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# Sensor Fusion for Precision Agriculture

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## 1. Introduction

With the rapid rise in demand for both agricultural crop quantity and quality and with the growing concern of non-point pollution caused by modern farming practices, the efficiency and environmental safety of agricultural production systems have been questioned (Gebbers and Adamchuk, 2010). While implementing best management practices around the world, it was observed that the most efficient quantities of agricultural inputs vary across the landscape due to various naturally occurring, as well as man-induced, differences in key productivity factors such as water and nutrient supply. Identifying and understanding these differences allow for varying crop management practices according to locally defined needs (Pierce and Nowak, 1999). Such spatially-variable management practices have become the central part of precision agriculture (PA) management strategies being adapted by many practitioners around the world (Sonka et al., 1997). PA is an excellent example of a system approach where the use of the sensor fusion concept is essential.

Among the different parameters that describe landscape variability, topography and soils are key factors that control variability in crop growing environments (Robert, 1993). Variations in crop vegetation growth typically respond to differences in these microenvironments together with the effects of management practice. Our ability to accurately recognize and account for any such differences can make production systems more efficient. Traditionally differences in physical, chemical and biological soil attributes have been detected through soil sampling and laboratory analysis (Wollenhaupt et al., 1997; de Gruijter et al., 2006). The cost of sampling and analysis are such that it is difficult to obtain enough samples to accurately characterize the landscape variability. This economic consideration resulting in low sampling density has been recognized as a major limiting factor.

Both proximal and remote sensing technologies have been implemented to provide high-resolution data relevant to the soil attributes of interest. Remote sensing involves the deployment of sensor systems using airborne or satellite platforms. Proximal sensing requires the operation of the sensor at close range, or even in contact, with the soil being

measured, allowing *in situ* determination of soil characteristics at, or below, the soil surface at specific locations (Viscarra Rossel et al., 2011).

Alternatively, the crop itself can be viewed as a bioindicator of variable growing conditions. The most frequently used crop-related data source is a yield map, particularly in locations where grain cropping is practiced in large fields. Yield maps summarize the overall impact of management activities and of natural conditions, such as weather and soils. However, yield data provide only a retrospective analysis and does not allow the user to address any spatial and temporal inconsistencies in crop growth during the corresponding growing season. Therefore, different in-season sensing scenarios have been implemented to provide feedback on crop performance in time to alter management decisions according to local needs. One example of this is online crop canopy sensing for in-season fertilizer management. Crop canopy reflectance in visible and near-infrared wavelengths is normally used to calculate vegetation indexes, which can be related to plant biomass, chlorophyll content, and/or nitrate stress (Shanahan et al., 2008). It has been demonstrated that detection and identification of weeds using machine vision systems is feasible as well; other crop status sensing techniques such as laser florescence, thermal imaging and ultrasonic proximity sensing are the subject of ongoing research.

One of the main limitations of any sensor-based management is that virtually every layer of information can respond to more than one soil, landscape, or crop property used to describe growing conditions and process. This makes a corresponding decision-making strategy uncertain and/or complex when attempting to deploy it over different production settings (McBratney et al. 2005). Using a combination of conceptually different sensing techniques and integrating the subsequent data holds promise for providing more accurate property estimates, leading to more robust management and increased adoptability of sensor-based crop management. The goal of this publication is to discuss the concept of sensor fusion relevant to precision agriculture and to provide the framework for future research in this area.

## 2. Proximal sensing sechnologies

Some proximal sensor systems can be operated in a stationary field position and can be used to: 1) make a single site measurement; 2) produce a set of measurements related to different depths at a given site; or 3) monitor changes in soil properties when installed at a site for a period of time. Although single site measurements can be beneficial for a variety of applications, high-resolution thematic soil maps are typically obtained when measurements are conducted while the sensor systems are moved across the landscape. These on-the-go proximal soil sensing technologies have become an interdisciplinary field of research and their development provides essential tools for precision agriculture and other areas of natural resources management (Hummel et al., 1996; Sudduth et al., 1997; Adamchuk et al., 2004; Shibusawa, 2006; Viscarra Rossel et al., 2011). Proximal crop sensors have been used to determine such physiological parameters as biomass, chlorophyll content, height, etc. that indicate a spatially non-consistent status of agricultural crops, such as nitrogen deficiency or water stress (Solari et al., 2008; Samborski et al., 2009).

Sensors have been used to supplement either predictive or reactive approaches to differentiated crop management. As shown in Figure 1, the reactive (real-time) method of sensor deployment means that the application rate changes in response to local conditions assessed by a sensor at the time of application. In contrast, for a predictive (map-based) strategy, many soil sensors are used to generate soil property maps that can be processed and interpreted off site prior to making decisions about the optimized distribution of

agricultural inputs. Unfortunately, real-time sensing is not feasible due to the time delay or is not optimal if the spatial distribution of sensed soil properties (e.g., soil electrical conductivity) does not change during the growing season. On the other hand, more dynamic parameters (e.g. crop performance indices) need to be defined in real-time so that differentiation of an agricultural input can be accomplished on time to address the cause of variable crop performance. Therefore, some research groups have focused their recent studies on the most promising integrated method (Figure 1c).
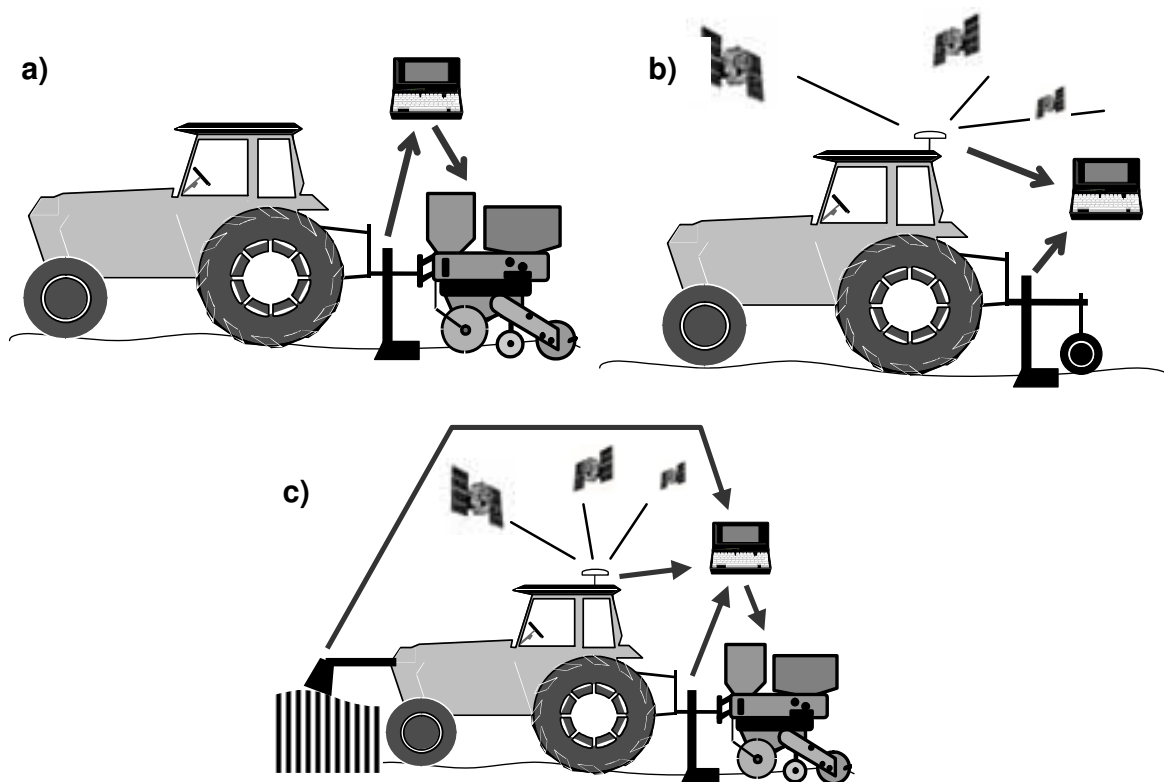


Fig. 1. Proximal sensing deployment strategies that are based on: real time (a), map-based (b), and integrated (c) approaches.

A great variety of design concepts exist, but most proximal soil sensors being developed rely on measuring the soil's ability to reflect or emit electromagnetic energy. In addition, some sensors have been used to quantify the amount of electrical charge that soil media can conduct and/ or accumulate. Also, electrochemical sensors directly detect the activity of specific ions, while mechanistic sensors provide signals relevant to the physical interaction between soil and a measuring tool. Table 1 summarizes different proximal soil sensing systems and classifies them according to the source of energy (active versus passive) and principle of operation (invasive versus non-invasive or stationary versus mobile). The physical and chemical properties of soil have been reported to have a direct (D) or indirect (I) relationship with the signal obtained using different types of sensors listed in Table 2.

In addition to locating sensor measurements, the availability of accurate global navigation satellite system (GNSS) receivers permit the collection of low cost digital elevation data. This data can then be used to provide information on surface geometry (e.g. slope, aspect,

| Sensor Type (wavelength, m) | Method[1] | Energy[2] | Interaction[3] | Operation[4] |
|---|---|---|---|---|
| Gamma-ray ($10^{-12}$) | INS | A | N | S/ M |
| | TNM | A | I | S |
| | Spectroscopy | A/ P | N | S/ M |
| X-ray ($10^{-10}$) | XRF | A | N | S |
| | XRD | A | N | S |
| | UV | A | N | S |
| Optical ($10^{-8}$-$10^{-4}$) | Visible | A/ P | N/ I | S/ M |
| | NIR | A/ P | N/ I | S/ M |
| | MIR | A | N | S |
| | LIBS | A | N | S |
| Microwave ($10^{-2}$) | Microwave | A | N | S |
| | TDR | A | I | S |
| | FDR/ Capacitance | A | I | S/ M |
| Radio wave ($10^{1}$-$10^{6}$) | GPR | A | N | S/ M |
| | NMR | A | N | S |
| | EMI | A | N | S/ M |
| Electrical | EC/ ER | A | I | M |
| | Soil matric potential | P | I | S |
| Electrochemical | ISE/ ISFET | P | N | S/ M |
| Mechanistic | Implement draft | P | I | M |
| | Mechanical impedance | P | I | S/ M |
| | Fluid permeability | A | I | S/ M |
| | Acoustic | P | I | S/ M |

[1] – inelastic neutron scattering (INS), (TNM), x-ray fluorescence (XRF), x-ray difraction (XRD), ultraviolet (UV), near-infrared (NIR), mid-infrared (MIR), laser induced breakdown spectroscopy (LIBS), time domain reflectometry (TDR), frequency domain reflectometry (TDR), ground penetrating radar (GPR), nuclear magnetic resonance (NMR), electromagnetic induction (EMI), electrical conductivity (EC), electrical resistivity (ER), ion-selective electrode (ISE), ion-selective field effect transistor (ISFET)

[2] – active sensors (A) provide their own source of energy, passive sensors (P) rely on ambient or emitted energy

[3] – invasive sensors (I) rely on a direct contact with soil, non-invasive sensors (N) are operated without any soil distortion

[4] – stationary operation (S) requires placing the sensor in a specific geographic location at a fixed or variable depth, mobile operation (M) allows on-the-go soil sensing.

Table 1. Classification of Proximal Soil Sensors (adapted from Viscarra Rossel et al., 2011)

landscape position) as an indirect descriptor of soil. Local variations in terrain control the movement of sediments, water and solutes in the landscape. Soil formation is strongly influenced by these processes and terrain-related attributes can be used to help characterize the spatial distribution of soil properties (Moore et al., 1993). Elevation data also provides the landscape framework for interpreting results from other sensors.

## 3. Sensor fusion

As every soil-sensing technology has strengths and weaknesses and no single sensor can measure all soil properties, the selection of a complementary set of sensors to measure the

| Soil property[1] | Sensor type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Gamma-ray | X-ray | Optical | Microwave | Radio wave | Electrical | Electrochemical | Mechanistic |
| **Chemical** | | | | | | | | |
| Total carbon | D | D | D | | | | | |
| Organic carbon | I | | D | | | | | |
| Inorganic carbon | I | | D | | | | | |
| Total nitrogen | D | D | D | | | | | |
| Nitrate-nitrogen | | | I | | I | I | D | |
| Total Phosphorus | D | D | I | | | | | |
| Extractable phosphorus | | | | | | | | |
| Total Potassium | D | D | D | | | | | |
| Extractable potassium | | | I | | | | I | |
| Other major nutrients | D | D | D | | | | | |
| Micronutrients, elements | D | D | D | | | | | |
| Total Iron | D | D | D | | I | | | |
| Iron oxides | I | | D | | I | | | |
| Heavy metals | D | D | I | | | | | |
| CEC | I | | I | | | I | | |
| Soil pH | I | | I | | D | | D | |
| Buffering capacity and LR | | | I | | | | I | |
| Salinity and sodicity | | | | | D | D | D | |
| **Physical** | | | | | | | | |
| Color | | | D | | | | | |
| Water content | D | | D | D | D | D | | I |
| Soil matric potential | I | | | | | D | | I |
| Particle size distribution | I | | I | | I | I | | I |
| Clay minerals | I | D | D | | | I | | I |
| Soil strength | | | | | | | | D |
| Bulk density | I | | I | | D | | | I |
| Porosity | | | | | | | | D |
| Rooting depth | | | | | I | | | D |

[1] – soil properties directly (D) or indirectly (I) predictable using different types of proximal soil sensors

Table 2. Predictability of Main Soil Properties Using Different Soil Sensing Concepts (adapted from Viscarra Rossel et al., 2011)

required suite of soil properties is important. Integrating multiple proximal soil sensors in a single multisensor platform can provide a number of operational benefits over single-sensor systems, such as: robust operational performance, increased confidence as independent measurements are made on the same soil, extended attribute coverage, and increased dimensionality of the measurement space (e.g., conceptually different sensors allow for an emphasis on different soil properties).

There are few reports of multisensor systems directed at PSS in the literature. For example, Lund et al. (2005) and later Jonjak et al. (2010) reported on a mobile sensor platform that simultaneously measures soil pH and apparent electrical conductivity (Figure 2). This system has been used to develop lime prescription maps, as electrical conductivity helps differentiate liming needs for soils with different texture at the same level of acidity. Adding a real time kinematic (RTK) level GNSS receiver allowed for the development of accurate elevation maps that together with the map of apparent electrical conductivity helped delineate field areas with different water holding capacity (Pan et al., 2008). Adamchuk et al. (2005) used the same apparatus to measure soil nitrate, soluble potassium and sodium at the same time as pH. An NIR sensor has also been suited for a later version of this multisensor platform (Christy, 2008).
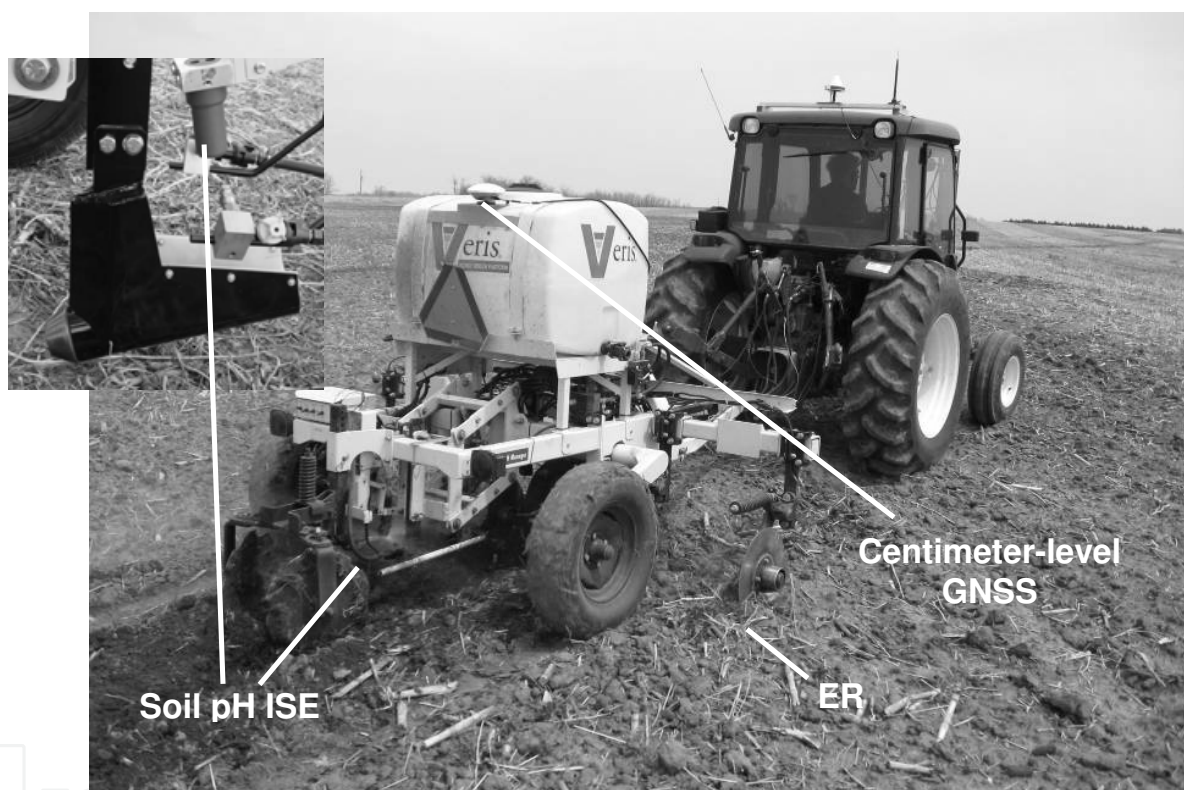


Fig. 2. Sensor system integrating soil electrical conductivity and pH mapping along with a centimeter-level GNSS receiver (Jonjak et al., 2010).

In other research, Adamchuk and Christensen (2005) described a system that simultaneously measured soil mechanical resistance, optical reflectance and capacitance (Figure 3). Integrating the three types of sensors addressed spatial variability in soil organic matter, water content and compaction. Taylor et al. (2006) reported on the development of a multisensor platform consisting of two EMI instruments, ER and pH sensors, a gamma-radiometer and a high-resolution DGPS (Figure 4). Such a system can be used to investigate the entire array of physical and chemical soil characteristics and represents an ultimate solution that can be simplified when adopted for a given application.

In addition to mapping spatial soil variability, there is a need to explore the way in which soil properties change with depth and time. For that reason a variety of penetrometers
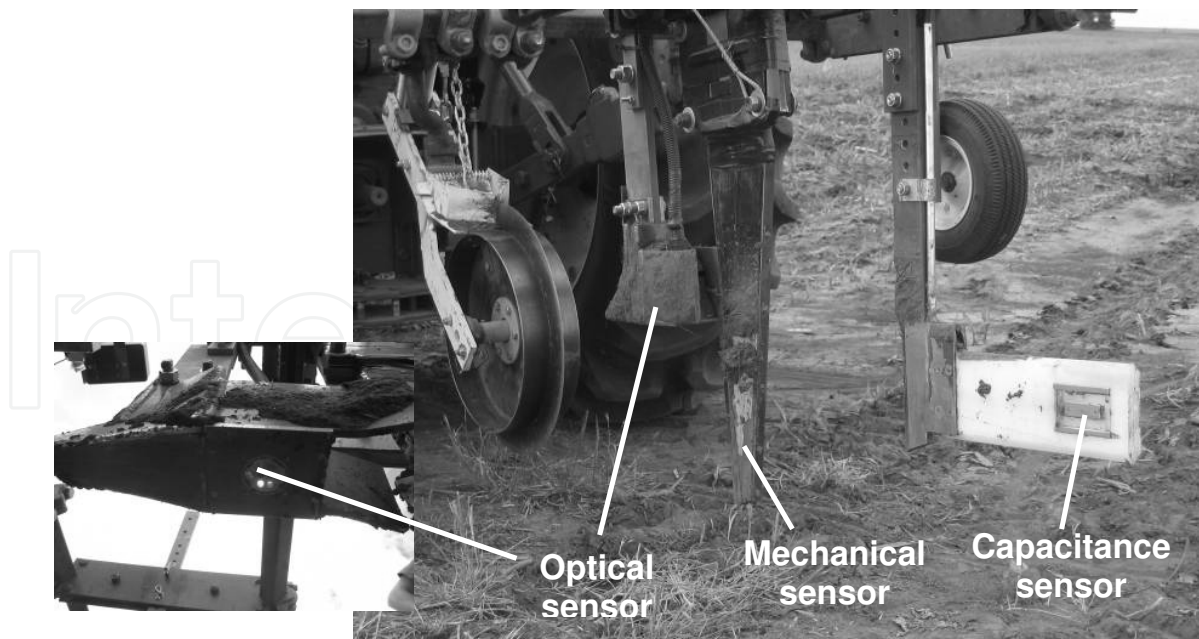
Fig. 3. Prototype sensor integrating optical, mechanical and capacitance components (Adamchuk et al., 2005).
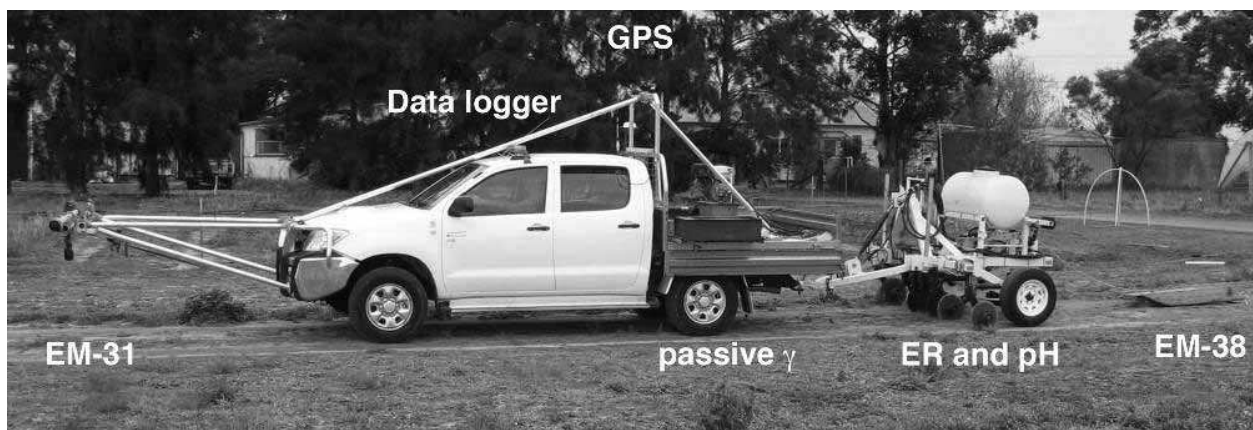


Fig. 4. A multisensor platform integrating several EC/ ER sensors with gamma radiometry and soil pH sensing capabilities (Taylor et al., 2006).

integrating different sensors has been developed. For example, Sun et al. (2008) reported on the development of a multisensor technique for measuring the physical properties of soil, including soil water, mechanical strength and electrical conductivity (Figure 5).

Wireless sensor networking allows sensor fusion to be employed in mobile or stationary sensor applications. A stationary soil probe application provides the instrumentation for the long term monitoring of soil conditions. For example, a network of soil water content monitoring sites (Figure 6) can be used to blend temporal data obtained from different locations across the landscape to alter irrigation scheduling to optimize water use efficiency (Pan et al., 2010). In addition, the wireless transfer of data and signals from mobile sensors extends multiple sensor integration to various positions on agricultural machinery. By minimizing the physical connections between sensors, smart sensor operations can be designed.

**1.Control box**
**2. Depth senor**
**3. Force sensor**
**4. Penetration rod**
**5. Water content sensor**
   **and EC sensor**
**6. Footplate**
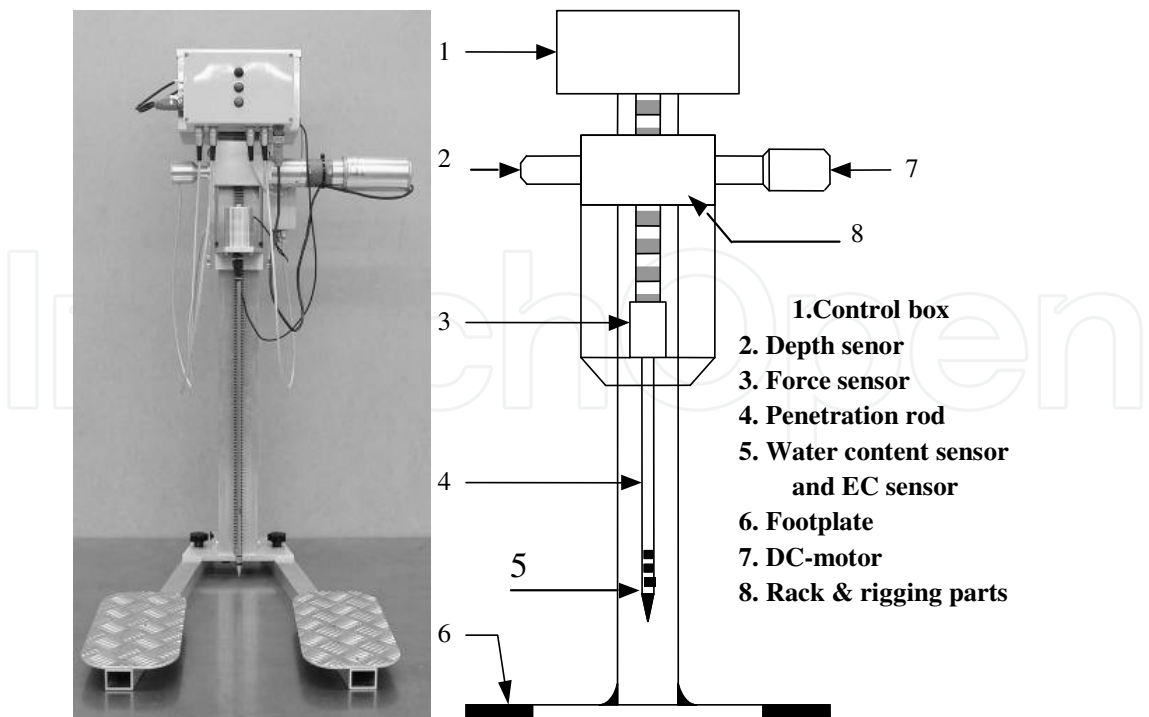**7. DC-motor**
**8. Rack & rigging parts**

Fig. 5. Vertical cone penetrometer with sensors for soil water content and apparent electrical conductivity (Sun et al., 2008).
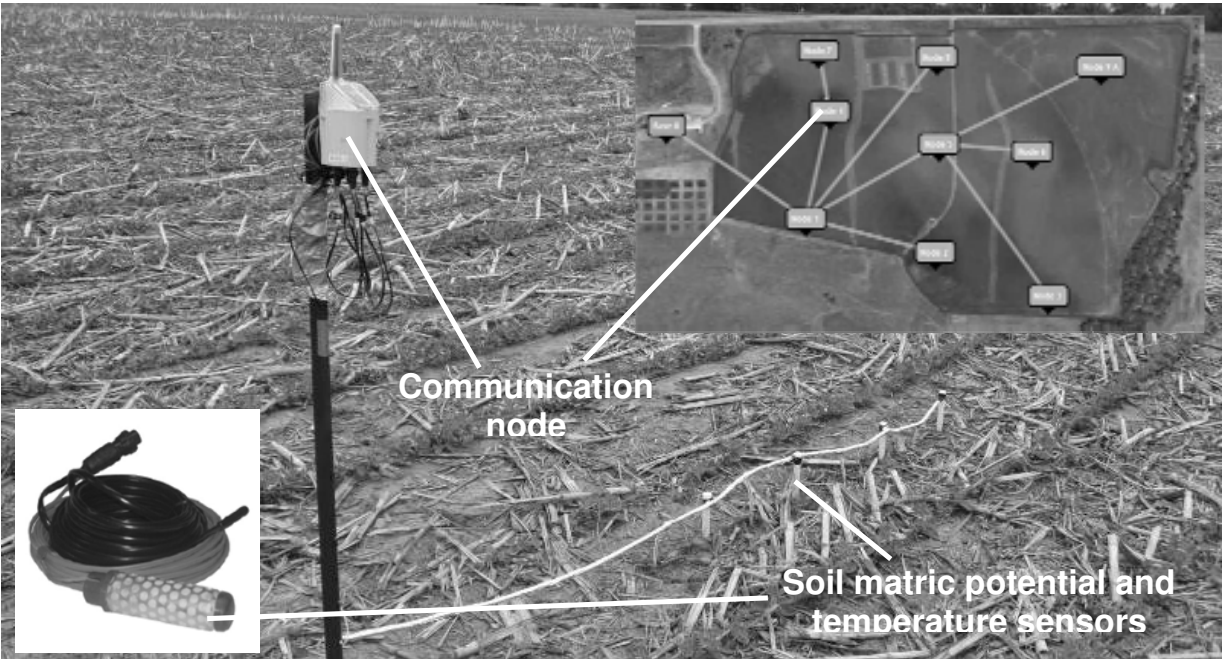


Fig. 6. An example of wireless sensor network (Pan et al., 2010).

With regards to proximal crop sensing, our on-going research (Shiratsuchi et al., 2009) employs a system integrating active crop canopy reflectance sensing with crop height assessment using ultrasonic sensors along with crop canopy temperature sensing (Figure 7). The need for such integration can be explained by the difference in crop physiology when either nitrogen or water stress conditions are observed.
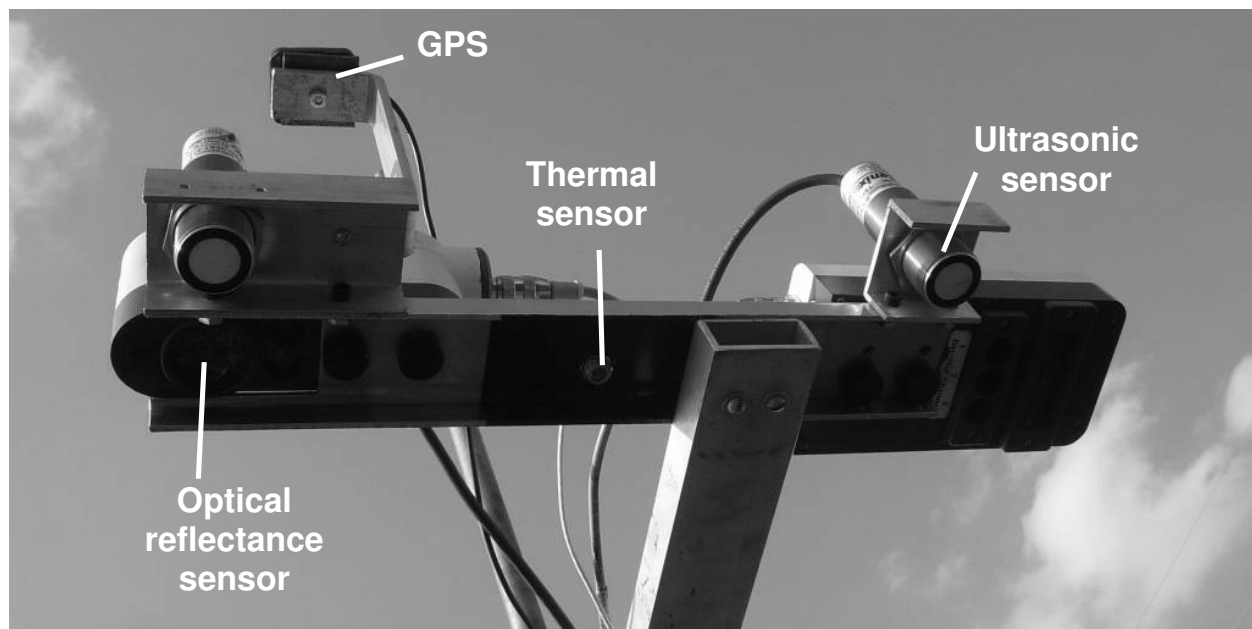
Fig. 7. An integrated crop sensing system (upgraded prototype from Shiratsuchi et al., 2009).

## 4. Data integration

Producers prefer sensors that provide direct inputs for existing prescription algorithms. Instead, commercially available sensors provide measurements such as apparent electrical conductivity that cannot be used directly since the absolute value depends on a number of physical and chemical soil properties such as texture, organic matter, salinity, moisture content, temperature, etc. In contrast, these sensors give valuable information about soil differences and similarities which make it possible to divide the field into smaller and relatively homogeneous areas referred to as finite management elements (FME) or management zones. For example, such FME could be defined according to the various soil types found within a field. In fact, electrical conductivity maps usually reveal boundaries of certain soil types better than conventional soil survey maps. Various anomalies such as eroded hillsides or ponding can also be easily identified on an EC map. Different levels of productivity observed in yield maps also frequently correspond to different levels of electrical conductivity.

Therefore, it seems reasonable to use electrical conductivity maps along with other data layers (e.g., yield maps, aerial imagery, terrain, management history, etc.) to discover the heterogeneity (variability) of crop growing conditions within a field. When based on multiple data layers, FMEs with a similar EC and relatively stable yield may receive a uniform treatment that can be prescribed based on a reduced number of soil samples located within each FME. In addition, soil sensors may be useful in identifying areas within fields which are less profitable or environmentally risky to farm. Work by Corwin and Lesch (2003), and by Heiniger et al. (2003), can serve as examples of site-specific data management that includes processing of electrical conductivity maps.

With regards to proximal crop sensing, optimization of application rates of crop inputs may require combining data from both crop and soil sensors. One type of crop sensor has been used to detect parameters related to the physical crop size using mechanical,

ultrasonic or other proximal sensing. Recently, optical reflectance sensors that detect the ability of the crop canopy to reflect light in the visible and near-infrared parts of the electromagnetic spectrum have become popular (Shanahan et al., 2008). Sensor-based information on physical crop size has been used to vary the application rate of agricultural chemicals according to the predicted demand, while crop reflectance sensing has been used to alter the in-season supply of fertilizer and/ or water to supplement what is locally available from the soil. However, in both cases information on soil variability may need to be combined with plant information to optimize in-season fertilization to account for a spatially different crop response (Roberts et al., 2010). Discussed earlier field terrain and soil electrical conductivity maps can be used to account for spatial differences in soil conditions.

Figure 8 illustrates the process of combining different sources of precision agriculture data that can be applied to assist with crop management decisions. Data can be obtained both from mobile, real-time sensing and from georeferenced maps of parameters such as crop yield and topography. The integration process may lead to management zone delineations and interpolated high-resolution maps that can be used to prescribe the spatially-variable management of agricultural inputs such as fertilizer. Alternatively, data integrated temporally could be used to manage an in-season farming operation, such as irrigation.
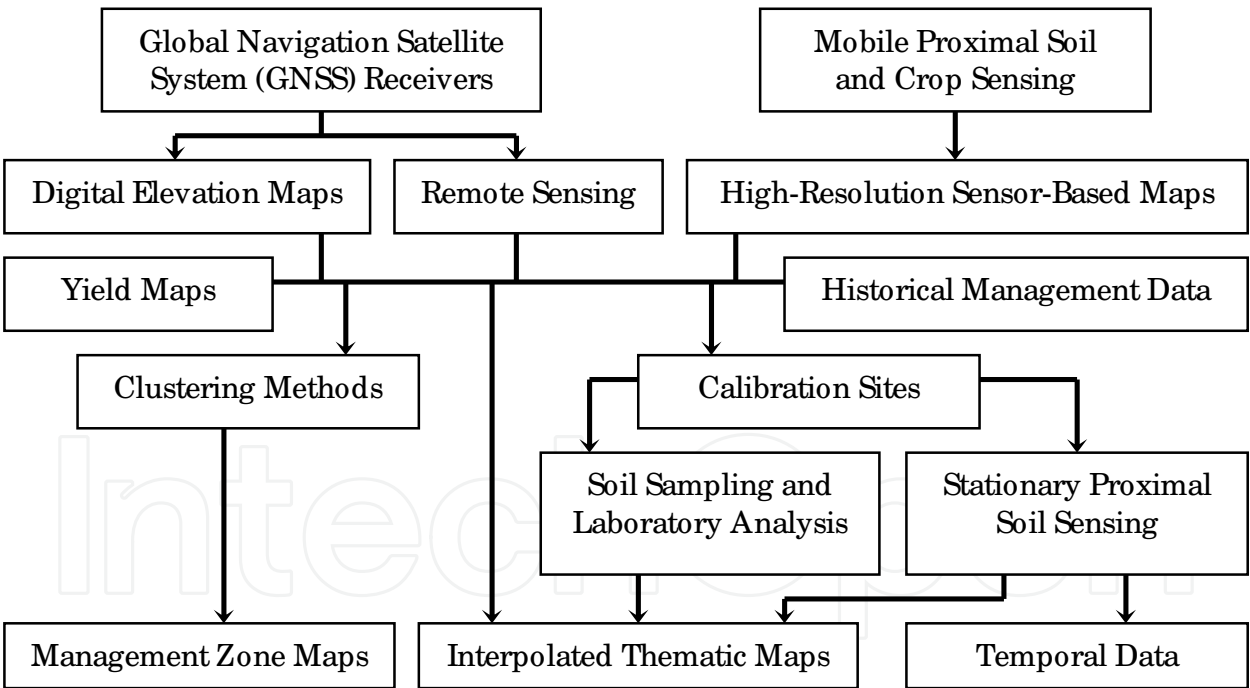


Fig. 8. Data integration in precision agriculture.

As illustrated in the flowchart, discrete management of finite field areas (zones) can be conducted based on maps produced using clustering methods that can integrate multiple layers of crop performance (e.g., yield) and/ or remote/ proximal sensing data (Fridgen et al, 2004. In many cases, each zone will need additional investigation or data collection to determine the most appropriate treatment plan. Another approach is to algorithmically

convert one or multiple layers of high-resolution sensor data into a thematic map. In this case, additional point-based measurements or calibration sampling may be needed to relate the sensor signal to the parameter of interest. Finally, high-density data can be used to locate temporal monitoring sites that will provide information on how different field areas behave during the growing season.

As many precision agricultural practices are specific to a given geographical area and to particular cropping systems, the set of most informative sensors and data layers may also vary from location to location and from practice to practice. On one hand, adding new data always requires additional costs, but does not always bring new information as many spatial data layers are highly correlated. Nevertheless, when different sensors are assigned different functions in the development of a multisensor system, more robust solutions can be found and deployed over a wider range of farm operations. New research in the area of sensor fusion for precision agriculture is expected to provide a variety of such examples.

## 6. Summary

Precision agriculture encompasses identifying, understanding and utilizing information that quantifies variations in soil and crop within agricultural fields. The information needed is generally spatially and/or temporally intensive, which has led to the development of various sensing technologies that assess the soil or crop. These sensing systems are based on diverse measurement concepts, including electrical and electromagnetic, optical and radiometric, mechanistic, and electrochemical.

Robustness of single-sensor measurements is often less than ideal because virtually all currently used sensor technologies can respond to more than one basic parameter of interest. For example, crop canopy reflectance sensors can be affected by multiple stressors such as water or nitrogen deficiencies, the reflectance of the underlying soil, and the size of the crop plants. A sensor fusion approach that integrates canopy reflectance sensing with other sensors measuring plant size and soil parameters has the potential to improve the measurement accuracy of agronomically important stresses in the crop. Accurate measurements are important to determine the best management treatment because the economic and/or environmental risk associated with applying the wrong treatment to the crop can be large.

Some examples of integrated soil and crop sensing systems that combine multiple sensors already exist, and others are in various stages of development. However, multisensor platforms are difficult to implement in an agricultural setting due to constraints such as cost and durability. Typically low profit margins mean that agricultural producers are not willing to adopt technology with a high added cost. Reliability of sensor systems in field conditions including dust, moisture and vibration is difficult to attain, particularly given the cost constraints. The need to keep multiple sensors functioning simultaneously magnifies this problem. Nevertheless, researchers and developers have recognized the benefits of integrating multiple sensor datasets for agricultural decision-making. Finding an appropriate set of sensors and spatial data layers for a given application is a research topic of current interest around the world. We expect that many more examples of sensor fusion for precision agriculture will appear in the near future.

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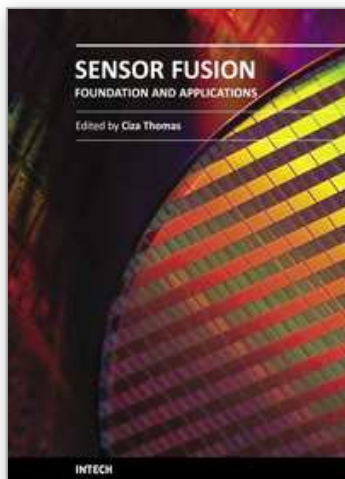
**Sensor Fusion - Foundation and Applications**

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Sensor Fusion - Foundation and Applications comprehensively covers the foundation and applications of sensor fusion. This book provides some novel ideas, theories, and solutions related to the research areas in the field of sensor fusion. The book explores some of the latest practices and research works in the area of sensor fusion. The book contains chapters with different methods of sensor fusion for different engineering as well as non-engineering applications. Advanced applications of sensor fusion in the areas of mobile robots, automatic vehicles, airborne threats, agriculture, medical field and intrusion detection are covered in this book. Sufficient evidences and analyses have been provided in the chapter to show the effectiveness of sensor fusion in various applications. This book would serve as an invaluable reference for professionals involved in various applications of sensor fusion.

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