Soil Constraints on Crop Production

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Edited by

Yash Dang, Neal Menzies and Ram Dalal

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FOREWORD

Agriculture is an undoubted success in continuing to feed and clothe the world and is increasingly mitigating the societal and environmental concerns that stem from global change. This continual adaptation of agriculture, fit for the future, is underwritten by research innovation, is manifest in bred varieties and modern agronomic practices, and is driven by dedicated and innovative farmers supported by agricultural science.

Sustainable agriculture is essential to meeting the Sustainable Development Goals (SDGs) to end poverty and contribute to economic growth at farm, national, and global levels. Critical to the SDGs is the continued increase in agricultural productivity to meet demands from population growth without expanding agricultural land.

The soil resource defines agricultural land and practices and, consequently, soil must be the foundation on which improved productivity is focused. If soils are constrained, naturally or through management, then plant growth is restricted, and agricultural productivity is constrained. Recent estimates suggest that only 24% of agricultural land worldwide is currently without any major soil constraint – e.g., from salinity, sodicity, erosion, nutrient deficiencies, acidity, and/or compaction. Improved understanding and management of soil constraints is critical for future productivity, growth, and food security.

This book provides a comprehensive compendium of global research on soil constraint management, with contributors from around the world providing insight into the identification of soil constraints, the types of soil constraints currently affecting agricultural production, and the latest techniques available to ameliorate constraints and/or support agricultural production in constrained areas. Importantly, it also contains a series of chapters detailing the nature of soil constraints and their management across different geographical and socioeconomic regions, authored by expert practitioners.

There is no doubt that how we farm in the future will continue to evolve. I firmly believe that this book is an invaluable compilation of expert opinions from around the world and a great resource for the future management of constrained soils worldwide. I congratulate the editors, contributors, and publishers for this most worthwhile initiative.

Dr Peter Carberry
General Manager, Applied Research, Development and Extension
Grains Research and Development Corporation
Australia

PREFACE

Over three quarters of the world's agricultural land is affected by some type of soil constraint, which leads to significant yield loss globally. The effective management of soil constraints is thus required if the world is to rise to the challenge of feeding our rapidly increasing population.

The type and severity of soil constraints varies from location to location. Constraints may occur singly or in combination and tend to vary both spatially across the landscape and within soil profiles, occurring in both top-soil and subsoil layers. In addition, appropriate management practices will be dependent on geographical location, the type of farming system employed, and farmer access to resources. Consequently, it is not possible to use a "one size fits all" approach to soil constraint management.

To help improve the resources available to researchers and land managers, we have collated global information regarding the latest developments in soil constraint identification, characterisation, and management. The contents of this book are divided into six sections and 25 chapters (see below). The introductory chapters outline the problem and impact of soil constraints globally and the challenges associated with their identification and mapping. The characteristics and management of the specific types of physical, chemical, and biological soil constraints most prevalent worldwide are then outlined in detail. This is followed by case studies from different geographical regions worldwide. Finally, we conclude with perspectives on the management of multiple soil constraints, and the socioeconomic and environmental impacts of soil constraints.

Introduction	• Introduction and soil constraint mapping
Physical Constraints	• Compaction, waterlogging, and erosion
Chemical Constraints	• Sodicity, salinity, acidity, nutrient deficiencies, and nutrient toxicities.
Biological Constraints	• Soil borne diseases, and soil fertility decline
Regional Case studies	• Southern Africa, Central Asia, South-east Asia, Southern Asia, the Middle East, Europe, North America, South America, and Australia
Perspectives and Conclusion	• Multiple constraints, socioeconomic impacts, environmental impacts, and conclusion

We hope that this book is a valuable resource for both scientific researchers and land managers. We would like to thank all the volunteer contributors to this book for their time and valuable scientific input, particularly at a time when the impact of the Covid-19 pandemic has made working conditions very challenging for many individuals.

Finally, we thank Dr Kathryn Page. Without her persistence, patience, and passion, it would have been a challenge to deliver this book on schedule.

Yash Dang, Ram Dalal, and Neal Menzies

PART A:

INTRODUCTION AND MAPPING

CHAPTER 1

SOIL CONSTRAINTS TO CROP PRODUCTION: AN OVERVIEW

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Abstract

Soil constraints limit crop production worldwide and are responsible for significant yield losses each year. Constraints can be defined as any soil characteristics that limit crop growth and thus negatively impact agricultural production. These can be physical (e.g., surface seals, compaction, waterlogging), chemical (e.g., acidity, salinity, nutrient deficiencies), or biological (e.g., soil borne diseases, declines in vesicular-arbuscular mycorrhizae). Soil constraints may occur singly or in combination and tend to vary both spatially across the landscape and within soil profiles, occurring in both top-soil and subsoil layers. This variability increases management complexity and improvements in our ability to identify what constraints occur, and where these are located, are essential to effectively target management and increase production. Constraint management approaches can generally be grouped into three broad categories, namely a) amelioration, which focuses on the removal of constraints or reduction in their severity; b) agronomic management, which uses techniques to maintain crop production despite the presence of soil constraints; and c) land use change, which is used when amelioration or agronomic management is not logistically or economically feasible. This chapter provides a brief overview of the different types of constraints affecting cropping systems, the impact of these on crop production, and management options available to improve farm productivity and profitability. This acts as an introduction to the more detailed chapters to follow in the remainder of the book.

Keywords: Acidity, alkalinity, salinity, sodicity, compaction.

Introduction

The world's population is expected to increase by around 2 billion people over the next 30 years (United Nations 2019). To feed these people will require us to boost food production, and this must occur even though our capacity to expand the area used for agriculture is limited and production on existing land is threatened by land degradation, water resource scarcity, and climate change. This conundrum means that our existing agricultural systems will need to evolve to produce more food, more efficiently.

Soil constraints currently limit agricultural production worldwide (Bot, Nachtergaele, and Young 2000). A soil constraint can be defined as any soil characteristic that restricts plant growth and lowers crop production. Constraints can be naturally occurring or induced by agricultural management and can either be:

- Physical – for example, surface seals, compaction, waterlogging, and erosion.
- Chemical – for example, salinity, sodicity, acidity, alkalinity, nutrient deficiencies, and the presence of toxic elements.
- Biological – for example, an increase in the incidence of harmful biological agents, such as soil-borne diseases, and a decrease in the activity of beneficial ones, such as vesicular-arbuscular mycorrhizae or earthworms.

Soil constraints can reduce crop growth a) by reducing the movement of water and air into and within the soil profile e.g., due to the development of surface seals or compacted layers that reduce hydraulic conductivity; or b) by restricting a plant's ability to grow and function, e.g., due to the presence of physically or chemically hostile layers that prevent root growth and/or water and nutrient uptake (Dang et al. 2006). This can have a major impact at a farm level by decreasing agricultural output, increasing management costs, and thus decreasing farm income (Orton et al. 2018). It can also impact society at a broader level by decreasing country wide productivity and food security. Many negative environmental problems can also arise from soil constraints. These can include increased runoff and erosion, and thus pollution of surrounding waterways, increased production of greenhouse gasses, and decreased soil carbon storage (Figure 1.1).

This chapter provides a brief outline of the impact of soil constraints on crop production worldwide and the broad management principles and considerations that can be used to develop effective management options.

This outline provides a concise summary that acts as an introduction to the more detailed analysis in the chapters to follow.

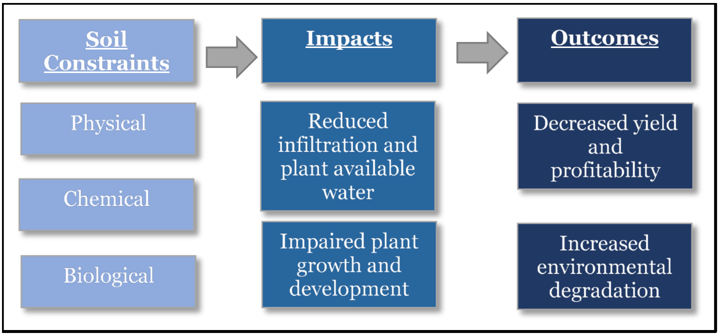

Figure 1.1 Summary of the major types of soil constraints, their impacts, and subsequent outcomes.

Distribution of soil constraints and their impact on crop production worldwide

Recent estimates suggest that only 24% of agricultural land worldwide is without any major soil constraint, and the areas affected are likely to increase by five to seven million hectares annually (Bot, Nachtergaele, and Young 2000). In many regions this can have a large impact on agricultural production. For example, much of Africa and Eastern Europe produce less than 40% of their potential yields, in part due to soil constraints (Pradhan et al. 2015). Similarly, in Australia the constraints of sodicity, salinity, and acidity are estimated to be responsible for annual production losses of nearly A$ 1,900 million dollars in the wheat crop alone (Orton et al. 2018).

The type and severity of the constraints present vary from location to location and are affected by factors such as climate, soil type, topography, and farming system. This is clearly illustrated in Table 1.1, which shows the areas of land affected by seven common soil constraints and how these vary between major regions worldwide. Constraints may occur singly or in combination and tend to change not only spatially across the landscape but also within soil profiles, occurring in both top-soil and subsoil layers. This increases management complexity and highlights the importance of understanding exactly what constraints occur, and where these are located, to effectively target management and increase production. On a national level this allows management agencies to effectively identify those constraints

Table 1.1 Area of land affected globally by seven common soil constraints. Data reproduced in modified form from Bot, Nachtergaele, and Young (2000)

	AREA AFFECTED ('000 KM)							
CONSTRAINT	**Sub-Saharan Africa**	**North Africa & Near East**	**Asia and Pacific**	**North Asia east of Urals[1]**	**South and Central America**	**North America**	**Europe**	**World Total**
POOR DRAINAGE	1,903	79	3,083	5,702	2,086	3,388	1,142	**17,382**
LOW CEC	3,716	292	1,105	11	982	0	44	**6,151**
AL TOXICITY	4,371	1	3,906	783	8,019	2,219	569	**19,867**
HIGH P FIXATION	1,009	0	1,395	0	3,016	1	0	**5,421**
SODICITY AND SALINITY	884	780	3,043	2,137	1,115	191	219	**8,369**
SHALLOW SOILS	3,007	2,854	4,829	2,796	2,313	2,497	780	**19,133**
EROSION HAZARD	3,627	1,185	4,655	3,349	3,923	3,851	1,386	**21,975**

[1] Including Kazakhstan, Kyrgyzstan, the Russian Federation, Tajikistan, Turkmenistan, Uzbekistan

having the most impact on a region's agricultural production and prioritise resources appropriately. On the farm and paddock scale it allows us to identify appropriate management on a site-specific basis. This allows for better resource use to both improve production and the sustainability of the food supply, and maintain environmental quality (Gebbers and Adamchuk 2010).

Management of soil constraints

Once it is understood what constraints occur, and where these are located, knowledge of the most effective techniques to manage crop production is required. Soil constraints rarely occur in isolation and interact in a site-specific way to create growing environments that vary from location to location. Consequently, it is not possible to use a "one size fits all" approach to management, and different combinations of techniques will be appropriate in different situations. However, the management options available can generally be grouped into three broad categories: amelioration, agronomic management, and land use change (Figure 1.2).

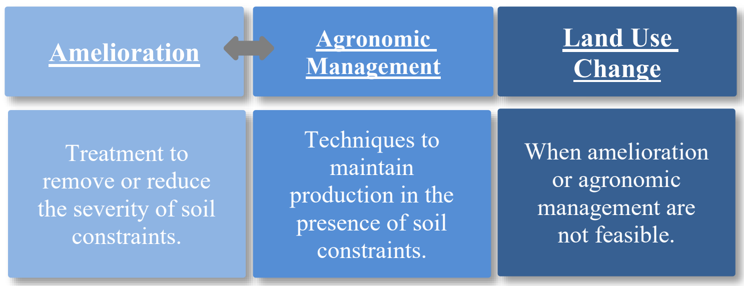

Figure 1.2 Illustration of the three broad approaches available for the management of soil constraints.

Amelioration

Amelioration is one of the most common approaches to the management of soil constraints and typically involves the use of some input to correct or improve a constraint. Common examples can include the application of lime to treat soil acidification, gypsum to treat soil sodicity, fertiliser to treat nutrient deficiencies, and cultivation to treat compaction. Because soil amelioration has been used extensively for many years, a broad knowledge base exists regarding how it can be best applied. However, significant gaps in our understanding still exist, particularly regarding a) the most appropriate and efficient use of ameliorants where multiple constraints exist, and each constraint needs to be treated before maximum yield can be achieved; and b) how best to use amelioration when constraints occur in a subsoil environment and it is difficult to apply ameliorants.

Agronomic management

Agronomic management refers to the manipulation of farming practices to help crops grow better despite the presence of a soil constraint. This can be used either in conjunction with amelioration, or as an alternative option where amelioration is uneconomic or likely to take an extended time. However, while agronomic management has the potential to improve production on constrained soils, there is often less emphasis on this approach compared to amelioration and improvement in our understanding of its potential is required. Examples of agronomic management can include:

- Accurate identification of constrained areas so that these can either be excluded from production or managed differently where there is a high risk of negative returns. For example, where farmers have a solid understanding of how constraints change across a farm/paddock they can vary the application of inputs (fertilisers, pesticides, ameliorants) to better match soil conditions and expected plant responses.
- The identification and use of plant species or crop cultivars that are best suited to growth in a particular soil. For example, in soils affected by salinity the use of salt tolerant species, such as barley or canola, in preference to more salt sensitive ones, such as chickpea or durum wheat, can help maintain production (Dang et al. 2010). Work on wheat has also indicated that a 10% increase in yield can be observed on lower yielding sodic sites when growing more tolerant cultivars (Schilling et al. 2019).
- The manipulation of cultural practices such as sowing times, row spacings, seeding densities, and tillage management to best manage constraints. For example, raised beds can help increase yields where crop growth is limited by waterlogging (Armstrong, Eagle, and Flood 2015; Robertson et al. 2016). Alternatively, the use of no-tillage with stubble retention can help retain organic matter and improve structural stability (Li et al. 2019; Blanco-Canqui and Ruis 2018).

Land use change

In some instances, soil constraints may be so severe or difficult to manage that sustaining crop production using either amelioration or agronomic management is not logistically or economically feasible. Under these circumstances a move to an alternative land use may be the most appropriate management option. For example, in severely saline soils, converting from cropping to agroforestry or pasture production may be more a more successful option to maintain production (Dang et al. 2010). In the most severe cases, the return of affected areas to native vegetation may also be required.

Conclusions

The successful identification and management of soil constraints is clearly required to maximise agricultural productivity in a world where there is increasing demand for food due to a growing population, but limited opportunity to expand the area used for agriculture. However, the complexity of this task is great, and sophisticated and coordinated management responses are required. This book will provide a comprehensive overview of the types of physical, chemical, and biological constraints that impact crop production worldwide. The extent of these constraints, their effect on crop production, and the most promising approaches to manage their impact will be discussed. In addition, comprehensive case studies of important cropping regions worldwide will be presented to outline the unique management challenges and current state of the art in soil constraint management in different geographical and climatic regions. The social, economic, and environmental impacts of soil constraints will also be discussed and assessed.

References

Armstrong, R.D., C. Eagle, and R. Flood. 2015. "Improving grain yields on a sodic clay soil in a temperate, medium-rainfall cropping environment." *Crop and Pasture Science.* 66 (5): 492-505. https://doi.org/10.1071/cp14210.

Blanco-Canqui, H., and S.J. Ruis. 2018. "No-tillage and soil physical environment." *Geoderma.* 326: 164-200. https://doi.org/https://doi.org/10.1016/j.geoderma.2018.03.011.

Bot, A.J., F.O. Nachtergaele, and A. Young. 2000. *World Soil Resources Report: Land resource potential and constraints at regional and country levels.* Rome: Food and Agriculture Organisation.

Dang, Y.P., R.C. Dalal, S.R. Buck, B. Harms, R. Kelly, Z. Hochman, G. Schwenke, A.J.W. Biggs, N.J. Ferguson, S. Norrish, R. Routley, M. McDonald, C. Hall, D. Singh, I.G. Daniells, R. Farquharson, W. Manning, S. Speirs, H.S. Grewal, P. Cornish, N. Bodapati, and D. Orange. 2010. "Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains cropping region of Australia." *Australian Journal of Soil Research.* 48: 105-119. https://doi.org/10.1071/SR09074

Dang, Y.P., R.C. Dalal, R. Routley, G.D. Schwenke, and I. Daniells. 2006. "Subsoil constraints to grain production in the cropping soils of the north-eastern region of Australia: an overview." *Australian Journal of Experimental Agriculture.* 46: 19-35. https://doi.org/10.1071/EA04079.

Gebbers, R., and V. I. Adamchuk. 2010. "Precision agriculture and food security." *Science* 327 (5967): 828-831. https://doi.org/10.1126/science.1183899.

Li, Y., Z. Li, S. Cui, S. Jagadamma, and Q. P. Zhang. 2019. "Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis." *Soil and Tillage Research.* 194. https://doi.org/10.1016/j.still.2019.06.009.

Orton, T.G., T. Mallawaarachchi, M. Pringle, N.W. Menzies, R.C. Dalal, P.M. Kopittke, R. Searle, Z. Hochman, and Y.P. Dang. 2018. "Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat." *Land Degradation and Development.* 29 (11): 3866-3875. https://doi.org/10.1002/ldr.3130.

Pradhan, P., G. Fischer, H. van Velthuizen, D.E. Reusser, and J.P. Kropp. 2015. "Closing yield gaps: How sustainable can we be?" *PLoS One.* 10 (6): e0129487.
https://doi.org/https://doi.org/10.1371/journal.pone.0129487.

Robertson, M., J. Kirkegaard, A. Peake, Z. Creelman, L. Bell, J. Lilley, J. Midwood, H.P. Zhang, S. Kleven, C. Duff, R. Lawes, and P. Riffkin. 2016. "Trends in grain production and yield gaps in the high-rainfall zone of southern Australia." *Crop and Pasture Science.* 67 (9): 921-937. https://doi.org/10.1071/cp16153.

Schilling, R.K., J. Taylor, R. Armstrong, J. Christopher, Y. Dang, P. Rengasamy, D.L. Sharma, R. Smith, E. Tavakkoli, and G.K. McDongald. 2019 "Improving yield on sodic soil: assessing the value of genetic improvement." In *Australian Agronomy Conference*, *Wagga Wagga 25-29 August.* Australian Society of Agronomy.

United Nations, Department of Economic and Social Affairs, Population Division. 2019. *World Population Prospects 2019: Highlights*. New York: UN Department of Economic and Social affairs. https://population.un.org/wpp.

CHAPTER 2

SOIL CONSTRAINT DIAGNOSIS AND MAPPING

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Abstract

Soil constraints significantly impact crop growth and yields. The ability to accurately measure and map these constraints has the potential to greatly improve on-farm productivity. Soil constraints have traditionally been assessed using farmer observations or conventional soil sampling and analysis techniques. Technological advancements have enabled the assessment of constraints using more formal sampling strategies, and proximal and remote sensing technologies. While regional and national soil databases and products contain valuable information about the soil environment, many lack information specific to soil constraints and have limited use on-farm due to their broad extent. The collection of field-scale data via point-based or spatial techniques provides an abundance of raw soil data. However, this information is often not presented in a useful or meaningful way for applied decision-making on-farm. Digital soil mapping (DSM) presents an opportunity to integrate the plethora of grower-sourced and publicly available soil data into useful decision-making tools. As techniques used to measure and map soil constraints continue to improve, the translation of this information into useful decision-making tools remains imperative.

Keywords: Digital soil mapping, soil sampling, soil constraints.

Introduction

Soil constraints have the potential to significantly impact crop growth and yield. Data on the soil landscape is becoming increasingly more accessible across a range of spatial and temporal extents. However, information specific to soil constraints and their impact on crops is either lacking or not portrayed in a way that is useful for guiding informed management decisions in the field. Growers must be able to measure and quantify soil constraints on farm to ameliorate or manage them accordingly.

This chapter will explore the range of soil sampling strategies and techniques available to understand soil physical, chemical, and biological constraints in both the surface and/or subsoil. The University of Sydney farm "L'lara" will be used as a case study throughout to demonstrate the range of soil sampling and mapping techniques available (Figure 2.1 to Figure 2.7). A range of sampling strategies, from arbitrary and ad hoc approaches, through to more formal systematic and stratified sampling methods will be discussed. Sample extraction techniques, including profile pits, augers, and cores, and analysis techniques such as proximal and remote sensing will be explored. Digital soil mapping (DSM) has been developing in recent decades and is an opportunity to integrate grower-sourced and publicly available data. The application of DSM to better understand the nature and extent of soil constraints will be discussed, and future directions will be explored.

Identifying a soil constraint to crop production

There are several ways to identify whether a soil constraint to crop production exists in a particular area. These include informal approaches, such as farmer experience and knowledge, as well as more systematic approaches that use yield data or satellite imagery. In the absence of more temporary constraints (pests, diseases, drought, frost), areas of poor and variable crop growth and yields over multiple seasons often indicate the presence of soil constraints (Lobell et al. 2017; Dang et al. 2011). While farmer observations play a key role in the initial identification of lower yielding areas, these visual assessments are often subjective, and a more formal assessment of this variability is increasingly being sought.

Many growers have access to yield monitor data and produce maps of yield variability (Bramley and Ouzman 2019). This may complement farmer observations and can be used to formally identify lower yielding areas within and between fields. Remote sensing, using satellite or airborne sensors and imagery, also presents an additional source of information to assess crop variability. For example, Normalised Difference Vegetation Index (NDVI) maps can be used to assess variability in crop vigour, canopy health, and may be used as an indirect indicator of soil condition. This may complement existing yield maps and on-the-ground observations. Multiple years of remotely sensed surrogate yield data may also be used to identify areas affected by soil constraints, where consistently low-performing yields over multiple seasons may infer the presence of a soil constraint when the impacts of more temporary constraints are filtered out (Lobell et al. 2007; Dang et al. 2011).

However, while yield maps may suggest the presence of at least one soil constraint, they cannot identify the nature of the constraint or separate the interactions and relationships between multiple soil attributes. Ground-truthing of visual observations, yield maps, and satellite imagery through the collection of soil data is thus required to identify the exact nature and extent of soil constraints. Attributing crop variability to a single constraint is often difficult due to the interactions between the physical and chemical properties of soil (Adcock et al. 2007). Interrelationships between soil properties also make it difficult to identify the relative effect of individual or multiple constraints, and antagonistic interactions between soil properties may result in yield or growth-limiting conditions, even if each individual soil property does not exceed defined threshold values (Adcock et al. 2007).

Soil sampling and analysis for ground-truthing constraints

Soil sampling strategies

Soil analysis is important for ground-truthing observations of suspected soil constraints. The accuracy with which a soil sample represents the broader soil landscape depends on the number of sampling units, the sampling technique, and the inherent variability of the soil (Cline 1944). Thus, it is important to know both where and how to sample to identify soil constraints.

Since the early 20th century, the inherent spatial variability of soils has been increasingly recognised and is now a key consideration when identifying where to sample. Over time, sampling approaches have become increasingly sophisticated, supported by emerging academic research, extension publications, and agronomic advice (Lawrence et al. 2020). Soil sampling approaches range from ad hoc or arbitrary techniques, through to more formal approaches including systematic and stratified sampling schemes. The ad hoc selection of sampling points "at random" over an area is not considered an effective method of randomisation as it may introduce strong personal bias and fail to effectively capture variability of the soil (Cline 1944). Prior observations and existing data, such as farmer knowledge, yield maps, or satellite imagery, may be used to arbitrarily guide the location of sampling points to capture sufficient variability. Ad hoc or arbitrary sampling approaches are commonplace due to their convenience and ease of use and depending on the experience and knowledge of the surveyor, may be time and cost-effective, particularly for exploratory investigations. However, unintended bias remains a concern.

Systematic sampling strategies select sample sites based on organised grids, patterns or transects and aim to objectively capture as much variability as possible across the study area and reduce personal bias. However, in practice, systematic sampling approaches using arbitrarily located transects or zig-zag patterns, for example, are likely to produce biased results as they fail to capture a truly randomised sample (Lawrence et al. 2020). The advent of Global Positioning System (GPS) and Geographic Information System (GIS) technologies have facilitated the use of grid-based sampling strategies to geo-locate soil information and produce digital soil maps. Grid soil sampling aims to capture soil variability most objectively by sampling based on a regular pattern of cells (Figure 2.1). However, soils are highly variable through space and some parts of a field may be more inherently variable than others. Grid sampling ignores this variability and has a uniform sampling density irrespective of the underlying variation present. While grid-based sampling can capture sufficient detail required for DSM, the process is time consuming and expensive (Dang et al. 2010). The variability of soil parameters, time, and financial constraints are important considerations when deciding upon grid sizes (Flowers, Weisz, and White 2005). While smaller grid cells can capture more variability (Flowers, Weisz, and White 2005), grid cell sizes may range anywhere from 10's to 100's of metres depending on logistical constraints. For inexperienced or non-technically trained individuals, grid sampling is generally preferred over sampling at random as it can limit potential bias (Cline 1944).

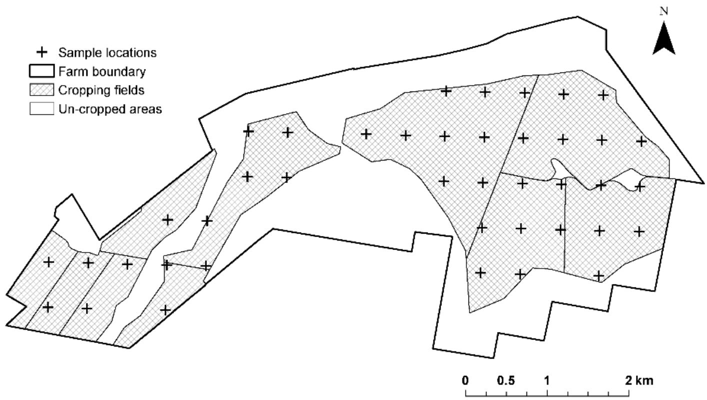

Figure 2.1. The distribution of sampling locations based on a regular-spaced grid pattern across "L'lara".

Statistical or stratified sampling separates the study area into sub-areas (i.e., strata). Strata may be derived by separating the study region into equal-area strata or by subdivision into more homogenous regions through a range of statistical methodologies including Latin hypercube sampling (Minasny and McBratney 2006) or k-means clustering (Taylor et al. 2003; Filippi et al. 2019) (Figure 2.2). Depending on the complexity of the stratification technique, heterogeneity of the study area, and number of desired strata, information used to delineate strata may include farmer observations (Fleming et al. 2000), yield data (Flowers, Weisz, and White 2005), satellite imagery (Filippi et al. 2019), or a combination of this information alongside other ancillary data. However, there is a trade-off between increased precision and increasing cost and complexity that must be considered when choosing the optimum number of strata.

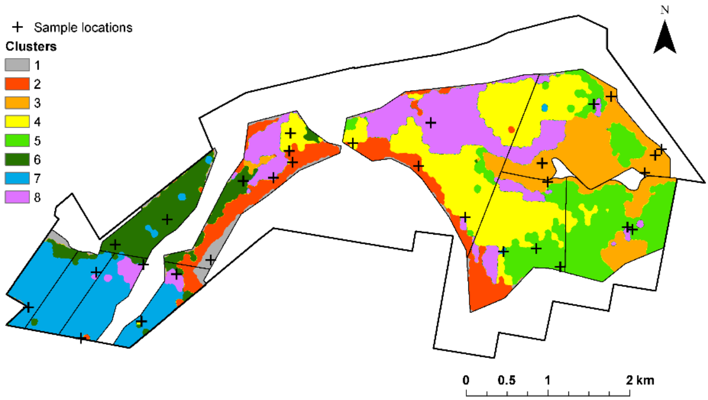

Figure 2.2 The distribution of eight clusters derived from a K-means clustering analysis, and the locations soil sampling sites randomly selected within each cluster across "L'lara" (Filippi et al. 2019).

Soil extraction techniques

Traditional soil sampling approaches treat fields or land management areas as homogenous regions (Dawson and Knowles 2018). As such, bulk or composite samples are created to represent the area of interest. Composite soil sampling is still widely used by farmers and agronomists in the field and is an approach best suited to more homogenous areas where there is existing knowledge about the soil condition (Dawson and Knowles 2018). Composite sampling operates under the assumption that if each individual sample was analysed and averaged, it would give the same result as for the larger composite sample (Tan 2005). The number of soil samples recommended to capture a sufficiently representative composite sample varies for different soil properties measured, although logistical constraints often determine the number of samples that can feasibly be collected (Lawrence et al. 2020). A general rule of thumb is that the more homogenous an area is, the larger the area the composite sample can represent (Dawson and Knowles 2018). Composite sampling is limited by its inability to capture the inherent spatial variability of soils, however, and sampling error will likely increase as sampling areas become more heterogenous (Tan 2005).

Point-based sampling strategies, including digging profile pits, hand augering, and soil core samples, can be used to capture spatially referenced soil information. Soil profile pits can provide detailed information about a soil's physical, chemical, and biological properties. When using ad hoc or arbitrary sampling approaches, soil profile pits may be dug based on observations of suspected constraints, historical yield maps, vegetation indices, or pre-existing soil surveys (Taylor et al. 2003). However, the time and labour required to dig and analyse soil profile pits means that they are rarely used on-farm (Earl et al. 2003), as they are impractical for spatial analysis and cannot be used to capture the inherent spatial variability of soils (Taylor et al. 2003).

Soil augers and cores offer cheaper, faster alternatives to soil pits that are highly suited to systematic or statistical sampling strategies. Hand auger sampling is typically used for the assessment of surface-soil or shallow subsurface properties, while mechanised soil cores enable the extraction of a high density of soil samples to depths typically up to 2 m. The mechanised extraction of soil cores is less time and labour intensive compared to hand augering (Earl et al. 2003), however, the vehicle access to fields required for mechanical sampling may be limited at certain crop growth stages and due to agronomic concerns, such as compaction. By geo-referencing the locations of samples, soil maps can be created through digital soil mapping (DSM) procedures.

Analysis of soil samples

Conventional soil analysis techniques continue to be a key contributor to our understanding of the soils physical, chemical, and biological condition. Soil samples may be analysed in situ or be transferred to a laboratory for analysis. Conventional analysis methods include the use of indicator dyes via a colourimetric method such as the Raupach and Tucker (1959) method for the in-field assessment of soil pH, the use of electrodes to measure pH and EC in soil solutions (Tan 2005), or a cylindrical core sampler to measure bulk density (Hao et al. 2008). There is an extensive body of literature available detailing local and national guidelines and recommendations for conventional soil analysis techniques (e.g., Tan 2005).

Proximal soil sensing may also be used to compliment, or replace, conventional techniques by providing quantitative results via portable and/or handheld sensors. Viscarra Rossel et al. (2011) offer a comprehensive review of proximal soil sensing. Here we explore their application for the analysis of soil constraints. Proximal soil sensors can facilitate the (near instantaneous) collection of vast amounts of data using simpler and less time and labour-intensive techniques than conventional approaches (Viscarra Rossel et al. 2011). For example, spectral sensors, such as portable X-Ray Fluorescence (pXRF), use elemental data as a proxy for the analysis of various soil attributes and have been used to assess soil pH (Sharma et al. 2014), CEC (Sharma et al. 2015), and salinity (Aldabaa et al. 2015). Neutron probes, nuclear density gauges, and low-activity nuclear density gauges have also been used to measure soil moisture and bulk density (Dep et al. 2021). Similarly, Visible-Near Infrared spectroscopy has been used to measure a suite of soil properties including salinity and soil organic carbon (Ahmadi et al. 2021). Today, proximal soil sensing techniques are increasingly shifting from the research and development phase into practical application.

However, while handheld or portable proximal soil sensors have been used with some success, the output from individual sensors is not as accurate as output derived from a combination of multiple sensors and ancillary data (Ji et al. 2019; Aldabaa et al. 2015). Proximal soil sensors do not directly measure soil constraint or attribute values. Rather, sensor outputs serve as a proxy that must be correlated via mathematical processing and modelling. As correlations are often made with calibration samples unique to a particular location or soil type, the use of proximal sensors is restricted by the soil condition(s) it has been calibrated for (Stenberg and Viscarra Rossel 2010). In addition, interrelationships between soil properties requires multivariate calibrations to account for the non-specificity of proximal soil sensor output for individual constraints or attributes (Stenberg and Viscarra Rossel 2010).

Mapping soil constraints

Changes in soil sampling and analysis techniques, from point-based measurements *in situ* to the use of spatial sensors, has rapidly expanded the volume and complexity of information collected about the soil landscape. In its raw form, this data gives minimal insight into the extent and distribution of soil constraints and must be converted into a mapping format before it can provide information about the spatial distribution of soil properties and the nature and extent of constraints across the landscape in a readily interpretable, easy to use format.

Conventional soil maps typically rely on qualitative inferences of soil information, including field observations and aerial imagery, to classify soil properties and features. While these maps served their purpose throughout much of the 20th century, conventional soil surveys and maps have been criticised for their subjectivity and non-replicability (Arrouays et al. 2020). The rise of precision agriculture and increasingly intensive broadacre cropping systems is generating more and more quantitative information and spatial data. DSM has emerged in recent decades following rapid growth and advancements in computational and information technologies (Arrouays et al. 2020). Early DSM simply represented point observations without