Chapter 2
Smart Farming Technologies – Description, Taxonomy and Economic Impact

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Abstract Precision Agriculture is a cyclic optimization process where data have to be collected from the field, analysed and evaluated and finally used for decision making for site-specific management of the field. Smart farming technologies (SFT) cover all these aspects of precision agriculture and can be categorized in data acquisition, data analysis and evaluation and precision application technologies. Data acquisition technologies include GNSS technologies, mapping technologies, data acquisition of environmental properties and machines and their properties. Data analysis and evaluation technologies comprise the delineation of management zones, decision support systems and farm management information systems. Finally, preci-

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sion application technologies embrace variable-rate application technologies, precision irrigation and weeding and machine guidance. In this chapter, the reader can find a technical description of the technologies included in each category accompanied by a taxonomy of all SFT in terms of farming system type, cropping system, availability, level of investment and farmers' motives to adopt them. Finally, the economic impact that each SFT has compared to conventional agricultural practices is given.

Keywords Precision agriculture • Smart farming technologies • Data acquisition • Variable application • Economic impact

2.1 Precision Agriculture as a Cyclic Optimization Process

Precision agriculture (PA) can be defined as the management of spatial and temporal variation in the fields with regard to soil, atmosphere and plants using information and communications technologies (ICT). Several definitions can be found in the literature (Bramley 2001; Pedersen 2003; Fountas et al. 2005; Zarco-Tejada et al. 2014). Precision agriculture is a management system for farms that aims to improve productivity and resources use either through increased yields or reduced inputs and adverse environmental effects. It can assist crop producers because it enables precise and optimized use of inputs leading to reduced costs and environmental impact, and because the concept provides a record (traceability) of farm activities that consumers and central administration increasingly require (Stafford 2000).

Precision agriculture is not a new idea. A few decades ago the farms were small and the farmer would walk all over the fields several times every year. It was possible to observe all within-field variation and take appropriate management decisions for each part. Adding more seeds in parts where emergence was poor or more fertilizer where growth was weak was the dominant practice. However, this knowledge depended on the farmer's memory, and in most cases the final decisions were influenced more by results from recent years that were kept in memory.But these yields were more influenced by weather or other factors that might not occur during the following years. The connection of the farmer with the fields and the knowledge of their specific characteristics were reduced with the mechanisation and the increase in farm size. The average rule was used to manage the fields. When the first yield monitors were developed and yield maps were created, it was proved that yield and soil properties varied considerably within a field. This fact marked the development of site-specific techniques, which are a core discipline of PA. Site-specific farming can be used for any field or crop for applying treatments to areas within a field that require different management from the field average allowing fine-tuning of crop management systems.

Precision agriculture is a cyclic system of data collection used for crop management and evaluation of the decisions, with the cycle continuing for the subsequent years. Each year data are stored in a database (library) and are used as historical data for future decisions. The system can be divided into data collection, data analysis, managerial decisions and variable-rate applications (VRA) of inputs, evaluation of the managerial decisions and a new cycle starts.

To apply the PA cyclic system, there is a need for a series of technologies called smart farming technologies (SFTs) that refer to marketable, affordable, reliable and time-saving technologies drawing from research in precision farming, farm management information systems (FMIS) and agricultural automation and robotics. Their benefits are related to more efficient application of inputs (seeds, fertilizers, chemicals, water, fuel and labour), increased work speed, comfort and enhanced flexibility on the farm.

The cyclic production process can be achieved by data acquisition, data analysis and evaluation (decision making) and precise application of operations (field implementation). Therefore, the SFTs presented in this chapter are classified based on this structure.

2.2 Smart Farming Technology Types

Smart farming technologies (SFTs) are divided into three main categories that, as stated above, cover the cyclic system of PA:

- **Data acquisition technologies**: this category contains all surveying, mapping, navigation and sensing technologies.
- **Data analysis and evaluation technologies**: these technologies range from simple computer-based decision models to complex farm management and information systems including many different variables.
- **Precision application technologies**: this category contains all application technologies, focusing on variable-rate application and guidance technologies.

There is a series of technologies that can be classified in each category of SFTs, as shown in Table 2.1.

Each technology referred in the table above will be analysed in this chapter.

2.2.1 Data Acquisition Technologies

The SFTs for recording and mapping field and crop characteristics are divided into the categories below:

- Global navigation satellite systems technologies (in fact these technologies record the actual position which can be used for different purposes such as guidance, mapping etc.)
- Mapping technologies
- Data acquisition of environmental properties (Camera based imaging, NDVI measurements, soil moisture sensors)
- Machines and their propertiesGlobal navigation satellite systems (GNSS) technologies

Table 2.1 Smart farming technologies list

PA technologies	Main categories	System
Data acquisition technologies	GNSS technologies	Global navigation satellite systems (GNSS)
		Differential GNSS
		Real time kinematic (RTK) and Network RTK (NRTK)
		Wide area RTK (WARTK)
		Un-differenced GNSS
		Precise point positioning (PPP)
		Fast PPP (FPPP)
	Mapping technologies	Elevation maps
		Soil mapping
		Yield mapping
		Yield monitor display
	Data acquisition of environmental properties echnologies (Camera based imaging)	RGB cameras
		LIDAR sensors
		ToF (IR) cameras
		Light curtains
		Multi/hyper-spectral cameras
		Thermal cameras
	Data acquisition of environmental properties technologies (NDVI Measurement)	Spectral sensors
		Fluorescence sensors
	Data acquisition of environmental properties technologies (Soil moisture sensors)	Frequency domain reflectometry (FDR)
		Time domain reflectometry (TDR)
		Amplitude domain reflectometry (Impedance)
		Phase transmission
		Time domain transmission
		Tensiometers
		Gipsum blocks
		Granular matrix sensors
		Heat dissipation sensors
	Machines and their properties	Travel speed sensor
		Tractor sensing systems using ISOBUS
		Unmanned aerial vehicles (UAVs)
		Unmanned ground vehicles (UGVs)
		Farm management information system
		Software for whole farm management, forecasting and crop monitoring

(continued)

Table 2.1 (continued)

PA technologies	Main categories	System
Data analysis & evaluation technologies		Management zone delineation
		Decision support system
Precision application technologies	Guidance technology	Auto-guidance systems
		Control traffic farming
	Variable rate application	Variable-rate fertilizer application
		Variable-rate lime spplication
		Variable-rate manure application
		Variable-rate pesticide application (Map-based system)
		Variable-aate pesticide application (Real-time sensor based system)
		Boom height control
		Variable-rate planting/seeding
		Precision physical weeding
		Precision irrigation and irrigation scheduling

2.2.1.1 Global Navigation Satellite Systems (GNSS)

Global navigation satellite systems (GNSS) is the standard generic term for satellite navigation systems that provide autonomous geo-spatial positioning with global coverage. Any GNSS is used to pinpoint the geographic location of a user's receiver anywhere in the world. Currently, there are two operational GNSS systems (GPS and GLONASS) and two systems in development (Galileo and BeiDou) that are expanding their coverage from regional coverage to global; both are expected to be fully functional in 2020. A brief summary of these different GNSS systems is presented in Table 2.2.

All GNSSs at the moment use over 70 satellites, but when all four systems (GPS, GLONASS, Galileo and BeiDou) are fully deployed it will reach 120 satellites (Li et al. 2015). The GPS has six orbital planes with a minimum of three satellites per plane (28–31 satellites that are constantly working). GLONASS has three orbital planes with eight satellites per plane (24 satellites in total). Galileo will have three orbital planes and a total of 30 satellites.

The precision of GNSS varies. For example, GPS signals originally used an intentional degradation (known as Selective Availability, SA) to prevent potential military adversaries from using the positioning data (military operated system). Therefore, GPS accuracy was limited to a 100-m range for civilian users, although military equipment enabled accuracy to within a metre. In May 2000, SA was discontinued and since then all GPS receivers are potentially accurate to within 5 m.

Table 2.2 Main GNSS systems

System	GPS	GLONASS	Galileo	BeiDou
Owner	United States	Russian Federation	European Union	People's Republic of China
Site	www.gps.gov	www.glonass-iac.ru	www.gsa.europa.eu	en.beidou.gov.cn
Type	Military	Military	Civilian Commercial	Military Commercial
Coding	CDMA	FDMA	CDMA	CDMA
Orbital altitude	20,180 km	19,130 km	23,222 km	21,150 km
Precision	5 m	3–10 m	1 m	10 m
			0.01 m encrypted	0.1 m encrypted
Period	11.97 hours	11.26 hours	14.08 hours	12.63 hours
N° satellites	**31** (at least 24 by design)	**28** (at least 24 by design),including:24 operational	**4** in-orbit validation satellites **+8** full operation capable satellites in orbit	**5** geostationary orbit (GEO) satellites
		2 under check by the satellite prime contractor	**22** operational satellites budgeted	**30** medium Earth orbit (MEO) satellites
		2 in flight tests phase		
Status	Operational **1995**	Operational **2015**	In development (expected full deployment by **2020**)	Operational (*regionally* **2012**)
				In development (global use by **2020**)

GLONASS showed an accuracy of 35 m in 2006, but after its modernization it reached less than 3 m, which is very similar to GPS. As of 23 January 2012, GLONASS's horizontal precision is in the order of 4–7 m, whereas the vertical error is in the order of 10–15 m. However, analysing the accuracy obtained with GPS at the same stations it has been shown that GLONASS is slightly less accurate than GPS. In the same way, the mean number of GLONASS satellites in view is fewer than GPS.[1]

When available, Galileo will provide position accuracy to within one metre for public use and 1 cm in the encrypted state. The first Galileo test satellite, the GIOVE-A, was launched on December 28 2005, while the first satellite to be part of the operational system was launched on October 21 2011. As of December 2015, the system will have 12 of 30 satellites in orbit and started offering early operational capability (EOC) from 2016 and will go to initial operational capability (IOC) in 2017–2018 and reach full operational capability (FOC) in 2019 (Galileo's contribution to the MEOSAR system, 2015). The complete 30-satellite Galileo system (24 operational and 6 active spares) is expected by 2020.[2]

2.2.1.2 GNSS Precise Positioning Techniques: Differential GNSS

Differential GNSS (DGNSS) is a GNSS augmentation system based on improving the accuracy of the user's receiver (or rover receiver) by means of differential information or corrections provided by a nearby reference GNSS station or a network of these stations. The application of this concept allows common sources of error between satellites and receivers to be cancelled or mitigated, because of dual-frequency carrier-phase measurements and the applyication of double-difference processing.

Classical DGNSS

In the DGNSS approach, we take advantage of knowing an accurate surveyed position of the reference station. In this way, it is possible to derive the deviations between the estimated position and the actual one, and thus compute corrections to the GNSS pseudoranges of each satellite. Such corrections are then useful to improve the user's receiver positioning.

Real Time Kinematic (RTK) and Network RTK (NRTK)

The RTK positioning system was introduced by Remondi (1985). It consists of a user receiver that benefits from a base receiver, with well-known coordinates, and a communication link between both to receive and use the common satellites-in-view measurements to perform the corresponding differences in order to achieve centimetre level positioning accuracy with a short convergence time (Landau et al. 2007).

[1] http://www.navipedia.net/index.php/GLONASS_Performances

[2] http://www.gsa.europa.eu/galileo/programme

Wide Area RTK (WARTK)
The WARTK technique, introduced 17 years ago and developed by IonSAT members under several ESA-funded projects, can be considered an extension of RTK/NRTK techniques to enable subdecimetre positioning accuracy with roving receivers hundreds of kilometres away from the reference receiver. To enable this, it is necessary to take as the basic observation the double differences of carrier phases and use additional specific corrections (namely very precise ionospheric Slant TEC estimations) computed at a central processing facility (CPF) from a permanent network of GNSS receivers (Hernández-Pajares et al. 2000).

2.2.1.3 GNSS Precise Positioning Techniques: Undifferenced GNSS

Undifferenced GNSS is a GNSS augmentation system to provide high precision positioning to a user's receiver in absolute mode (i.e. without the need to receive the direct measurements taken from any reference receiver or network of receivers nearby). Instead of that an estimate of specific corrections for satellite orbits and clocks, and ionospheric corrections, among others, is broadcast. As was the case with DGNSS techniques, it is also based on dual-frequency carrier-phase measurements. The application of this concept allows common sources of error between satellites and receivers to be cancelled or mitigated, by using dual-frequency carrier-phase measurements and applying double-difference processing.

Precise Point Positioning (PPP)
Real time PPP (Héroux and Kouba 1995; Zumberge et al. 1997) can be provided in a reliable way by means of a world-wide sparse reference network in order to compute precise reference satellite orbits and clock features in real-time at a CPF. Its architecture allows the applicability of PPP to any user located in a global reference frame without being referred to any local base station or network of stations. In addition, the technique can diminish considerably the impact of failures of certain reference stations by considering a significant number of permanent receivers in order to derive the precise orbit and clock data.

Fast PPP (FPPP)
Fast PPP technique is an evolved version of the classic PPP to achieve decimetre level positioning and also faster convergence time (for double-frequency user receivers) in undifferenced mode. This means that the user navigates without the need for a reference receiver (single receiver navigation).

GNSS Antenna (Receives Satellite Signal)
When a GNSS antenna is applied, then the whole system converts to a mapping system. Therefore, the data received by all sensors are combined with position for every time interval set (average is 1 Hz, but some accurate GNSS receivers used in kinematic applications can reach a frequency of 2–50 Hz and even higher up to 100 Hz) (Yigit 2016).

2.2.2 *Mapping Technologies*

2.2.2.1 Elevation Maps

Elevation is a critical layer in PA because it is very useful to help farmers understand yield response. It influences soil formation, water movement and cropping aspects (Whelan and Taylor 2013). It can determine waterlogged areas, erosion risk, drainage restrictions, and often is related to soil type.[3] Using data from GNSS receivers, it is possible to produce a digital elevation model (DEM) of a field or a farm that can be used to classify terrain characteristics such as slope, aspect, curvature, solar radiation interception, landscape water flow directions and topographic wetness indices. Elevation maps can help to identify how topography can affect agronomic results in a field and of course to level the field (Whelan and Taylor 2013). Using this information, it is possible to produce (i) contours and topography maps, (ii) 3-D modelling of ponding risk, runoff and velocity maps, (iii) farm layout designs, (iv) contour bank design, drainage plans and on-ground implementation and (v) cut and fill land levelling designs.

2.2.2.2 Soil Mapping

Soil sampling is vital to collect information about soil texture (sand, silt, clay contnets), availability of nutrients for crops to grow (N, P, K, Ca, Mg, pH, lime) and other soil chemical properties (organic matter, salinity, nitrate, sulphate, heavy metals) (Foth and Ellis 1988). In addition, it can be used to identify soil compaction, moisture content and other mechanical and physical soil properties. Soil sampling can be executed using the random, adaptive or grid technique. In random sampling, soil cores are obtained from random locations within the field. In adaptive sampling, selected sample locations depend on prior information. Grid sampling involves systematically collecting samples from predetermined points in the field. None of the existing soil sampling practices has been recognized as the most effective (Wollenhaupt et al. 1997).

Another method to map a field's soil properties is the use of on-the-go sensors that have the potential to provide benefits from the increased density of measurements at a relatively low cost. These sensors can be either combined with a GNSS receiver and produce maps of soil properties or they can be used as real-time sensors where the output of the sensor is used immediately for variable-rate application of fertilizers, lime and manure (Fig. 2.1).

[3] http://www.precisionagriculture.com.au/topography-and-drainage.php

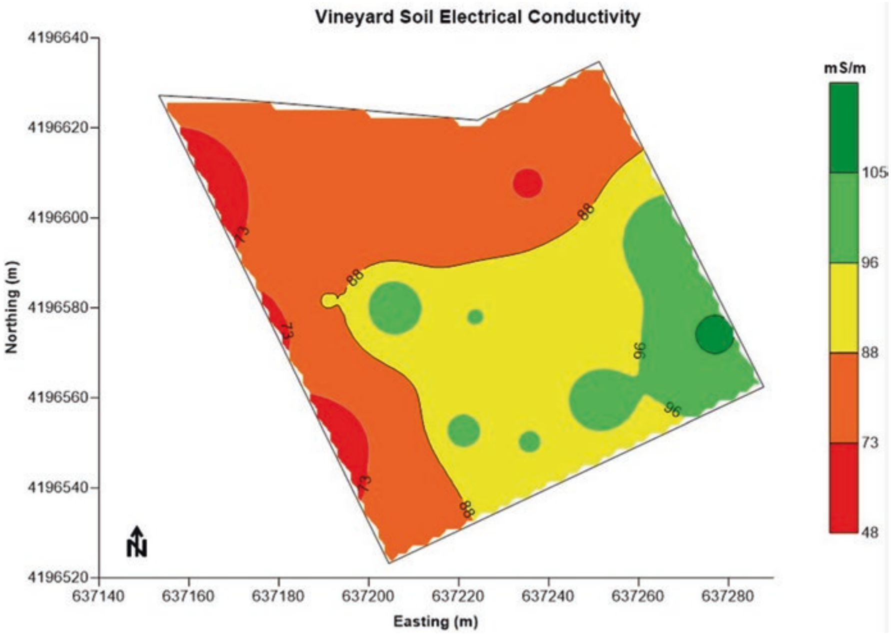

Fig. 2.1 Soil electrical conductivity (ECa) map (Source: Fountas et al. 2014)

There are different kinds of on-the-go soil sensors which can indicate different agronomic soil properties (Adamchuk et al. 2004; Adamchuk and Viscarra Rossel 2014):

- Electrical and electromagnetic sensors measure electrical resistivity or conductivity, capacitance or inductance affected by the composition of the soil. The most common instruments used in research and practice are the EM38 (Geonics, Canada) and the VERIS (VERISTech, USA).
- Mole gamma radiometer (The Soil Company, Groningen, The Netherlands) for predicting clay percent and CEC (cation exchange capacity) of soil.
- Optical and radiometric sensors use electromagnetic waves to detect the level of energy absorbed or reflected by soil particles.
- Mechanical sensors measure forces resulting from a tool engaged with the soil.
- Acoustic sensors quantify the sound produced by a tool interacting with the soil (ex. horizontal penetrometers).
- Pneumatic sensors assess the ability to inject air into the soil.
- Electrochemical sensors use ion-selective membranes that produce a voltage output in response to the activity of selected ions (H^+, K^+, NO_3^-, Na^+, etc.)

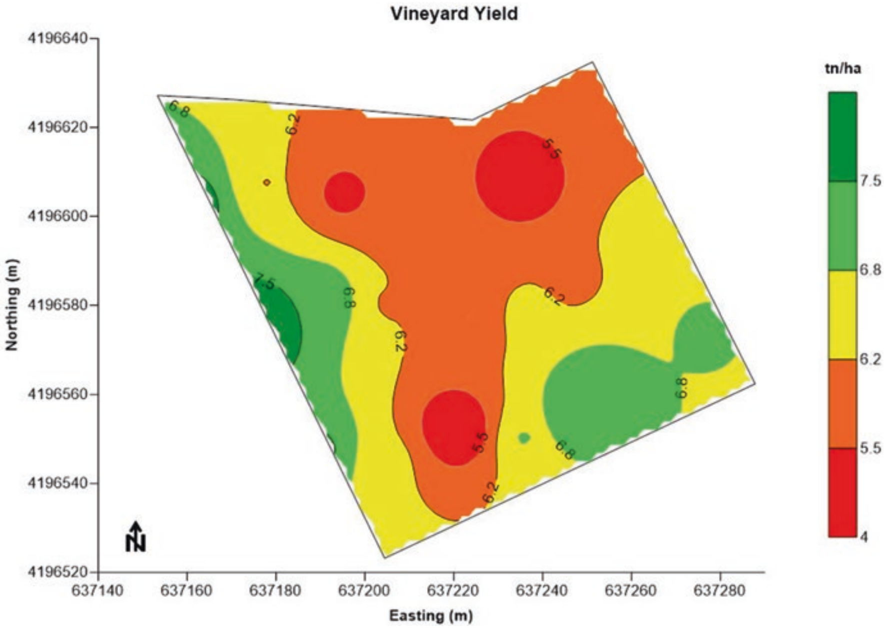

Fig. 2.2 Yield maps (Source: Fountas et al. 2014)

2.2.2.3 Yield Mapping

Yield mapping or yield monitoring is a technique in agriculture of using GNSS data to analyse variables such as crop yield and moisture content in a given field (Fig. 2.2). The components of a grain yield mapping system include a grain flow sensor that measures grain volume, a grain moisture sensor that quantifies moisture variation, a grain elevator speed sensor that measures grain speed to calculate grain mass, a GNSS antenna that geo-references grain measurements, a header position sensor that initiates grain measurement when the header is lowered and a travel speed sensor that provides the distance that the harvester has covered during a certain logging interval.

There are many types of grain sensors that are commercially available, such as a paddle wheel volume flow sensor, momentum plate sensor, gamma ray sensor, strain gauge based impact sensors, infrared sensor. Other yield sensors are also found in literature that are not commercially available, such as pivoted auger, piezo-film strips, capacitive sensor, ultrasonic sensor, elevator based flow sensor, X-ray techniques.

Yield Monitor Display with a GNSS Receiver (Georeference and Record Data)

It is a tablet-type screen in the harvester cabin combined with a processor, data inputs and storage capabilities that allows the operator to import filed information, calibration functions, visual sampling display of the yield and moisture (Whelan and Taylor 2013).

2.2.3 Recording of Environmental Parameters

2.2.3.1 Camera Based Imaging

RGB Cameras

Red, Green and Blue (RGB) cameras combine the colours red, green and blue to depict the range of colours that exist in the environment and in the agricultural fields. There is a series of measurements and correlations that RGB images can be used for. Vollmann et al. (2011) used a digital camera Sony DSC F707 (Sony Corp., Tokyo, Japan) to study the phenotype of soybean varieties. Through the use of digital image analysis, a significant correlation of the red, green and blue of digital images with the protein content of soybean plants was found. Thorp and Dierig (2011) used the camera EOS Digital Rebel XT (Canon Inc., New York, USA) for counting the flowers and the whole course of flowering in *Lesquerella fendleri* (Fendler's bladderpod). Wang and Li (2014) used an RGB camera of a Kinect sensor (Microsoft Inc., Seattle, USA) to measure the diameter of two varieties of onions.

LiDAR Sensors

LiDAR sensors (Light Detection and Ranging) are instruments that measure the distance from the target by laser. This technology has been used to study the phenotypic variation by creating three-dimensional models of plants. The principle of LiDAR devices is that they send rapid pulses of laser light to a surface and a sensor on the instrument measures the amount of time it takes for each pulse to bounce back. As the velocity of light is known, the LiDAR devices can calculate the distance between them and the target with high accuracy. When LiDAR is used as a ground sensor, it is required to have a GNSS receiver for the location of the device. As for airborne LiDAR devices, things become more complex when it is required that the moving height, location and orientation of the device are known to determine the position of the laser pulse at the time of sending and the time of return. Generally, there are two types of LiDAR detection methods. "Direct energy detection", also known as incoherent, which is principally an amplitude measurement and "Coherent detection" that are best for Doppler[4] or phase sensitive measurements and generally use optical heterodyne detection. This allows them to operate at much lower power, but has the expense of more complex transceiver requirements. They consist of a laser that produces the beam, a scanner and optics that scan the beam, a photodetector and receiver to receive the beam after its reflection and GNSS receiver with horizontal and vertical accuracies of <3 cm and <15 cm, respectively, to obtain the location of the sensor (Reutebuch et al. 2003).

LiDAR can be used in agricultural applications, such as the creation of topographical maps, slope and sun exposure of the farm. Another application of LiDAR is crop mapping in orchards and vineyards. Foliage growth can be measured to determine if pruning or any other agricultural practice is required, detect variations in fruit

[4] The Doppler Effect is the difference between the observed frequency and the emitted frequency of a wave for an observer moving relative to the source of the waves.

production or perform automated tree counts. Also tree area index (TAI) and leaf area index (LAI) can be estimated with ground LiDAR sensors (Arnó et al. 2013, 2015). For vehicle-based determination of crop biomass, commercially available laser scanners have been analysed and tested to measure aboveground biomass in oilseed rape, winter rye, winter wheat, oats and grassland (Ehlert et al. 2010). Laser scanners are also used for crop height detection (Hoffmeister et al. 2016). Paulus et al. (2014) used the sensor ScanWorks v5 Perceptron (Hexagon Metrology Inc., Plymouth, USA) to create three-dimensional models of barley plants and organs. In this way they measured leaf area, stem height, plant height and thickness of the plant. Hosoi and Omasa (2012) used the sensor TDS-130 L (Pulstec Industrial Co., Ltd., Japan) to calculate the density of winter wheat plants at different growth stages with good results ($r^2 = 0.95$). From the same experiment they calculated the biomass of plant organs (with $r^2 = 0.94$–0.96). Hosoi and Omasa (2012) conducted the same experiment in rice plants. The biomass of the organs of rice was calculated by a LiDAR sensor showing a strong correlation with the direct measurement ($r^2 = 0.94$–0.99). Rosell et al. (2009) used the sensor LIDAR SICK LMS 200 (SICK AG, Waldkirch, Germany) and they were able to reproduce three-dimensional models of fruit trees such as pear, apple, orange and tangerine in real orchards. The correlation showed that three-dimensional models were strongly correlated with the real ones (up to $r^2 = 0.976$). They say that the three-dimensional models can be used for the calculation of height, volume, thickness, leaf area index of the tree and for other traits.

ToF (IR) Cameras

Time of Flight (ToF) cameras have the ability to produce shaped and incoherent infrared light in the space. Smart sensors at pixels of the camera record the reflected light and calculate the time to return. In this way a three-dimensional model is produced (Verdu et al. 2013). Nakarmi and Tang (2012) used the ToF camera SwissRanger SR4000 (Mesa Imaging AG, Zurich, Switzerland) to measure the distance between the corn plants in a row. Their method showed strong correlation ($r^2 = 0.95$) with the actual distance of maize plants on the row. Wang and Li (2014) calculated the diameter and volume of onions using the Kinect sensor (Microsoft Inc., Seattle, USA) with accuracy of measurements of around 96%. Chene et al. (2012) used the same sensor to measure the curvature, the morphology and the leaf orientation of a rosebush.

Light Curtains

Light curtains are a new system that is used to study the phenotypic traits. The system consists of a couple of bars which are placed in parallel. One bar emits light beams that end up at the other parallel bar. In this way the system records if the light beams are blocked by an object. Fanourakis et al. (2014) used light curtains (INFRASCAN 5000, Sitronic GmbH, Austria) to measure the height and leaf area of corn, tomato, barley and oilseed rape plants. Montes et al. (2011) used the light curtains KONTURflex (Leuze electronic GmbH + Co.KG, Owen, Germany) to measure biomass of 10 hybrids and 10 varieties of corn. They found a strong correlation between the biomass and the results light curtains gave ($r^2 = 0.82$–0.87).

Multi- or Hyper-Spectral Cameras
Multispectral cameras are cameras that can photograph the environment with a limited number of spectra in the visible and infrared spectrum. Thus, the normalized difference vegetation index (NDVI) can be produced by this method, which can be used to calculate biomass, distinguish different plant species, maturation of plant, nutrient status, efficiency of photosynthesis or water content and to detect diseases and insect pests. Hyperspectral cameras, as opposed to multispectral cameras, can produce images at hundreds of positions of the electromagnetic spectrum. As a result, hyperspectral cameras can produce a larger number of vegetation indices than multispectral ones. Liu et al. (2014) used the VideometerLab (Videometer A/S, Horsholm, Denmark) to calculate quality properties such as consistency, concentration of sugars and ripening in strawberries. They found a correlation of $r = 0.94$ for the consistency of strawberry and $r = 0.83$ for the concentration of sugars in relation to the actual values. Zarco-Tejada et al. (2013a) used the hyperspectral camera Micro-Hyperspec VNIR (Headwall Photonics, MA, USA), which was adapted onto a UAV to calculate carotenoids in vineyards with very good correlation ($r^2 = 0.84$). Berni et al. (2009) used multispectral camera MCA-6 (Tetracam Inc., CA, USA) in an unmanned aerial vehicle (UAV) to produce vegetation indices in corn plants and olive trees. Calderon et al. (2013) used a multispectral (MCA-6, Tetracam Inc., California, USA) and a hyperspectral camera (Micro-Hyperspec VNIR, Headwall Photonics, MA, USA), which were mounted on a UAV to locate olives infected by the pathogen *Verticillium* wilt through various vegetation indices.

Thermal Cameras
Thermal cameras have the ability to generate images related to the ambient temperature. This is because they work in the long wavelength infrared (to 14,000 nm) resulting in perceiving the radiation emitted by the target because of its heat. Thermal cameras have been used to study the phenotypic variance for predicting water stress of plants, to detect diseases and pathogens and for the ripening of fruits. Zarco-Tejada et al. (2013b) used a thermal camera (Miricle 307, Thermoteknix Systems Ltd., Cambridge, UK) to study the water stress of vines through the index CWSI and found a strong correlation with the water potential of the leaves ($r = 0.95$). Benavente et al. (2013) used the thermal camera FLIR SC305 (Inframetrics, FLIR Systems Inc., OR, USA) to assess the durability of various genotypes of *Brachypodium distachyon* and *Brachypodium hybridum* in drought tolerance. They found that the genotypes of the species *Brachypodium Hybridum* showed greater resilience to drought, which they related to the better functioning of stomata of this species to water stress in relation to the *Brachypodium Distachyon* species.

2.2.3.2 Normalized Difference Vegetation Index (NDVI)

The most important application for precision agriculture is measuring vegetation indices and more particularly NDVI (Fig. 2.3). The NDVI is a numerical index based on the visible and near-infrared bands of the electromagnetic spectrum that

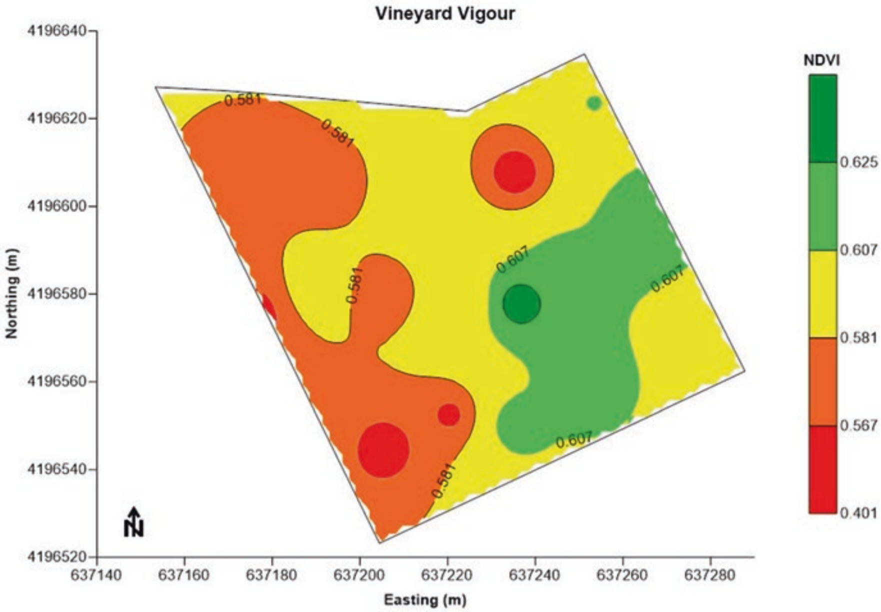

Fig. 2.3 NDVI map (Fountas et al. 2014)

indicates if a target being observed contains live green vegetation or not; it takes values between 0 and 1.

There are many applications of NDVI for either agriculture or environmental solutions. It can be used to estimate crop yields, percentage ground cover, photosynthetic activity of the plant, surface water, leaf area index, the amount of biomass, pasture performance, rangeland carrying capacities, etc. The NDVI was first used in 1973 by Rouse et al. (1973) from the Remote Sensing Centre of Texas A&M University.

There are several commercial products that can be used for NDVI measurements on ground (active) sensors based on the principle of light emission. More particularly, they emit light towards the plant canopy in visible (VIS) and near infra-red (NIR) light that is either reflected, transmitted or absorbed. According to the plant characteristics, the percentage of each of the three behaviours of the light is differentiated (Inman et al. 2005).

On-the-go NDVI ground sensors can be combined with either a GNSS receiver to produce maps of NDVI or they can be used as real-time sensors where the output of the sensor is used immediately for variable-rate fertilizer or spraying applications.

Spectral Sensors

Spectral sensors are instruments that can sense the amount of light reflecting from objects, which they convert to an electrical signal. They measure light in the visible (400–700 nm) and infrared spectrum (700–2500 nm). Spectral sensors are used widely in agriculture because it has been found that these measurements are related to a plant's physiology and development. These sensors may be either passive or active. The passive spectral sensors use sunlight, whereas active sensors have light sources that generate radiation for conducting the measurements. For this reason, the active spectral sensors are less dependent on weather conditions. There are many types of spectral sensors of both categories such as spectrometers, spectroradiometers and canopy sensors (Erdle et al. 2011). Feng et al. (2008) used the spectrometer ASD Field Spec Pro (Analytical Spectral Devices, CO, USA) for the measurement of nitrogen content of leaves of winter wheat varieties. Andrade-Sanchez et al. (2014) used the active canopy sensor Crop Circle ACS-470 (Holland Scientific, NE, USA) to evaluate vigour of 25 cotton varieties. Ramirez et al. (2014) used the spectral instrument SPAD-502 (Konica Minolta, Osaka, Japan) for measuring chlorophyll to assess the resistance of a variety of potato in drought tolerance.

Fluorescence Sensors
Fluorescence induced by ultraviolet radiation has been used as a non-destructive method for estimating plants status. Specifically, the fluorescence of plants caused by UV radiation has been used for the identification of species of plants, for plant growth, for lack of nutrients in plants, for lack of water, for temperature effects on plants and for detecting attacks by pathogens of plants (Cerovic et al. 1999). Thus, various types of sensors have been developed to study fluorescence of plants. Christen et al. (2007) used the fluorometer Handy-PEA (Handy-Plant Efficiency Analyser, Hansatech Instruments, Norfolk, UK) for the detection of *Esca* disease in vines and the results were compared to water stress. Thoren et al. (2010) used the sensor N-detector (Planto GmbH, Germany) to study the fluorescence caused by different common wheat plant fertilizers. Ghozlen et al. (2010) used the optical fluorescence sensor Multiplex (FORCE-A, Orsay, France) to measure the content of anthocyanins in the red grape variety Champagne by a non-destructive method.

2.2.3.3 Soil Moisture Sensors

Information on the spatial and temporal evolution of soil moisture is of great importance for the use of soils and for vegetation, in particular where the water resources are scarce. There are several reliable ways to measure soil moisture. Various *in situ* sensors are available and suitable for precise and reliable measurement of soil moisture (Munoz-Carpena 2017).

Frequency Domain Reflectometry (FDR) Sensors (Capacitance)
When a capacitor uses the soil as a dielectric, its electrical capacitance depends on the soil water content. Such capacitors can be made of metal plates or rods. If this capacitor type is connected with an oscillator to form an electrical circuit, any change in the circuit's operating frequency indicates changes in soil moisture. This is the working principle of capacitance and frequency domain reflectometry (FDR) sensors.

These sensors have probes that consist of two or more electrodes, both inserted into the soil. If an electrical field is applied, the oscillating circuit is completed by the formation of the dielectric of the capacitor by the soil around the electrodes. It is possible to use an access tube that allows installation of multiple sensors at different soil depths. Soil-specific calibration of these sensors is recommended because of their low operating frequency (below 100 MHz), which affects the bulk permittivity of soil minerals and properties such as temperature, salinity, bulk density and clay content may change the measurement.

Therefore, these sensors are accurate after soil-specific calibration, they can read in high salinity levels, they offer better resolution than TDR (see below), can be connected to conventional loggers, are flexible in probe design and are relatively inexpensive. However, their sensing sphere of influence is relatively small, it is extremely critical to have good contact between these sensors and soil, careful installation is necessary to avoid air gaps. They tend to have greater sensitivity to temperature, bulk density, clay content and air gaps than TDR and they require soil-specific calibration.

Time-Domain Reflectometry (TDR) Sensors

These sensors are based on measuring the time it takes for an electromagnetic pulse (wave) to propagate along a transmission line surrounded by the soil. Therefore, TDR sensors produce a series of precisely timed electrical pulses with a wide range of high frequencies, that travel along a transmission line that is built with a coaxial cable and a probe. In contrast to FDR sensors, the high frequency of operation makes measurements less dependent on soil-specific properties such as texture, salinity or temperature. The TDR sensors usually have probes consisting of 2–3 parallel metal rods that are inserted into the soil acting as waveguides, while they have a device for measuring and digitizing the energy (voltage) level of the transmission line at intervals of around 100 picoseconds. As the electromagnetic pulse travels along the transmission line, it faces a discontinuity (i.e. probe-waveguides surrounded by soil) and a part of the pulse is reflected, producing a change in the energy level of the transmission line.

These sensors are accurate, they do not require soil specific-calibration (with minor exceptions), they can easily be expanded by multiplexing, they have minimal soil disturbance and they can provide simultaneous measurements of soil electrical conductivity. However, they are relatively expensive because of the complex electronics, they are not good for highly saline conditions or in strongly conductive heavy clay soils, they need to be calibrated for some soil types (with large amounts of bound water, with large organic matter content, volcanic soil, and so on) and they have a relatively small sensing volume.

Amplitude Domain Reflectometry (Impedance)

The working principle of these sensors is based on the reflection of a part of the energy transmitted (electromagnetic wave travelling along a transmission line) back to the transmitter when the wave reaches a section with different impedance. A voltage standing wave along the transmission line is produced when the reflected wave interacts with the incident wave. These sensors minimize the effect of soil electrical conductivity by choosing a signal frequency so that soil water content can be estimated from the soil or probe impedance.

An electromagnetic wave at a fixed frequency is generated by an oscillator to be applied to a coaxial transmission line that continues in the soil through parallel metal rods that have an electrical shield in the outer part and a central signal rod.

The impedance of this rod arrangement depends on the dielectric constant of the soil between the rods.

These sensors are accurate with soil-specific calibration, enable measurements in very saline conditions, produce minimal soil disturbance, can be connected to conventional loggers, are inexpensive, are not affected by temperature and can estimate soil bulk density. However, they have a small sensing volume, therefore, it is recommended to calibrate them for reliable measurements and their measurements are affected by air gaps, stones or water channeled directly on to the probe rods.

Phase Transmission

The principle of these sensors is based on the phase shift that an electromagnetic wave at a fixed frequency will express in relation to its phase at the origin after travelling a fixed distance. The properties that produce this phase shift are the length of travel along the transmission line, the frequency and the velocity of propagation. Therefore, knowing that velocity of propagation is related to soil moisture content, when a fixed frequency is used and the length of travel is stable, soil water content can be determined by this phase shift. The probe of these sensors consists of two open concentric metal rings to apply phase measuring electronics at the beginning and end of the wave guides.

These sensors are very accurate with soil-specific calibration, they have large soil sensing volume, they can be connected to conventional data loggers and they are inexpensive. However, they cause considerable soil disturbance during installation because of the concentric rings sensor configuration, require soil-specific calibration, are sensitive to salinity levels, have reduced precision because the pulse generated gets distorted during transmission and it needs to be installed permanently in the field.

Time Domain Transmission

These sensors measure the time that an electromagnetic pulse requires to propagate along a transmission line (one-way). They are similar to TDR sensors, but in this case an electrical connection at the beginning and end of the transmission line is needed. The probe consists of bent metal rods to achieve the insertion at the beginning and end of the transmission line in the electronic block.

These sensors are accurate, have large sensing soil volume, can be connected to conventional loggers and are inexpensive. However, they have reduced precision because the pulse generated is distorted during transmission, it disturbs the soil during installation and need to be installed permanently in the field.

Tensiometers

Tensiometers are based on the principle of water equilibrium between the soil solution and the water content of a sealed water-filled tube installed in the soil through a permeable and saturated porous material. This equilibrium results from achieving the same pressure potential for both the water in the tube and the water held in the soil matrix. Hence, the soil water matric potential is equivalent to the vacuum or suction created inside the tube. These sensors consist of a sealed water-filled plastic tube with a ceramic cup at one end and a negative pressure gauge at the other. There are many shapes and sizes of the ceramic cup and the accuracy can vary depending on the gauge or transducer used. Tensiometers for fine soil have a measurement range between 0–80 kPa but for coarse soil there are low-tension versions (0–40 kPa).

Tensiometers provide direct readings up to a 10 cm measurement sphere radius, continuous is reading possible when a pressure transducer is used, avoid electronics and power consumption, are well-suited for high frequency sampling or irrigation schedules, need minimal skill for maintenance, not affected by soil salinity and are inexpensive. However, they have limited soil suction range (<100 kPa), a relatively slow response time, require intimate contact with soil around the ceramic cup for consistent readings and require frequent maintenance (refilling) to keep the tube full of water, especially in hot dry weather.

Gypsum Blocks

These sensors determine soil moisture by measuring the resistance between two electrodes inside the gypsum blocks, which is proportional to water content of the block (low resistance when water content gets smaller). Gypsum blocks are porous, so their water content is related to the moisture of the soil that in which it is being installed. The condition for reliable measurements is optimal contact between sensor and soil. The gypsum blocks are buried permanently in the soil at the desired depth with a life expectancy of 3 to 5 years (depending on the type of soil). The meter is practical and is constructed of sturdy synthetic material. It has a measuring range of 0–100% for 3–100 kPa of water pressure and is applied in places where a typical tensiometer cannot be used (dry soil). The advantages of these sensors are that they are simple and cheap with a large measurement range, they do not need maintenance and they are well suited to area where the soil becomes dry (where there are trees). The disadvantages are that they have low resolution, they react quickly on wetting, but are slow on drying, they are temperature dependent and they are not frost and salt resistant. In addition, the fact that gypsum dissolves over time in different ways for each sensor installed in a field = means that it does not maintain the quality of measurement over time and from site to site.

Granular Matrix Sensors

Water conditions inside granular matrix sensors change with corresponding variation in water conditions in the soil.[5] These changes within the sensor are reflected by differences in electrical resistance between two electrodes imbedded in the sensor. Resistance between the electrodes decreases with increasing soil water. These sensors have a porous ceramic external shell with an internal matrix structure that contains two electrodes. An internal cylindrical gypsum tablet buffers against soil salinity levels that occur in some types of irrigated soil. A synthetic porous membrane is surrounded by a stainless steel casing or sleeve with holes. In this case there is a transmission material that is used to respond to soil wetting and drying cycles.

These sensors are simple and inexpensive; they do not dissolve in the soil over time like gypsum blocks and they do not need maintenance. However, they have low resolution and a slow reaction time, they are temperature dependent and if they dry out they need to be uninstalled, re-saturated and installed again.

[5] http://extensionpublications.unl.edu/assets/pdf/ec783.pdf

Heat Dissipation Sensors
These sensors are based on the fact that dry materials heat up faster than wet materials because of heat dissipation produced by the thermal conductivity of water. Therefore, increased water content in a porous material increases in proportion to heat flow. A thermal heat probe has a porous block combined with a heat source and an accurate temperature sensor. The heat source works for a few seconds and the temperature sensor measures the temperature before and after heating to calculate the difference. These sensors are sold with the calibrated relation between the measured change in temperature and soil water potential.

These sensors have a wide measurement range, need no maintenance, have a 10-cm measurement cylinder radius, can give continuous reading and are not affected by salinity because measurements are based on thermal conductivity. However, they need a sophisticated controller or data logger to control heating and measurement operations, have a slow reaction time (do not work well in sandy soil where water drains more quickly than the instrument can equilibrate to) and have fairly large power consumption for frequent readings.

2.2.4 Machines and Their Properties

2.2.4.1 Travel Speed Sensor

This sensor determines the distance the tractor or combine harvester travels. Sometimes travel speed is measured with a GNSS receiver or a radar or ultrasonic sensor. An average radar or ultrasonic sensor speed sensor has an accuracy $<\pm 5\%$ for speeds up to 3 km $hour^{-1}$ and $<\pm 3\%$ for larger speeds.[6]

2.2.4.2 Tractor Sensing Systems with ISOBUS

From the early 1980s with the development of microcomputers, the first attempts to record tractor performance data started by measuring draft forces, velocity, fuel consumption, engine load and wheel slip values (Harter and Kaufman 1979; Grevis-James et al. 1983). The technological innovations of on-board tractor performance monitoring systems and the recent advances in tractor technology enable the acquisition of tractor and implementation status. This has been achieved through the agricultural machinery industry protocols SAE J1939 (Society of Automotive Engineers 1995) and ISO 11783 (or ISOBUS) and provide useful information to optimize overall field productivity (Scarlett 2001; Backman et al. 2013). Combined with the GNSS, the system could be used for spatial mapping of tractor–implement field performances (Taylor et al. 2002; Yahya et al. 2009). Moreover, the ability to monitor and collect tractor and implement performance data can benefit management decisions and lead to fuel savings (Tsiropoulos et al. 2015).

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[6] http://www.dickey-john.com/product/radar-ii/

Information-to-action decision-making processes, as well as precision agriculture applications, require sensors for on-the-go data collection of crop and soil variation(e.g. soil moisture content, NDVI, crop density, and so on). The ISOBUS protocol can play an important role in the development of precision agriculture and helps information to be exchanged and stored more efficiently between sensors, processors, controllers and software packages from different manufacturers within the same tractor or vehicle (Stafford 2000).

From 2001 on, the ISOBUS standard matured and became the international standard that was adopted by the agricultural machinery industry. Tens of thousands of ISOBUS implements, tractors and components were sold successfully worldwide, but despite this large number there were also 'incompatibility problems' to be solved. Farmers or contractors that purchased equipment based on this standard were often promised that the investment in ISOBUS was a secure investment and would give a "Plug and Play" solution for all their needs. However, after a few years in practice this promise appeared to be very different. While the industry, together with DLG (the only ISOBUS test entity in the world), focused on the technical aspects for testing and certifying components, the practical implementations in the field appeared to be problematic sometimes leading to situations where the end-customer simply did not have a working solution between cross-branded equipment (Vlugt 2013).

Another basic problem is the challenge to integrate the data of these new technologies into a coherent farm management system. The main problem arises from the heterogeneous nature of these data resulting in a variety of data formats and interfaces. Incompatibility of different data formats is usually a fundamental problem and considerable manual effort is required just to convert data from one format to another. Therefore, there is an imperative need for continuous data exchange, either between the farm's computer and the computing devices mounted on the farm machinery or between the farm's computer and the external farming systems such as contractors, suppliers and advisory services, and so on. A research team at Iowa State University has developed a data logging platform (CyCAN), a standalone ECU aimed specifically at quantifying the key properties of agricultural machinery (Darr 2012). The CyCAN data logger connects directly to the ISOBUS port in the tractor cab and provides direct access to all available CAN Bus information. Steinberger et al. (2009) presented a prototype implementation of an agricultural process-data service that enables flexible data networking based on the farming standard without much complexity for the farmers or farm managers. The data are recorded through the ISOBUS port and transferred to a server where data are analysed and aggregated to completed jobs and can be requested for further use by a web portal and a web service interface. Tsiropoulos et al. (2013) presented a management information system for spatial analysis of tractor-implement draft forces. The system can record and combine data in real-time from ISOBUS, CAN Bus and various types of analog and digital sensors (fuel meters, load-cells, etc.). The data can be transferred in real time to the system database and the results are analysed spatially. The system was expanded (Gravalos et al. 2014), and the measurements with soil moisture sensors were transferred to the management system with remote terminal units and a wireless gateway installed into tractor cabin.

In farming businesses, however, data exchange requirements are not fixed and changes occur frequently. The data exchange techniques usually lack flexibility with regard to efficient management of required changes, and the system often needs manual maintenance. The low-level hand held data conversion from one format to another usually requires a lot of manual work, which causes problems and is confusing for ordinary farmers. Iftikhar and Pedersen (2011) proposed an easy-to-use and flexible solution for ISOBUS based bi-directional data exchange as well as efficient requirements weth changes in management. The system uses an XML-based graphical user interface that generates high-level data exchange specifications that can be used by farmers or farm managers. The solution is expected to work well in low-bandwidth and partially disconnected environments, and where the data exchange requirements are not fixed and changes occur frequently, as in the farming business. The authors also pointed out the future need to implement a rule-based tool for bi-directional exchange of data that will provide the underlying rules of an interactive procedure for generating high-level data exchange specifications with ease-of-use.

2.2.4.3 Unmanned Aerial Vehicles (UAVs)

An unmanned aerial vehicle (UAV), commonly known as a “drone” is an aircraft without a human pilot aboard. The flight of UAVs may be controlled either autonomously by on-board computers or by the remote control of a pilot on the ground or in another vehicle. There are two main platforms for UAVs: fixed wing and multi-rotor.

A fixed wing platform has the advantage of covering large areas efficiently, whereas a multirotor is able to remain very stable in challenging conditions with large loads. The UAVs are equipped with a GNSS receiver that is used primarily for location information for the autopilot and of course for the data recorded to be linked to its spatial position. In addition, UAVs have autopilots in order to be programmed to fly over a certain area and record the desired data. In many cases, UAVs communicate with a ground control station (GCS) by radio link. The GCS is usually just a laptop computer with software such as Mission Planner. The same software is also used to set the flight paths for the UAV missions. Many UAVs are equipped with a u-blox GNSS receiver or similar, which is compact and provides 1 m and 2 m vertical and horizontal accuracy, respectively.[7] These receivers also include an inertial measurement unit (IMU) for detecting changes in pitch, roll and yaw and for enabling dead reckoning capabilities. These systems are affordable and are accurate for most situations.

The UAVs already offer new alternatives for agriculture and other applications in which high spatial resolution imagery delivered in near-real time is needed (Herwitz et al. 2004). Diagnostic information derived from images recorded from on-board sensors such as biomass, leaf area index (LAI), disease and water stress can thus inform decision-making in crop management, yield forecasting and environmental protection (Zhang and Kovacs 2012). When imaging sensors are used with UAVs,

[7] http://www.dji.com

overlapping images are required to achieve full cover of the field under investigation to produce an ortho-mosaiced image.

Comparison with manned aircraft:

- UAVs can be flown in dangerous situations (no pilot or scientist on board).
- UAVs can fly for long durations, on dull missions such as mapping or for diurnal measurements without inconveniencing pilot or crew.
- UAVs with long endurance can remain still during an emergency, enabling long-term awareness of a situation.
- UAVs with a long range capability can be launched from or flown to a remote location.
- UAVs with high altitude capability can fly safely above theweather and above air traffic.

Comparison with satellites:

- UAV pictures are not disturbed by clouds because their flying height is low.
- UAVs can fly to precisely selected locations at precisely selected times.
- UAVs can be tasked to remain over arbitrary targets for long durations.
- UAVs can carry a variety of interchangeable high resolution imaging instruments.
- UAVs are recoverable for maintenance and upgrades of sensor and communication systems.

2.2.4.4 Unmanned Ground Vehicles (UGVs)

Basic characteristics for prototype robots are their light weight, small size and energetic autonomy (Blackmore 2007). Light weight means that the vehicle requires less energy and induces less soil compaction, and they must be small for safety reasons, to achieve greater precision on their tasks and to have more manoeuvrability.

Mechanical design of the prototypes depends on its main tasks or developers' goals. The UGVs can run on tracks or wheels. Even though tracks have many advantages compared to wheels with zero turn radius, better flotation, smoother ride on rough surfaces, greater efficiency over a wider range of soil conditions and more stability on hillsides, their main disadvantages for use on robots are the motion control and the pose estimation (Martínez et al. 2005). Most researchers use wheels on their prototypes because tracks require the use of complex dynamics (or effective kinematics approximation), combined with their higher price and higher cost of maintenance. To achieve maximum manoeuvrability, which is very important for autonomous vehicles, 4-wheel drive and steering (4WD/4WS) is commonly used (*BoniRob*, Ruckelshausen et al. 2009, *HortiBot*, Jorgensen et al. 2007, *Roboturk*, Tekin et al. 2013, *Zeus*, Tressos 2011, *API*, Danish Technical University 2006, *AgRover*, Tu 2013). To be able to work with different types of crop and for maximum flexibility, many prototypes have variable track width and height configuration (Bonirob, Zeus, API, AgRover). This is achieved with the use of fixed wheels on arms or legs that can move separately. The problem with this type of approach is the vehicle's centre of gravity, especially when the height increases, which make prototypes unstable on slopes. To reduce stability problems on slopes, HortiBot and Roboturk have very low centres of gravity; HortiBot can work on slopes up to 40°. One other interesting approach for working on slopes is AgRover, which has a self-levelling pneumatic system for maintaining the platform flat and stable. In addition, there are some totally different approaches based on needs such as the Agricultural Mobile Robot (Tabile et al. 2011), which was constructed to operate in crops up to 1.8 m in height with variable intra-row spacing. Most of prototype chassis are made from steel for greater durability (BoniRob, HortiBot, Roboturk, Zeus) or aluminum (API, AgRover, SlugBot) for less weight. Almost all prototypes are lightweight starting from 100 kg (*Dionysus*, Hau and Cereteth 2013) with very few prototypes over 400 kg (e.g. Roboturk).

Power sources that are commonly used on prototypes are petrol engines (HortiBot, Agrobot, Dionysus) or electric motors (BoniRob, Roboturk, Zeus, AgRover). Electric motors are environmentally friendly, but petrol engines have more power. For that reason the selection of power source depends on the tasks, use and design. Some researchers have created hybrid prototypes (Halmstad weeding robot, Åstrand and Baerveldt 2002), but generally this approach is being rejected because of the increase in total prototype weight. A unique and interesting project was the SlugBot project (Kelly and Melhuish 2001) which aimed to create a robot predator developed to investigate issues of energy autonomy, by harvesting slugs and putting them into a digester to power the robot. From all agricultural attempts to create robots, it was shown that energy efficiency can be improved by constructing the robots with light but strong materials such as carbon fibre and aluminium, and by using decentralised modern low power controllers and electronics where possible (instead of a single high speed central processor).

2.2.5 Data Analysis and Evaluation Technologies

These SFTs are used for analysis of the data obtained from the data acquisition SFTs and are categorised as follows:

- Management zone delineation
- Decision-support systems (DSS)
- Farm management information systems (FMIS)

2.2.5.1 Management Zone Delineation

All data collected have to be analysed and interpreted if a meaning is to be drawn from them. There are generally too many data and appropriate methods that exist or have to be developed for the analysis need to be applied. Simple exploratory (descriptive) statistics can give a first impression of the values, their spread, the range and the distribution. Geostatistics, based on what is called 'the theory of regionalised variables', is basically a probabilistic method of spatial interpolation. Final construction of the map at the local level is made possible from estimated values based on the variogram by kriging; the variogram describes the structure of the spatial variation of the sampled data. This type of information, which can be obtained for different properties and for successive years, opens new and interesting possibilities in agronomic crop analysis and management (Arnó et al. 2009).

Variograms are used to assess the spatial variation of the measured values. For each property semivariances are plotted against the distance (lag) between the points. A model is fitted to the experimental variogram, which is the theoretical variogram. Maps covering the whole field can be produced and indicate the variation in the properties. There are several methods of data analysis, although that there is not a clear way to compare the maps produced. This is still based on an optical impression for comparison of the maps. Correlations between parts of the field with different peoperties can be carried out to assess their relations. Kitchen et al. (2005) tried to delineate productivity management zones based on soil electrical conductivity (ECa), elevation and yield maps by management zone analysis (MZA). They used the agreement between pixel in zones to compare the zones based on different variables. Tagarakis et al. (2011) have applied this methodology to precision viticulture with encouraging results.

The analysis of the data aims to define parts of the field with common characteristics that can be managed separately. These are the management zones. Delineation of management zones should create homogeneous parts of the field where inputs or other practices can be applied in the same way. The management zones should be large enough to permit variable-rate application of inputs, but small enough to be homogeneous.

2.2.5.2 Decision-Support Systems

A decision-support system (DSS) is a computer-based system that supports business decisions. In agriculture it refers to the decisions taken by the farmer for farm management. Precision agriculture is connected directly to decision making by the farmer. It can be described as an example of the conversion of data into decisions (McBratney et al. 2005). It is quite true that research has not been successful in developing DSS at the moment. The lack of functional tools for decision-taking explains, to certain extent, the difficulty for a rapid and widespread adoption of PA. Arnó et al. (2009) pointed out that the development of DSS in PA undoubtedly remains a pending assignment. Kitchen et al. (2005) indicated that more precise crop models in PA might help in the development of successful DSS. The inadequate development of control and decision support systems for implementing PA decisions has been identified as a major stumbling block to the adoption of PA (McBratney et al. 2005).

2.2.5.3 Farm Management Information Systems (FMIS)

Agriculture has become very complex and farmers using Smart Farming Technologies (SFTs) acquire a vast amount of data that have to analyse and derive the best decisions for their crop management. The key to success is access to timely information and elaborated decision making. Decision making is an important aspect in farm management and has been studied by numerous authors and with different applications (i.e. Sørensen 1999; Fountas et al. 2006). Farm Management Information Systems (FMIS) is defined as a planned system for collecting, processing, storing, and disseminating data in the form needed to carry out farm operations and functions (Sørensen et al. 2010). The fundamental components of FMIS include specific farmer-oriented designs, dedicated user interfaces, automated data processing functions, expert knowledge and standardized data communication and scalability. To improve functionality, various management systems, database network structures and software architectures have been proposed, where FMIS have increased in sophistication through the integration of new technologies, such as web-based applications and applications for smart phones and tablets (Nikkila et al. 2010). As agriculture is a complex system it incorporates a number of interactions between farmers, advisors, traders, sellers, governmental bodies, farm machinery, environmental regulations, economic estimations and others. FMIS can cover a large number of functions, such as inventory, calendar, direct sales, site-specific management functions. A set of 10 functions are presented (Table 2.3), modified by the set of functions proposed by Fountas et al. (2015).

There is a large discrepancy between the functions that are provided by research FMIS and their commercial counterparts. Fountas et al. (2015) compared the published FMIS from academic institutes and 141 commercial software and they concluded that academic research tends to analyse more complex systems, capturing new trends involving spatial and temporal management, distributed systems involving internet of things, future internet and web services. Commercial applications tend to focus on solving daily farm tasks with the aim to generate income for the farmers through better resource management and field operations planning. The advances that are needed in the development of FMIS include improvements in technology, adaptation motives, specific new functionalities and greater emphasis on software design governed by usability and human–computer interaction. The diffusion of information management as business innovation in the farming community could benefit from the comprehensive research developed in the last decades on the adoption of ICT and e-commerce among both consumers and small businesses.

The profitability and adoption of FMIS cannot be estimated easily and there is limited research or commercial research available to support this. An adoption study by Lawson et al. (2011) in four EU countries (Denmark, Germany, Finland, Greece) revealed that the benefits from reduced labour costs of introducing advanced FMIS could be related to budgeting procedures, field planning and paperwork for subsidy applications and public authorities. Northern European farmers are inclined to spend more time working with computers than their Southern colleagues, probably because of the more developed and more business-oriented types of farms that exist in Northern Europe. About 30% German, less than 20% Danish and over 20% Finish respondents were positive about the use of computers for documentation when dealing with government agencies. In Germany, the majority of the respondents spent 20 hours per week on inside-office tasks (i.e. time at the computer, for preparation of applications for area subsidy etc.) as well as learning new procedures etc. The 20 weekly hours spent by German respondents is significantly different from the 7, 3 and 1 hours spent, respectively, for Denmark, Finland and Greece. The average of 25% of the inside-office time allocated to field management planning by the German respondents is considerable larger than the 14, 15 and 16% allocated by Greek, Finnish and Danish farmers, respectively. The 3% of the time budget allocated to private tasks in the office by the Greeks is significantly less that of the 14, 11 and 8, respectively, for the Danish, Finnish and German respondents. In Northern European countries, spring time is the most intensive when farmers finalize field plans and fill complex subsidy applications at the same time.

The FMIS could be classified according to the application. There is software available for crop monitoring, for whole-farm management, for precision agriculture only and specialized software for specific applications (scheduling irrigation, spraying prognosis, accurate weather forecasts).

2.2.5.4 Software for Whole Farm Management, Forecasting and Crop Monitoring

In Table 2.4 there are examples of software offered for different purposes. Some software is multi-purpose focusing on whole-farm management in the fields, for precision agriculture applications, inventories, sales, planning and reporting for the single payment scheme. Some other software is dedicated to specific applications, such as for forecasting specific diseases or pests, for irrigation only or for pasture management.

We have to note that these are some examples of software packages in the market. There are many 'start-up' companies that have developed their own software and these also operate as international companies. The purpose of Table 2.4 is to demonstrate the variation in software available in the market and their functions. For more information on clustering of software in agriculture, a review study can be found at Fountas et al. (2015).

2.2.6 Precision Application Technologies

This category of SFTs refers to the technologies that are used to apply the decisions taken (using data analysis & evaluation technologies) after receiving the information on the condition of the farm (using data acquisition technologies). They are divided in:

- Variable-rate application technologies
- Precision irrigation
- Precision weeding
- Machine Guidance

Table 2.3 Farm management Information systems functions

Function title	Function description
Field operations management	Recording of farm activities to help farmer optimize crop production by planning activities and observing the actual execution of planned tasks. Preventive measures may be initiated based on the monitored data.
Best practice (including yield estimation)	Production tasks and methods related to applying best practices according to agricultural standards (e.g. organic standards, integrated crop management (ICM)). A yield estimate is feasible through the comparison of actual demands and alternative possibilities, given hypothetical scenarios of best practices.
Finance	Estimation of the cost of every farm activity, input–outputs calculations, equipment charge-outs, labour requirements per unit area. Projected and actual costs are also compared and input into the final evaluation of the farm's economic viability.
Inventory	Monitoring and management of all production materials, equipment, chemicals, fertilizers, and seeding and planting materials. The quantities are adjusted according to the farmer's plans and customer orders.
Traceability	Crop recall, using an ID labelling system to control the produce of each production section, including use of inputs, employees, and equipment, which can be easily archived for rapid recall.
Reporting	Creation of farming reports, such as planning and management, work progress, work sheets and instructions, orders purchases cost reporting, and plant information.
Site Specific	Mapping the features of the field, analysis of the collected data, generation of variable rate inputs to optimize input and increase output. This is the SFT component. It could be a separate software or could be integrated.
Sales	Management of orders, charges for services, online sales.
Machinery management	Includes the details of equipment usage, the average cost per work-hour or per unit area. It also includes fleet management and logistics.
Human resource management	Employee management, availability of employees in time and space, handling work times, payment, qualifications, training, performance, and expertise.

Modified by Fountas et al. (2015)

2.2.6.1 Variable-Rate (VR) Application Technologies

Variable-Rate Granular Fertilizer Application

Variable-rate application of fertilizer implies that the mass flow rate and subsequently the application rate of fertilizer needs to be varied within the field. The spinner and pneumatic spreader are generally the most used of fertilizer application machinery, also fertilizer drills are used frequently. In general, the application rate is changed by changing the mass flow of fertilizer to the delivery system of the spreader (spinning disks or air boom). Current technology allows the rate between different swaths and in the longitudinal direction within one swath to be changed.

The spinner spreader, also called centrifugal spreader, is the most commonly used. Particles fall on a spinning disk which is equipped with vanes and throws the particles into the field. Variable-rate control systems generally change the mass flow rate from the hopper to the delivery system. In the case of the centrifugal spreader, this is generally done in two ways: by changing the size of the orifice at the bottom of the hopper (Chen and Shiping 2011), or by changing the speed of the conveyor belt (Akdemir et al. 2007; Fulton et al. 2001) or metering rollers (Behic and Okyay Sındır 2013) that deliver fertilizer to the spinning disks. Some systems use load cells to measure the dynamic (measured around 100 Hz) weight of the spreader with fertilizer, based on this, they predict the flow rate and provide online feedback. A second reference sensor (often an accelerometer) is then used to compensate for varying field conditions (Van Liedekerke et al. 2006). Measurement of the mass flow is also possible by measuring the torque to rotate the spreading disks. This allows differentiation of fertilizer quantities spread from the left and right spreading disk.

Pneumatic spreaders use airflow to convey fertilizer particles from the metering units to distributors on the spreading boom. In contrast to the spinner spreader, material is distributed uniformly through the distributors along the length of the boom. Therefore, no overlap is necessary between subsequent swaths.

Fertilizer drills can be used to aim for more accuracy placement (Maleki et al. 2008a) and can be mounted on a row-crop planter (Maleki et al. 2008b). In contrast to the above mentioned broadcast spreaders, the width of the machine equals the working width and particles are not thrown into the air which reduces the sensitivity of the application system (e.g. for wind). Based on the ground speed of the tractor and the prescription map or online sensor values (Maleki et al. 2008a), the mass flow rate of fertilizer is changed by controlling a metering screw (Forouzanmehr and Loghavi 2012) or an electrical actuator changing the rotational speed of the fertilizer metering devices (Maleki et al. 2008a). Important factors that increase the accuracy of the VR system are the different delay times that occur in the process. If an online sensor is installed to determine the application rate, the acquisition and processing time of the data should be taken into account. Secondly, changing the position of a metering screw or actuator takes time. Another source of lag time is the time required to reach the end of the fertilizer tube (positioned at the furrow openers) after setting the new mass flow rate at the metering device.

Variable-Rate Lime Application

Under application of lime can cause large yield losses. However, its over application can be as detrimental as under-liming because it is costly and can create problems with availability of some nutrients (e.g. inhibits P and Zn or leads to toxic concentrations of available Mn), disease pressure, reduced herbicide performance and herbicide degradation (Weisz et al. 2003; Kuang et al. 2014). Over- and under-liming cannot be avoided if lime is applied uniformly throughout the field. Variable-rate (VR) lime (primarily $CaCO_3$) application can increase crop yields and the economic return of the farm (Weisz et al. 2003). Lime application increases the soil's pH to a desired level and an optimal pH level in the soil is important to achieve optimum yields and consistent quality (Kuang et al. 2014). Also, lime improves the uptake and availability of plant nutrients and can also improve water penetration.

Both spinner type spreaders and pneumatic applicators exist for lime applications. In spinner spreaders a conveyer belt or chain transfers the materials from the

Table 2.4 Software packages offered in agriculture

Software	Description
FARMSTAR	FARMSTAR is a satellite technology-based service devised and delivered by Airbus Defence and Space since 2003. FARMSTAR's users are taking advice on precision agro-management knowing the exact time and area where they should apply **fertilizer and pesticides**. Satellites flying over the fields take accurate measurements of the radiant solar energy absorbed and reflected from the surface across the farm terrain. The value of the reflected energy varies according to the level of growth of the vegetation, thus satellite measurements can indicate crucial field factors such as soil moisture, surface temperature, leaf cover and level of chlorophyll. Personalised "recommendation cards" divided into very small areas of the field are provided to each user, offering her/him prescriptions for the necessary amounts of chemicals that should be applied, as well as where and when to be applied. The average price for FARMSTAR services to the farmer **is €10/ha**. By 2011, coverage was 440,000 hectares and 10,000 farmers had subscribed to it, while the number of hectares has already reached to 1 million hectares this year (personal communication).
Akkerweb	Akkerweb is Dutch software used for **whole-farm management** of the fields with **precision agriculture** capabilities. It has a number of applications such as herbicide application, nitrogen fertilisation and pesticides applications. So far, it has about 25,000 fields registered in their database.
365farmnet	365farmnet is a **whole-farm management software**, which is sold to farmers to optimize their production including inventory, sales, precision agriculture functions and connections to sensors.
Farmworks	Farmworks is a Trimble company that offers **whole-farm management** including inventory, sales, planning and all **precision agriculture** functions for VR seeding, fertilization and spraying. It offers different packages to contractors and single farmers.
John-Deere Farmnet	John-Deere Farmnet is a **whole-farm management** system to provide **precision agriculture** functions together with other farm management services. It is linked to John Deere equipment and generates site-specific maps based on field data.
SST-toolbox	SST-toolbox is a USA-based company that offers **whole-farm management** software focusing on **precision agriculture** applications, having different packages for contractors and single farmers.
PIXAGRI	TerraNIS' PIXAGRI is a decision support tool for farmers based on remotely sensed data which allows detection of sub- and inter-field variations and is designed to optimise the application of agricultural inputs. It is a generic product suite based on optical satellite imagery allowing farmers to **identify and control the agronomic factors limiting their yield**. Aimed primarily at farmer's cooperatives, PIXAGRI is available for all types of crops and most suitable to large areas (+2000 ha). The product suite is comprised of agriculture maps over the territory, analysis of yielding capacities in a region and heterogeneity and vigour maps. It is sold as a service that delivers maps providing crop status information and is commercialized through a yearly subscription over a fixed territory. The price is **5–10 €/ha/year**, depending on the level of information required. Currently, TerraNIS commercialises the PIXAGRI product range in Midi-Pyrenees and other regions in France, Canada, Hungary, Serbia (via Airbus Defense and Space).

(continued)

Table 2.4 (continued)

Software	Description
SOYLsense	SOYLsense uses satellite imagery to measure crop canopy variations. Leaf Area Index (LAI) maps with information of the requirements of **nitrogen application** are produced based on the data obtained, allowing the optimization of nitrogen rates. SOYLsense enables farmers to monitor their field and acquire advices about the application of nitrogen fertilizers. Moreover, users can view their LAI map online and have the ability to create and process their own nitrogen application maps.
FarmRite	BlackBridge's RapidEye constellation of satellites in cooperation with SST Software, a global provider of GIS software for agriculture, delivered the SST FarmRite service offering farmers and agronomists the appropriate data in order to generate **nutrient and pesticide application maps on their own**. Users can order products and acquire the desire end products, while management reports are provided to users, allowing them to track the success of product offerings and make the appropriate adjustments.
FarmingTruth	The FarmingTruth project -funded by ESA- aimed to deliver a precision agriculture service that enables users to collect and utilize crop and soil data from various data sources including Earth Observation and Satellite Navigation. Among FarmingTruth providing data are recommendations about variable rate **fertilizer and lime application**.
Ag Data Viewer	Ag Data Viewer is a precision farming software package that provides a wide range of precision agriculture practices from satellite imagery. Among others it offers variable rate application maps with recommendations about **fertilizer inputs**.
TalkingFields	Started as an ESA-led project, TalkingFields is an operational cost-effective Precision Farming service, combining GNSS technologies with Earth Observation (EO). For a terrain located using Navigation Technologies, the user requests a specific service from the TalkingField's catalogue, such as the "Improved Soil Mapping", the "Economic Evaluation" or the "Yield Estimation". Based on navigation information, EO measurements and land surface modelling, the provider prepares the **custom made service and offers users recommendations for individual farm treatment**, application of cost-effective practices and more effective farming systems.
HydroBio	HydroBio provides farmers with an **irrigation decision support system using weather and Earth Observation data** to estimate the precise water needs of each field along with crop monitoring. HydroBio users receive information that enables them to deliver an optimal irrigation strategy to their field including maps for the previous water use, recommended irrigation schedules, strategies to meet irrigation deficit when necessary, information about the best applied practices and what needs to be improved.
SPIDERwebGIS	SPIDERwebGIS is an Information System, open source, based on Web 2.0 designed as a participatory tool to aid decision making applied to improve **agroforestry environments** at different levels of management and whose main source of information are products obtained from time series of Earth observation satellite images.

(continued)

Table 2.4 (continued)

Software	Description
PiMapping	eLEAF's PiMapping (Pixel Intelligence Mapping) Technology uses satellite imagery, weather information and precipitation data to create "smart pixel" images providing information about cropped surfaces and enabling the development of applications for the agricultural sector. It provides farmers with information such as growth, moisture and yield for almost all cropped surfaces, and offers them the ability to better manage their **irrigation practices** by delivering daily data about their crop's actual evapotranspiration, biomass production and crop water requirements.
Synfield	Synfield is a system that utilizes meteorological data for estimation of evapotranspiration and together with soil moisture sensors it estimates the **irrigation needs**. It has developed a web interface to estimate the water needs and installs electro-valves in the field to remotely activate irrigation.
CropLook	CropLook inform farmers with potatoes and wheat crops about their crop growth in a weekly basis, offering them growth parameters such as **crop evaporation, nitrogen content, and yield figures**. CropLook using remote sensing, the satellite information are processed with the ETLook algorithm to be translated into crop data, and this data are provided directly to the user via a web portal.
GrapeLook	The GrapeLook project, based on satellite technologies (earth observation, satellite communication and navigation) as well as terrestrial technologies, aimed to help **grape farmers with the irrigation water resources and nitrogen applications in the Western Cape, South Africa**. All data obtained, such as soil moisture levels; irrigation retrieval from evapotranspiration updates; and digital boundaries of vineyard blocks, were uploaded on the project website, which were publicly accessible. Moreover, farmers received an irrigation forecasting tool and a SMS/MMS service with information on irrigation scheduling and fertilizer application.
FruitLook	FruitLook, a successor of GrapeLook, covers a larger area of crops including deciduous fruit trees. Weekly data on crop's growth, **water use and nitrogen conten**t are available to farmers for free. In the near future, the developers of FruitLook will release an "irrigation planner" which will inform farmers about when, where and how much they should irrigate to avoid water stress in their crops.
The Pastures from Space	The Pastures from Space project aimed to deliver near real-time information tools at a **whole-farm and within-paddock level of forage crop production**. The Pastures from Space provides estimates of pasture production during the growing season by means of remote sensing. Satellite data is used to accurately and quantitatively estimate Pasture Biomass or Feed On Offer (FOO) or combined with climate and soil data is used to produce Pasture Growth Rate (PGR) estimates.
URSULA Agriculture	URSULA Agriculture provides a suite of services based on imagery from drones, aircraft and satellites. Products include Ursula **Crop Performance** (a crop monitoring service which measures within field variation across the growing season), URSULA Scout (a rapid mapping and quantification tool for highlighting areas of crop stress), URSULA Trials (a quantitative comparison tool enabling the evaluation of agricultural trials), URSULA Farm View (aerial imaging tool enabling visual assessment of crop progress) and URSULA Compliance (a service aimed at supporting CAP subsidy claims).

(continued)

Table 2.4 (continued)

Software	Description
Irrisat	Irrisat is a research project that is focused on providing information on **irrigation needs** to the farmers and Irrigation User Associations based on Earth Observation satellites. Except of irrigation related information, it offers crop vigor information along with meteorological data.
Oenoview	Oenoview is an innovative remote sensing tool that produces a cartography of vineyards. This information is used by viticulturists in order to apply **site specific management at their vineyards** and monitor them at sub parcel level.
AGRIVI	AGRIVI is a platform that offers **complete farm management**. It has the ability to monitor weather and provide alerts on crop pests and diseases. It offers tools for crop management, farm economics, resources and inventory, growing analytics and reports.
FARMBRELLA	FARMBRELLA is a software service addressing the real farmers' needs of the meteorological data and analysis. It offers the ability to the farmers to have **hyper local weather informatio**n of their fields while it measures heat sum and provides alerts on extreme crop conditions.

https://www.farmstar-conseil.fr/
http://terranis.fr/en/pixagri/
http://www.soyl.com/index.php/services/soylsense
www.sstsoftware.com/products/farmrite/
www.farmingtruth.com/
http://www.geektechforag.com/
www.talkingfields.org
http://hydrobioars.com/
http://www.spiderwebgis.org/
www.eleaf.com/technology-pimapping
www.synelixis.com
www.croplook.com/
https://artes-apps.esa.int/projects/grapelook
www.fruitlook.co.za/
www.pasturesfromspace.csiro.au/
www.ursula-agriculture.com/

hopper to spinning disks. In variable-rate systems the application rate is controlled by adjusting the gate opening and or changing the speed of the conveyor (and thus the input rate of material). In pneumatic applicators the material is spread by an air stream through a piped boom (Grisso et al. 2011).

Variable Rate Manure Application

There are two different levels for variable-rate slurry application. For the first level, only the application rate, i.e. the flow of slurry from the tank to the application hoses, is varied. However, because manure is not consistent in nutrient content, a second level was designed. Therefore, at the second level, the nutrient content of the slurry should be measured online by sensors that measure electrical conductivity or use NIRS (Calcante et al. 2015).

In general, slurry can be delivered in two ways to the delivery system: (1) by putting the tank under pressure or (2) by pumping the slurry. With a pressurized tank, the application rate can be modified by changing the size of the gate opening that delivers slurry from the tank to the delivery system. Calcante et al. (2015) used a variable gate hydraulic valve, powered by the main hydraulic system of the tractor. Based on the nitrogen content of the slurry (measured before application), the ground speed of the vehicle (measured with a sensor or using GPS information) and working width, the required slurry flowrate can be calculated and set by the controller (Brambilla et al. 2015). Sensors that measure flowrate are used for feedback to the rate control system, such as Doppler effect sensors (Calcante et al. 2015; Brambilla et al. 2015) and electromagnetic flowmeters (Morris et al. 1999). In general, these give a more accurate estimate of the flowrate than load cell measurements (Morris et al. 1999). Funk and Robert (2003) used a pneumatic pinch valve for both flow metering and flow measuring.

In the other case, slurry is pumped from the tank to the applicator by a centrifugal or positive displacement pump controlled by the tractor PTO (Funk and Robert 2003). In most cases, the pump is driven by the tractor PTO. The application rate is varied by changing pump or valve settings based on the online measured flowrate.

Variable Rate Pesticide Application – Map-Based System

The VR pesticide application technologies enable changes in the rate of application to match actual or potential pest stress in the field and avoid application to undesired areas of the field or plant canopies (Karkee et al. 2013). They can also significantly reduce spray overlap (Batte and Ehsani 2006). In general, weeds have received the greatest attention from developers of site-specific technologies because of their immobility (Swinton 2003). The VR technologies for pesticide application can also be used to apply fertilizer at variable rates (Ess et al. 2001).

Map-based VR pesticide application adjusts the application rate based on an electronic map, also called prescription map or application map. Using the field position from a GPS receiver and a prescription map of desired rate, the input concentration is changed as the applicator moves through the field (Grisso et al. 2011). Two main categories can be distinguished, i.e. (i) rate control, including flow-based control systems, direct chemical injection systems and chemical injection systems with carrier control and (ii) nozzle control, including modulated spraying nozzle control systems.

Variable Rate Pesticide Application – Real-Time Sensor Based Spraying

Real-time sensor based spraying controls the application rate based on the current situation of pest stress or canopy characteristics. These systems involve both contact and non-contact sensing to identify either pests that need to be controlled or the crop and foliage or canopy that needs to be protected. Various types of sensors can be used such as colour cameras, photodetectors, laser scanners, multispectral and hyperspectral cameras, thermal cameras, and ultrasonic sensors. These sensors have been used to determine variables such as colour, shape, size, texture, reflectance and temperatures of pests. This information is then used to categorize pest or canopy patterns, and to identify and locate them. The sensor input can also be used to control the direction and rate of chemical application (Karkee et al. 2013). The same rate and nozzle control systems as in map-based VRA can be used.

In addition, sprayers that use information on the environment to reduce drift are currently being developed. These sprayers use, for example, sensors that measure the wind speed and direction and change the sprayer settings (spray pressure, nozzle type) accordingly depending on where the sprayer is in the field in relation to vulnerable areas based on GPS (Doruchowski et al. 2009).

Boom Height Control

Boom oscillations and vibrations are disastrous for the homogeneity of the spray liquid distribution on the crop, resulting in under- and over-applications of chemicals with, respectively, a missed treatment effect and remaining residues (Hostens et al. 2000). From simulations performed by Ramon et al. (1997), it was concluded that both rolling motions and horizontal vibrations of the boom can severely disturb the spray deposition pattern. Local under- and over-applications caused by boom rolling varied between zero and 10 times the desired dose. Horizontal boom vibrations caused variations between 0.3 and 4.0 times the prescribed dose. Varying ground speed, changing tyre pressure and ground unevenness can lead to significant under- or over-application of spray because of oscillation of a sprayer boom above its horizontal axis. Boom height control is used to minimize such effects and improve the uniformity of chemical application (Karkee et al. 2013).

Ultrasonic sensors measure (40 times per second) the distance to the ground. This information allows the control system to make responsive height adjustments. The system has shown reliable control with average speeds more than 29 km $hour^{-1}$ in all kinds of uneven terrain. Although boom height control is not a VRA technology, it eliminates streaks and improper overlaps, and improves coverage (Grisso et al. 2011). Similar control mechanisms can also be used to position the spray tower an appropriate distance from the crop canopy in orchards and ornamental nurseries (Karkee et al. 2013).

Variable Rate Planting and Seeding

The VR planters and seeders can vary the rate of planting and seeding during application. This is often accomplished by disconnecting the planting or seeding system from the ground drive wheel, which usually keeps the planting or seeding rate constant when the speed of the tractor varies. The planting or seeding rate can also be adjusted to the local soil potential by driving the planting or seeding system with an independent engine, gear box (to change speed of the ground wheel input) or hydraulic drive (Grisso et al. 2011).

Most VR planters or seeders will be matched with a prescription map. The VR planting and seeding is useful in very heterogeneous fields (i.e. fields with large wtihin-field variation in water holding capacity or soil organic matter). The VR planting or seeding is ideal for fields with centre pivot irrigation systems, where areas outside the reach of the irrigation system are planted or sown at a reduced rate to avoid water scarcity caused by a too high a plant density (Grisso et al. 2011).

2.2.6.2 Precision Irrigation and Irrigation Scheduling Technology

A number of theoretical and practical foundations can be seen as important in approaching and appreciating a study on irrigation scheduling and associated support functions. Notably these foundations include understanding of:

- water balance in crop production
- commercial irrigation scheduling methods
- remote sensing principles including the electromagnetic interaction with soil and crop media

Better irrigation scheduling can be achieved mainly when water balance components in crop production are known. The most important factors that constitute the water balance equation are[8]:

- Radiation and temperature
- Evaporation from soil surface and crops
- Transpiration from crops
- Land surface water runoff characteristics
- Sub-surface water flow, in and out of the crop location
- Deep soil percolation
- Capillary rise within the soil
- Irrigation (by various methods)
- Rainfall

Research and development into irrigation scheduling methods and systems for irrigation support is a recurring and important theme in PA, with attention to further developments in:

- Soil water status (current)
- FAO (Food and Agricultural Organisation of The United Nations) – method that uses crop coefficient (currently favoured)
- Crop water stress scheduling

Techniques are now emerging that exploit integrated sensor platforms to determine soil moisture and canopy estimates of evapotranspiration as a basis for improving irrigation scheduling and real-time, stress related control techniques for delivery of adaptively-controlled, plant-level irrigation. Water management for irrigation is seen as an essential activity that requires not only considerations for individual farms, but also in a broader context of national assessment needs and as part of the strategic agenda for global monitoring for environment and security (GMES)[9,10]

Self-propelled irrigation systems consist of centre pivot and lateral move systems that apply water to pasture or crops, generally from above the canopy (Berne

[8] See for example the FAO Guidelines on Irrigation and Drainage, FAO Paper 56, Crop Evapotranspiration

[9] www.nereus-regions.eu

[10] www.esa.int/gmes

2015). These systems are most used in irrigation today (e.g. 72% of irrigation systems in USA were sprinkler-based in 2000 according to Colaizzi et al. 2009). In 2009, most self-propelled irrigation systems used mid elevation spray application (MESA), which has an irrigation efficiency of 85%. The latest and future systems consist of low-energy (elevation) precision application (LEPA – low energy pressure application or LESA – low energy spray application), which has a higher irrigation efficiency (97%). These devices (bubblers, sprayers, spinners, and other related spray techniques to apply water) are usually on drop tubes in or just above the crop canopy.

Micro-irrigation is used especially in areas with very scarce water supply. These systems have, compared to sprinkler systems, a greater crop yield, better water use efficiency, less pesticide use because water is emitted at the surface of the desired high value crop, tree or vine and warmer soil temperature (in case of subsurface) (Camp 1998). This system is especially useful in orchards and vineyards or high value crops because of the larger costs.

There are three types:

- Drip and trickle emitters
- micro-sprinkling and microspray
- subsurface irrigation

Although there has been substantial interest in site-specific management, research on spatially variable micro-irrigation systems has been limited. Using pressure or flow sensors, water and dissolved fertilizer applications at each micro-sprinkler could be monitored and controlled. The volume scheduled irrigation strategy and emitter fault diagnosis routines could be made more effective with a differential pressure sensor across each valve to determine individual micro-sprinkler flow rates. Other control strategies would be possible with alternative types of sensors to measure tree water and nutrient demand, and monitor system status.

2.2.6.3 Precision Physical Weeding

The challenge of physical weeding is to obtain a high degree of selective weed control without producing considerable crop damage as a result of weeding (burning, mechanical weed control with knives, discs, hoes, harrows, etc.). Non-chemical weed control methods need to be directed towards a site-specific weeding approach in order to compete with conventional plant protection product applications. Different approaches and prototype systems have been proposed, adjusting the hoeing or harrowing or burning intensity based on the (earlieror real-time) observed soil density or weed density. Precise guidance and detection systems are prerequisites for successful site-specific weed management. Effective detection and identification is a primary obstacle toward commercial development and industry acceptance of robotic weed control machines. The most promising approach for weed detection is a continuous ground-based system that uses image analysis (Martelloni 2014).

2.2.6.4 Machinery Guidance

Auto-Guidance Systems

Auto-guidance systems have gained increasing interest among farmers as they enable farm machinery to follow straight lines to reduce overlaps of the tractor and equipment passes. These systems help farmers to reduce fuel costs, input costs, time, labour, soil compaction and increase the overall field efficiency. Auto-guidance systems are offered as two options, the lightbar and the auto-steer. Both systems use a high accuracy GNSS receiver (Horizontal <1 cm, Vertical <2 cm) to identify the tractor's location in the field (Gan-Mor et al. 2007).

The basic difference between the two systems is that lightbar guidance requires the operator to manually adjust steering, whereas auto-steer technology adjusts the steering automatically, allowing the operator to monitor the field operation of the implement instead of steering. Lightbar technology is offered at a much lower cost and can be easily transferred from one vehicle to another compared to auto-steer technology, which requires higher investment and it can differ from one machinery manufacturer to another.

Guidance systems are regarded as the most adopted PA technologies worldwide and can be used for many field operations such as seeding, tillage, planting, weeding and harvesting (Abidine et al. 2002), and for use with autonomous vehicles (UGVs – unmanned ground vehicles) with the full utilization of the ISOBUS standard ISO 11783 (Backman et al. 2013). It is especially used if the UGV's IMU for enabling dead reckoning capabilities is needed.

Many studies have compared automatic guidance and manually-guided operation. The use of auto-guidance systems on sugar cane planting operations achieved an accuracy of 0.033 m pass-to-pass, which was five times greater than that obtained by the manual steering system (Baio and Moratelli 2011). Rojo and Fabio (2012) evaluated the accuracy, the cane loss and operational field efficiency achieved by an auto-guidance system used to guide a sugar cane harvester over the field when compared to a manually-guided machine. They showed that the use of an auto-guidance system during the day and night periods increased the field pass-to-pass accuracy relative to the planned row track, whereas it did not significantly decrease the sugar cane loss, once the crop was well cultivated. Shinners et al. (2012) studied the effect of driving experience and operating speeds with manually and automatically guided mowers in a variety of field conditions on 15 farms. They estimated an overlap range between 0.4 and 16.13% of machine cutting width with an average loss at 5% of cutting width. They concluded that auto-guidance has been purported to improve efficiency by eliminating time spent covering ground already mowed, reducing operator fatigue and ensuring a uniform cutting pattern and swath density, and showed that auto-guidance systems to steer the mower reduced overlap loss from 5.03% to 2.34%.

Auto-steer reduces the overlap of multiple passes with the tractor, which is caused mainly by operator error or fatigue. The ability to increase speeds during headland turns and more quickly identify re-entry points were recorded to reduce machinery time requirements by 5% for planting and 10% for fertilizer application (Shockley et al. 2011). An RTK-based guidance system was tested for location mapping of planting events occurring on a tractor-drawn tomato transplanter that can automatically create centimetre-accuracy plant maps for subsequent precision plant specific treatment systems (Perez-Ruiz et al. 2013).

Controlled Traffic Farming (CTF)

The CTF is a system that confines all machinery loads to the least possible area of permanent traffic lanes. Current farming systems allow machines to run at random over the land, compacting around 75% of the area within one season and at least the whole area by the second season. A proper CTF system on the other hand can reduce tracking to just 15% and this is always in the same place. The permanent traffic lanes are usually parallel to each other and this is the most efficient way of achieving CTF, but the definition does not preclude tracking at an angle. The permanent traffic lanes may be cropped or non-cropped depending on a wide range of variables and local constraints. Techniques like CTF have the capacity to benefit all types of crop farming. The CTF also allows optimised driving patterns, more efficient operations (i.e. reduced overlaps). As all operations are aligned, input applications can be targeted very precisely relative to the crop rows.

The CTF management can play a key role in sustaining soils and future crop production that are threatened currently by heavy machinery traffic and intensive production systems. To play this role in sustainable intensification, CTF needs to be developed to become a mainstream technology rather than continuing as a niche practice. Therefore, there is a need to facilitate and support the development and mainstreaming of CTF at a time where development in allied technologies such as headland management systems are increasing growers' openness to the adoption of these systems.

When CTF is combined with headland management type systems it further alleviates soil compaction from continually increasing machine weight, and is of paramount importance for EU farmers (estimated approximately 33 Million ha compacted) in terms of yield loss, reduced nutrient and water efficiency, soil degradation and alleviation costs. While management practices such as deep soil loosening, use of certain cover crops and crop rotations can help alleviate some of the damage to soil structure; these approaches are costly and at best only partly successful. Preventing or avoiding damage to soil structure is preferable to alleviation. The CTF offers scope to restrict the extent of soil structure damage. It involves the configuration and application of field or machinery operations in a way that minimises the soil compaction by using permanent traffic tracks. The CTF also enables other compaction minimising traffic patterns, such as load determined traffic routing.

2.3 Smart Farming Technologies Taxonomy

The SFTs can be classified according to the following parameters:

- Farming system type, which is divided into three major farming systems:
  - **Organic farming**: The farming system that relies on biological control and mechanical cultivation to maintain soil productivity and pest control.
  - **Extensive farming**: Low energy input farming that uses small inputs of labour, fertilizer and capital relative to the land being farmed and where conventional practices are carried out.

  - **Integrated farming**: The farming system that use good agricultural practices and or integrated crop management strategies to produce high quality and certified agricultural products.

- Cropping systems type, which can be divided into the main clusters that correspond to main cropping environment within EU-28 and have distinctive differences among themselves:
  - **Arable crops**
  - **Forage crops**
  - **Orchards**
  - **Vineyards**
  - **Field vegetables**
- Availability of the technique that is divided into three categories.
  - **Now available**: Precision Agricultural Technologies (PAT)s that are commercially available to be used by farmers today.
  - **Next 5 years**: The availability in the next 5 years is seen as PATs currently under development or at prototype stage.
  - **In the future** (>10 years): PATs that are at the experimental stage in the laboratories or research institutes, such as robotic harvesters, robotic hoeing, etc.
- Level of investment cost that gives the cost involvement of farmers in SFT adoption and is divided into three levels.
  - **Low**: A low cost investment (e.g. parallel guidance with light bars, yield mapping or soil mapping).
  - **Medium**: A medium cost investment (e.g. on-line sensors combined with direct controlling, on-board computers or terminals, parallel guidance with terminals, Variable-rate application of nitrogen).
  - **High**: A high cost investment (e.g. fully applicable PA software, variable-rate applications in many operations, automated guidance system).
- Farmers' motives that correspond to the reasons for farmers to adopt these technologies.
  - **Operational excellence**
  - **License to operate**
  - **Improving the whole-farm information anagement**.

In the following table, the reader can see the taxonomy of all SFTs according to the above mentioned criteria (Table 2.5).

2.4 Smart Farming Technologies Economic Impact

The use of SFTs can provide to the farmers economic benefits that can be seen in Table 2.6.

Table 2.5 Smart farming technologies taxonomy

Main categories	SFT	Farming system	Cropping system	Availability	Investment	Farmers' motives
GNSS Technologies	Global aavigation satellite systems (GNSS)	All	All	Now available	Low to medium	Improving the whole-farm information management
	Differential GNSS					
	Real time kinematic (RTK)					
	Network RTK (NRTK)			Available in 5 years (Galilleo)		
	Wide area RTK (WARTK)					
	Undifferenced GNSS					
	Precise point positioning (PPP)					
	Fast PPP (FPPP)					
Mapping technologies	Elevation maps	All	All	Now available	Low	Improving the whole-farm Information management
	Soil mapping			Now available (some on-the-go sensors are on prototype stage)	Medium	
	Yield mapping			Now available	Low	
	Yield monitor display					
Data acquisition of environmental parameters technologies (Camera based imaging)	RGB cameras	All	All	Now available (Prototypes are also available for reduced size)	Low to medium (depending on the device)	Improving the ahole-farm Information management
	LiDAR sensors					
	ToF (IR) cameras					
	Light curtains					
	Multi/Hyper-spectral cameras					
	Thermal cameras					
Data acquisition of environmental parameters technologies (NDVI measurement)	Spectral sensors	All	All	Now available (prototypes are also available for reduced size)	Low to medium (depending on the device)	Improving the whole-farm information management
	Fluorescence sensors					

(continued)

Table 2.5 (continued)

Main categories	SFT	Farming system	Cropping system	Availability	Investment	Farmers' motives
Data acquisition of environmental parameters technologies (Soil moisture sensors)	Frequency domain reflectometry	All	All	Now available	Low	Operational Excellence/Improving the Whole farm information management
	Time domain reflectometry					
	Amplitude domain reflectometry					
	Phase transmission					
	Time domain transmission					
	Tensiometers					
	Gipsum blocks					
	Granular matrix sensors					
	Heat dissipation sensors					
Machines and their parameters	Travel speed sensor	All	All	Now available/available in the next 5 years (some technologies are already well established others are still under development).	Medium to high	Improving the whole farm information management
	Tractor sensing systems using ISOBUS					
	Unmanned aerial vehicles (UAVs)					
	Unmanned ground vehicles (UGVs)					
Data analysis & evaluation technologies	Management zones delineation	All	All	Now available/available in the next 5 years (some technologies are already well established others are still under development).	Low to medium	Improving the Whole farm Information Management
	Decision support system					
	Farm management information system (FMIS)					
	Farm management, forecasting and crop monitoring software					
Guidance technology	Auto-guidance systems	All	All	Now available	Low	Operational Excellence / Improving the Whole-farm Information Management
	Control traffic farming					

Variable rate applications	Variable rate fertilizer application	All	All	Now available (automatic calibration)	Medium	Operational Excellence / License to operate / Improving the whole-farm information management.
				Available in the next 5 years (Online sensors for spread pattern determination)		
	Variable rate lime application			Now available	Low	Operational Excellence / Improving the Whole-farm Information Management.
	Variable rate manure application			Now available (flow control systems)	Low	Operational excellence / License to operate
				Available in the next 5 years (On-board nutrient sensing)		
	Variable rate pesticide application (Map-based system)			Now available	Medium	Operational Excellence/Improving the Whole farm information management
	Variable rate pesticide application (Real-time sensor based system)			Available now/available in the next 5 years (Some technologies are already well established others are still under development).	Medium to high	
	Boom height control			Now available		
	Variable rate planting/seeding		All (not in Orchards and Vineyards)		Medium	
	Precision physical weeding		All	Available in the next 5 years	N/A	Operational excellence / Improving the whole farm Information management
	Precision irrigation and irrigation scheduling			Now available	Low to medium	Operational excellence / Improving the whole farm Information management

Table 2.6 Smart farming technologies economic impact

SFT	Economic impact
Global navigation satellite systems (GNSS)	GNSS technologies do not have direct economic impact, but it is a requirement for most PA applications and therefore the technologies may have an indirect benefit.
Differential GNSS	
Real time kinematic (RTK)	
Network RTK (NRTK)	
Wide area RTK (WARTK)	
Undifferenced GNSS	
Precise point positioning (PPP)	
Fast PPP (FPPP)	
Elevation maps	Elevation, soil parameters (ECa, pH, moisture content) and yield mapping does not offer direct economic impact if it is not interpreted from Crop Consultants together with the farmer to apply site-specific crop management.
Soil mapping	
Yield mapping	
Yield monitor display	
RGB cameras	Imaging does not offer direct economic impact, but if it is used for VR application, the reduction in inputs will reflect on the farm income.
LiDAR sensors	
ToF (IR) cameras	
Light curtains	
Multi/Hyper-spectral Cameras	
Thermal cameras	
Spectral sensors	NDVI measurement does not offer direct economic impact, but if it is used for VR application, the reduction in inputs will reflect on the farm income.
Fluorescence sensors	
Frequency domain reflectometry	Soil moisture sensors measurements do not offer direct economic impact, but if it is used together with irrigation services they can be used for the reduction of irrigation water which reflects on the farm income.
Time domain reflectometry	
Amplitude domain reflectometry	
Phase transmission	
Time domain transmission	
Tensiometers	
Gipsum blocks	
Granular matrix sensors	
Heat dissipation sensors	

(continued)

Table 2.6 (continued)

SFT	Economic impact
Travel speed sensor	These technologies do not offer specific direct economic gains for the farmer, but they may have an indirect benefit when applied together with VR applications.
Tractor sensing systems using ISOBUS	
Unmanned aerial vehicles	Unmanned vehicles can provide profit for the farm, mainly due to limited/absent labour cost and less fuel costs compared with tractor mounted systems. Small low weight vehicles may reduce costs in relation to soil compaction and damage.
Unmanned ground vehicles	
Management zone delineation	Delineation of zones does not offer direct economic impact, except if they are taken into consideration for farm management optimization.
Decision support system	FMIS provides to farmers/farm managers detailed budgeting procedures, field planning, book-keeping for subsidy applications and for public authorities audits (Lawson et al. 2011). If data coming from SFTs of all kinds are imported in a general FMIS, then a series of documentation data will be able to automatically be developed, management time will be reduced significantly and due to improved management quality the farmer/farm manager will supply any regulatory body with detailed information from the farm that without the interference of SFTs would not be available (Steffe 2000).
Farm management information System (FMIS)	
Farm management, forecasting and crop monitoring software	
Auto-guidance systems	The economic benefit of using guidance technologies, either lightbar or auto-steer, comes from improved pass-to-pass efficiency and limitation of overlapping. This means that the applied agricultural inputs (seeds, fertilizers and pesticides) will be reduced with a direct positive impact on farm's economics. An example of such impact from application of guidance systems was given by Shockley et al. (2011) where the use of auto-steer improved performance during planting and fertilizer application leading to reduced inputs with cost benefit of approximately 2.4, 2.2 and 10.4% for seed, fertilizer and tractor fuel, respectively. Another case of auto-steer use was for peanut digging operations, where the traditional row deviation was 180 mm and when auto-steer was applied there were average net returns of 94–695 US$/ha depending on row deviations (Ortiz et al. 2013).
Controlled traffic farming (CTF)	CTF is based on the principle of using the same tramlines for all operations, which has a direct increase of farm's profit, because it reduce dramatically input costs related to farm machinery (time, fuel & machinery), while reducing significantly soil compaction with direct positive effect on crop yields. It has been seen that farms in Australia have cut their machinery costs by as much as 75% while their crop yields have risen. In the UK, the Colworth project showed that the fact that CTF reduce inputs results in healthier crops and soils showing also the sustainability profile of CTF.

(continued)

Table 2.6 (continued)

SFT	Economic impact
Variable rate fertilizer application	Crop yield is dependent on nitrogen supply. Sogaard and Kierkegaard (1994) showed that this relationship can be achieved using a quadratic equation, where the parabolic shape of this equation depicts that the marginal increase of yield decreases after a certain point with increased supply of nitrogen. The application of fertilizers reaches an economic optimum at some point depending on the site-specific soil type, precipitation etc. In principle, when a field is divided into management zones and fertilizers are applied near the economic optimum in these management zones, higher returns for the farm can be achieved. In addition, some studies have shown that when variable fertilizer application is used there is a reduction in the total amount of fertilizer used (Koch et al. 2004), reflecting in Nitrogen Use Efficiency (NUE) increase. Raun et al. (2001) found an average NUE increase of more than 15% in winter wheat in comparison to uniform application of fertilizer. More specifically, in-season application at 1 m^2 spatial resolution (based on optical sensing) increased their simple estimate of revenue (grain revenue minus fertilizer cost) by 11 US$/ha, when fertilizer was also applied before planting (fixed rate) and more than 28US$/ha when fertilizer was only applied in-season. Mamo et al. (2003) have seen that variable rate nitrogen application in corn increased farm profit by 8–23 US$/ha compared to uniform application. Although similar yields were found, less fertilizer was used. Other studies based on simulation models have shown moderate results from variable rate fertilizer application in cereals (Pedersen et al. 2003) and (Pedersen and Pedersen 2002). Variable rate fertilizer application requires both fixed and variable costs to be invested in, such as soil sampling, online sensing, delineation of management zones, VR equipment (e.g. GPS receiver, onboard computer, software, VR system, etc.). Farm size plays a significant role in absorbing these costs (economics of scale) and large farms can spread them over a larger area (Koch et al. 2004). Koch et al. (2004) found an increase of 25.6–38.6 US$/ha in net returns for VR nitrogen application on Colorado corn compared to uniform application rates, both in a farmer and custom applied scenario. Variable rate application based on grid soil sampling resulted in the lowest net return, primarily due to increased fertilizer uses and soil sampling costs. The highest returns for VR application are expected on fields with high and spatially variable nutrient requirements (Raun et al. 2001).

(continued)

Table 2.6 (continued)

SFT	Economic impact
Variable rate lime application	Variable rate application of lime, as opposed to uniform application, increases soil pH, reduces in-field variability and increases soybean yield (Weisz et al. 2003). While investigating VR lime application in four studies, 75% of the studies showed positive economic effect, while the rest 25% indicated mixed results. It have been seen that precise lime application has better results in legumes than in corn and wheat, because legumes respond to pH up to 6, while corn and wheat are limited to pH 5–5.5 (Weisz et al. 2003). The main cost of VR lime application is grid sampling. The actual amount of lime used depends on the soil variability, the sampling method and the sampling resolution, as well as on drought stress, environmental factors, variability level and acidity in the field, etc. (Weisz et al. 2003). VR lime application appears to be only profitable for high value crops (Swinton and Lowenberg-DeBoer 1998).
	Kuang et al. (2014) found an increase in lime consumption in Danish spring barley with simultaneous yield increase and net profit (US$4.1/ha) when VR approach was applied compared to the conventional approach. Weisz et al. (2003) performed grid sampling and VR lime application for 3 consecutive years in no-till soybean fields and found a net loss of US$12.99/ha compared to uniform lime application. However, when grid sampling was executed only in year 1 and 3, and performed the VR lime in each year (with year 2 based on the PH map of year 1) this turns into a net gain of US$4.86/ha over 3 years. Similarly, using the pH map from year 1 to apply lime for 3 years in the areas were lime was initially required leads to a net gain of US$7.31/ha. Like fertilizer, variable rate lime application requires investment in both fixed and variable costs, such as soil sampling, delineation of management zones, VR equipment (e.g. GPS receiver, on-board computer, software and VR system).
Variable rate manure application	Managing manure as fertilizer resource for crop production can increase the return for the producer and the overall production efficiency of an animal-crop farming system (Huber et al. 1993). Precision management of manure has the potential to further improve farming system production efficiency (Morris et al. 1999). The key to VR manure application in general is the existence of an application map, which is laborious and time consuming to generate when acquired without sensor technology (Schellberg and Reiner 2009). Although no literature is available considering the economic return of VR manure application, many similarities with VR granular (inorganic) fertilizer applications can be seen. The main difference is the fact that here the applied product is much more bulky, heterogeneous and lower in nutrient content and financial value. It should be noted that some VR manure systems can be retrofitted to the tanker that farmers already have (Brambilla et al. 2015).

(continued)

Table 2.6 (continued)

SFT	Economic impact
Variable rate pesticide application (Map-based system)	Site-specific pest management has costs as well as benefits. Costs of map-based VRA are attributed to mapping, data processing, decision making, and site-specific application technology. Commercial mapping services typically charge 4.5–9.0 €/ha to map field boundaries including waterways and other physical features (Batte and Ehsani 2006). Gerhards and Sökefeld (2003) estimated the costs of a direct injection system on 3.9 €/ha (in addition to the costs of the sprayer) for weed control in sugar beet, maize, winter wheat and winter barley in a German study. Batte and Ehsani (2006) stated that the extra cost of a precision controlled sprayer equipped with nozzles controlled individually based on GPS information would be about 8000 €. However, Timmermann et al. (2003) commented that several components of variable rate technology, including GPS, board computer and GIS, can also be used for other precision farming activities such as planting, fertilisation and harvest, being beneficial for other farming practices as well.
	Benefits in variable rate spraying are mainly associated with savings on pesticide use. Swinton (2003) stated that results on the likely profitability of site-specific weed management are uneven because certain studies focused on potential reduced cost from less herbicide spraying, while ignoring the increased capital cost of variable rate application equipment and the increased variable cost of information processing. Timmermann et al. (2003) found that the monetary savings resulting from the reduction in herbicide use varied between crops, depending on the amount of herbicides saved and the price of herbicide. In maize, winter wheat, winter barley and sugar beet, savings of respectively 42 €/ha, 32 €/ha, 27 €/ha, and 20 €/ha were realised. In this regard, savings also depend on the different economic thresholds for pest control and the different competitive power of the crops. Batte and Ehsani (2006) estimated spray material savings of about 4 €/ha for a map-based spraying system compared to a self-propelled sprayer without any form of GPS for guidance assistance or sprayer control. The magnitude of input savings further increased as waterways were added to the field. Those authors also calculated the costs of the spraying system. Most of the costs related to the fixed investment which diminished per hectare as farm size increased. They also concluded that the benefits will increase proportionally to the cost of the pesticide being applied and will increase with the number of annual applications and with the driver error-rate of the non-precision spraying system. Oriade et al. (1996) suggested that weed patchiness is the most important factor justifying the use of site-specific weed control. Using simulation, they show that economic and environmental benefits are almost zero at low weed pressures, particularly if weeds are evenly spread. The benefits were larger as weed populations and level of patchiness increased. At high weed patchiness, return values of 17 €/ha to 33 €/ha were found in corn and soybean. The authors concluded that returns from site-specific management less than 14 €/ha are not sufficient to warrant the practice. The costs of information collection, time effects, and human capital were not considered in this model.

(continued)

Table 2.6 (continued)

SFT	Economic impact
Variable rate pesticide application (Real-time sensor based system)	As with map-based VRA, benefits are mainly associated with savings on pesticides (especially herbicides and to some extend fungicides) use and these savings depend on crop type, pest distribution, pesticide price, etc. In contrast to map-based VRA, an additional step of generating an application map with the help of GIS is not necessary. Therefore, there are no additional costs for computers, GIS software or DGPS. However, the sensor technology can be very expensive, although cheap sensors are available as well. Gerhards and Sökefeld (2003) estimated the cost of a camera system for weed detection to 40,000 €, whereas Dammer and Wartenberg (2007) used an optoelectronic weed sensor of about 2000 €. The latter could however not distinguish between crops and weeds and was therefore limited to operations within the tramlines. Gerhards and Sökefeld (2003) evaluated the economic benefits of a real-time, automatic, site-specific weed control system compared to conventional field spraying. They found that although the costs for the VRA technology were larger (9.56 €/ha vs. 5.20 €/ha), the average costs for weed control were lower due to herbicide savings (32 €/ha vs. 68 €/ha in winter wheat and winter barley, 69 €/ha vs. 148 €/ha in sugar beet, and 96 €/ha vs. 103 €/ha in maize). Based on these economic calculations, Dammer and Wartenberg (2007) comment that if sensors were available on the market, it would be profitable for farmers to invest in variable rate technologies. In summary, the net benefit of variable rate pesticide application will depend on the crop value, weed distribution, cost of pest/weed mapping, sensor systems as well as pesticide prices etc.
Boom height control	The uneven distribution due to boom height differentiation in the field may results in yield losses or in additional pesticide costs, however, no studies were found that calculated these economic effects.

(continued)

Table 2.6 (continued)

SFT	Economic impact
Variable rate planting/seeding	Soil variability is the main factor driving the economic performance of variable-rate seeding/planting. The return on investment of VR planting/seeding is low in very uniform fields, while in heterogeneous fields with clear high and especially low crop performance zones, the return on investment will be much higher. In the early years of VR planting/seeding development, its economic impact was unclear. In 1998, Bullock et al. (1998) observed differences in economically optimal plant densities as a function of yield potential in an extensive study in the Corn Belt region of the US, but they concluded that variable rate seeding would be infeasible, because of the high cost associated with characterizing site variability. Lowenberg-DeBoer (1998) stated that the investments necessary for adopting variable rate corn seeding would only be economically justifiable for farmers with some low yield potential land, but not for farmers with a mix of solely medium and high potential land. Taylor and Staggenborg (2000) concluded that variable rate seeding was only economically feasible on their fields of study if less expensive ways to generate the prescription map was available or if corn showed a greater yield response to seeding rate. In 2004, Shanahan et al. (2004) stated that "site-specific management of plant densities may be feasible", most likely due to technological advances. Dillon et al. (2009) performed sensitivity analysis with respect to alternative soils, seed price, wheat price and cost of VR seeding technology to determine its economic feasibility and concluded that the practice of VR seeding of wheat in France is feasible.
Precision physical weeding	As this technology is still in its infancy, no specific economic impact figures are readily available. However, a significant reduction of manual labour during physical weeding can be expected, especially in organic agriculture, which may lead to significant cost reductions.
Precision irrigation and irrigation scheduling	Lambert and Lowenberg-DeBoer (Lambert and Lowenberg-Deboer 2000) reported a possible economic benefit in corn yield and water use when using VR irrigation, but it was not described in numbers. Many authors (Booker et al. 2015; Colaizzi et al. 2009; Evans and King 2012) have mentioned the high costs of such systems, and a beneficiary in yield, work load, water use, pesticide use, etc. especially in climatic unfavourable years. However, numbers or comparisons are not given.

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