FARMING IN THE DIGITAL AGE

Report

Prepared for

The Worshipful Company of Farmers

Prepared by

Dr Shamal Mohammed
PhD, MSc, BSc, PG Dip, M.I. Soil Sci.

Chief Technical Officer

Agri-EPI Centre Ltd

February 2020

Table of Contents

Executive summary

Agri-EPI was commissioned by The Worshipful Company of Farmers to produce this report exploring 'Farming in the Digital Age'.

Increasing global population, climate change, dwindling natural resources, and unprecedented political events are placing the food supply chain under tremendous and intractable pressure. Digital technology offers one critical solution to the required transformation of global food systems. However, along with great potential, the growth of new and useful data-driven advances comes with challenges. This report offers an overview of the key technologies and techniques playing their part in the evolution of farming and food production in the 21st Century.

Precision agriculture

The advent of precision agriculture has brought many new technologies and techniques into modern farming. The most prominent and impactful technologies to date can be identified as:

- **Global Positioning Systems (GPS):** The advent of satellite data has transformed many industries by connecting information and location and was the basis for the concept of Precision Agriculture. While still prone to errors, it currently provides an accuracy of 4-5 metres, but this can be enhanced using Real-Time Kinematic (RTK) to 1cm.
- **Yield mapping:** Yield mapping has given farmers the means of improving understanding of yield variability and factors limiting productivity using technology fitted onto a combine harvester. Four key steps should be taken to optimise the use of yield mapping: removing 'errors' from yield data; only using data for crops that can provide a coherent map, such as winter wheat, oats and barley; zoning of the field to identify seasonal variations; and using data spanning several years to improve understanding of overall conditions.
- **Soil management zoning and site-specific management:** Soil variation is a fundamental factor in managing fields on a zonal basis. Delineating soil management zones can determine specific nutrient requirements for each zone to improve uniformity over the whole field.
- **Variable-rate application:** This is one of the most common practices when using a soil management zone approach. As the most expensive fertiliser input, Nitrogen (N) is of the most interest to farmers and researchers with regard to the variable-rate application, but it is also the most difficult to get right. Measuring the reflection from the crop canopy is one of the most common methods of assessing variable rate N application. However, there is some debate over the financial benefits of applying N at a variable rate, with AHDB having concluded that this technique provides no improvement in input efficiency.
- **Tractors with auto-steering systems:** This has been one of the main areas of development of precision farming over the past two decades, as auto-steer tractors provide clear economic, social and environmental gains. It has also led to the transformative Controlled Traffic Farming (CTF) which confines vehicles to minimal areas of traffic lanes using GPS. Although the adoption of CFT requires investment and adaptation of farm operations, and there are some challenges to implementation, its benefits include better crop establishment, less soil compaction and erosion and reduced input costs.

- **Precision Farming adoption:** There are many reasons for farmers to adopt precision farming, including input and waste reduction and maximisation of productivity. It has also brought new challenges for farmers, particularly around the storage, analysis and sharing of data.

Agriculture and the data explosion

This report considers essential forms of, and concepts around, data, which are fundamental to the growth of precision agriculture:

- **Earth Observations Data (EO):** EO is collected by remote sensors thousands of kilometres above the Earth. It has many applications at farm level for assessing crop performance, soil properties and input requirements. At a national scale, EO provides valuable information about landscapes' environmental characteristics. The Normalised Difference Vegetation Index (NDVI) is one of the most popular products of EO, which shows variances in crop health at field level. The two main types of EO – hyperspectral and multispectral - offer a range of applications in agriculture such as irrigation scheduling, disease detection and soil mapping. Recent advancements in technology and a reduction in costs has further increased EO-base farming tools.
- **Big Data:** Big Data involves massive, uncleaned data sets which can be collected and stored quickly. Its analysis allows complex questions to be answered and there are extensive opportunities for adding value in agriculture, including benchmarking, predictive modelling and improvements in feed efficiency and livestock systems. Challenges to maximising the positive impact of Big Data on agriculture include the need to quantify its value for farm businesses, including return-on-investment (ROI); the development of automated data collection systems; ensuring gathered data is of a high quality, and effective integration of data from multiple sources to create a beneficial data pool.
- **Internet of Things:** The key enabler for Big Data is connectivity. It is essential that, without human intervention, data can be collected from all connected devices, shared and analysed. This process is known as the Internet of Things (IoT). The main applications of IoT in farming at present are the monitoring of parameters affecting crop performance; documentation of farm information; forecasting of events that affect crop growth; and controlling and processing data to make real-time decisions. While further opportunities for the industry are significant, however, the challenges include the need for interoperability of devices; proving ROI; combining data from multiple sources; the lack of rural connectivity in many areas; the modelling and forecasting of complex agricultural systems; and a need for workers in the sector who possess both industry knowledge and IoT expertise.

Toward more intelligent-based agriculture

- **Artificial Intelligence and machine learning:** The advent of Artificial Intelligence (AI) has led to a new era for farming, known as 'Agriculture 4.0', where farmers can use sophisticated technologies, e.g. robots and sensors, to be precise in their management at an individual unit of production levels, such as a single plant or animal. It will enable farms to be more profitable, safe, productive and sustainable. Techniques are advancing rapidly and are likely to continue to grow, with a prediction of market growth of around $600 million in 2018, rising by >38% compound per annum over the coming years.

- **Robotics and autonomous systems (RAS):** Although the digitisation of the farming industry has picked up pace in recent years and robots and AI now make possible the automation of non-standardised tasks, RAS is not yet widely available in farming. Challenges to growth include developing robots which can adapt to variable agricultural environments; the need for smaller, better-integrated robots; and a better understanding of human-robot interaction (RHI). The latter has come to the fore as a potential solution to the issue of labour shortages. While it is only a matter of time before agricultural robotic systems become fully autonomous, there is likely to be a gradual transition period where humans and robots work increasingly together. There are excellent opportunities for the UK to become a global leader in RAS if the correct approach is taken to tackling identified challenges.
- **Blockchain and the food supply chain:** Blockchain is an emerging digital technology that is defined as an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way. It has several applications in food production, notably that it allows products to be traced through the supply chain from farm to fork. The four main benefits of blockchain are traceability; optimising the food supply chain; increased visibility across the supply chain; and enhancing the cost and efficiency of transactions. Blockchain is being trialled or implemented in a growing number of areas within food production. Its further application will depend on trust, understanding and buy-in on the part of producers, processors, traders and retailers.

As the global food system comes under increasing pressure to be more productive yet sustainable, digital technology can play a critical role in transforming the food supply chain.

Specifically, digital technology can:

- Increase efficiency
- Reduce waste
- Provide an accurate picture of the value of food, including its economic and natural capital costs
- Help to redesign a diverse agricultural system
- Provide a route to multifunctional landscapes
- Create space for bio-energy capture and storage

Challenges that lie ahead and which may limit the application of digital technology for transformative change, include:

- Data ownership issues
- Moving from the traditional supplier-customer transaction to a new business model based on the value chain
- The need for technology providers to engage farmers and understand their pain points at an early stage of technology development
- The need to integrate the various technologies, machinery and farmer-collected data to create compelling digital solutions
- Connectivity across all the sources and players at a time when rural connectivity is still poor across much of the UK

Introduction

The agriculture industry is under conflicting pressure from factors including rapid population growth, changes in dietary demands, food waste and the impact of climate change. The global market for food, energy and water is increasing at an unprecedented rate, leading to the expansion and intensification of agriculture.

Intensification brings inevitable adverse effects on climate change and soil. With the expansion of agricultural activities will come an increased risk of biodiversity loss. This will, in turn, have an adverse impact on food production while also reducing the utilisation of land for bioenergy options to capture and store carbon (e.g. planting trees).

The need for more efficient and greener food production systems and integrated supply chains is increasing, to minimise waste, diversify farm businesses, enhance nutrition, improve human health and meet changing global dietary demands.

Over the last three decades, digital technologies have transformed many industries. In the case of agriculture, the transformation began with the development and availability of Global Positioning Systems (GPS) and Geographic Information Systems (GIS). These provided the ability to capture, collect and store data with geolocation information and to process and present geospatial data. GPS created a new concept of farming: precision agriculture, or site-specific agriculture. GPS-based applications in precision farming such as field mapping, soil sampling, tractor guidance, crop scouting, variable rate applications, and yield mapping are now commonly available.

During the last decade, digital technologies have changed the agriculture industry in three ways: (i) by reducting the cost of capturing and storing geospatial data (e.g. satellite imagery); (ii) connectivity and mobile technology has made accessing data easier and (iii) data processing power and data analytic capabilities have increased significantly. The advancement in Artificial Intelligence (AI), Robotics and Automation and blockchain will create a new value chain in the food industry by enabling better decision-making processes to reduce waste, optimise outputs and minimise environmental impacts.

Climate change and the challenges facing the industry are complex, interconnected and multifaceted. A new approach is needed to achieve global food and nutrition security and to reduce carbon emissions. These critical challenges need novel solutions and a new business model, which can provide a collaborative environment throughout the food supply chain to create new value chains.

Digital technologies provide enormous opportunities for the development of more integrated, transparent and efficient systems that can meet the needs and demands of consumers for healthier and more nutritious diets, as well as helping to capture and store carbon in the soils.

The purpose of this report is to provide an overview of the journey of digital technologies in agriculture during the past 30 years and present related current and future challenges and opportunities. It aims to contribute to the current debate about the future of the agriculture industry and help the industry to recognise the challenges as well as opportunities for farming in the digital age.

Part 1: Precision agriculture

1.1. Global Positioning Systems (GPS)

The United States Government's Global Positioning System (GPS) provides geolocation information and time to a GPS receiver anywhere on Earth. The system has 24 satellites orbiting around the earth (Figure 1), each carrying a synchronised atomic clock. The satellites work out a location using 3D trilateration. Trilateration can locate the GPS receiver on earth by measuring its distance from at least three satellites (Figure-2). The locations of all 24 satellites are known all the time, with the distance between each satellite and the receiver measured by the time taken for the radio waves to travel (by speed of light).

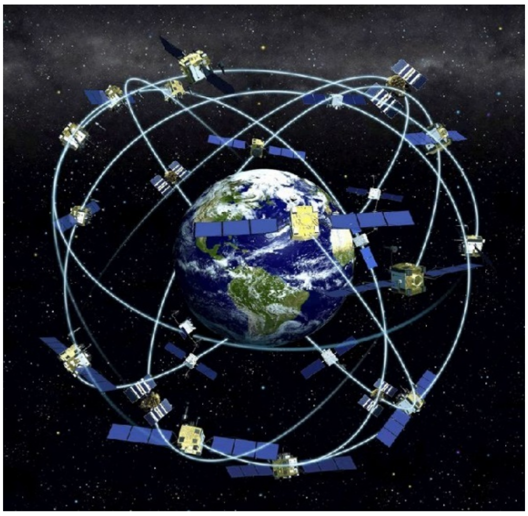


Figure 1: Satellite Positioning System

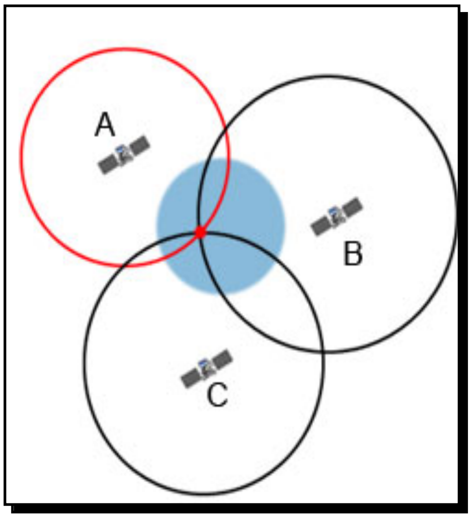


Figure 2: GPS - Trilateration

The GPS technology has transformed many industries by connecting information with location, which has opened opportunities for mapping and geospatial analysis. Agriculture is one of the industries to have been disrupted by GPS enabling location-based data collection. Precision Agriculture became a new concept of identifying geospatial variation in the field to optimise input applications and maximise productivity.

The accuracy of determining location by GPS is not exact and contains errors. However, accuracy can be improved, especially for military purposes. GPS, as developed initially by the US government to support its military operations, had achieved accuracies of 3m by the early 1990s. Currently, GPS provides an accuracy of 4-5m for civilian purposes, but this can be enhanced to about 1cm by using a technology such as Real-Time Kinematic (RTK). RTK uses a fixed base station which transmits correction data to reduce errors and enhance the precision of position data derived from GPS.

1.2. Yield Mapping

Even before GPS, farmers and advisors had reasonable information about field performance and productivity. Early research focused on using other variables, for example, Schueller and Bae (1987) used the variation in the speed (with constant throttle and cutting head height) of the combine harvester as a proxy for grain flow to the combine. GPS and sensor technologies made yield mapping possible, providing a better understanding of yield variability and factors limiting productivity. In the UK, yield mapping (Figure-3) began in the early 1990s using a yield monitor system and GPS technology which is currently fitted on many makes of the combine harvester.

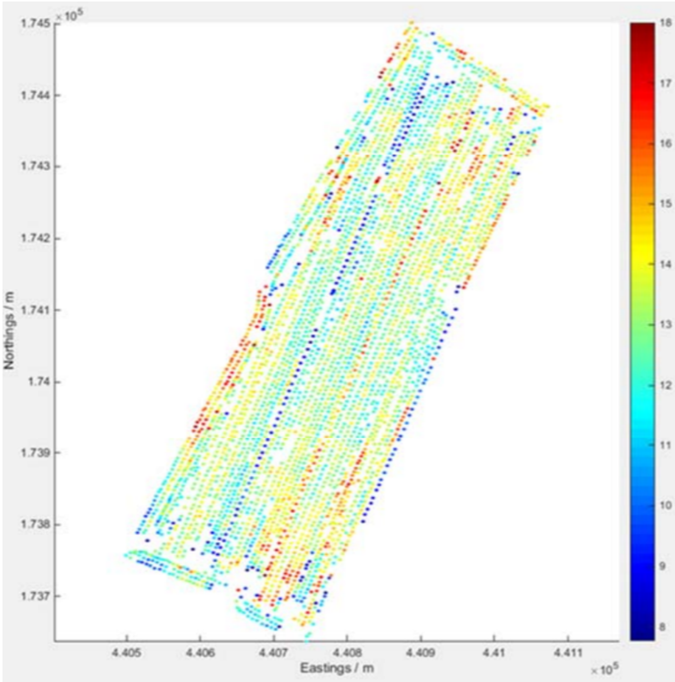


Figure 3: Yield Map [SOURCE: AHDB report No.565]

Yield maps provide field-scale visibility of crop performance and show variability with high spatial accuracy. However, the yield data recorded on the combine harvester is affected by many sources of error due to:

- Time delay (known as flow delay) between crop entering the combine harvester (header) and when this is recorded by the sensor (yield monitor).
- Inaccurate recording of the combine's travel distance, and the record of the location of the combine on the move. High accuracy GPS systems can minimise this error significantly.
- Time lag when the combine turns around at the end of the field. Usually the operator raises the header to turn around; therefore the yield looks lower in these areas, because the yield monitor starts and stops based on the position of the header (it stops logging data when the header is high).
- Other factors, such as grain moisture content, delay when starting a new pass or at the end of the pass, can result in inaccuracy in measuring grain yield.

Yield data from monitors can be corrected to remove these errors to provide a reasonable representation of field performance and provide crucial information about field variation, usually reflecting soil, nutrient content and availability or topographic variation. Sudduth et al. (1996) analysed more than 300 yield data samples from multiple years and developed a regression model to the soil, nutrient deficit and topography. They found that 50-75% of yield variation can be explained by four factors: elevation was the most important, followed by soil depth, organic matter content and nutrient content.

One of the limitations of using yield data to inform site-specific decisions is that yield changes from one year to another due to factors such as weather, disease pressure, rainfall and the amount of solar radiation. By using yield data from multiple years, these effects can be eliminated so that field potential can be zoned (Figure 4) to inform an effective soil sampling strategy and site-specific management. Blackmore et al. (2003) concluded that the spatial variability within the field is always better explained by the soil characteristics than by temporal variation and seasonal changes.

There are four key steps to maximising the utilisation of yield maps by farmers and advisors:

1- Yield data needs to be 'cleaned' and errors removed. Various tools can do this, for example, the ROTH-YE programme developed by Rothamsted Research (Muhammed et al., 2017).

2- It is only using yield data for crops that can provide a coherent map, such as winter wheat, oats and barley, rather than oilseeds or peas and beans. The latter produces a low-quality yield map due to inconsistency in the flow.

3- Cluster analysis and zoning of the field to help farmers identify high performance and low-performance areas.

4- Using several recent maps (e.g. over the last five years) to provide a better understanding of the overall field conditions (Figure- 4).

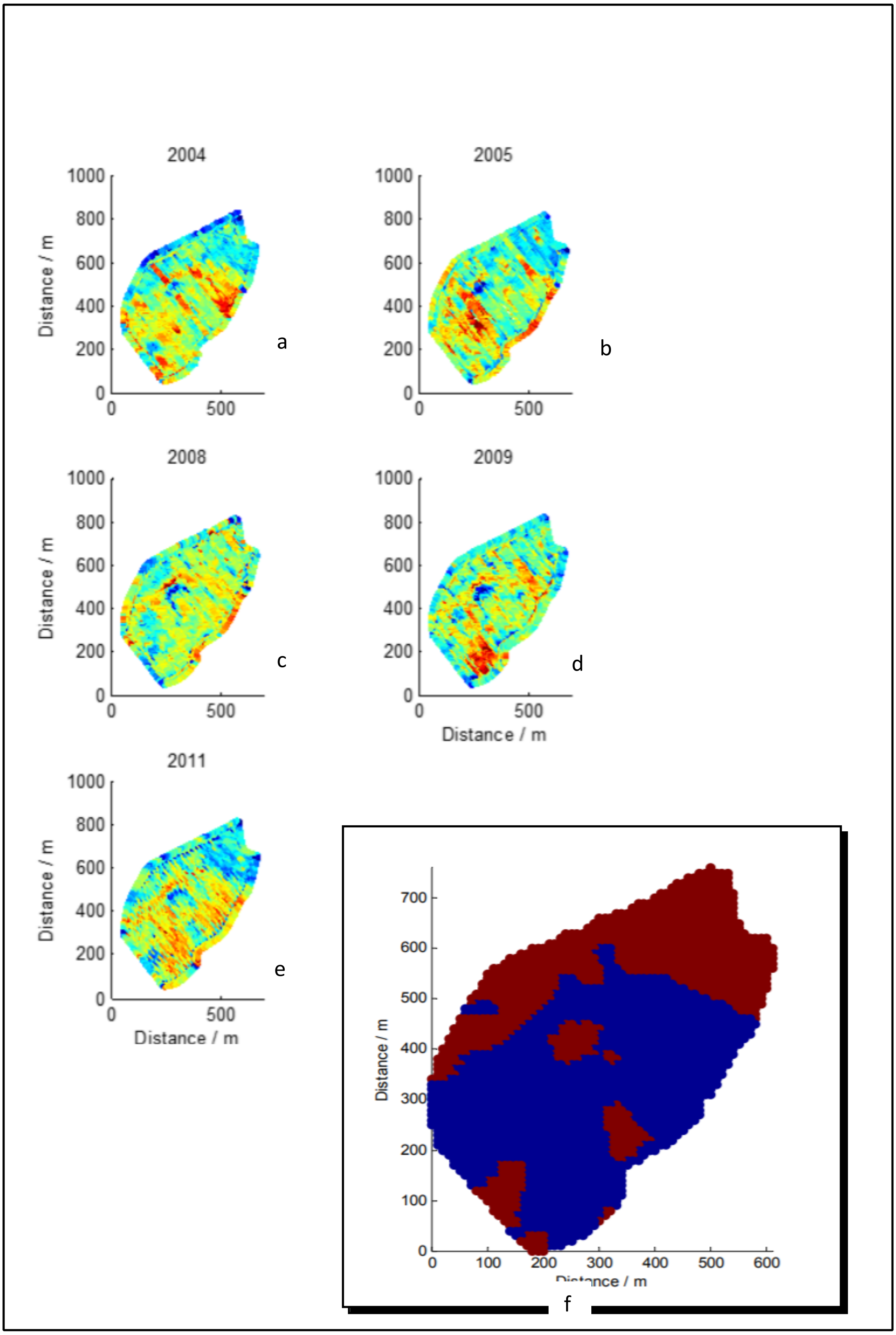


Figure 4: Five years of yield maps of winter wheat from 2004-2011 (a-e) combined and clustered (f) into two different zones high yield (blue zone) and low yield (brown zone) [Muhammed et al., 2017]

1.3. Soil management zoning and site-specific management

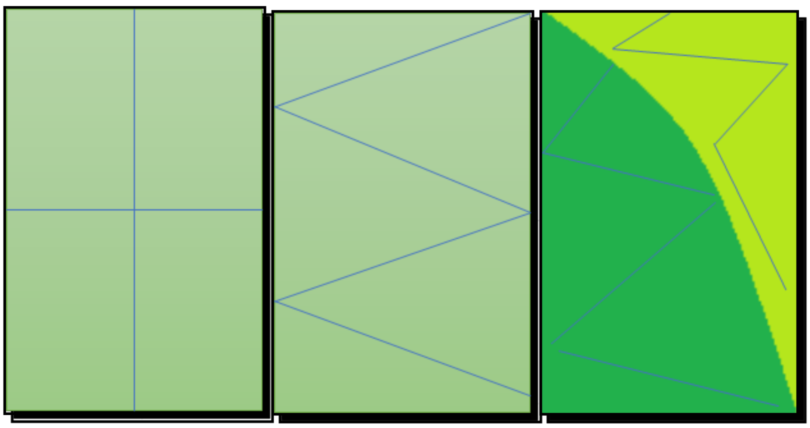
Technology has enabled farmers to map yield and other types of variation within a field, to identify factors limiting productivity within smaller zones and treat these more specifically. Soil variation is a fundamental factor in managing fields on a zonal basis. Some of these smaller zones within the field are the legacy of farm and field enlargement i.e. where a current field amalgamates what were several smaller fields in the past. Delineating soil management zones can determine specific nutrient requirements for these and bring the field to uniformity.

Identifying soil variation is the first step in site-specific management. The second step is to quantify the difference. There are many approaches which need to balance the time, cost and quality of information for each soil sampling scheme. Figure-5 shows three commonly used schemes:

Grid-based scheme (a): with samples taken on a hectare grid.

W-pattern scheme (b): with samples taken across the whole field.

Zone-based scheme with a W-sampling pattern in each zone (c): with the field divided into zones based on variation in yield (yield map), satellite imagery or electroconductivity, and soil samples taken within each zone.



(a) (b) (c)

Figure 5: Soil Sampling Schemes: (a) Grid, (b) W-pattern, and (c) Zone-based scheme with W-pattern sampling.

1.4. Variable-rate application

The main benefit of site-specific management is to optimise inputs, reduce in-field variation and improve productivity. In most cases, soil characteristics determine nutrient requirements; therefore, soil management zoning will allow the application of nutrients at appropriate rates to meet the crop requirement in each zone.

Variable-rate application of the main fertilisers is one of the most common practices when using a soil management zone approach, especially for applying Phosphate (P), potash (K) and magnesium (Mg) and Lime. Case studies have reported that, by applying P and K by variable rate on half of 500ha land, compared to the other half where a standard rate was used, a farm could gain £5/ha in yield improvement and £3/ha in fertiliser savings, with a net benefit of £2/ha (Knight et al., 2009). For correcting pH and applying lime by variable rate, there are much higher benefits. Some European studies have shown that adjusting pH by using lime at a variable rate could increase the annual return by €22/ha (Bongiovanni and Lowenberg-DeBoer, 2000). Similarly, in North America, correcting pH significantly improved farm profitability when both lime and nitrogen fertiliser was applied at a variable rate (Wang *et al.,* 2003).

Nitrogen (N) fertiliser, as the costliest fertiliser input, was and still is the primary input of interest for variable rate application for both farmers and researchers. The spatial variability of the N fertiliser requirement is the most varied compared to other inputs, within the field as well as over time. The very dynamic nature of the soil and crop N makes quantification of the requirement on the spatial scale a challenging task. Many strategies and methods have been developed to obtain a reasonable estimate of optimum N and support decisions around applying the right amount of fertiliser in the right place at the right time (three-quarters of the '4Rs'). Measuring the reflection from the crop canopy is one of the most common ways of planning the variable rate recommendation for N. Canopy reflection can capture crop characteristics such as canopy size, biomass, greenness and crop growth stage.

The financial benefits of applying N at a variable rate are not clear, however, with various 'net benefit' figures reported by researchers. Recent research by AHDB concluded that applying N using precision technologies did not improve N use efficiency. This was mainly due to the difficulty in predicting the considerable variation in Optimum N (Figure 6), which depends on estimating Crop N Demand (CND), Soil N Supply (SNS) and Fertiliser Recovery (FR), with the interactions between these three factors determining the final N requirement.

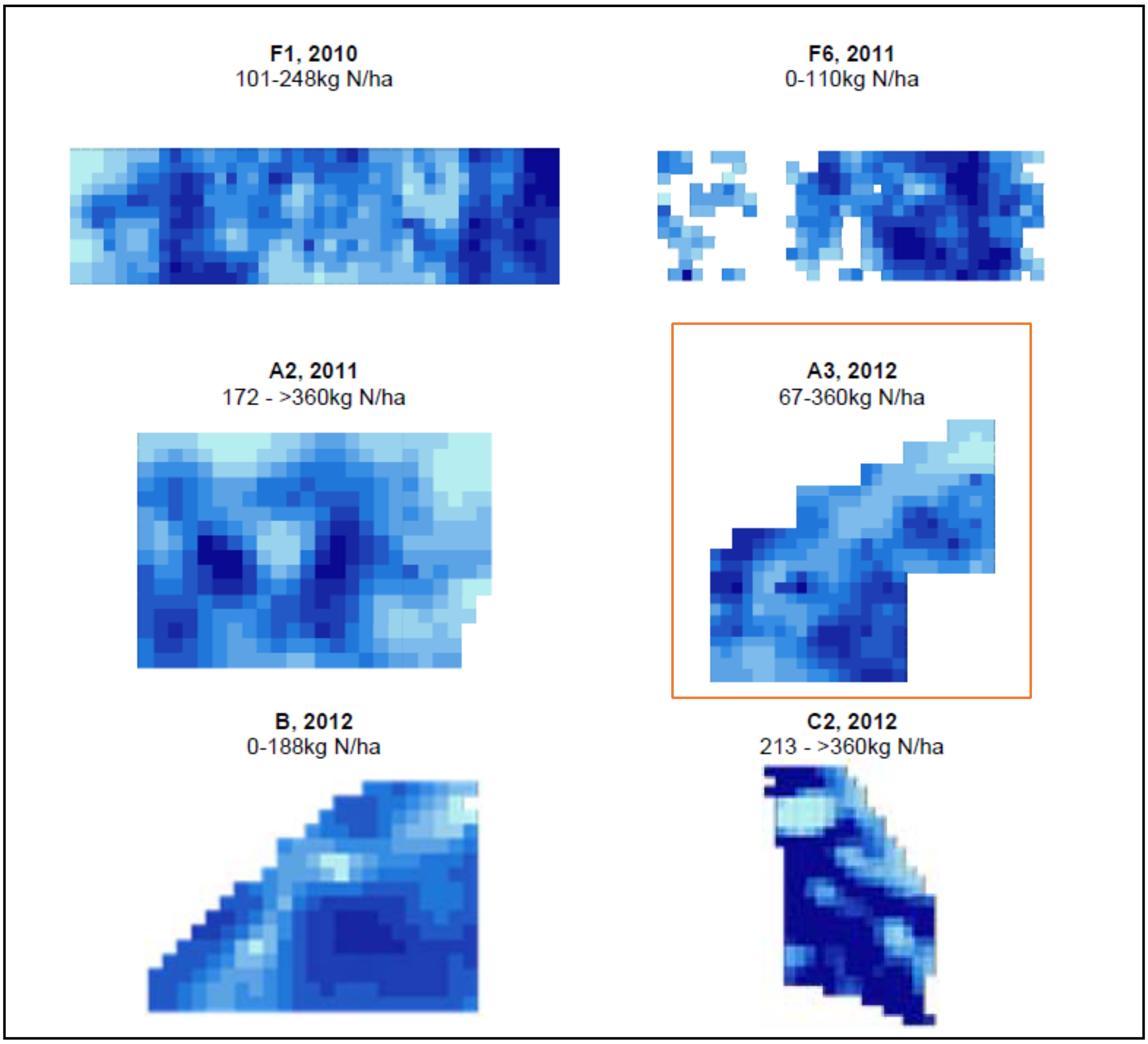


Figure 6: Within-field variation of N requirements (minimum and maximum values) for six different fields; the darker the colour, the higher the N requirement [SOURCE: Kindred et al., 2016]

As Figure 6 shows, there is often considerable variation in the N requirements within a field, with a range as big as 67 to 360Kg/ha. Predicting such change using any precision technology is difficult and the error associated with any recommendations can be significant. Therefore it is most likely that the uniform application of N might provide a better financial return (Kindred et al., 2016).

1.5. Tractors with auto-steering systems

Auto-steering and guidance systems using differential GPS have been one of the critical components of precision agriculture over the past two decades. They provide clear benefits to the farm business in terms of economic, social and environmental gains. Auto-steering makes it possible to reduce overlap during input applications or cultivation, which minimises the cost of inputs and fuels. There is a significant cost associated with investing in these systems, such as the guidance system and an accurate GPS using RTK. However, the benefits from overlap reduction will more than match the cost of the system, especially for farms with more than 300ha of land (Knight et al., 2009).

Auto-steering has transformed field trafficability by introducing a new concept, Controlled Traffic Farming (CTF). CTF confines all field vehicles to a minimal area of permanent traffic lanes with the aid of GPS (Figure 7). CTF requires a substantial investment in machinery and equipment, as well as the adaptation of farm operations to accommodate it. In return, however, CTF results in better crop establishment (less damage to the crop and soil), improved soil structure (less compaction) and a reduction in input costs (including fuel), as well as environmental benefits such as reduced soil erosion.

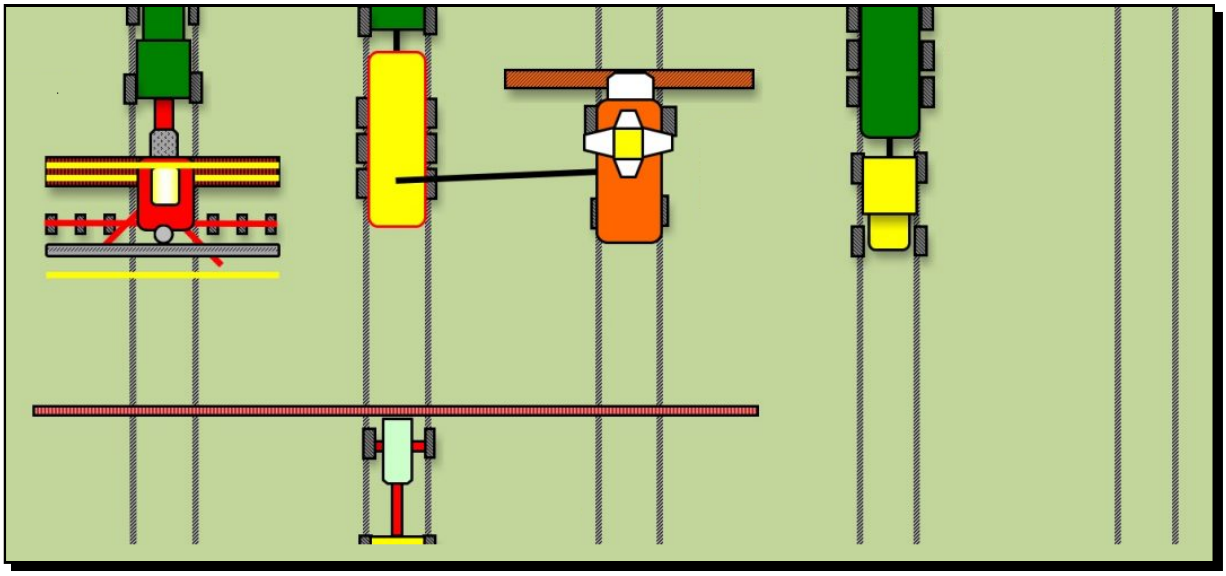


Figure 7: Illustration of Controlled Traffic Farming

The main challenges to implementing CTF (CTF, 2019) are:

- Designing CTF around the existing farming system, especially machinery.
- Introducing and maintaining the soil-based wheelways, particularly in areas of high rainfall.
- If mouldboard ploughing is the principal method of cultivation, switching to a non-inversion or zero tillage system.

1.6. Precision Farming adoption

There are many reasons for farmers and agribusinesses to adopt precision agriculture as a tool for better decision making. The main drivers are:

- Optimising input applications using variable rate application.
- Reducing labour costs using auto-steering and other forms of automation.
- Reducing waste by minimising the cost of overlapping i.e. wasting fertiliser inputs (using auto-steering systems).
- Maximising productivity by identifying low-performance areas using historical yield maps.

Precision agriculture has also brought new challenges to the farming industry that have limited its full potential:

- Diversity in the format, storage and structure of on-farm data streams.
- Dysconnectivity of these datasets has made the analysis and processing of datasets more difficult.
- Lack of an industry standard and agreed protocols to faciliate the data sharing between various systems.
- Lack of skill sets and independent advice to unlock the value of collected data.

Part 2: Agriculture and the Data Explosion

2.1. Earth Observation data

Earth Observation (EO) data is collected by remote sensors mounted on satellites about 36,000km above the Earth. The satellites collect data by recording the reflection of sunlight (electromagnetic spectrum) from soil, crops, buildings and everything on Earth's surface. The development of EO satellite technology began in the early 1970s, but in the past decade, the number of satellite platforms and the resolution of the data collected has increased substantially and at significantly reduced cost. There are satellite platforms (publicly owned) providing data with a reasonable spatial resolution (10 metres) free of charge. Higher spatial resolution (less than half a metre) is available for a smaller area but at a cost, for example, Worldview imagery with 30cm spatial resolution costing \$22.5/Km

Satellite data has many applications at farm level for assessing crop performance, soil properties and input requirements. At a national scale, remotely sensed data provide information about land-use and landcover, cropping area and other environmental characteristics of the landscape. The ability to collect vast amounts of spatial and temporal data on farmland provides an opportunity to build a multi-layered picture at a single farm or field level (Figure 8).

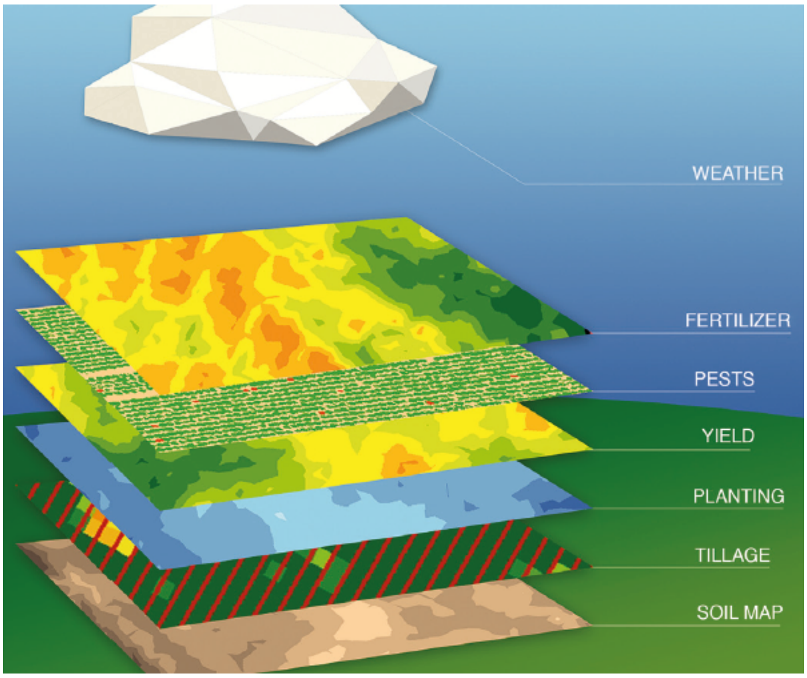
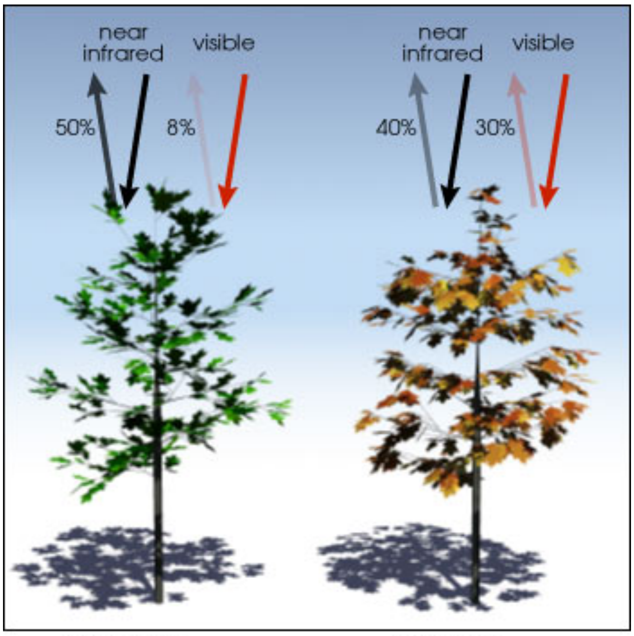


Figure 8: Multi-layer datasets for a single field [SOURCE Satellite Application Catapult and AHDB, 2018]

EO data is used extensively in many applications to improve the agricultural decision-making processes. One of the most popular products of EO is the Normalised Difference Vegetation Index (NDVI), which is a graphical indicator based on the proportion of visible and Near Infrared (NIR) reflections. For example, as shown in Figure 9, a healthy green crop will appear to have a higher NDVI value compared to yellowish (possibly diseased or N-deficient) plant. NDVI imagery is now widely used for many variable-rate decisions such as N application, biomass/yield estimation and crop establishment.



$$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72 \qquad \frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$$

Figure 9: Illustration of the Normalized Difference Vegetation Index, with green canopy absorbing more visible light (reflect less) and less NIR light (reflect more) making NDVI value high (0.72) compare to lesser green canopy (0.14) [SOURCE: NASA]

However, EO data contains information about the spectral characteristics (reflection and absorption) across the entire electromagnetic spectrum which can widen the application of EO in agriculture, such as irrigation scheduling, disease detection and soil mapping. Depending on the type of sensors and cameras onboard the satellite, there are two main types of EO data:

- **Hyperspectral sensors**: can measure reflections for many wavelengths (more than 200) at narrow bandwidth (10nm).
- **Multispectral sensors**: only measures reflections of several specific wavelengths in the electromagnetic spectrum, such as blue, green, red (BGR), and the lower near-infrared wavelength.

The advantage of hyperspectral imagery is that it provides much clearer images and much more detailed information (Figure 10) about the reflectance properties of crop or soils. For example, crop pigments such as chlorophyll absorb light with a wavelength between 430-450 and 650-550nm (Pinter et al. 2003); a hyperspectral image can record both wavelengths to calculate a spectral index. The reflectance properties of the crop are also affected by changes in crop biomass, Leaf Area Index (LAI), canopy structure, and leaf density. Hyperspectral imagery can be used to map these parameters by using the specific wavelength(s) sensitive to them. For example, N status can be detected with a red-edge band at 700 and 740nm (Shiratsuchi et al. 2011), biomass at 687 nm (Red) and crop moisture at 970 nm (a narrow near-infrared band) (Thenkabail et al. 2011).

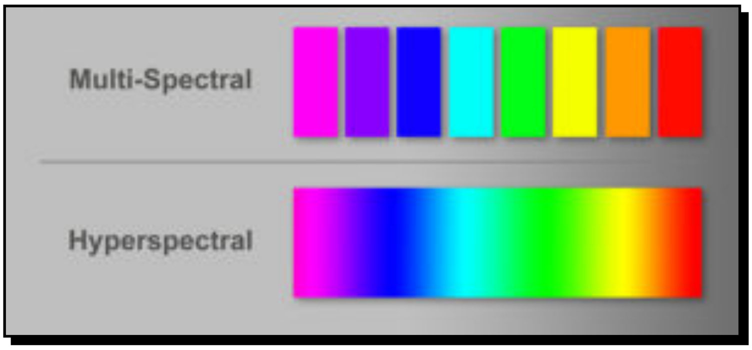


Figure 10: Differences between Hyperspectral and Multispectral wavelength availability

Earth observation from not-so-remote sensing

The advancement in sensor (mobile and portable) technologies, a reduction in the cost of data storage and connectivity over the past two decades has led to the development of a wide range of tools for EO. Proximal Sensing of soil is an example of deploying hyperspectral and multispectral sensors on farm machinery for better understanding soil and crop variations. Proximal sensing is not a new concept - for instance, using electroconductivity as a tool to measure soil variation has been around for some time - but digital technology has significantly increased its application in agriculture. The main constraint for the proximal sensors is labour, cost and limited coverage compared to satellite-based platforms.

In recent years, Unmanned Aerial Vehicles (UAV), commonly known as drones, have opened new opportunities to utilise sensor technologies in agriculture. UAV provide better spatial coverage, high spatial resolution imageries and cheaper options compared to proximal sensors. However, there are challenges for the UAV applications such as the payload to carry multiple sensors; flight restrictions due to regulations; and data processing, along with the fact that using UAVs often demands some effort. The main application of UAVs in precision agriculture are:

- Crop scouting and plant counting
- Crop assessment
- Disease detection
- Input application mapping
- Crop health assessment

With the advancement in connectivity technologies such as 5G, increases in data processing power, along with new automation capabilities, there will provide more opportunities for UAVs to play a more critical role in on-farm decision-making processes. Agri-EPI Centre uses a UAV to demonstrate the value of high connectivity 5G for dairy farmers (Figure-11), a use case to show how UAV can be used to assess grass biomass, thereby maximising grass utilisation and reducing production costs.

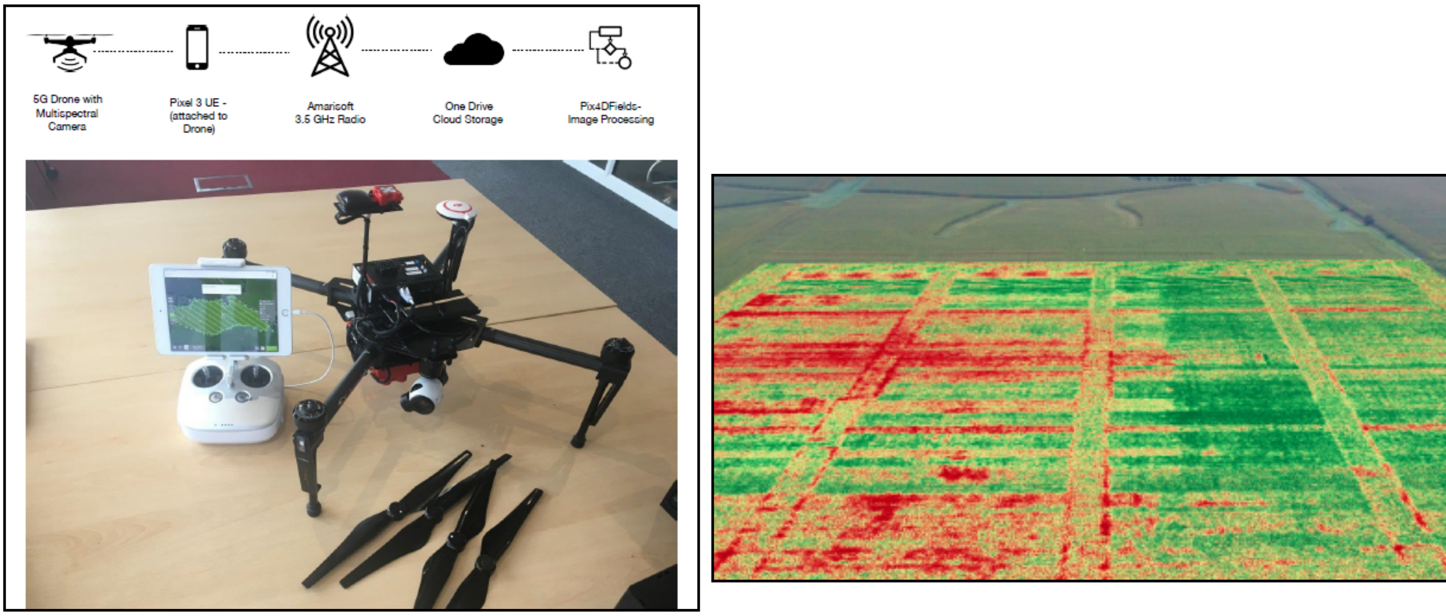


Figure 11: (a) Enabled 5g UAV with multispectral camera (b) Grass biomass map

2.2. Big Data

The concept of Big Data involves massive data sets in volumes that are not cleaned (e.g. data sets containing incomplete or inaccurate records), drawn from a variety of sources that can be collected and stored quickly. In other words, Big Data has a volume, variety, veracity and speed of acquisition (Figure 12) that enable it to be stored, analysed and visualised quickly to answer complex questions. In agriculture and the wider food supply chain, there are many opportunities for the application of Big Data to add additional value to the industry e.g. benchmarking, predictive modelling, and improvements in feed efficiency in livestock systems.

The challenges facing global food security are complex and multi-dimensional. We need new capabilities to collect data, process it and provide solutions. Human decisions will depend more and more on computers. The complexities in problems and solutions will also bring changes to the organisation, structure and operation of the farm businesses (Poppe et al., 2015). One of the main changes will be a move towards real-time observation, analysis and decision making, especially in forecasting, machinery (or animal) tracking and business operations.

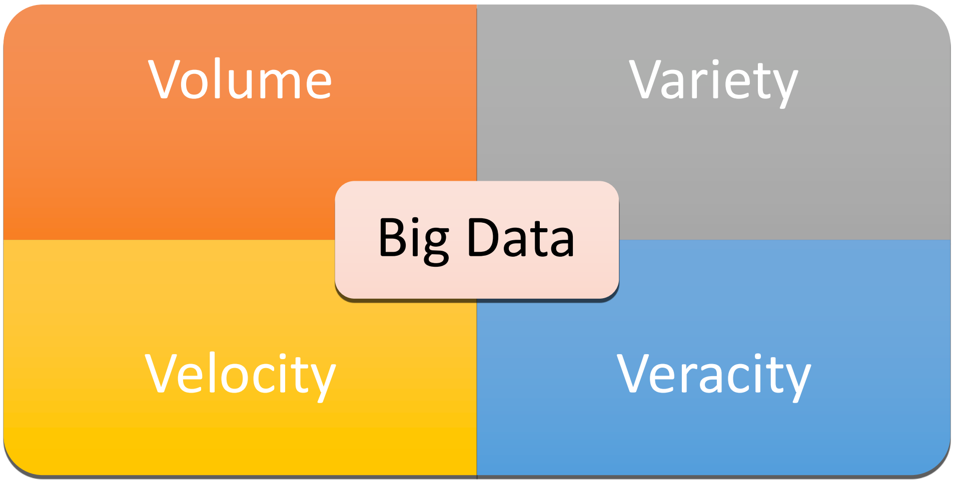


Figure 12: Big Data main components

As any with new technological changes, those in Big Data will be driven by push-pull mechanisms:

Pull factors:

- Farm businesses are under pressure to improve efficiency and productivity from both economic and environmental purposes. This demands better decision-making systems and management processes.
- There will be less demand for traditional advisory services, but more generally available knowledge based on research experiments and trials, and a higher demand for customised and localised solutions and advice.
- An increase in the frequency of extreme weather events, because of climate change, will require better decision making that can help farmers cope with, and minimise, the impacts of these events.
- Regulatory requirements will demand a more transparent food supply chain, for better traceability, environmental concerns, health and safety.
- Consumers will demand improved safety, nutritional value and source identification of food.

Push factors:

- Advances in the connectivity of mobile devices, sensors, machinery and advice.
- Precision agriculture has already created a wealth of data at the farm level and will continue to do so. This needs to be utilised.
- Big Data has already created many decision-making capabilities and data platforms which did not exist a decade ago.

- A significant increase in start-ups and agri-tech companies is attracting investors and players outside the traditional agri-food industry.

- Easy access to data via mobile technologies now allows farmers to make informed decisions in real-time (and remotely) about agronomy, markets and operations.

Nevertheless, there remain several challenges if Big Data is to have a significant impact on the agriculture industry and add value to farm businesses. The most important of these is the need for robust solutions to the issues of privacy, security and ownership presented by the advent of Big Data. Other key challenges include:

- The need to quantify the value of solutions driven by Big Data for farm businesses. This is dependent upon how much technology providers understand the challenges and the problems facing the agriculture industry.

- A clear evidence for the return-on-investment in the digital services for farmers as well as investors.

- The development of automated data collection systems to minimise the cost and hassle factor.

- Ensuring the quality and availability of farm data.

- Effective integration of data from multiple sources and suppliers to create a big agriculture data pool.

2.3. Internet of Things

The key enabler for creating Big Data is connectivity. It is essential that data can be collected from all connected devices, shared and analysed without human intervention. In the 20th century, connectivity and communication were limited to voice (telephone) or words (letters). In the past two decades, the internet has transformed the communication and connectivity of the global population. This connectivity will expand to include devices and objects to become the 'Internet of Things' (Figure 13). Elkhodr et al. (2013) defined the Internet of Things (IoT) as a "*global infrastructure for Information Society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving, interoperable information and communication technologies*".

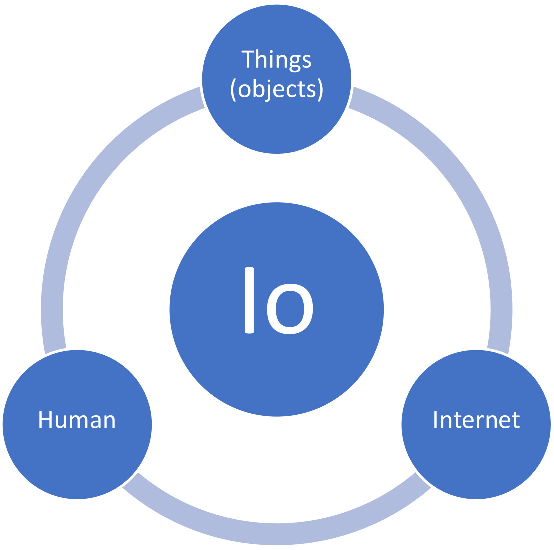


Figure 13: Internet of Things connecting Humans with Devices via internet

The internet has gone through many phases of technological development:

1. Content sent in digital forms such as emails and file attachments.

2. Expansion to commercialisation, such as e-products and e-commerce.

3. Increase to connecting people on a global scale and the explosion of social media and mobile technologies.

4. The current phase - the connection of objects and the automation of processes and operations with little or no human intervention.

There are three main components of IoT technologies: device, network and application layers (Figure 14). The device component covers the physical objects (things), such as machinery, that can sense or collect data and share it, via a gateway (cloud server), with other data streams, such as weather forecasts, via the network (internet). Then all the data can feed into a model and algorithm to generate an application so the farmer and adviser can access the result.

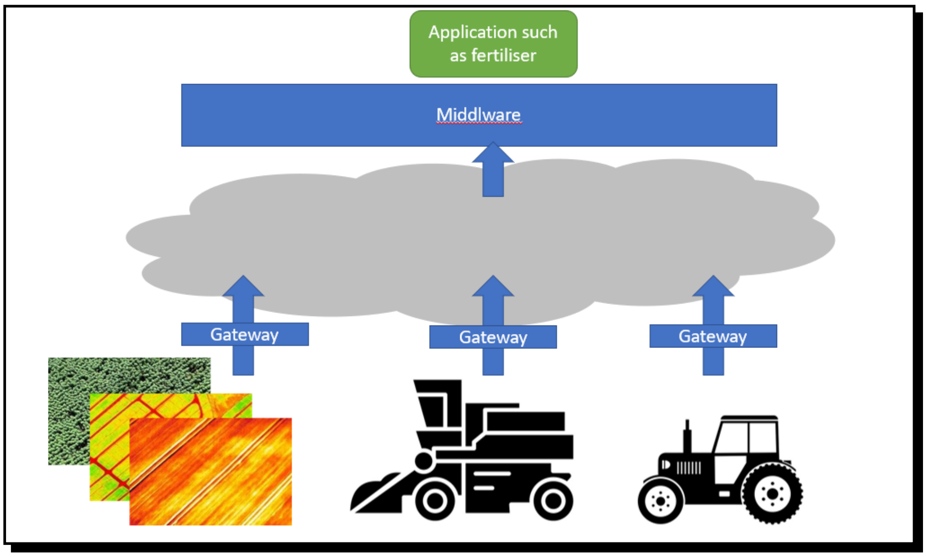


Figure 14: Illustrated diagram for IoT in agriculture

The concept of IoT technology has the potential to provide connectivity on-farm of machinery, agronomy and market data, to provide an interoperability solution to the current 'data silo' problem in the farming industry. However, the present application of IoT technologies in agriculture is still limited and evolving. The main application of IoT technologies in the arable sector are:

- Monitoring of parameters affecting crop performance.
- Documentation of farm information such as soil and crop sample data and agronomic inputs.
- Forecasting events that affect crop growth based on specific models and algorithms.
- Controlling and processing data to make real-time decisions.

By enabling the industry to collect vast amounts of data by developing algorithms and models using machine learning, IoT will open new possibilities for better decision making to improve the efficiency and profitability of agri-businesses. However, there are many challenges ahead for IoT in the agriculture industry, such as:

- Interoperability: by far the biggest challenge for the broader application of IoT.
- Proving a return-on-investment in IoT, to rectify the current lack of capital investment and affordability in redesigning farm systems and operations.
- Data heterogeneity from multiple sources and sensor manufacturers, with no standards in systems, data structures and data formats.
- Robustness of the system, such as the current lack of effective internet connectivity in most rural areas.

- The complexity of agricultural systems due to interactions of physical, chemical and biological processes within the wider environment and climate. This makes modelling and forecasting events extremely difficult.

- The need to bring talented people into agriculture with advanced knowledge of technology and a deep understanding of the industry.

Part 3: Toward more intelligent-based agriculture

3.1. Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) in a generic sense is usually defined as machines (or computers) that mimic cognitive functions that we associate with the human mind, such as learning and problem-solving.

In the complex biological environment in which foodstuffs are produced, there are many interactions, processes and variables which affect the nature, quality and quantity of whatever is produced. In the current context of the transformative data "revolution" in agriculture, and the emergence of something called "Agriculture 4.0". The concept of Agriculture 4.0 is a fundamental transformation towards a greener industry, which is driven by the advancement in science and technology, that can provide integrated solutions to food supply chains (De Clercq et al., 2018). Applications of AI will be required to synthesise management information and decision-support actions from the large volume of data generated.

It is recognised that Agriculture 4.0 will, for example, no longer depend on applying water, fertilisers, and pesticides uniformly across entire fields. Instead, farmers will for example, use the minimum quantities required and target particular areas, even plants. To capitalise on this, producer operations will have to be run very differently, primarily due to the incorporation of advanced technologies such as sensors, devices and machines. It is likely that in future, agriculture will use a collective of sophisticated technologies such as robots and sensors which measure factors such as temperature, moisture and even nutrient content and soil health. These advanced devices, with precision agriculture and robotic systems, will allow farms to be more profitable, efficient, safe, and environmentally-friendly (Figure 15).

Figure 15: The prototype of an autonomous weeding machine by the Swiss start-up ecoRobotix, pictured during tests on a sugar beet field near Bavois, Switzerland [Source: REUTERS/Denis Balibouse]

AI is the main driver of many of these systems. Whether it is to steer a robot in a complex environment automatically, decide which plants need treatment based on the synthesis of complex imaging inputs, or assimilate multiple sources of data streams into actionable insights, AI techniques are the engine room of these processes.

AI and Machine Learning (ML) techniques are advancing at a rapid rate. Cognitive computing is set to become the most disruptive technology in agriculture services because it can understand, learn, and respond to different situations (based on learning) to increase efficiency.

Examples of AI techniques vary from Artificial Neural Networks (ANN), which are computing systems vaguely inspired by the biological neural networks that constitute human and animal brains. Such systems "learn" to perform tasks by considering examples, generally without being programmed with task-specific rules. They can effectively learn by training on exemplar data and then “learn” or understand new data (or say images) based on this prior learning. The architecture is somewhat like interconnected neurons, in layers, with various weights (i.e. degrees of importance) placed on the inter-dependences. These weights are calculated from exhaustive training on exemplar data, with the expectation that new data is likely to take a similar (but multi-dimensional) form.

Machine Learning is another popular AI technique. Again, it is “experience and learning” based, without relying on a predetermined equation as a model. The algorithms adaptively improve their performance as the number of samples available for learning increases. Deep learning is a specialised form of machine learning, which Deng and Yu (2014) defined as “a class of machine learning techniques that exploit many layers of non-linear information processing for supervised or unsupervised feature extraction and transformation, and for pattern analysis and classification”.

Machine learning takes two forms: 'supervised' and 'unsupervised' learning. Supervised learning is a bit like ANN techniques. There is a training element based on known inputs and outputs. For example, if a biological process like lameness in dairy cattle is the target, and the sensory modality is vision-based, one can attribute from observations and expert input, the condition of each cow and use machine learning to adapt the outputs of the imaging system to learn to spot degrees of lameness.

Unsupervised learning is when the machine learning model works on its own to predict outcomes or unravel hidden structure from unlabelled inputs (or data). There are a few methodologies within this general group, including clustering, which attempt to group unknown data. Unsupervised learning is generally more inaccurate than supervised learning.

Some AI techniques involve human interaction and assistance. As an example, Microsoft (Microsoft, 2020) worked with a group of almost 200 farmers in India using an AI based sowing application, that was phone-text compatible, to advise on sowing, land, fertilizer requirements. The initiative has already resulted in 30% higher yields per hectare on an average compared to the previous year.

AI is likely to grow in its applications in agricultural production support. This is reinforced by one market analyst’s prediction of a current market of about $600M in 2018, rising by >38% compound per annum over the coming years. It is sure to be a growth industry within the agri-food sector.

3.2. Robotics and Autonomous Systems

“Robotics and Autonomous Systems (RAS) are set to transform global industries. These technologies will have the greatest impact on large sectors of the economy with relatively low productivity, such as Agri-Food. The UK Agri-Food chain, from primary farming through to retail, generates over £108bn p.a., with 3.7 million employees in a truly international industry yielding £20bn of exports in 2016." Quoted from “Agricultural Robotics: The Future of Robotic Agriculture” A white paper produced by the UK Robotics and Autonomous Systems Network (UK-RAS, 2018).

The combination of rapid population growth, where people live, how people eat, climate change, dwindling natural resources, and unprecedented political events are putting the global food chain under immense and increasing pressure.

Digital technology is seen as a critical element in the essential transformation of the food chain to sustainably feed and nourish the global population. The 2018 paper quoted above, cites RAS opportunities in food production as including the development of field robots to assist workers and undertake tasks including crop and livestock sensing, weeding and drilling, the integration of autonomous systems into tractors and other existing equipment, robotic harvesting, augmentation of worker productivity, farm management and decision-making, and also advanced applications to drive productivity beyond the farm gate into factories and retail. The paper sets out a vision of “…a new generation of smart, flexible, robust, compliant, interconnected robotics and autonomous systems working seamlessly alongside their human co-workers in farm and food factories.”

In the past 15 years, the agricultural industry has begun to digitise (Marinoudi et al., 2019). Robots and AI are now advanced enough to be used for non-standardised tasks such as weeding, crop sensing, fruit picking. Many jobs can be augmented, if not replaced by robots. This robot-human collaboration creates ethical, legislative and social impacts, and there is not yet an accurate means of evaluating and predicting the short- and mid-term effects of different levels of robotised agriculture on sector jobs and employment, particularly low-skilled labour.

There have been many research and demonstration projects to date but, despite recent progress, RAS technology is not yet widely available in food production. There remains a range of challenges which must be overcome to progress its growth (Bechar and Vigneault, 2016). Robots are complex systems which must be synchronised and able to operate to the same standards as current systems in unstructured agricultural environments, where there are constantly changing conditions and variability. This requires intelligent systems which are cost-effective, safe and reliable for humans, crops and the environment. Information acquisition systems such as sensors and data analysis need to be adjusted to unstructured agricultural environments. The size of agricultural robotic systems needs to be reduced and their integration improved. Another critical area of focus is on improving the understanding of the combination of human operators with robots for increased performance and reliability.

Human-Robot Interaction

Research into human-robot interactions (HRI) has been gaining importance in recent years. A study by Vasconez et al. (2019) has explored how HRI has been applied to solve complicated problems, and agriculture is one of the most challenging areas that can benefit from HRI.

Farm labour shortages have brought this issue into the spotlight as they have impacted on production in some countries. HRI offers opportunities to address this problem by helping to improve working conditions, agility, efficiency, safety, productivity and profitability of agricultural systems in cases where robots cannot completely replace manual activities.

There is still much to be done to maximise the capabilities of HRI in agriculture e.g. in the adaptability and flexibility of these techniques to increase productivity and increase economic impact. HRI can also improve farm management processes by gathering information from humans, machines and the environment. This is generating new opportunities for technology companies to develop products, creating new marketing chains from HRI technology through to farmers.

It is only a matter of time before agricultural robotic systems become fully autonomous but, to achieve this and to reap maximum benefits, further research is required to understand how intelligent they must be and to define their appropriate behaviours. The economic feasibility of such robotics will become more evident as labour costs and the demand for high-quality produce grow, while the cost of producing the technology decreases.

Most farmers will need technologies that can be introduced gradually, and there will be a transition period during which humans and robots will work together, before robots increasingly take on more complex tasks (Figure 16), enabling human jobs to move up the value chain.

Figure 16: Robotic milking system in the South West Dairy Centre; source Agri-EPI centre

From a UK point of view, several key steps must yet be achieved to establish global leadership in RAS:

1. The defragmentation and expansion of the UK RAS community.
2. Specific training paths for increasing UK RAS human resources. The launch in February 2019 of the world's first Centre for Doctoral Training for Agri-food Robotics by the University of Lincoln in collaboration with the University of Cambridge and the University of East Anglia is a significant step forward, creating the largest ever cohort of RAS specialists for the global food and farming sectors.
3. An increase in the volume of basic research at Low Technological Readiness Levels, a scientific proof of concept for the technology, to underpin industry innovation.
4. Further development of the discreet technologies which play a role in tackling RAS challenges (e.g. navigation, safe operation, grasping and manipulation), while also selecting the number of appropriate large-scale collaborative projects which will resolve integration and interoperability issues.
5. Closer collaboration between the RAS community, industry and academia.

3.3. Block-chain and food supply chain

The agri-food supply chain consists of an array of supply elements that may be both fragmented and interconnected. Agricultural food production businesses generally transact with customers using traditional mechanisms, including relatively simple computerised logging and sometimes still paper-based systems. Certain agri-food supply chains are highly vertically integrated, e.g. in aquaculture and poultry. However, for several agri-food supply chains, there is significant fragmentation. There have been attempts at de-fragmentation using co-operative and producer and marketing group professional models, which does help to both lever market value and streamline trading practices. Many businesses, however, still rely on manual methods at the point of transaction.

Blockchain is an emerging digital technology which is the same as that behind cryptocurrencies such as bitcoin. It is defined as being an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way. A blockchain is a distributed database of records in the form of encrypted 'blocks' (smaller datasets), or a public ledger of all transactions or digital events that have been executed and shared among participating parties, and which can be verified at any time in the future. Each transaction in the public ledger is verified by consensus of most participants in the system; information, once inserted, cannot be removed (Antonucci et al., 2019).

For use as a distributed ledger, a blockchain is typically managed by something called a "peer-to-peer network" in which participants collectively adhere to a protocol for communication, and also to validate "new" blocks. The critical aspect is that once recorded, the data in any given block cannot be altered retrospectively without alteration of all subsequent blocks, which then requires consensus of the network majority. It is perhaps a different concept to visualise, but it does provide transaction security. It can also record and provide information on both the source and transport of agricultural products. With proper visibility and implementation, this can significantly assist in the management of supply chain networks (Figure 17).

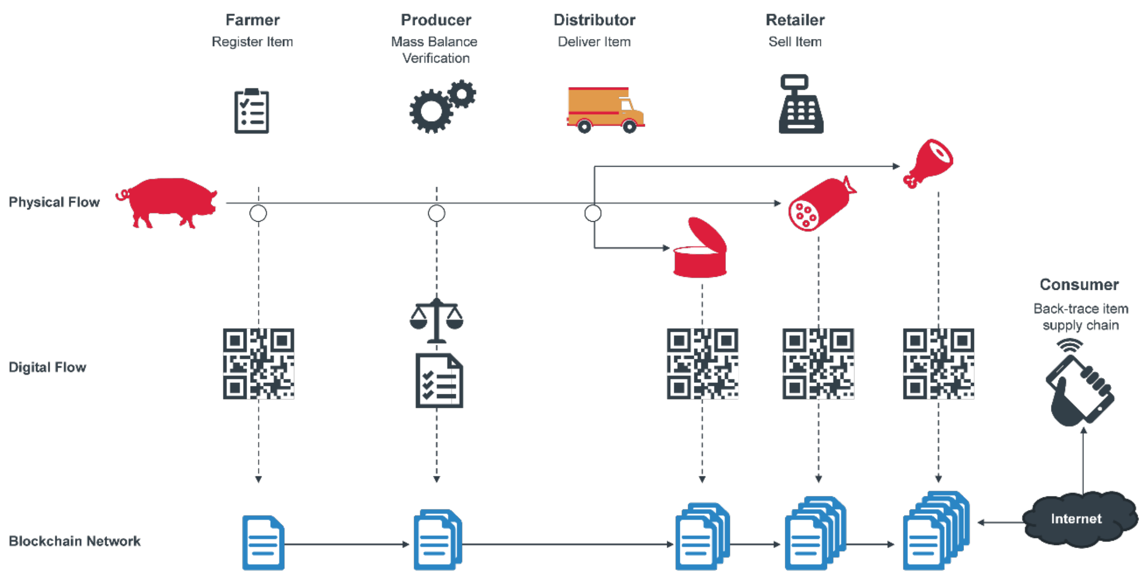


Figure 17: Blockchain of the pork supply chain

Applications

Applying Blockchain to food production means that products can be traced through the supply chain from farm to fork, with identifiable information being recorded as the product moves through each stage of the supply chain. Each Agri-food supply chain involves numerous different stakeholders (farmers, processors, traders, wholesalers, retailers and consumers), with each party having different information requirements but each still requiring high quality, trustworthy and traceable information on the goods they are handling.

Blockchain can not only be applied to the supply chain but also at farm level in many different production systems. For example, in beef production, blockchain companies are looking at integrating farm management information with everything from genetics, diet, weight, medical data and more in a blockchain format. This allows a farmer to trade stock with other farmers and processors, with traceable information about their herd, stored on an individual animal basis.

The recent rise of IoT sensors at both farm level and throughout the supply chain has created substantial research and innovation interest in creating a reliable, auditable and transparent traceability system. Current systems are based on a centralised approach, which is vulnerable to poor data integrity, tampering and failure from a single point. Utilising blockchain technology is a way of decentralising traceability while also integrating data from IoT devices along the chain (Figure 18).

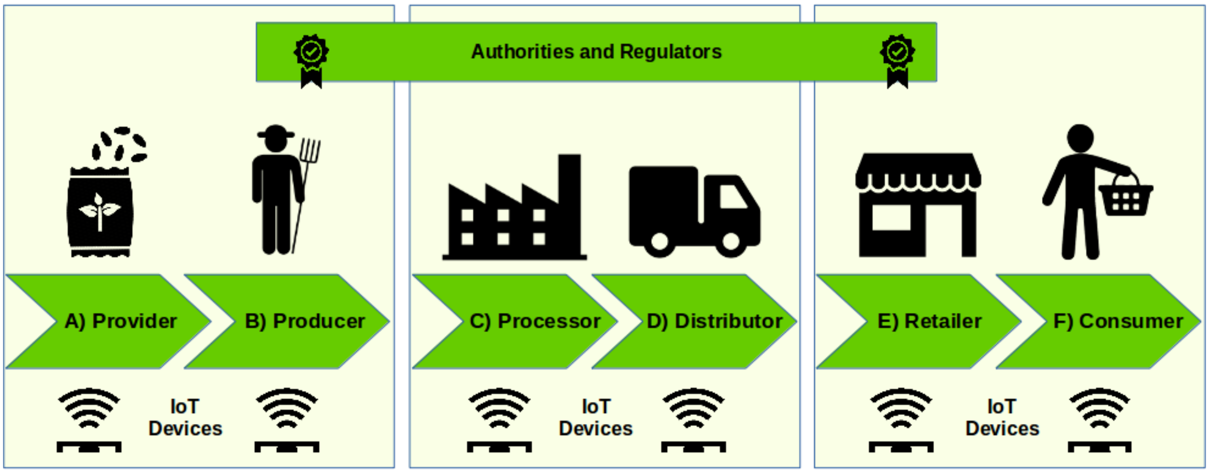


Figure 18: Blockchain technology provides decentralising traceability in the grain supply chain

Information likely to be recorded at each step of the process is:

- Provider: Information about the crop/livestock variety, chemicals, fertilisers and machinery provided plus transactions with the producer and farmer.
- Producer/farmer: Information about the farming practices used, farm management practices, weather conditions, animal feeding regimes, growth rates.
- Processing: Information about the factory, the processing methods used, batch numbers, transactions that take place with the producers and with the distributors.

- Distribution: Shipping details, trajectories followed, storage conditions (e.g. temperature, humidity), time in transit and transport method. All transactions between the distributors and the final recipients (i.e. retailers) are recorded.
- Retailer: Detailed information about each food item, it's quality and stock, expiry dates, storage conditions and time spent on the shelf are listed on the chain.

At the final stage, the consumer can use a mobile phone app to scan a QR code associated with a food product and see in detail all the information, from the provenance of the farm on which it was produced to the supply chain used to reach the retailer.

The benefits of applying blockchain technology in agriculture are many, but they can be broken down into four key areas:

Traceability:

- Consumers can see where their food has come from and how it has been processed.
- It reduces food waste and keeps products fresh.
- Accurate data on harvest/processing dates are available.
- Farm management data on an individual animal/field management zone (arable) basis can be seen throughout the supply chain.

Optimising the Food Supply Chain

- Farmers can adequately set their prices and sell when it suits them.
- Parties can perform due diligence on each other.
- Up-to-date supply and demand information can be provided to stakeholders.
- Crop Insurance data is available.
- Loads, geo-waypoints and necessary compliance information can be communicated to stakeholders.

More visibility across the supply chain

- Parties involved, prices, dates and location and state of the product can be registered.
- Secure insurance documents can be provided.

Transactions

- Farmers are helped to sell commodities, lowering transaction fees.
- Price coercion and retroactive payments are prevented.
- Opportunities to receive payments and micro-financing are provided.
- Lower costs and faster payment options are available to agri-commerce participants.

Areas of the agri-food chain where blockchain is being trialled or even implemented include forward transacting of crop products, traceability and authenticity verification, the underpinning of food safety, and the simplification and improved efficiency of transactions between actors in the supply chain. Examples include better prediction of supply, earlier in the production process. Solutions using blockchain trading methods, integrated with EO techniques, are being investigated to establish new trading practices associated with field-grown crops, where it may be possible to, for example, procure more accurately a quantified supply before harvest, benefitting producer cash-flow and trader/buyer security of supply.

Food safety is another important consideration. The World Health Organisation states that diseases transmitted through contaminated food are a persistent concern, not only for consumers but also for governments. As an example, they report that 582 million people around the world became ill from contaminated food in 2010.

Many cases of food-borne illnesses can be the result of inefficient tracking. Tracing the origin of food products when outbreaks occur can be a time-demanding and challenging process. Implementation of Blockchain methods could be an effective solution and the retail sector is already picking up on this technology. The US company Walmart has recently employed blockchain to track and trace its lettuce supply chains, claiming that they can trace food back to its grower in as little as 2.2 seconds. Other large companies are involved in technology partnerships, offering blockchain into many sectors. IBM, for example, market a multi-sector solution that they claim, if implemented ubiquitously, could increase global GDP by 5% and global trade by 15%.

Other UK-based SME's are looking at this market concerning agri-food. Trade-in-Space is progressing its solution for fusing EO with blockchain pre-farm gate. Nexus is developing Crypto ID's that could contain any desired information such as farm location, expiry dates, temperature conditions, farmer details and growing conditions. This Electronic Identification (EID) can then be tracked throughout the various stages of distribution and stored on the immutable ledger. Any changes or disruptions to the process could be traced back to the source, or flagged to the necessary parties, thus significantly improving the efficiency and transparency of the supply chain. As a whole, Nexus states, blockchain would help to prevent food waste, food fraud, and enhance the process of making food recalls.

Nexus is also interested in the processes used by many small farmers (and even some of the significant firms) which rely on sophisticated tracking and trading systems that are slow and inefficient by nature. These systems can result in mistakes or management because they are often fragmented and heavily dependent on paper-based contracts or verbal agreements. In agri-food systems, there could be many stakeholders in any such supply chain, e.g. buyers, banks, producers, sellers, suppliers, couriers and customs officers. The value of the product can often be tied up for a time while the paper-based forms of documentation are transported to the appropriate parties. Delays can result in wasted food, increased costs and potentially damaged stakeholder relationships. Blockchain methods create a far more robust, traceable and secure system, while also allowing the smart execution of binding financial contracts (and related efficiency of payments) that can be set up instantly at point of receipt.

Other data may be gathered at source or during the supply chain and permanently annotated to a batch or bulk of an agricultural product. In an era of the IoT and growing data capture on-farm and throughout the supply chain, metrics such as sustainability and carbon-cost, as well as environmental monitoring in the supply chain (e.g. for perishables), could all be logged and ported with the goods, providing visibility to both seller and buyer, and be passed along the supply chain.

The potential of Blockchain is significant, and we are now starting to see real examples emerge from initiatives in the food supply chain. There is an expectation that applications will grow, but this is critically dependent on trust and understanding on the part of producers, processors, traders and retailers, and requires "buy-in" from them all to energise this technology for the agri-food sector.

Part 4: Summary

The need for food, energy and water will continue to increase to meet the global demand for the fast-growing population. This puts food systems under considerable pressure. Also, agriculture needs to adapt to a wide range of uncertainties as to the result of climate change, such as extreme weather events (drought and flooding), and to reduce emissions to mitigate its effects. Increasing productivity is one part of the challenge, which requires either more land for food production or the intensification of the current system. Both options could have a negative impact on biodiversity loss and climate change, leading to soil depletion and increased waste and health-related issues.

Advancements in digital technology have the potential to transform the food supply chain by providing innovative solutions to:

- Increased system efficiency and decreased waste.
- Increased sustainability and resilience in food production systems.
- Provide an accurate value of food to include economic and natural capital costs.
- Redesign a diverse agriculture system (circular system, e.g. mixed farms).
- Provide a capability for a landscape approach to farming and thus multi-functional landscapes.
- Create space for Bio-Energy Carbon Capture and Storage by increasing efficiency and diversity.

Digital technologies can transform the industry by providing customised solutions, and farm-specific instead of generic advice, identifying inefficiency, reducing wastage and matching demand and supply. However, many challenges can limit the application of these technologies to make transformative changes. The main challenges are:

- Data ownership: The main requirements of these technologies are the sharing of data and its connectivity to realise their full potential, associated with a real concern about data security and ownership.
- Business model: A new way of collaborating between the various players in the industry is crucial to facilitate connectivity and data sharing and overcome data ownership challenges. A business model needs to be based on the value chain rather than the traditional supplier-customer transaction.

- Customised solution design: Technology providers need to understand the pain points of farmers and their exact needs at a very early stage of development. Engaging farmers is part of developing solutions.
- Data and technology integration: A digital solution is a combination of various technologies, machinery and data collected by farmers and others. Therefore, the integration of these capabilities is critical in digital agriculture.
- Connectivity: The integration of technologies and data require wireless connectivity between field operations, agronomy, data and end-users, whereas most farms still do not have sufficient connectivity.

References

- Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L. and Menesatti, P., 2019. A review on blockchain applications in the agri-food sector. Journal of the Science of Food and Agriculture, 99(14), pp.6129-6138.
- Blackmore, S., Godwin, R.J. and Fountas, S., 2003. The analysis of spatial and temporal trends in yield map data over six years. *Biosystems engineering*, *84*(4), pp.455-466.
- Bechar, A. and Vigneault, C., 2016. Agricultural robots for field operations: Concepts and components. *Biosystems Engineering*, *149*, pp.94-111.
- Bongiovanni, R. and Lowenberg-DeBoer, J., 2000. Economics of variable rate lime in Indiana. Precision Agriculture, 2(1), pp.55-70.
- De Clercq, M., Vats, A. and Biel, A., 2018. Agriculture 4.0: The future of farming technology. *Proceedings of the World Government Summit, Dubai, UAE*, pp.11-13.
- Deng, L. and Yu, D., 2014. Deep learning: methods and applications. *Foundations and Trends® in Signal Processing*, *7*(3–4), pp.197-387.
- Elkhodr, M., Shahrestani, S. and Cheung, H., 2013, April. The internet of things: Vision & challenges. In IEEE 2013 Tencon-Spring (pp. 218-222). IEEE.
- Knight, S., Miller, P. and Orson, J., 2009. An up-to-date cost/benefit analysis of precision farming techniques to guide growers of cereals and oilseeds. *HGCA Research Review*, (71).
- Kindred, D.R., Hatley, D., Ginsburg, D., Catalayud, A., Storer, K., Wilson, L., Hockridge, B., Milne, A.E., Marchant, B.P., Miller, P. and Sylvester-Bradley, R., 2016. Automating nitrogen fertiliser management for cereals (Auto-N). AHDB Project Report No. 561.
- Marinoudi, V., Sørensen, C.G., Pearson, S. and Bochtis, D., 2019. Robotics and labour in agriculture. A context consideration. *Biosystems Engineering*, *184*, pp.111-121.
- Microsoft, 2020, Digital Agriculture: Farmers in India are using AI to increase crop yields. Available online https://news.microsoft.com/en-in/features/ai-agriculture-icrisat-upl-india/ Accessed on 03.01.2020
- Muhammed, S., Milne, A., Marchant, B., Griffin, S. and Whitmore, A., 2017. *Exploiting yield maps and soil management zones* (No. 565). AHDB Project Report.
- Pinter Jr, P.J., Hatfield, J.L., Schepers, J.S., Barnes, E.M., Moran, M.S., Daughtry, C.S. and Upchurch, D.R., 2003. Remote sensing for crop management. *Photogrammetric Engineering & Remote Sensing*, *69*(6), pp.647-664.
- Poppe, K., Wolfert, J., Verdouw, C. and Renwick, A., 2015. A European perspective on the economics of big data. *Farm Policy Journal*, *12*(1), pp.11-19.
- Satellite Application Catapult and AHDB, 2018, Satellite for Agriculture. Available Online on https://ahdb.org.uk/knowledge-library/satellites-for-agriculture Accessed on: 10th November 2019.
- Schueller, J.K. and Bae, Y.H., 1987. Spatially attributed automatic combine data acquisition. *Computers and Electronics in Agriculture*, *2*(2), pp.119-127.

- Shiratsuchi, L., Ferguson, R., Shanahan, J., Adamchuk, V., Rundquist, D., Marx, D. and Slater, G., 2011. Water and nitrogen effects on active canopy sensor vegetation indices. *Agronomy journal*, *103*(6), pp.1815-1826.

- Sudduth, K.A., Drummond, S.T., Birrell, S.J. and Kitchen, N.R., 1996. Analysis of spatial factors influencing crop yield. *Precision Agriculture*, (precisionagricu3), pp.129-139.

- Thenkabail, P.S., Lyon, J.G. and Huete, A., 2011. Hyperspectral remote sensing of vegetation and agricultural crops: knowledge gain and knowledge gap after 40 years of research: Chapter 28. Vasconez, J.P., Kantor, G.A. and Cheein, F.A.A., 2019. Human–robot interaction in agriculture: A survey and current challenges. *Biosystems engineering*, *179*, pp.35-48.

- UK-RAS, 2018. The Future of Robotic Agriculture. White Paper published by UK- Robotic & Automation Systems. Published online and available at:https://www.ukras.org/wp-content/uploads/2018/10/UK_RAS_wp_Agri_web-res_single.pdf. Accessed on 19.01.2020.

- Vasconez, J.P., Kantor, G.A. and Cheein, F.A.A., 2019. Human–robot interaction in agriculture: A survey and current challenges. *Biosystems engineering*, *179*, pp.35-48.

- Wang, D., Prato, T., Qiu, Z., Kitchen, N.R. and Sudduth, K.A., 2003. Economic and environmental evaluation of variable rate nitrogen and lime application for claypan soil fields. *Precision Agriculture*, *4*(1), pp.35-52.