6 shows the spectral signature from a number of winter wheat seed and fertiliser N rate treatments (Kindred *et al.,* 2016). Although the different spectra all have a similar shape, there are clear differences between the treatments, with the denser crop canopies in the higher seed and N rate treatments reflecting less visible light and more NIR radiation.

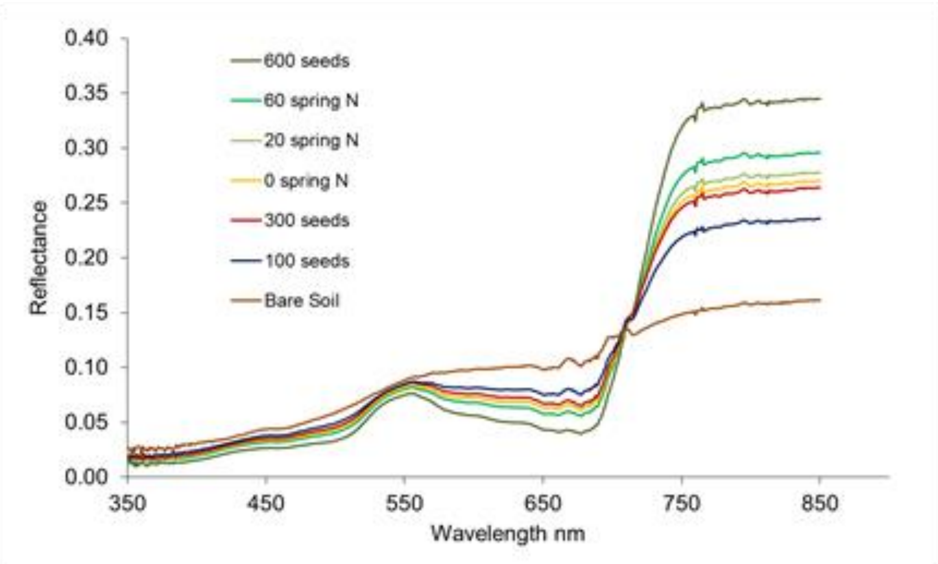

Figure 6. Winter wheat canopy reflectance measured by a LICOR spectroradiometer (Kindred et al., 2016).

A range of vegetation indices have been developed, commonly using reflectance from the visible and NIR spectra (Wiegand *et al*., 1991; Raun *et al*., 1998). Vegetation indices simplify the comparison of canopy spectral signatures and cheaper instruments have been developed which allow more rapid assessment of canopy reflectance at just two or three individual wavelengths (Kindred *et al*., 2016). The most commonly used vegetation index is the normalised difference vegetation index (NDVI) which is simply reflectance in the NIR minus reflectance in visible divided by the sum of NIR and visible reflectance (Haboudane *et al*., 2004). The exact wavelengths used for NDVI vary between studies and sensors but are generally around 650nm and 800nm. Values for NDVI can range from 0 to 1, but typically range from 0.1-0.2 for bare soil to 0.8-0.9 for a completely closed canopy. Indices such as NDVI are often considered as measures of the 'green biomass' of the crop, however this is not necessarily the case, as large green canopies reflect less green light (550 nm) than smaller yellow-looking canopies, but they appear greener because the absorb proportionally more red (650 nm) and blue (450 nm) light.

The use of NDVI has two major limitations, firstly it can be affected by the underlying soil, especially by soil wetness; secondly, it becomes saturated with dense canopies and large canopies (Wang et al., 2012). Various other indices have been developed to help overcome these issues.

Spectral measurements can be assessed in either broad spectral bands (200nm - 400 nm), narrow spectral bands (50 – 100 nm), or high–resolution bands (5-10nm, as with hyperspectral sensors). Most sensors are multispectral, i.e. detecting more than one band. The sensed data can be obtained from a variety of platforms, including satellite, airplanes, UAVs, tractor mounted or handheld.

Satellite

Remote sensing from satellites has dramatically improved in spatial and spectral resolution and return frequencies since the launch of Landsat in the 1970s with the advent of RapidEye, GeoEye and WorldView imagery (Mulla & Miao, 2016). Remote sensing satellite platforms such as Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) provide high frequency observations, however their spatial resolution is quite coarse. MODIS data are available at 25, 500, and 100 m depending on the product (Justice *et al*., 1998). AVHRR data are available at spatial resolutions of 1 km for local coverage and 4 km globally (Kidwell, 1998, cited in Bolton & Friedl 2013). Higher spatial resolution data from sensors such as the Landsat Thermic Mapper (30 m) are also available (Thenkabail *et al*., 1994), although repeat period for Landsat is relatively infrequent at 16 days. The completion of the European Space Agency's Sentinel 2 mission in 2017 has enabled a step change for low-cost satellite imagery, both resolution now 10 m and frequency, revisiting every 5 days

Aerial remote imagery from UAV's or aeroplanes

The spatial resolution of aerial remote sensing is typically less than a metre and can be down to 2 cm. The spectral resolution ranges from broadband blue, green, red and NIR to hyperspectral imaging. Aerial imaging can usually be obtained when and where it is needed with high reliability, although cloud cover can be an issue with airplanes, where shadows from the clouds or plane can cause difficulties in interpreting data. Unmanned aerial Vehicles (UAVs) include fixed-wing aircraft or heli/opticopters which fly at altitudes of roughly 100 m (Zhang & Kovacs, 2012). UAVs are relatively inexpensive and can be used quickly at low altitudes and have the flexibility to be flown in partially cloudy conditions (Mulla & Miao, 2016). Due to the low altitude many images are acquired, which must be tiled or mosaicked together to produce a continuous image. Fixed-wing aircraft usually have a longer flight time and payload capacity than heli/opticopters. They also have faster flight speeds, which at low altitudes may result in blurred images. Heli/opticopters have the advantage of vertical take-off and landing, hover and fly in multiple directions, which gives them more flexibility compared to fixed-wing UAVs (Huang *et al*., 2013).

Remote sensing from UAVs can offer high spatial resolution which can allow individual plants to be studied. Cameras used on UAVs range from inexpensive digital cameras to expensive multispectral cameras that provide narrowband reflectance in the blue, yellow, green, red, red edge, and NIR regions of the spectrum (Mulla & Miao, 2016). Limitations include the requirement of licences for commercial use; weight limit on mounted cameras and GPS units; and battery life (Mulla & Miao, 2016). Promising results have been obtained using UAVs to estimate crop leaf area index (LAI), biomass, plant height, nitrogen status, water stress, weed infestation, yield, and grain protein content (Berni *et al.,* 2009; Swain *et al.,* 2010; Samseemoung *et al*., 2012; Bendig *et al*., 2013).

Proximal sensing – tractor mounted and hand held sensors

Sensors used for proximal sensing are usually limited to two or three narrow bands of reflectance, which limits the number of indices which can be used. Commercial reflectance sensors can be classified as passive and active depending on their light source. Passive crop sensors measure crop canopy reflectance provided by sunlight. Active sensors have their own light source. Most commercial sensors are designed around the detection of crop N status. Ground based sensors such as Greenseeker and Crop Circle measure two or three wavelengths (Govaerts et al., 2007; Havrankova et al., 2008; Raun et al., 2002; 2008) whilst the Yara N sensor can measure several wavelengths (Zillman et al., 2006). Spectroradiometers measure many wavelengths (Wiltshire et al., 2002) and can be used commercially, but are more likely to be used proximally as research tools.

3.6.2. Applications

Variable rate fertiliser application

Nutrient deficiencies often cause changes in leaf pigment concentrations, particularly chlorophyll, which can be detected using remote sensing in the green and red edge wavelengths (Mulla & Miao, 2016). Reflectance of deficient canopies alone is insufficient in many cases to determine which nutrient is responsible for the deficiency and what rate of fertiliser is required. Additionally, crop deficiencies also cause changes in crop biomass that can be detected using NIR reflectance (Mulla & Miao, 2016). Correct identification of which nutrient is deficient, via colouration, pattern, location and timing is essential. Nutrient deficiencies that are detected remotely can be corrected with variable rate technology.

Commercial sensors in precision farming have mainly focused on the detection of N deficiency and are mainly active crop canopy sensors with their own light source to avoid the influence of different environmental light conditions. These include the green seeker, Crop Circle, CropSpec and Yara N-sensor **Error! Reference source not found.**2 lists these sensors and the spectral bands at which they operate (Barker & Sawyer, 2010; Kitchen *et al*., 2010; Shaver *et al*., 2011).

Table 2. Crop canopy sensors commonly used for N detection and the spectral bands they operate at. (Mulla & Miao, 2016; Cao et al., 2013).

Sensor	Blue (nm)	Green (nm)	Red (nm)	Red Edge (nm)	NIR (nm)
GreenSeeker	-	-	650	-	770
Crop Circle ACS 210	-	590	-	-	880
Crop Circle ACS 430	-	-	670	730	780
Crop Circle ACS 470	450	550	650, 670	730	>760
CropSpec	-	-	-	730	805
Yara N sensor traditional	-	-	730	760	-
Yara N sensor ALS	-	-	730	760	900, 970

One limitation of these sensors is that they do not directly estimate the amount of N fertiliser needed (Samborski *et al*., 2009), they need to be compared to reference strips which have received sufficient fertiliser (Kitchen *et al*., 2010), these comparisons are the basis for N fertiliser response functions that relate the sensor readings to the amount of N fertiliser required (Scharf *et al*., 2011). In practice, this is not useful for real-time in-field application. Most commercial tractor mounted sensors have pre-determined algorithms or allow the grower to set the N rate for the field and then by how much to vary the N rate in response to the sensor readings.

Thinner, paler crops are associated with a lower soil nitrogen supply (SNS) and warrant extra N application in relation to thicker and greener areas of the crop (Kindred *et al*., 2016). This is the basis of most commercial variable rate systems, i.e. increasing N applications where growth is less and reducing N applications where crops are lush (Bernsten et al., 2006, Zilman et al., 2006). However, many systems change tack later in the season, where greener areas receive more N, which can account for the higher N requirement of higher yielding crops. Higher yielding areas tend to show greater greenness in canopy reflectance measures late in the season and the application of additional N for yield later in the season is appropriate, once the canopy has been built and lodging risks minimised (where appropriate; Kindred *et al*., 2016). Kindred *et al*., (2016) concluded in the Auto-N project that it was surprising how small the calculated benefits of variable rate N applications are in terms of profitability, yield, N savings, N leaching and GHG emissions. However, it is noted that other studies have claimed larger benefits (e.g. Biermacher *et al*., 2009; Knight *et al*., 2009). It is important to know the cause of the spatial variation seen in order to have confidence that it can be rectified by varying N fertiliser; if the reason for poor performing areas is not known the best response may be to reduce input costs (Oliver et al., 2010)

There has been little research on remote methods which can distinguish between N, P and K decencies in crops (Pimstein *et al.,* 2011; Mahajan *et al.*, 2014). Spectral signatures for deficiencies in these nutrients show changes at different wavelengths (Pimstein *et al.,* 2011). Pimstein *et al.*, 2011, proposed indices which collected reflectance from the short wave infrared (SWIR) region

(1450, 1645, 1715 nm) to predict P or K deficiency, but accuracy decreased with increasing variability in biomass. Mahajan *et al*., 2014 could distinguish between S and N deficiency in wheat using SWIR data (1260 nm) in a normalised ratio with a red band (660 nm). The commercial detection and distinction of other nutrient deficiencies requires further work, which may necessitate not only the collection of spectral data, but information of where on the crop the deficiency is occurring (e.g. upper or lower leaves, leaf tips or edges).

Water stress

In precision or variable rate irrigation, sprinkler heads or nozzle spray rates can be varied depending on spatial patterns in soil moisture (Hedley & Yule, 2009), crop stress (Bastiaanssen & Bos, 1999) or soil or landscape patterns (Sadler *et al*., 2005). Variable rate irrigation has the potential to use water more efficiently than uniform irrigation, conserving water without affecting crop yield (Mulla & Miao, 2016). Water absorbs light at certain wavelengths in the NIR region. There are two major regions which can be associated with water stress in vegetation, one in the NIR and one in the middle infrared region. There are also absorption bands at 970 and 760 nm, as well as those at 2950, 1940 and 1450 nm, due to the OH bonds of water (Peñulas *et al*., 1993). Peñulas *et al*., (1993 and 1996) showed that the ratio of reflectance at 970 nm and 900nm (water index, WI) closely tracked a number of plant water status variables in gerbera (Daisy), pepper and bean plants under control conditions and a field wheat crop. In 1997, Peñulas *et al*., reversed the ratio to obtain parallel variations to plant water content. Water stress can also be remotely monitored through thermal infrared (TIR) (Moran *et al*., 2004; Rud *et al*., 2014) or microwave (Vereecken *et al*., 2012) sensing. TIR can be used to measure canopy temperature and water stress, and when combined with reflectance measurements in the red and NIR regions, can be used to construct reflectance index-temperature graphs, which can be used to identify field locations where nutrient or water stress occurs (Lamb *et al*., 2014). TIR can also be used by measuring a crop water stress index (CWSI) that is proportional to the difference between canopy and air temperatures (Moran *et al*., 2004). An artificial reference surface approach was developed (Meron *et al*., 2010) and has been used to develop maps showing spatial patterns in crop water stress with 82% accuracy relative to leaf water potential measurements (Rud *et al*., 2014). However, care must be taken with partial canopy cover to eliminate areas of soil, which can lead to errors.

Weed identification

Weeds compete with crops for light, water and nutrients and above critical weed density thresholds crop yields and quality will decline. Weeds tend to occur in patches, leaving most of the field weed free, which makes weed control by variable rate herbicide application an interesting option. Weeds can be identified based on spectral signatures, leaf shape and organisation of the plant. Remote sensing of weeds requires the weed to have a different spectral signature from the surrounding bare soil or the crops and if the spatial resolution of images is fine enough to detect individual weeds or patches of weeds (Lamb & Brown, 2001). Remote sensing with satellites or airplanes is adequate for detecting weeds that occur in large dense areas within a crop or bare soil (Lamb & Brown, 2009), whereas ground based proximal sensing is better suited to identifying isolated small weeds (Thorp and Tian, 2004). Images at a spatial resolution of tens of centimetres to a metre are needed to distinguish weeds from crops (Lamb & Brown, 2001; Rasmussen *et al*., 2013). When bare soil is present, reflectance values at two wavelengths (e.g. 758 nm and 658 nm) have been used with discriminant analysis to crops from weeds from soil (Borregaard *et al*., 2000). Additionally, the vegetation indices RVI (NIR/R) and NDVI have been used to discriminate between weeds and crops, especially when the crops are in systematic rows and the weeds occur as patches between the rows (Mulla & Miao, 2016). Detection of weeds at early growth stages is challenging, particularly if in a recently germinated crop with similar physiology. Weed detection is easier at later growth stages when spectral differences between weed and crops are greatest (López-Granados, 2011). However, it has been noted that crops and weeds frequently have similar reflectance signatures and that they are may be more easily distinguished based on differences in their canopy, leaf shapes, heights and structures, these features can be identified using vision analysis of colour images (Mulla & Miao, 2016). A commercial example of remote weed sensing and herbicide application is the WeedSeeker (Hanks & Beck, 1998), which uses photoelectric emitters to detect weeds growing in bare soil or a crop canopy (Sui *et al*., 2008) and then sprays the weed directly with a herbicide.

Disease detection

Most disease infestations are not evenly distributed across the field but occur in patches and at the early stages of epidemics large area of the field are disease free. Targeting pesticides on those areas of the field that require it could reduce pesticide use and have positive financial and environmental impacts. Disease infection can affect the spectral properties of crops, with propagules often influencing the VIS spectrum, necrotic or chlorotic damage affecting the green and red-edge regions due to chlorophyll damage, senescence affects reflectance in the red to NIR region, stunting and reduced leaf area can influence the NIR, while impacts on photosynthesis can be detected in the 450-550 nm and 690-740 nm regions (West *et al*., 2003). Remote sensing is not widely used to detect crop disease, but it does have the potential to be used in this way.

Moshou *et al*., (2005) demonstrated the feasibility of detecting diseases in arable crops in field conditions, using both hyper-spectral reflectance and fluorescence imaging, and tested yellow rust in winter wheat as a model system. Remote sensing has been used to detect fungal and viral infections in soybean (Das *et al*., 2013) and wheat (Muhammed, 2005; Huang *et al.*, 2007; Mewes *et al*., 2011; Mirik *et al*., 2011). Huang *et al*., 2007 detected yellow rust infections of wheat in China using aerial hyperspectral remote sensing and a photochemical reflectance index (PRI) with 91% - 97% accuracy over two years. There are other examples in the literature of research in this area, which presumably will eventually be used in commercial practice after further refinement.

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Appendix 1

Precision farming (PF) review – survey of precision farming companies

1. **Precision farming services**

   Thinking about the following 3 areas -

   a. **Tractor and machine control**
   b. **Targeted agronomy**
   c. **Data and record keeping**

      - Which PF tools/techniques do you currently offer?
      - How do these PF tools/techniques work?
      - How can these PF techniques benefit growers (yields/profitability)?
      - What are the costs to growers of adopting these PF tools/techniques?
      - Have these tools/techniques been developed in-house or by another company?
      - Has there been any independent testing of the PF tools/techniques being offered?
      - What R&D has been done?
      - Plans/priorities for future R&D?

2. **Market penetration**
   - For which crops do you provide PF services?
   - Which horticultural crops/rotations?
   - Do you market your company to the horticulture sector (generally/specifically)?

3. **Horticulture**
   - Generally, what experience do you have with applying PF tools/techniques to horticultural crops?
   - Are the PF tools/techniques you offer applicable to horticultural crops, if so which ones? If not, why?
   - Are there challenges in expanding the update of your PF tools in horticulture, if so what?

Precision farming (PF) review – survey of machine manufacturers

1. Yield mapping

- Overview of harvesting equipment, including crop types
- For which crops/machines do you offer a yield mapping facility?
- Do you offer yield mapping for any horticultural crops?
- What is the potential to yield map horticultural crops?
    - Crop types
    - Challenges
    - Any current developments

2. Guidance systems

- Do you offer guidance systems for horticulture crop machinery?
    - Crop types
    - Challenges
    - Any current developments

3. Controlled traffic farming

- What experience do you have with CTF?
    - Which rotations?
    - Have you adapted machinery for CTF?
    - Have you worked with any horticultural growers using CTF?

4. Novel soil compaction detection and alleviation techniques

- Do you have any experience with:
    - Variable depth cultivation?
    - Detection of soil compaction?
- Any relevant current R&D/areas for future development

5. Future developments

- Are you working on any other projects to change the nature of machinery in horticulture production systems?
- If so, what is the nature of the machinery and what is its main objective

Precision farming (PF) review – survey of horticultural growers adopting PF techniques

1. **Overview of farm**
    - What is the size of your farm?
    - What crops are grown (& what area)?
    - What rotations are used on the farm?
    - Location of farm and main soil types?

2. **Precision farming tools/techniques being used**

    Thinking about the following 3 areas -

    a. **Tractor and machine control**
    b. **Targeted agronomy**
    c. **Data and record keeping**

    - Which PF tools/techniques are being used?
    - For how long have they used them?
    - Why did you choose to adopt PF tools/techniques?
    - Which companies/advisers/other individuals or organisations have you worked with in adopting the PF tools/techniques?

3. **Benefits and limitations**
    - Have you seen benefits from use of PF tools/techniques?
        - If so what (yield/crop quality/profitability) – subjective/quantified?
    - What challenges have you faced in adopting PF tools/techniques?
    - What have been the costs in adopting PF techniques?
        - Equipment, advice, other costs

4. **Future plans**
    - Will you continue with the PF tools/techniques?
    - Will you expand the area/crops covered?
    - Are you considering adopting any other PF tools/techniques?