BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Advances in sensor technology for sustainable crop production

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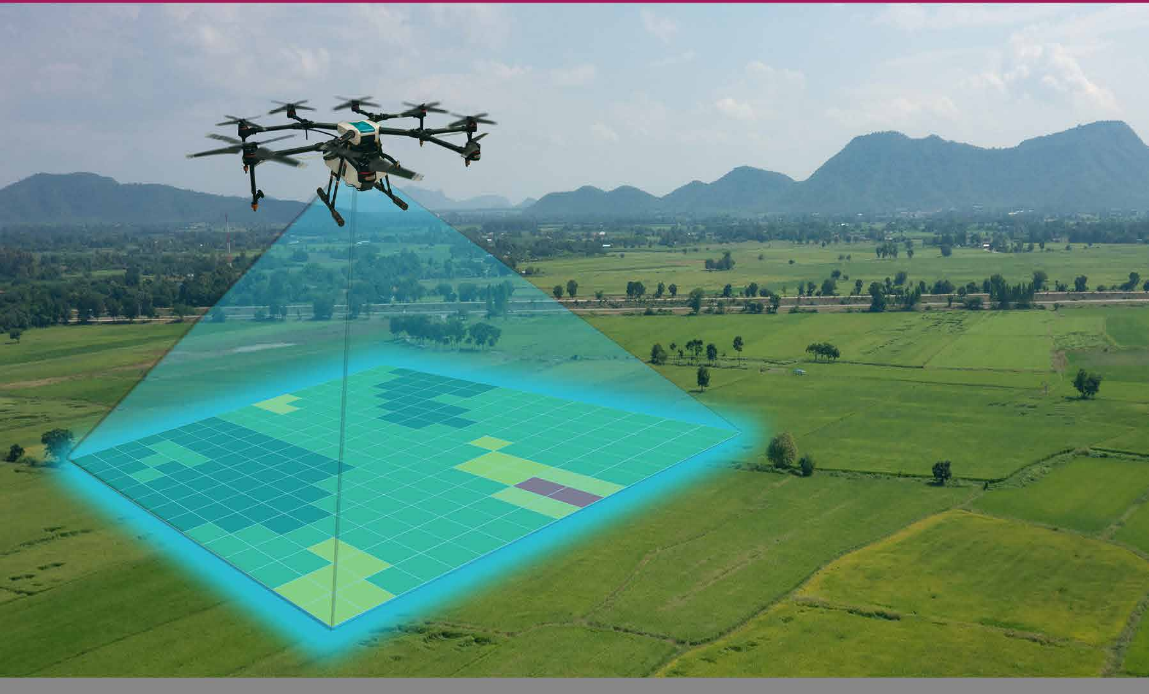

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Introduction

The global agri-food sector is under increasing pressure to produce more food from less inputs, while at the same time preserving important environmental resources. Greater emphasis is being placed on the sustainable management of food production systems, which are a function of numerous complex interactions between many different components, such as soil health and biodiversity.

Soil and crop information is critical to improving both our understanding, and the management of these systems. Better soil and crop information will enable new data-driven solutions that support more productive, resilient and sustainable agri-food systems. However, acquiring the necessary data is a significant challenge. This data must reflect the many key variables driving these systems, which are highly variable across different scales in space and time.

Sensors offer the opportunity to measure crop and soil health at unparalleled scales and resolution. The development of sensor technology will help improve our current understanding and optimisation of complex agri-food systems and support emerging data-driven solutions that improve the productivity and sustainability of crop production.

This volume provides a comprehensive review of key developments in sensor technology to improve monitoring and management of crop health, soil health, invasive plants and diseases. The volume is divided into three parts: In Part 1 each chapter will focus on advances in remote sensing technologies and techniques, that assess crop water status, crop health and soil health. Chapters in Part 2 highlight various proximal sensing technologies to assess soil health and water status. Part 3 draws attention to advances in sensor data analytics, such as machine vision technologies, the use of machine learning and proximal sensor fusion/multi-sensor platforms.

Part 1 Advances in remote sensing technologies

The first chapter of the book examines advances in remote and aerial sensing of crop water status. Chapter 1 begins by discussing the quantification of plant water status and the various methods used to assess plant water stress. It then moves on to examine the use of electromagnetic radiation and how it can interact with matter. A section on optical remote sensing of plant water status is also provided, followed by sections on thermal infrared remote sensing and microwave remote sensing of plant water status. The chapter also offers potential areas for future research development and other sources for further information.

The next chapter explores how current advances in remote sensing can contribute to improve the monitoring of plant health in response to stresses such as disease. Chapter 2 includes a case study that demonstrates how very high-resolution remote sensing data from drones, combined with deep learning models, can be used to evaluate stripe rust in the field. The chapter also discusses current limitations of remote sensing to provide accurate and specific data on plant health and disease and how these might be addressed.

The final chapter of Part 1 looks at advances in remote and aerial sensing techniques for monitoring soil health. Chapter 3 first discusses how active microwave remote sensing has been used to map soil moisture, providing theoretical, empirical and semi-empirical approaches that have been developed as a result of this form of sensor. A section on passive microwave sensing is also included, focusing on the impact of vertical soil moisture and temperature profiles, as well as the impact of surface roughness and the vegetation canopy layer. This section is then followed by an overview of how remote sensing can be used for the analysis of soil properties, such as soil moisture, roughness and salinity. A case study on the Murrumbidgee River Catchment in Australia is also provided to support the chapter's main discussion.

Part 2 Advances in proximal sensing technologies

Part 2 opens with a chapter that highlights advances in using proximal spectroscopic sensors to assess soil health. Chapter 4 introduces the concept of soil health and the need for sensor-based soil health measurements. It then reviews methods of soil spectroscopy, including instrumentation and modeling methods for both laboratory and in-situ sensing. The ability of spectroscopy to estimate key soil health properties is covered along with the potential advantages of merging other sensor data with spectral data. The chapter concludes with a case-study example, an exploration of future trends, and suggested sources of additional information.

Chapter 5 looks at advances in using proximal ground penetrating radar (GPR) sensors to assess soil health. The chapter summarises the GPR background needed to apply this technique to agriculture, including a review of basic principles, data acquisition, and data processing methods. Recent advances in each of these areas are described. Applications to soil mapping, soil water content characterization, compaction, and root mass detection are discussed. A case study using GPR groundwaves to map the soil water content at two depths is presented. The chapter concludes with a summary of current capabilities and suggestions for future work.

The subject of Chapter 6 is using proximal electromagnetic/electrical resistivity (ER)/electrical sensors to assess soil health. After a short summary of the soil health concern, the chapter recalls the definitions of the three relevant properties (conductivity, permittivity, magnetic susceptibility), and details the different electrical and electromagnetic techniques used in the soil domain. Two case studies in temperate and arid climates illustrate what can be obtained when using these techniques. A short discussion underlines the perspectives offered by a holistic approach to evaluate soil health characteristics from geophysical measurements.

Moving on from Chapter 6, Chapter 7 looks at using GPR to map agricultural subsurface drainage systems for economic and environmental benefit. The chapter first describes the evaluation of GPR against other proximal soil sensing methods. It then considers the factors potentially impacting GPR drainage pipe detection, goes on to examine GPR assessment of agricultural drainage pipe conditions and associated functionality implications, the effects of GPR antenna orientation relative to drain line directional trends and the integration of GPR with Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) technology. A section on drainage mapping with a multichannel, stepped-frequency, continuous wave 3D-GPR system is also provided which is then followed by a review of complementary employment of GPR and unmanned aerial vehicle (UAV) imagery for drainage system characterization. The chapter concludes with a summary and recommendations for future research.

Part 3 Advances in sensor data analysis

The first chapter of Part 3 examines advances in machine vision technologies for the measurement of soil texture, structure and topography. Chapter 8 begins by providing an overview of the basic principles of machine vision technologies, focusing on areas such as 3D surface modelling and various methods of soil thin section microscopy. Two case studies are also provided in the chapter to support the main text discussion.

Chapter 9 draws attention to using machine learning to identify and diagnose crop disease. The chapter introduces how deep learning for image analysis and classification works and explain the requirements for collecting a dataset of plant disease images for use with deep learning networks. The chapter then discusses the results and successes of various previous studies and highlight pitfalls with individual methods. It is clear that deep learning is capable of handling complex disease classification problems where one disease is present. There is plenty of room for growth to work with the presence of multiple diseases in a single image or to quantify the amount of disease present.

The subject of Chapter 10 is advances in proximal sensor fusion and multi-sensor platforms for improved crop management. The chapter begins by first describing how a plant's height can determine how healthy it is and the importance of using proximal and remote sensing to assess this. The chapter moves on to examine remote sensing and weather data analysis and then goes on to describe multi-sensor approaches. A section on the statistical tools that can be used for fusing multi-sensor data is also included focusing on emerging machine learning tools.

The final chapter of the book reviews key issues in using sensor data in precision agriculture and, in particular, their mode of deployment (proximal or remote). Chapter 11 assesses relative strengths and weaknesses of proximal sensing techniques, compared with imaging data typically acquired from remote sensing platforms, before assessing trade-offs in sensor data resolution, as well as sources of error in the way data is processed. The chapter concludes by looking at ways of integrating remote and proximal sensor data, to utilise the beneficial characteristics of each type of data to improve the impact precision agriculture in improving efficiency and sustainability.

Chapter 1

Advances in remote/aerial sensing of crop water status

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1 Introduction

Water is the most critical input for crop production, and agriculture is the top water user, especially in arid and semiarid regions. Irrigated agriculture accounts for approximately 70% of worldwide freshwater withdrawals, making agricultural water use one of the leading drivers of global water shortages (Tshwene and Oladele, 2016). As the world population increases, agriculture is under pressure to produce more in limited arable land while consuming less water per unit of output (Zwart and Bastiaanssen, 2004; Tshwene and Oladele, 2016; Guo et al., 2015). The extensive ranges in water use efficiency (WUE) indicate agricultural production can be sustained with 20–40% less water use if improved water management strategies are implemented (Zwart and Bastiaanssen, 2004). Various technologies are applied to improve WUE and water conservation. For example, precision irrigation technologies incorporate spatial and temporal plant water needs into irrigation scheduling for optimizing water management. Site-specific and real-time crop water status is critical for decision support in irrigation scheduling and precision water management.

http://dx.doi.org/10.19103/AS.2022.0107.01

Water typically accounts for more than 70% of the weight of non-woody plants (Hopkins and Huner, 2009). Most water in leaves resides in mesophyll cells (Fig. 1). Sufficient water supply is critical for the plant to maintain physiological processes and healthy growth and development (Gardner, 1984), such as transpiration, photosynthesis, phloem transport, respiration, and other metabolic activities. Water changes in the leaves affect internal conditions of the plant, such as tension in the cell walls, exchange of water and CO_2 across cell membranes, cell-to-cell contact and transport of water, and cell and tissue turgor (Govender et al., 2009).

The water status of a given tissue in a plant is determined by three factors, including soil water potential, transport resistance, and transpiration rate (Buckley, 2019). When water supply is insufficient, plants will suffer water stress with decreased leaf water potential and cell turgor that inhibits normal plant functions (Hsiao, 1973; Kim et al., 2018). Turgor pressure, also referred to as hydrostatic pressure, is the pressure exerted by the cell fluid against the cell wall. The stomata will close due to lack of water to maintain pressure in the guard cells. Stomatal closure prevents water loss, the movement of CO_2 into the plant, and photosynthetic rates of the leaves (Loka et al., 2011). Significant correlations between leaf water potential and stomatal conductance under water deficit stress have been reported (Loka et al., 2011). At the plant or canopy scale, plant water stress can result in decreased physiological activities and inhibition of growth, development, and survival (Govender et al., 2009). The effects of water stress on different physiological processes are complicated and interrelated (Loka et al., 2011). They are dependent on the duration and severity of water stress, plant genetics, and growth and developmental stages. Cell elongation is the most affected by water stress during early plant growth and development (Hsiao et al., 1976). Moderate water stress with relative water content (RWC) greater than 70% may cause structural variations, such as tissue thickness reductions, which in turn can affect foliar optical properties and

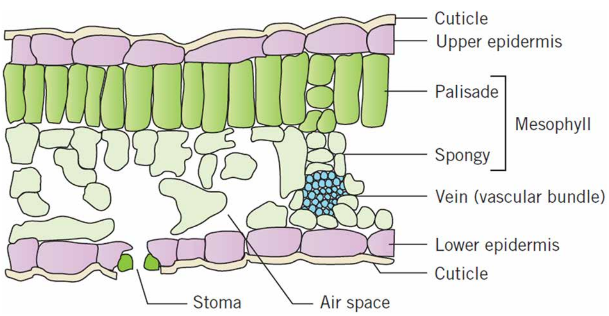

Figure 1 Diagrammatic cross-section representation of a typical mesomorphic leaf with extensive intercellular spaces with access to the ambient air through the open stomata. Source: Hopkins and Huner (2009).

spectral signatures. Severe water stress results in irreversible plant damage, accentuated drop in pigment content, reduced leaf area, dwarfed plant stature, or plant death (Baranoski and Van Leeuwen, 2017). In addition, plant water stress causes reduced transpiration rates and increased leaf temperature as less latent heat associated with transpiration is lost from the leaf. Water stress ultimately affects crop yield. The effects of water stress on yield depend on stress severity in relation to crop type, genotype, growth stage, management, and environmental conditions. Therefore, effective and efficient determination of plant water status can help minimize the impact of water stress on crop growth, maximize WUE, enhance water conservation, and improve crop production.

2 Quantification of plant water status

Accurate and timely information about plant water stress in relation to soil moisture and weather conditions at different crop growth stages is required for the evaluation of plant physiological conditions and decision support in precision water management, especially irrigation scheduling. Plant water status, soil moisture conditions, and crop evapotranspiration (ET_c) can be used as decision support in irrigation scheduling. The widely applied soil water balance approach calculates water inputs and losses to determine irrigation needs. A potential issue with this method is that many plant physiological features respond directly to changes in water status in the plant tissues rather than to changes in the bulk soil water content. In addition, the plant response to soil water content varies as a complex function of evaporative demand. Therefore, greater precision in the application of irrigation can be obtained through determining or sensing plant water stress conditions (Jones, 1990, 2004). Plant-based irrigation scheduling is complementary to soil- or ET_c-based methods as plant water status provides information on when to irrigate in response to plant water stress.

Assessment of plant water stress is usually based on the level of selected physiological parameters, such as water potential, RWC, stomatal reactions, photosynthesis rate, or osmotic adjustment (Bolat et al., 2014). The determination of leaf water content is widely used to estimate the water status of the plants. Plant water content is commonly described by the leaf RWC and equivalent water thickness (EWT). RWC is the ratio of the actual leaf water content to the maximum water content at full turgor pressure. It is calculated as:

$$\mathrm{RWC} = \frac{M_{\mathrm{fresh}} - M_{\mathrm{dry}}}{M_{\mathrm{turgor}} - M_{\mathrm{dry}}} \times 100\%,$$

where M_{fresh} is the fresh leaf mass immediately after sampling and M_{turgor} is the leaf mass at full turgor pressure obtained after saturating the leaves in water, and dry mass (M_{dry}) is obtained after oven drying samples at 85°C for 24 h (Yamasaki and Dillenburg, 1999; Turner, 1981). RWC is a measure of water deficit in the plant leaf. It is an important indicator of water status in the plant as it reflects the balance between water supply to the leaf tissue and transpiration rate (Lugojan and Ciulca, 2011; Schonfeld et al., 1988).

The leaf water content per unit leaf area or EWT is defined as the quantity of water per unit leaf area (Danson et al., 1992). It is calculated as:

$$\mathrm{EWT} = \frac{M_{\mathrm{fresh}} - M_{\mathrm{dry}}}{A_{\mathrm{leaf}}} \left(\mathrm{g/cm^2}\right)$$

where A_{leaf} denotes the leaf area. Therefore, EWT represents a hypothetical thickness of a single layer of water averaged over the whole leaf area (Danson et al., 1992). EWT is an area-weighted indicator of leaf water content. It is related to a range of physiological and ecosystem processes, including leaf-level tolerance to dehydration (Wright et al., 2004). Therefore, EWT reflects crop water content relative to plant growth status (Yao et al., 2014).

Another plant water measurement is the fuel moisture content (FMC), expressed as the ratio between the quantity of water in vegetation and the dry weight of vegetation. It is calculated as:

$$\mathrm{FMC} = \frac{\mathrm{FM} - \mathrm{DW}}{\mathrm{DW}} \times 100\%$$

where FW is the fresh leaf weight of vegetation measured in the field and DW is the sample weight after it has been oven-dried. FMC is an optimum indicator of vegetation water status, especially for fire risk assessment in forestry or ecology (Maki et al., 2004). In recent years, it has been applied to monitor the water status of agricultural crops, such as corn, soybean, and wheat (Wu et al., 2009; Zhang et al., 2010; Shu et al., 2022).

The direct measurement of water content using RWC, EWT, FMC, or other methods is relatively challenging due to the complexity of determining the parameters in these calculations. Therefore, measures of water status based on the energy status of water in the plant have advantages over volumetric or absolute mass-based measures (Jones, 2007). A prevalent method of energy-based measurement is to determine the leaf water potential using a pressure chamber. A pressure chamber measures the leaf water potential by applying air pressure to a leaf and forcing the water out of it. In this process, the major part of a leaf is placed inside the chamber, with a small part of the leaf stem exposed to the outside of the chamber through a seal for observation. The pressure applied to the chamber that forces the water and sap out measures the water status of the leaf. A high-pressure value indicates a relatively low amount of

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