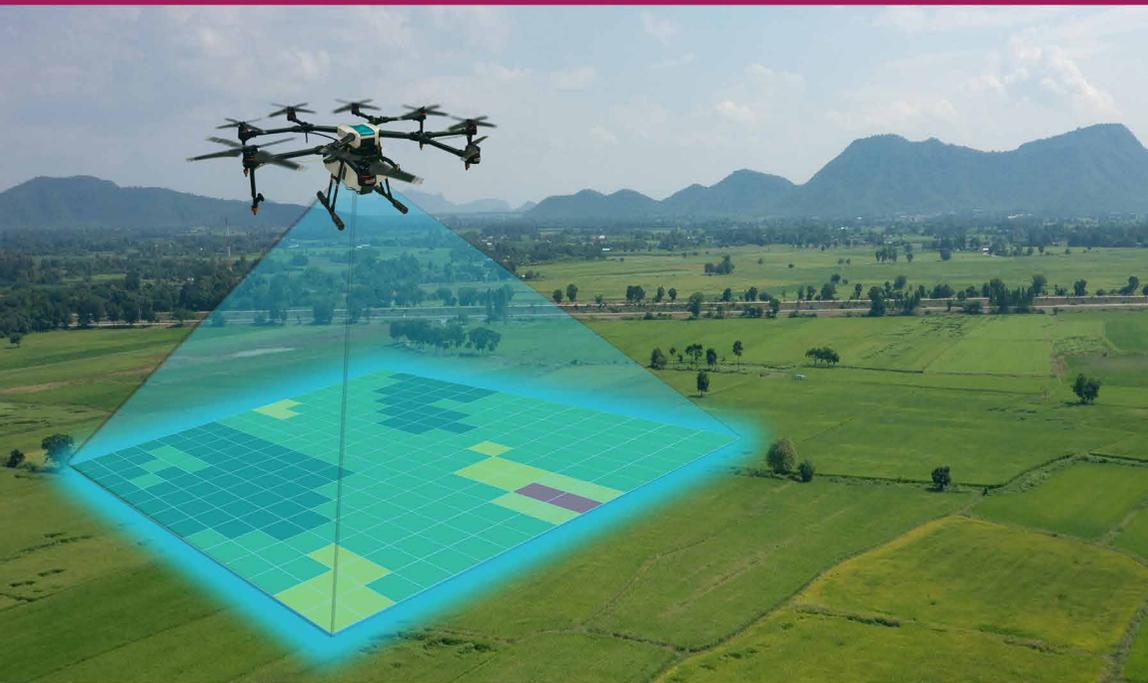


BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Advances in sensor technology for sustainable crop production

Edited by Dr Craig Lobsey, University of Southern Queensland, Australia and Professor Asim Biswas, University of Guelph, Canada



Contents

Series list	x
Introduction	xx
Part 1 Advances in remote sensing technologies	
1 Advances in remote/aerial sensing of crop water status <i>Wenxuan Guo, Texas Tech University and Texas A&M AgriLife Research, USA; and Haibin Gu, Bishnu Ghimire and Oluwatola Adedeji, Texas Tech University, USA</i>	3
1 Introduction	3
2 Quantification of plant water status	5
3 Electromagnetic radiation and interaction with matter	7
4 Optical remote sensing of plant water status	9
5 Remote sensing of plant water status using thermal infrared	16
6 Microwave remote sensing of plant water status	20
7 Conclusion and future trends in research	25
8 Where to look for further information	30
9 References	31
2 Advances in remote sensing technologies for assessing crop health <i>Michael Schirrmann, Leibniz Institute for Agricultural Engineering and Bioeconomy, Germany</i>	43
1 Introduction	43
2 Remote sensing of crop health	45
3 Remote sensing of crop diseases	47
4 Case study: detecting stripe rust using very high-resolution imaging	51
5 Conclusion and future trends	57
6 Where to look for further information	59
7 References	59

3	Advances in remote/aerial sensing techniques for monitoring soil health	65
	<i>Jeffrey P. Walker and Nan Ye, Monash University, Australia; and Liujun Zhu, Monash University, Australia and Yangtze Institute for Conservation and Development, Hohai University, China</i>	
1	Introduction	65
2	Active microwave remote sensing	68
3	Passive microwave remote sensing	71
4	Remote sensing of soil properties	79
5	Case study	84
6	Future trends in research	92
7	Where to look for further information	94
8	References	94

Part 2 Advances in proximal sensing technologies

4	Advances in using proximal spectroscopic sensors to assess soil health	107
	<i>Kenneth A. Sudduth and Kristen S. Veum, USDA-ARS, USA</i>	
1	Introduction	107
2	Soil spectroscopy methods	108
3	Estimation of soil health indicators and indices	116
4	Case study: combining spectra and auxiliary sensor data for improved soil health estimation	120
5	Conclusion	124
6	Future trends in research	124
7	Where to look for further information	125
8	References	125
5	Advances in using proximal ground penetrating radar sensors to assess soil health	133
	<i>Katherine Grote, Missouri University of Science and Technology, USA</i>	
1	Introduction	133
2	Electromagnetic parameters and ground penetrating radar surveying and data processing	134
3	Soil structure	148
4	Soil water content	150
5	Soil density/compaction	154
6	Root detection	155
7	Case study: soil water content measurement using ground penetrating radar groundwaves	157
8	Conclusion and future trends	158

9	Where to look for further information	160
10	References	161
6	Using proximal electromagnetic/electrical resistivity/electrical sensors to assess soil health	171
	<i>Alain Tabbagh, Sorbonne Université, EPHE, UMR7619, Métis, 4 place Jussieu 75252 Paris CEDEX 05, France; and Seger Maud and Cousin Isabelle, INRAE, Centre Val de Loire, UR0272 SOLS, 2163 Avenue de la Pomme de Pin, CS40001 Ardon, F-45075 Orléans Cedex 2, France</i>	
1	Introduction	171
2	Soil physical properties involved in electrical and electromagnetic domains	174
3	Measurement techniques	178
4	Field examples	182
5	The use of electrical and electromagnetic tools to evaluate soil health	188
6	Conclusion	190
7	Where to look for further information	190
8	References	190
7	Using ground-penetrating radar to map agricultural subsurface drainage systems for economic and environmental benefit	195
	<i>Barry Allred, USDA-ARS - Soil Drainage Research Unit, USA; and Triven Koganti, Aarhus University, Denmark</i>	
1	Introduction	195
2	Comparison of proximal soil-sensing methods for drainage pipe detection	197
3	Factors potentially impacting ground-penetrating radar drainage pipe detection	200
4	Ground-penetrating radar assessment of drainage pipe conditions and associated functionality implications	205
5	Effects of ground-penetrating radar antenna orientation relative to drain line directional trends	208
6	Integration of ground-penetrating radar with real-time kinematic global navigation satellite system technology	209
7	Drainage mapping with a multichannel, stepped-frequency, continuous-wave three-dimensional ground-penetrating radar system	212
8	Complementary employment of ground-penetrating radar and unmanned aerial vehicle imagery for Drainage System Characterization	214
9	Conclusion	216
10	Future trends in research	217
11	Where to look for further information	217
12	References	218

Part 3 Advances in sensor data analytics

8	Advances in machine vision technologies for the measurement of soil texture, structure and topography	223
	<i>Jean-Marc Gilliot, AgroParisTech Paris Saclay University, France; and Ophélie Sauzet, University of Applied Sciences of Western Switzerland, The Geneva Institute of Technology, Architecture and Landscape (HEPIA), Soils and Substrates Group, Institute Land-Nature-Environment (inTNE Institute), Switzerland</i>	
1	Introduction	223
2	Basic principles	228
3	Case studies	260
4	Conclusion and future trends	270
5	Where to look for further information	271
6	Acknowledgements	273
7	References	273
9	Using machine learning to identify and diagnose crop disease	285
	<i>Megan Long, John Innes Centre, UK</i>	
1	Introduction	285
2	A quick introduction to deep learning	286
3	Preparation of data for deep learning experiments	288
4	Crop disease classification	291
5	Different visualisation techniques	295
6	Hyperspectral imaging for early disease detection	297
7	Case study: identification and classification of diseases on wheat	298
8	Conclusion and future trends	301
9	Where to look for more information	302
10	References	302
10	Advances in proximal sensor fusion and multi-sensor platforms for improved crop management	307
	<i>David W. Franzen and Anne M. Denton, North Dakota State University, USA</i>	
1	Introduction	307
2	Use of plant height and proximal/remote sensing	309
3	Sensors and weather data	310
4	Multi-sensor approaches	315
5	Statistical tools for fusing multi-sensor data	317
6	Conclusion and future trends	320
7	Where to look for further information	320
8	References	321

11	Using remote and proximal sensor data in precision agriculture applications	327
	<i>Luciano S. Shiratsuchi and Franciele M. Carneiro, Louisiana State University, USA; Francielle M. Ferreira, São Paulo State University (UNESP), Brazil; Phillip Lanza and Fagner A. Rontani, Louisiana State University, USA; Armando L. Brito Filho, São Paulo State University (UNESP), Brazil; Getúlio F. Seben Junior, State University of Mato Grosso (UNEMAT), Brazil; Ziany N. Brandao, Brazilian Agricultural Research Corporation (EMBRAPA), Brazil; Carlos A. Silva Junior, State University of Mato Grosso (UNEMAT), Brazil; Paulo E. Teodoro, Federal University of Mato Grosso do Sul (UFMS), Brazil; and Syam Dodla, Louisiana State University, USA</i>	
1	Introduction	327
2	Remote and proximal sensing in agriculture	328
3	Active and passive sensors	332
4	Trade-offs in sensor data resolution	334
5	Processing sensor data: sources of error and their resolution	338
6	Integrating remote and proximal sensor data for precision agriculture	342
7	Conclusion	344
8	References	345
	Index	353

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

Wenxuan Guo, Texas Tech University and Texas A&M AgriLife Research, USA; and Haibin Gu, Bishnu Ghimire and Oluwatola Adedeji, Texas Tech University, USA

- 1 Introduction
- 2 Quantification of plant water status
- 3 Electromagnetic radiation and interaction with matter
- 4 Optical remote sensing of plant water status
- 5 Remote sensing of plant water status using thermal infrared
- 6 Microwave remote sensing of plant water status
- 7 Conclusion and future trends in research
- 8 Where to look for further information
- 9 References

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.

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 CO₂ 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 CO₂ 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

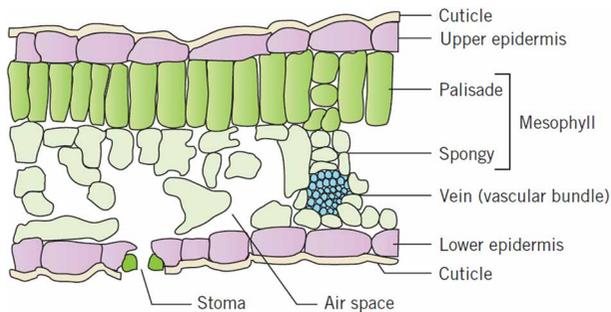


Figure 1 Diagrammatic cross-section representation of a typical mesomorphic leaf with extensive intercellular spaces with access to the ambient air through the open stomata. Source: Hopkins and Huner (2009).

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:

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

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:

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

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:

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

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

Index

- Absorbance spectrum 109
- Accuracy of laboratory visible and near-infrared spectroscopy 122
- Accurate and timely spatial monitoring 44
- Acoustic height measurements 310
- Active canopy sensors (ACS) 329
- Active microwave remote sensing 67
- Advanced Very High Resolution Radiometer (AVHRR) platform 314
- Air-launched GPR surveys 145
- Air-launched ground penetrating radar 139-141
- Airwave and groundwave data 158
- AlexNet 292-295
- AliceVision 241
- Artificial neural networks (ANN) 286
- AVHRR. *see* Advanced Very High Resolution Radiometer (AVHRR) platform

- Back propagation neural network (BPNN) 309
- Backpropagation neural networks (BNNs) 319
- Base sensor 308
- Beam phase shift 234
- BNNs. *see* Backpropagation neural networks (BNNs)
- Borehole ground penetrating radar 141-142
- BPNN. *see* Back propagation neural network (BPNN)
- Bundler package 241

- Canola 314
- Canopy chlorophyll content index (CCCI) 46
- 'Caring for Soil is Caring for Life' 171
- CASIs. *see* Cover-adjusted spectral indices (CASIs)
- Cation exchange capacity (CEC) 317
- CBERS 4 satellite 338
- CCCI. *see* Canopy chlorophyll content index (CCCI)

- CEC. *see* Cation exchange capacity (CEC)
- Chain index (CI) 232
- Chemical soil health indicators 118
- Chlorophyll fluorescence 48-49
- CI. *see* Chain index (CI)
- CNN. *see* Convolutional neural network (CNN)
- Coefficient of variation (CV) 341
- Colmap 241
- Combining spectra and auxiliary sensor data, improved soil health estimation 120
 - improving Vis-NIR soil health estimates, auxiliary data 121-122
 - laboratory Vis-NIR estimation, soil health indicators and scoring functions 121
 - laboratory Vis-NIR estimation, soil organic carbon 120-121
 - profile in situ soil sensing using Vis-NIR spectra and auxiliary data 122-124
- Common-offset data 157
- Computer vision (CV) techniques 228, 232
 - for soil 230, 231
- Conductivity 174-175
- Convolutional neural network (CNN) 286, 291, 296, 297, 319
- Correlative microscopy approach 258
- Corrugated plastic tubing (CPT) 196
- Cover-adjusted spectral indices (CASIs) 315
- CPT. *see* Corrugated plastic tubing (CPT)
- Crop Circle Phenom 316
- Crop diseases, remote sensing 47-51
 - chlorophyll fluorescence 49
 - electronic nose 48
 - hyperspectral measurements 50
 - multispectral camera systems 50-51
 - pathogens 47-48
 - pesticides 48
 - red edge disease stress index (REDSI) 51
 - sun-induced fluorescence (SIF) 49-50
 - volatile organic compounds (VOCs) 48

- Crop health 43
 remote sensing
 red edge 46
 UAV platform 47
 vegetation monitoring 46-47
 visible and near-infrared range 45
- Crop scouting 44
- Crop water stress index (CWSI) 16-17, 19
- CV. see Coefficient of variation (CV);
 Computer vision (CV) techniques
- CWSI. see Crop water stress index (CWSI)
- DA. see Domain adaptation (DA)
- DAI. see Days after inoculation (DAI)
- Data processing methods 230
- Days after inoculation (DAI) 54-55
- Deep neural networks 319
- Dielectric constant 66
- Difference of Gaussian (DOG) 239
- Diffuse reflectance spectroscopy (DRS) 108
- Digital image processing 251
- Digital surface model (DSM) 242-245
- Digital video loggers (DVLs) 211-212
- Direct measurement of water content 6
- DOG. see Difference of Gaussian (DOG)
- Domain adaptation (DA) 320
- Drop-shatter tests 227
- DRS. see Diffuse reflectance spectroscopy (DRS)
- DSM. see Digital surface model (DSM)
- DVLs. see Digital video loggers (DVLs)
- Early time analysis 146-147
- Economic optimum nitrogen rate (EONR) 312
- Electrical resistivity tomography (ERT) 179
- Electric charges 174-175
- Electromagnetic induction (EMI) 182
- Electromagnetic radiation spectrum 7-8
- Electron microprobe 254
- EMI. see Electromagnetic induction (EMI)
- Emitted electromagnetic (EM) radiation 7-9
- EONR. see Economic optimum nitrogen rate (EONR)
- EPO. see External parameter orthogonalization (EPO)
- Equipment and survey setup, GPR drainage systems
 antenna frequency 200-201
 measurement transect orientation (unidirectional *versus* bidirectional) 203
 signal trace stacking and station interval 201-203
- Equivalent water thickness (EWT) 5-6
- ERT. see Electrical resistivity tomography (ERT)
- Estimation of, soil health indicators and indices
 soil biological properties 116-117
 soil chemical properties 118
 soil health indices 118-120
 soil physical properties 117
- EU Biodiversity Strategy 43
- EWT. see Equivalent water thickness (EWT)
- External parameter orthogonalization (EPO) 113
- Extreme water stress conditions 18
- Fuel moisture content (FMC) 6
- Full-spectrum calibration 109-110
- Full waveform inversion 146
- GCPs. see Ground control points (GCPs)
- Geometric preprocessing 230
- Geophysical methods 133
- Geophysical techniques 133-134
- Global navigation satellite system (GNSS) 209, 211-212
- GoogLeNet 292, 294
- GPR. see Ground penetrating radar (GPR)
- GPR four-step processing flow 156-157
- GPR mapping agricultural subsurface drainage systems, economic and environmental benefit
 assessment of, pipe conditions and associated functionality implications
 computer modeling and field research 205
 computer-simulated and actual test plot GPR profiles over the top and along trend 207
 computer-simulated and actual test plot GPR profiles perpendicular to drain line 206
 radar signals 206
 research results 205-206
 response to air- and water-filled drainage pipes 207-208
 comparison of proximal soil-sensing methods, drainage pipe detection methods 197
 radar signal 198
 representative GPR results 199-200

- system operation 197-198
- two-way travel time 198-199
- complementary employment of GPR and unmanned aerial vehicle imagery, characterization 214-216
- effects of, antenna orientation, drain line directional trends 208-209
- factors impacting, drainage pipe detection 200
 - computer processing 205
 - equipment and survey setup 200-203
 - site conditions 203-204
- integration, realtime kinematic global navigation satellite system technology 209-212
- mapping, multichannel, stepped-frequency and continuous-wave three-dimensional GPR 212-214
- multichannel, stepped-frequency, continuous-wave 3D GPR system 213
- overview 195-197
- synopsis 216-217
- UAV survey results 215
- GPR profiles exhibiting antenna frequency effects 202
- Ground control points (GCPs) 260, 261
- Ground-coupled, common-offset GPR reflection data 148-149
- Ground-coupled ground penetrating radar
 - CMP and WARR surveys 138-139
 - common-offset profiling 137-138
 - electromagnetic energy paths 136-137
 - spherical wavefront 136
 - trace 137-138
 - variableoffset profiling 138
- Ground penetrating radar (GPR) 134
- Guided waves 147-148

- HCP. see Horizontal coplanar (HCP)
- Homologous points 237
- Horizons 225
- Horizontal coplanar (HCP) 181
- Hover & Capture 246
- Hybrid-Maize model 313
- Hyperspectral measurements 50

- IEEE microwave frequencies and application. agriculture 21
- ILSVRC. see ImageNet Large Scale Visual Recognition Challenge (ILSVRC)
- ImageNet dataset 288
- ImageNet Large Scale Visual Recognition Challenge (ILSVRC) 289
- In-field soil sensors 111
- In-season estimate of yield (INSEY) 312
- In situ sensing 111
- Interferometric method 234
- International Society of Precision Agriculture (ISPA) 327
- IR radiation 11
- Irrigation scheduling 6
- ISPA. see International Society of Precision Agriculture (ISPA)

- Key points 237

- Laboratory reflectance spectra 10
- LAI. see Leaf area index (LAI)
- LASSO. see Least absolute shrinkage and selection operator (LASSO)
- Leaf area index (LAI) 313, 314
- Least absolute shrinkage and selection operator (LASSO) 318
- Leica Disto laser telemeter 246
- Linear regression 317, 318
- Liquid water absorption spectrum 8-9
- Long-short term memory (LSTM) models 320

- Machine learning, identify and diagnose crop disease
 - crop disease classification 291-294
 - deep learning 286-288
 - data preparation 288-291
 - future trends 301-302
 - hyperspectral imaging 297-298
 - overview 285-286
 - visualisation techniques 295-297
 - wheat diseases, identification and classification 298-301
- Machine learning approaches 110
- Machine vision technologies
 - case studies
 - Nicodrilus nocturnus* and *Allolobophora icterica* effects 267-270
 - photogrammetric approach applied to slaking mapping 260-263
 - quantify biological porosity, image analysis procedure 263-267
 - future trends 270-271
 - soil texture, structure and topography measurement 228-232

- soil thin-section microscopy
 - limitations and perspectives 258-263
 - micromorphological approach 248-250
 - microstructure
 - characterization 251-252
 - pedofeature identification, characterization and quantification 253-256
 - pore quantification, two-dimensional images 251-252
 - quantitative micromorphology 251
 - sampling, fabrication and observation techniques 250-251
 - three-dimensional pore quantification 252-253
 - 2D and 3D images combining, pedofeature characterization and quantification 256-258
 - three-dimensional surface modelling, soil topography analysis 232-248
- Magnetic susceptibility 174-175
- MAIZE-N model 311
- Manual methods of determining crop water status 6
- Map soil structure 148-150
- Metashape 241
- Microscopes 229
- Microsoft Kinect depth camera 246, 247
- Microwave band designations 66
- Microwave interaction, vegetation and soil 23
- Microwave remote sensing measures 66
- Mobile near-infrared spectrophotometer 112
- Moderate Resolution Image Spectroradiometer (MODIS) sensor 313
- Motion blur 246
- Multichannel, stepped-frequency, continuous-wave 3D GPR system 213-214
- Multiple sensors 308
- Multispectral sensors 15

- NBMI. *see* Normalized backscatter moisture index (NBMI)
- NDRE. *see* Normalized Difference Red Edge (NDRE)
- NDVI. *see* Normalized difference vegetation index (NDVI)
- NDWI. *see* Normalized difference water index (NDWI)

- Near-infrared (NIR) waves 332, 333
- N fertilization management 328
- NIR. *see* Near-infrared (NIR) waves
- Nonlinear regression algorithms 318
- Normalized backscatter moisture index (NBMI) 70
- Normalized Difference Red Edge (NDRE) 333, 334
- Normalized difference vegetation index (NDVI) 13, 46, 312-314, 333, 334
- Normalized difference water index (NDWI) 14
- No-till (NT) practices 225

- 'On-the-go' sensors 227
- Optical *in situ* sensors 228
- Optical sensor methods 234
- Optical sensors 14-15, 229
- Organic soil 149

- Palmort, field case study 260, 261
- Partial least squares regression (PLSR) 109-110
- Passive microwave remote sensing 67
- PCA. *see* Principal component analysis (PCA)
- PCR. *see* Principal components regression (PCR)
- Pedotransfer rule 227
- Permittivity 174-175
- Perpendicular (PERP) 181
- Petrophysical relationships 150-151
- Photo alignment 239
- Physical soil properties 117
- Plant Village dataset 289, 292-294
- Plant water measurement 6
- Plant water stress 5-6
- PLSR. *see* Partial least squares regression (PLSR)
- Point cloud densification 239
- Polystyrene hemispheres 241, 243
- Principal component analysis (PCA) 318
- Principal components regression (PCR) 109-110
- Profile meter 246, 247
- Proximal electromagnetic/electrical resistivity/electrical sensors, assess soil health
 - electrical and electromagnetic tools, evaluate soil health 188-189
 - field examples 182-188
 - granulometry and saturated past extract conductivity 187

- measurement techniques
 - electrical method 178-180
 - electromagnetic induction 180-182
- mobile multipole 180
- non-exhaustive reference study 174
- overview 171-174
- soil electrical resistivity map 183
- soil physical properties, electrical and
 - electromagnetic domains 174-177
- soil properties 172
- soil thickness map 184
- soil typology map 185
- synopsis 190
- two-dimensional tomography
 - principle 179
- Proximal ground penetrating radar sensors,
 - assess soil health
 - airwave and groundwave data 158
 - borehole data, transillumination mode
 - and tomographic mode 141
 - common-midpoint data 140
 - common-offset data 139
 - common-offset data acquired, six
 - traverses 157
 - data processing and
 - interpretation 142-148
 - electromagnetic parameters 134-135
 - future trends 158-160
 - ground-coupled, common-offset GPR
 - reflection data 148-149
 - ground penetrating radar data acquisition
 - methods 135-142
 - organic soil tends 149
 - overview 133-134
 - point reflectors 143
 - radargram 138
 - ray paths representation 136
 - root detection 155-157
 - soil density/compaction 154-155
 - soil moisture study 152-153
 - soil structure 148-150
 - soil water content 150-154
 - soil water content measurement,
 - groundwaves 157-158
 - synopsis 158-160
 - trace, time series of amplitudes 137
 - volumetric water content
 - distribution 159
 - WARR data 140
- Proximal sensor fusion and multi-sensor
 - platforms, crop management
 - fusing multi-sensor data, statistical
 - tools 317-320
 - future trends 320
 - multi-sensor approaches 315-317
 - overview 307-309
 - plant height and proximal/remote
 - sensing 309-310
 - sensors and weather data 310-315
- Proximal soil sensing (PSS) 328
- Proximal soil sensing technologies 226
- Proximal spectroscopic sensors, assess soil
 - health
 - accuracy of laboratory visible and near-
 - infrared spectroscopy 122
 - combining spectra and auxiliary
 - sensor data, improved
 - estimation 120-124
 - estimation of, indicators and
 - indices 116-120
 - future trends 124
 - improvements, SMAF total, categorical
 - chemical, biological and physical
 - scores 123
 - overview 107-108
 - soil spectra 123
 - soil spectroscopy methods 108-116
 - synopsis 124
 - typical absorbance spectrum of moist
 - soil 109
- PSS. *see* Proximal soil sensing (PSS)
- Python script 262
- Quantitative amplitude analysis 145
- Radial basis function neural network
 - (RBFNN) 308-309, 319
- Random forest (RF) approach 313
- RBFNN. *see* Radial basis function neural
 - network (RBFNN)
- Real-time kinematic (RTK) 209, 211-212
- Recurrent neural networks (RNN) 320
- Red edge disease stress index (REDSI) 51
- Red edge-related indices 46
- REDSI. *see* Red edge disease stress index
 - (REDSI)
- Reflectance spectra of vegetation 12
- Reflection amplitude analysis 145
- Relative water content (RWC) 4-6
- Relative water content and reflectance
 - pattern, peanut 12
- Remote/aerial sensing of crop water status
 - electromagnetic radiation and interaction
 - with matter 7-9
 - future trends 25-30

- microwave remote sensing of plant water status 20-25
- optical remote sensing of plant water status 9-15
- overview 3-5
- quantification of plant water status
 - assessment 5
 - fuel moisture content (FMC) 6
 - irrigation scheduling 5
 - relative water content (RWC) 5-6
- remote sensing of plant water status using thermal infrared 16-20
- Remote/aerial sensing techniques, monitoring soil health 90
 - active microwave remote sensing 68-69
 - empirical approaches 70-71
 - semi-empirical approaches 71
 - theoretical approaches 69-70
- future trends 92-93
- irrigator-based soil moisture remote sensing experiment 91
- irrigator/tower/unmanned aerial vehicle-based remote sensing of soil moisture 90-92
- location of, OzNet monitoring stations and SMAPEX-4/5 study area 85
- maps of airborne brightness temperature 86
- murrumbidgee river catchment 84-85
- overview 65-68
- passive microwave remote sensing 71-73
 - impact of surface roughness 75-77
 - impact of vegetation canopy 77-79
 - impact of vertical soil moisture and temperature profiles 73-75
- passive microwave remote sensing of soil moisture 87-88
- radar remote sensing of soil moisture 88-90
- remote sensing of soil properties 79-80
 - backscattering mechanics of vegetated soil 69
 - brightness temperature, function of moisture content 75
 - soil dielectric constant 67
 - soil moisture 80-82
 - soil roughness 82-83
 - soil salinity 83-84
- retrieved soil moisture maps 89
- in situ* vs. retrieved soil moisture 90
- SMAPEX-4 and -5 airborne PLMR soil moisture vs. SMAPL2 passive/radiometer 88
- SMAP validation flight area 88
- soil moisture active passive experiments 85-86
- soil moisture measurements, ELBARA III transect 91-92
- soil moisture measurements vs. soil moisture retrieved 87
- stochastic ensemble framework 89
- Remote and proximal sensor data, precision agriculture applications
 - active and passive sensors 332-334
 - integration of 342-344
 - overview 327-328
 - proximal and terrestrial sensors 328-330
 - remote sensors 330-332
 - sensor data processing 338-339
 - data analysis and evaluation 342
 - data filtering 340-341
 - sensor calibration 339-340
 - sensor data resolution
 - radiometric resolution 337
 - spatial resolution 334-335
 - spectral resolution 335-337
 - temporal resolution 337-338
 - trade-offs in 338
- Remote sensing 45
- Remote sensing technologies, assessing crop health
 - assessing crop changes, disease infections 49
 - detecting stripe rust, very high-resolution imaging
 - days after inoculation (DAI) 54-55
 - field experiment 52
 - fungal disease 51
 - leaf-level imagery 52
 - plant-level imagery 53
 - residual convolution neural network (ResNet) 52
 - results of deep learning 54
 - TGI images 56-57
 - typical symptoms 53-54
 - UAV images, control and infected plot calculated 56
- future trends 57-59
- overview 43-45
- remote sensing of crop diseases 47-51
- remote sensing of crop health 45-47
- Representative elementary volume (REV) 259
- RF. see Random forest (RF) approach
- RMSE. see Root mean square error (RMSE)
- RNN. see Recurrent neural networks (RNN)

- Root biomass 156
 Root mapping 155-156
 Root mean square error (RMSE) 309
 Roughness index 233
 RTK. *see* Real-time kinematic (RTK)
 RWC. *see* Relative water content (RWC)
- SAR. *see* Synthetic aperture radar (SAR)
 SAVI. *see* Soil-adjusted vegetative index (SAVI)
 Scale space 238, 240
 SCI. *see* Surface chain index (SCI)
 Sensitivity of soil ecosystem 107
 Sentinel-2 satellite system 58
 SfM. *see* Structure from motion (SfM) theorem
 SIFT algorithm 238, 239
 Simple Ratio (SR) 333
 Single sensor 308
 Site conditions, GPR drainage systems
 clay tile vs. corrugated plastic tubing
 drainage pipe 203-204
 shallow hydrology 204
 soil type 204
 Site-specific management (SSM) 328
 SMAF. *see* Soil Management Assessment Framework (SMAF)
 Soil-adjusted vegetative index (SAVI) 315
 Soil dielectric constant 67
 Soil electrical resistivity map 183
 Soil health 115
 Soil health indicators 118-120
 Soil Management Assessment Framework (SMAF) 119
 Soil moisture, ground penetrating radar 152-153
 Soil properties 172, 174
 Soil spectroscopy methods 108-109
 auxiliary data and sensor data
 fusion 115-116
 calibration approaches 109-110
 field systems 111-112
 lab-based soil spectroscopy 110-111
 moisture and interfering factors 112-113
 soil profile information 113-115
 Soil spectroscopy techniques 107-108
 Soil surface roughness (SSR) 225, 229, 233
 Soil thickness map 184
 Soil typology map 185
 Soil workability 225
 Spatial interpolation methods 230
 Spatial overlap 235
- Spectra 108
 Spectrometers 229
 SR. *see* Simple Ratio (SR)
 SSM. *see* Site-specific management (SSM); Sustainable soil management (SSM)
 SSR. *see* Soil surface roughness (SSR)
 Standard organic soil layer mapping 150
 Stereo matching 237
 STI. *see* Surface tortuosity index (STI)
 Structure from motion (SfM) theorem 239, 248
 Sufficient water supply 4
 Support vector regression (SVR) 318
 Surface chain index (SCI) 233
 Surface tortuosity index (STI) 233
 Sustainable soil management (SSM) 223
 soil characteristics associated with 224
 SVR. *see* Support vector regression (SVR)
 Synthetic aperture radar (SAR) 313
- Table scanners 229
 Temperature-based methods 19
 Temperature vegetation dryness index (TVDI) 19
 Terrestrial laser scanner (TLS) 247, 248
 Terrestrial LIDAR 234
 TGI images 57
 Thermal infrared (TIR) 214
 Thermal sensors 316
 3D artificial model 241
 3D cloud 239
 3D vector Mesh model 239
 Thresholding 252
 Time of flight (TOF) method 234
 TIR. *see* Thermal infrared (TIR)
 TLS. *see* Terrestrial laser scanner (TLS)
 TOF. *see* Time of flight (TOF) method
 Train-test split 294
 Travel time methods
 diffraction hyperbolae from isolated
 'point' reflectors 142-143
 groundwaves 144-145
 return reflection to surface 143-144
 variable-offset survey 142
 Tree-based techniques 318
 Triangulation method 234
 Turgor pressure 4
 TVDI. *see* Temperature vegetation dryness index (TVDI)
 Two-dimensional tomography
 principle 179

- UAS-mounted sensors 331
- Unmanned aerial vehicles (UAVs) 15, 45, 47, 214-216, 236, 237, 329-331
- Unmanned aircraft systems (UASs) 330, 331

- VCP. *see* Vertical coplanar (VCP)
- Vegetation indices (VIs) 12-13
- Vegetation monitoring 46
- Veris P4000 instrument 115-116
- Vertical coplanar (VCP) 181
- Verticillium wilt (VW) 50
- VIs. *see* Vegetation indices (VIs)
- Vis-NIR spectroscopy-estimated vs. laboratory-measured values, SOC 121
- VisualSFM 241

- Volatile organic compounds (VOCs) 48
- Volumetric water content distribution 159
- Voluntary Guidelines for Sustainable Soil Management 224
- VW. *see* Verticillium wilt (VW)

- Water content estimation 153-154
- Water deficit index 18
- Water stress conditions 18
- Water use efficiency (WUE) 3-4

- X-ray absorption 254
- X-ray computed tomography (CT) scanners 252
- X-ray fluorescence sensor 317
- X-ray micro-fluorescence 255
- X-ray tomography 230