Delivery of soil survey information to non-soil specialists to support land management by means of special purpose classifications and conceptual toposequence models

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Abstract

The link between soil information and good decisions about land use and management, or even the recognition that a decision is needed and that soil information can play a role, needs to be improved. The link between soil information and applying it is critical to maximise the use of the soil resource in a sustainable way.

Good management decisions require correct and understandable soil information for a location; confusing and inappropriate data can lead to suboptimal practices. Uncertainty about appropriate management arises because soils are highly variable both spatially (horizontally and vertically) and temporally. To support land management decisions that are generally made by non-soil specialists, information about the soil needs to be delivered in a format that they can understand, afford and apply.

The aim of this work was to deliver soil information to improve land management by development of an approach to convey soil survey information by means of special purpose soil classifications and conceptual toposequence models. The approach is presented to: (i) salvage and reinterpret valuable soil survey legacy data from the plethora of detailed published soil survey technical reports and their numerous appendices of quantitative and qualitative data for future science and (ii) deliver complex or intricate soil survey information to non-soil specialists using a vocabulary and diagrams that they can understand.

This was achieved by re-interpreting soil survey data in a framework comprising special purpose soil classifications and conceptual toposequence models for specific geographic regions and/or practical applications. The process involved an experienced soil surveyor to acquire and interpret conventional soil data. Then to distil the highly technical soil survey information into a format for a non-soil specialist audience, by constructing simple but readily understandable descriptive conceptual toposequence models and to develop a soil identification key. The soil identification key honours the same international (or national) classification sequence but is constructed in plain language that non-technical people understand and can apply to determine soil types. Soil types classified using the special purpose soil classification systems are correlated to formal international and national soil classification systems allowing technical soil property data and land suitability evaluations to be applied.

To illustrate the wide applicability of this approach, case studies were conducted in three different parts of the world – Kuwait, Brunei, and Australia, each of which exhibit vastly different landscapes, climates, soil types and land use problems. The studies were driven by demands to
contribute to on-going projects, having a direct impact on current and significant investment decisions.

This thesis is submitted in the publication format through six papers as thesis chapters. The chapters and their objectives are as follows:

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The approach improved the delivery of soil information by addressing issues that included: communication - through the use of plain language and simple words; scale - using diagrams to mimic the landscape; identification of soils – by using readily recognisable observable soil features; technology transfer – by associating local soil types with national or international taxonomic soil classifications; and timely –achieved by reworking legacy soil survey data.

Uptake of the information to answer current questions is discussed in the case studies and confirmed the value of this approach for presenting soil survey information in a user friendly non-technical format that a non-soil specialist audience understood.

The approach developed and used is applicable to other locations throughout the world outside of: (i) Brunei, especially in tropical landscapes, (ii) Kuwait, especially in arid and semi-arid landscapes and (iii) Australian winter rainfall landscapes, especially in Mediterranean landscapes - in order to establish similar local classifications and conceptual models.
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The University of Adelaide encourages the publication of papers during candidature and permits theses to be presented as a collection of published papers. This thesis is submitted in the publication format consisting of five papers and a book chapter (Chapters 2 to 7), plus four refereed and published conference proceedings papers included in the Appendix.

Chapter 1 provides an overview of the need for soil survey information, decision maker requirements, and what part of the soil information delivery this thesis addresses. The objectives and aims of this research are presented.

Chapter 2 provides an overview of the conceptual toposequence model approach, demonstrating how toposequence models describe, explain and predict soil variability in a range of complex landscapes and used to deliver soil information to non-technical users.

Chapter 3 describes the approach to aid the translation of soil survey information into a form suitable for a non soil specialist audience demonstrated with a case study from the hill country of Negara Brunei Darussalam. The soil types are linked to international soil classifications that allow information about crops and their management to be applied, thereby assisting with improving Brunei food security.

Chapter 4 describes for the first time formal recognition of a diverse range of acid sulfate soils in Brunei. Soils were characterised and conceptual soil hydro-toposequence models together with a soil identification key helped to visualize and illustrate the complexities in this low relief landscape. This assisted with targeting management practices towards these potentially hazardous soils.

Chapter 5 applies the approach presented in previous chapters to guide non-soil experts with identifying soil types in Kuwait. Supporting rangeland restoration program that targets the planting of vegetation communities according to identified soil types, assisting with mitigating land degradation.

Chapter 6 demonstrates the approach to provide an understanding of acid sulfate soil distribution for a large regional area of wetlands associated with the River Murray in South Australia, how to recognise these soils and their likely distribution. Supporting the prioritization of areas to be monitored and development of management plans to maintain wetland and river water quality.

Chapter 7 brings the findings from the case studies together, describing the generic approach, the benefits, limitations, possible improvements, and the philosophy underpinning the approach.
Publications arising from this Thesis Research

Included as Chapters forming part of the Thesis work (as senior author)


Additional directly related conference proceedings papers refereed and published, included for reference in the appendix of this Thesis (as senior author)


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Chapter 1

Introduction

In many countries soil survey datasets comprise a plethora of large published soil survey technical reports with numerous maps, soil and map unit descriptions, analytical data and appendices of qualitative and quantitative data. These are valuable sources of soil information to help guide land management decisions, but are commonly undervalued and underused. The link between soil information and good decisions about land use and management, or even the recognition that a decision is needed and that soil information can play a role, needs to be improved. On the world stage, most soil survey information is more than thirty years old and may not be in a form applicable to answer current questions; also, many of those who have the ability to apply and interpret the data are being pensioned off (Dent & Dalal-Clayton, 2014).

Soil information is important

Soils provide vital ecosystem services that support human needs for food, fibre, fuel and water (Costanza et al., 1997; Daily et al., 1997; De Groot, 1992), e.g. soils shelter seeds, provide physical support for plants, moderate the water cycle, and retain and deliver nutrients to plants. They play a major role in decomposition of organic matter and wastes, and in regulating the earth’s major element cycles (carbon, nitrogen and sulfur). Soil information is traditionally associated with food and fibre production, but can also be applied to a number of other important ecosystem services that affect the quality of human life. These include water quality, the carbon cycle and locating sources of building and road construction materials, all of which require improved understanding of the distribution and properties of soil types. Soil knowledge can contribute and provide an effective linking role for sustainable development and land related issues (Bouma, 2014).

Human activities on landscapes need to be carefully planned and managed. Inefficient and inappropriate use of soil resources increases the risk of land degradation and reduces future opportunities. Land degradation includes irreversible deterioration of soil quality through intensification of soil acidity, salinity, soil structure and loss of soil organic matter and biodiversity (UNEP, 2007). The detrimental impact of land degradation reduces soil functions and therefore the soils ability to provide ecosystem services and goods (Lal, 2010).

Total land area is fixed, therefore our soil resources are finite due to the long time to form naturally (Jenny, 1994), and to meet an estimated 70% increase in demand for food and fibre for
the increasing human population from 2009 to 2050 (FAO, 2011) the soil resources will need to be optimally used and sustainably managed. Climate change is also likely to stress agricultural land areas through droughts and more intense rain storms (Cai et al., 2014). Good management decisions require correct and understandable soil information for a location; confusing and inappropriate data can lead to suboptimal practices. Uncertainty about appropriate management arises because soils are highly variable both spatially (horizontally and vertically) and temporally (Beckett and Burrough, 1971; Beckett and Webster, 1971; Wilding and Drees, 1983).

Increasing food production using sustainable farming requires knowledge about the soil and how it can be managed. The farmer could do this on their land by trial and error, learning what works and doesn’t, but this approach takes time over many seasons and there are risks of failure and harmful damage to the soil resource. Alternatively, understanding soils allows transfer of successful technologies and management practices from elsewhere, reducing risk and time.

**How soil information is acquired**

Soil information to guide decisions comes from conducting a soil survey, specific soil assessment, or from legacy soil survey reports, maps and databases. Detailed descriptions on how to conduct a soil survey are provided in operation manuals e.g. for Australia (McKenzie et al, 2008) and for the United States of America (Soil Survey Division Staff, 1993). The work uses a combination of observed, measured and analytical data to generate maps and reports. Experienced pedologists summarise many observed morphological properties and limited analytical data into soil types and to then predict their occurrence in the landscape using conceptual models. Large data sets are gathered during a survey, and to handle the volume and complexity of soil data, taxonomic classifications are used to summarise the many soil features and describe map units.

The cost to conduct a soil survey is considered expensive, but the benefits in terms of dollar value are rarely quantified when it supports a decision or the savings made when a damaging action is not taken (avoiding a mistake), or the long time frames that soil data can be used and reused. Broad scale soil survey was supported by governments for strategic planning and development of new areas, providing an overview of the soil distribution and soil properties. But detailed mapping to support site specific management is rarely conducted routinely, and when conducted, it is often by industry to support development of a high value land use such as intensive agriculture or suitability to construct infrastructure.
Legacy soil survey data, in many countries, is a huge source of soil information. But it usually requires specialist soil scientists to reinterpret for current questions because of the conceptual (or mental) models developed by the past soil surveyors. These conceptual models are generally not explicit, but represented in map legends, reports and the map unit boundary placement. Generally soil survey procedures are poorly understood by non-soil survey specialists and outcomes from the soil survey also appear to be commonly underestimated and underused (e.g. see examples presented as case studies in Dent & Dalal-Clayton, 2014).

Digital soil mapping is a developing area of research that has accelerated significantly in recent years due to advances in information technologies (Sanchez et al., 2009) and offers the potential to map soil properties from broad to detailed scales (Hartemink et al., 2008). Digital soil mapping uses numerical models to spatially predict variations of soil properties based on soil and environmental related information (Lagacherie et al., 2006). This method of mapping has been applied rarely for routine production mapping or addressing land management questions; it is still very much used in a research setting to improve data acquisition and ordering, and the development of analytical tools and processes that could be applied. Recently, digital soil mapping approaches have been used to support irrigation development in Tasmania (Kidd et al., 2014) and reinterpretation of legacy data (Holmes et al., 2014), demonstrating the potential of this approach to support land management. However, there are barriers before digital soil mapping is routinely applied because the technologies are not readily available or affordable, and the skills required to use it are not yet widespread (Cook et al., 2008). But in time will become a very important part of the soil surveyor’s tool kit and approach.

**How soil information is used**

Land management decisions are generally made by non-soil specialists who require soil data to be evaluated and presented by soil experts in an interpreted or user-friendly format. However, there is a growing shortage of trained pedologists, the people who have the skill and experience to reinterpret legacy soil survey data or to obtain new data (Dent & Dalal-Clayton, 2014; Basher, 1997, Soils Research, Development and Extension Working Group, 2011). Therefore approaches need to be developed to provide soil information in a form that a wider audience can understand and apply without the need for re-interpretation by specialists for each specific application.

Soil information as a commodity does not have value until it is interpreted and applied to a particular question to support a decision. Certain soil properties will influence the performance
of land for specific purposes. Consequently, the demand for soil information is highly selective, as it is specific to the purpose and selects from the total range of measured soil properties.

Knowledge of soil helps the site-specific management of agricultural inputs, such as seed rate, fertilizer, agrochemicals and irrigation. Soil knowledge also improves selection of appropriate crop types, land uses, infrastructure development or environmental management requirements. This in turn helps increase profitability of crop production, improves product quality, protects the environment, and promotes the best use of natural resources. In the justice system (e.g. police) information about soil properties at a specific location, how they change and how confidently can they be predicted is an important forensic tool. Drohan et al., (2010) says that we must rethink soil information delivery, and suggests that soil information delivery and education must use modern information delivery techniques, coupled with simple landscape-based presentations of interpreted data.

To apply soil data for site specific management, soil specialists interpret data to answer specific questions. This can be conducted by considering the soil against a set of criteria e.g. land suitability (FAO, 1976), fertility capability classification for tropical agricultural (Sanchez et al. 2003), inputs to models such as catchment hydrology modelling (e.g. Bouma, 1989; Wösten et al. 2001) and carbon sequestration prediction (e.g. FAO 2004), compared against contaminate environmental threshold limits (e.g. Arshad and Martin 2002; NEPM, 2013), or geotechnical engineering limits (e.g. Murphy 2002).

Land management decisions are generally made by people who do not have specialist soil technical skills to understand and apply the available soil data. Decision makers include individuals such as farmers and farm advisers; and groups from government, industry and the community who determine policy and actions on the land for farming, infrastructure development or conservation. They require soil information to be closely linked to the decision making process in a format to assist understanding and delivery at the scale of interest whether that is for a location, paddock, farm, watershed, national or global areas.

**Problems with soil survey information delivery**

Decline and inadequate use of soil survey information by potential users has been highlighted as a world-wide problem for many years (Dent & Dalal-Clayton, 2014; Basher, 1997, Soils Research, Development and Extension Working Group, 2011). Basher (1997) discussed these problems and they would be considered still relevant, as outlined in the following summary list:
1. Inadequate presentation of results, including excessive cartographic detail and poorly defined map units and boundary criteria.
2. Poor accuracy in the placement of boundaries between map units because of inherent soil variability, and partial loss of information on variability during the process of making maps and legends.
3. Inadequate use of soil class criteria that are important to land use (e.g. physical properties such as porosity, infiltration rate and permeability, properties of the surface layer of soil) and an overemphasis on taxonomic class criteria.
4. Insufficient attention given to presenting information in an accessible, purpose-orientated, user-friendly language and format.
5. The specialised terminology used to name and classify soils in soil map legends and reports, and the range of systems in use for classifying soils.
6. The need for adjustments in soil survey techniques and soil classification to meet the requirements of potential users.
7. Insufficient data interpretation by pedologists.
8. A lack of communication among soil scientists, agriculturalists, and economists to ensure the value of uptake of soil survey data is recognised.
9. Lack of interest by planners or decision makers in soil survey information.

The factors listed above contribute to the risk that decision makers may make a wrong decision. Soil properties affecting land use mostly occur below the land surface, making it difficult to observe and measure them. Therefore it is difficult to predict what the soil property characteristics are and their impact, creating uncertainty. Variation in soils determines variation in the capacity of the environment to provide ecosystem services. It is an improved understanding of this variability that decision makers require to better assist with managing land use.

Drohan et al. (2010) argues that we must rethink soil information delivery, “Some could effectively argue that in the last 20 years, the detail of Soil Taxonomy, and the information one needs to classify soil, has moved beyond the knowledge of non-soil scientists and even most soil scientists working outside of pedology (let’s put aside the costs of characterizing a profile, too). This must change or Soil Taxonomy will certainly go the way of most extinct languages.”
Soil maps and accompanying soil survey reports is the traditional repository for describing soil distribution information and in more recent times this can also be presented in the form of digital maps, databases and electronic reports. Where land use decisions are to be made, soil maps can be incomplete and for most areas are produced at too broad a scale to be useful for specific on ground decisions. Time and resources may not be available as part of the decision making process to collect the required data at an appropriate scale. Bridging the gap between available soil information and linking it with application, still remains a problem.

**Decision maker requirements**

Characterization of soil properties is needed to inform the users about the current conditions of the soil and to assist with determining the predicted outcome that would be associated with action on the land. Accurate data at the appropriate level is required to reduce the risk of their decision failing and to guide the appropriate level of land use change and investment. Information requirements will vary but need to be closely linked to the decision making process, provided in a form that they can use, at their level of skill/knowledge, and within their timeframe.

Historically it could be considered that soil survey reports and maps were regarded as the final end product. People producing the survey products focused on understanding soil landscape relationships and taxonomic classification of soils, with little linkage made to how this highly technical soil information was to be used. The focus of early soil survey work, often conducted at reconnaissance scale, was to support agricultural development.

The demand now is for more site-specific soil attributes data to address a variety of local, national and global issues. These include, but are not limited to, precision agriculture, assessment of environmental quality, conservation management, water quality, engineering infrastructure, sustainable land resource management, carbon sequestration, climate change and soil forensic investigations. Decision makers such as in the justice system (e.g. police) want information to provide answers to questions - what is the soil like at a location and how does it change? And what are the specific properties and how confidently can they be predicted?

Users of soil information have different levels of risk and therefore information requirements e.g. a farmer decision is very different to that of a land-use planner or policy maker. All have different levels of training and capability of understanding the results. Soil information, likely contributes to only a portion of the information required to make a decision, there will be a number of other factors to consider. Decision makers have conflicting goals and values and view the analysis from
their own perspective (Rowe, 1994). The linking of soil information for it to be applied needs to consider the decision makers ability and be focussed on their needs.

Policy makers require information at general level to establish if there is a problem, where it is and the means to deal with it. This is often served by broad reconnaissance scale survey maps and data that are often available. Whereas, local communities and land managers require information at a detailed field scale to take into account local variability that would allow sustainable and profitable land use and adoption of new practices. They are generally not served as the cost for individual land holders or community, particularly in the developing world is too high (Dent & Dalal-Clayton, 2014). They have good local knowledge about their land but it is difficult to link this with more formal soil and land resource information.

Delivery of soil information, the issues that this Thesis addresses

The uptake and application of soil data to support decisions has not been maximised because of inability to communicate soil information and providing it in a form that decision makers can readily use. There is a need to provide it in a form that non-specialists can use for their particular area as well as encourage ownership (empower them) to make use of the soil data, thus maximising the uptake and application of soil data.

To deliver the soil information, the following issues should be addressed:

1. Communication - by presenting in a language (vocabulary) that end users readily understand.
2. Dissemination – allows a wider audience to use and apply.
3. Scale – provide an understanding of soil distribution for the area and at the level of detail required to make changes.
4. Identification – identification tools to allow soil types to be recognised using limited technical expertise and resources.
5. Technology transfer – ability to link soil information with how the soil performs elsewhere, allowing new management techniques to be adopted.
6. Timely – ability to provide information now.
Delivery of soil information, approach developed in this Thesis

The approach presented in this thesis provides a framework which builds on recognised and proven soil survey tools, namely conceptual soil toposequence models and special purpose soil classifications (Fitzpatrick 2013), but developed to address current decision maker requirements.

Conceptual soil toposequence models:

Conventional soil maps are produced based on the surveyors’ understanding of soil classes and their distribution in the landscape. Soil toposequence models are a two-dimensional representations of the soil property variation across the landscape, primarily related to topography. It could be regarded as simple, but in fact is a powerful means of capturing and conveying understanding of soil variation in the landscape.

The soil toposequence model is based on the catena concept, which was developed by Milne (1935) in central Uganda. It describes the close relationship between hillslope and soil sequences, strongly emphasizing pedogenic processes, drainage, erosion, sediment transport and hydrogeology (Brown et al., 2004). Topographic variation influences soil processes such as soil erosion and soil solute movement that impacts on the other downhill members of the soil sequence, thereby developing the linkage between soil types (Conacher & Dalrymple, 1977; Huggett, 1975; Milne, 1935). Soil associations describe a geographic association of soil types rather than a process-based relationship (Conacher & Dalrymple, 1977). A soil toposequence describes a soil association that can be defined in terms of topography, but does not necessarily imply the more strictly defined process-based linkage of a soil catena.

To construct maps, soil surveyors creates models that relate observable features and measureable soil properties to a landscape position (McKenzie et al., 2000). Through an iterative process of observation, field testing and refinement of multiple hypotheses, the conceptual model is tightened to a stage whereby map boundaries can be placed to predict the location of a soil class or soil properties. This consolidated understanding is then used to extrapolate that knowledge across an area of interest. This mental model development is a prerequisite to any mapping of soil variation over an area, but is often only intuitively understood by the map maker and rarely explicitly presented (Bui et al., 1999; McKenzie et al., 2000).

Fritsch and Fitzpatrick (1994) used conceptual toposequence models to provide a better understanding of soil-regolith processes and then used them to explain causes of land degradation. Conceptual two-dimensional toposequence models provide the ability to present a variety of soil, regolith, water movement, and soil property changes in one diagram that can
communicate complicated information in a form that assists land management decisions (Fitzpatrick et al., 1996; Fitzpatrick and Merry, 2002; Fitzpatrick, 2005). It is this explicit presentation, which also includes the depiction of soil profiles as simple diagrams illustrating different layers or processes (e.g. Switoniak and Charzynski, 2014) with inclusion of colour photographs (e.g. Hartemink 2009) that adds value to an initial understanding of soil variation.

Soil toposequence models provide a conceptual understanding of soil and landscape relationships on a hillslope (Huggett, 1975) and are developed intuitively by soil surveyors to extrapolate their observations to delineation of map units and soil mapping. A farmer’s understanding of soil variation is also strongly influenced by terrain, so reasonable agreement is likely (Barrera-Bassols et al., 2009). While soil survey maps and map legends provide information on how soils vary across an area, soil toposequence models can be used to graphically convey information about soil variation in a form that non-soil experts can understand and apply to land-use decision making and directing on-ground activities.

**Special purpose soil classifications:**

Soil classification systems provide methods for ordering soils into groups with similar properties that facilitates transfer of knowledge about the soil and land management performance (e.g. Wilding & Drees, 1983; Dudal, 1987; Yaalon, 1996; Fitzpatrick, 2013). Soil Taxonomy (Soil Survey Staff, 1999, 2014) and the World Reference Base (2006) are general purpose soil classification systems used to communicate soil information internationally.

For local users, national and international classifications such as Soil Taxonomy have limitations that include reliance on laboratory analyses and the use of specialized terminology and language to classify and name soils (Drohan et al., 2010; Fitzpatrick, 2013). To improve the impact of soil survey data, the knowledge and ability of local land users need to be taken into account (Sillitoe, 1998). Linking soil data and extension of the information could be achieved by synthesizing soil survey data into simplified non technical language and or diagrams (Chang and Burrough, 1987; Chukwu et al., 2014). Presenting soil information in the form of a simplified soil classification allows local, nontechnical users to identify soils using their own language and should improve the uptake and use of soil data (Fitzpatrick, 2013).
Describe soil variability

How this is conducted

Approach

What this is used for

Improve land use and management decisions

Why this is important

Soil ecosystem services used sustainably

Figure 1. How the approach links soil data, providing soil information to enhance soil ecosystem services.

Table 1: List of studies presented in each chapter, which all have different objectives and purposes, occurring in different locations with contrasting landscapes and climates.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Delivery objective</th>
<th>Location</th>
<th>Landscape</th>
<th>Climate</th>
<th>Information is used for</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>The delivery approach</td>
<td>Diverse</td>
<td>Diverse</td>
<td>Diverse</td>
<td>Overview of approach, conceptual toposequence models.</td>
</tr>
<tr>
<td>3</td>
<td>Improve food security</td>
<td>Brunei</td>
<td>Hill slopes</td>
<td>Tropical</td>
<td>Recognition of soil types to guide suitable crop selection and their management.</td>
</tr>
<tr>
<td>4</td>
<td>Minimise impact on environment</td>
<td>Brunei</td>
<td>Flat</td>
<td>Tropical</td>
<td>Recognition of acid sulfate soils for the first time here, allows options for management to be prepared.</td>
</tr>
<tr>
<td>5</td>
<td>Mitigate land degradation</td>
<td>Kuwait</td>
<td>Desert</td>
<td>Arid</td>
<td>Rangeland restoration by targeting vegetation communities to soil types to improve success.</td>
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<tr>
<td>6</td>
<td>Maintain water quality</td>
<td>Australia</td>
<td>Wetlands</td>
<td>Mediterranean</td>
<td>Distribution of acid sulfate soil to assist with wetland management, particularly during drought.</td>
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<td>7</td>
<td>Rescue legacy soil survey information</td>
<td>Brunei, Kuwait, Australia</td>
<td>Diverse</td>
<td></td>
<td>Summarizes and describes findings.</td>
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Aim

The aim of this thesis was to deliver soil information to improve land management by development of an approach and framework to convey soil survey information by means of special-purpose soil classifications and conceptual toposequence models.

Bridging the gap between complex or intricate technical soil survey information into a format for non-soil specialists using a vocabulary and diagrams that they can understand and have available to apply when they need it. The soil information is delivered in a way that is directly applicable to pressing land use decisions, affordable, and readily available to be applied by a wide audience, thereby encouraging sustainable use of soil ecosystem services (Figure 1).

The approach was demonstrated through case studies conducted in three different parts of the world, namely in Kuwait, Brunei, and Australia (Figure 2), each of which exhibit vastly different landscapes, climates, soil types and land use problems (Table 1). Each case study was driven by demands to contribute to on-going projects tackling difficult environmental problems involving highly complex soil issues, all with different objectives that have a direct impact on significant current and future investment decisions.

The hypothesis of this work was that a systematic approach could be developed that includes the application of conceptual soil toposequence models and a special purpose soil classification to enhance delivery of soil information that would address shortcomings for soil information delivery. The test of the approach and hence of the thesis will be how well the lower part of Figure 1 accepts the outputs and then responds. If the information provided is used by decision makers (with or without other sources of information) then the consolidation, construction and delivery of information and understanding would be considered successful.

This thesis is submitted in the publication format through case studies published in soil journals. We specifically decided not to target "soil specialist journals" such as Catena (pedological), Soil Horizons (Pedological), Soil Science Society of America Journal, European Journal of Soil Science or Geoderma (strong focus on basic soil science). But those soil related journals linked strongly to land use and management hence: "Soil Use and Management" and "Arid Land Research and Management" and "Geoderma Regional" as we wanted to communicate to those scientists that straddle the area from soil data collection/interpretation to delivery/application of land management information. The findings of the thesis are summarised in a paper prepared for the GeoResJ Journal Special Issue Title: Rescuing Legacy Data for Future Science.
Figure 2: Case study locations.

References


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Chapter 2

Conceptual soil-regolith toposequence models to support soil survey and land evaluation

This chapter develops and presents examples for the use of conceptual toposequence models to describe soil variation both spatially and temporally. It provides an overview of the conceptual toposequence model approach, demonstrates how they can be used to describe, explain and predict soil variability in a range of complex landscapes and can then be used to deliver soil information to non-technical users.

This work was presented orally at the International Conference on Soil Classification and Reclamation of Degraded Lands in Arid Environments, held in Abu Dhabi in 2010 (see Appendix for Conference Abstract). It was then elaborated on and published as an invited book chapter. This paper is presented in the following pages.

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Title of Paper: Conceptual Soil-Regolith Toposequence Models to Support Soil Survey and Land Evaluation

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Chapter 3

Assisting nonsoil specialists to identify soil types for land management: an approach using a soil identification key and toposquence models

This chapter describes the approach using a soil identification key and conceptual toposquence models to aid the translation of soil survey information into a form suitable for a non soil specialist audience, and is demonstrated with a case study from the hill country of Negara Brunei Darussalam. The soil types are linked to international soil taxonomic classifications that allow information about crops and their management to be applied, thereby assisting with improving Brunei food security.

Data reported here comes from an earlier soil survey conducted in Brunei where I: (a) conducted a series of reconnaissance and detailed field soil survey investigations, and (b) was the field team leader responsible for soil assessment, interpretation of data, linking with crop and land use requirements and reporting. Reinterpretation of this work for the thesis was first presented as a refereed poster paper at the 19th World Congress of Soil Science, Soil Solutions for a Changing World 1-6 August 2010, Brisbane, Australia (see Appendix for paper). The study was then expanded and published in Soil Use and Management. This paper is presented in the following pages.

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<tr>
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<td>Developed structure of paper, obtained and interpreted data, wrote manuscript and acted as corresponding author.</td>
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Chapter 4

Acid sulphate soil characterization in Negara Brunei Darussalam: a case study to inform management decisions

This chapter describes for the first time formal recognition of a diverse range of acid sulfate soils in Brunei. Soils were characterised and conceptual soil hydro- toposquence models together with the soil identification key helped to easily visualize and illustrate the complexities in this low relief landscape. Illustrating that conceptual toposquence models can be used where there is minimal relief and successfully convey soil information allowing appropriate management practices to be targeted towards the soils.

Data reported here comes from an earlier soil survey conducted in Brunei where I: (a) conducted a series of reconnaissance and detailed field soil survey investigations, and (b) was the field team leader responsible for soil assessment, interpretation of data, linking with crop and land use requirements and reporting. Reinterpretation of this work for the thesis was first presented as a refereed poster paper at the 19th World Congress of Soil Science, Soil Solutions for a Changing World 1-6 August 2010, Brisbane, Australia (see Appendix for paper). The study was expanded and published in Soil Use and Management. This paper is presented in the following pages.

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Chapter 5

Assisting non-soil experts to identify soil types for land management to support restoration of arid rangeland native vegetation in Kuwait

This chapter applies the approach presented in previous chapters to guide non-soil experts with identifying soil types in Kuwait. The work supports rangeland restoration by enabling the planting of vegetation communities according to identified soil types, thereby assisting with mitigating land degradation. The work demonstrates that the approach using conceptual toposequence models and a local specific soil identification key can be applied in other countries, landscapes and soil types.

Data reported here comes from an earlier soil survey conducted in Kuwait where I: (a) conducted a series of reconnaissance and detailed field soil survey investigations for the 3.5 year project, and (b) was the field team leader responsible for teams conducting soil assessment and interpretations for land management, which included maintaining operational guidelines and quality control, evaluation of data and reporting to the client. Reinterpretation of the soil survey information was conducted for this thesis work and was published in *Arid Land Research and Management*. This paper is presented in the following pages.

# Statement of Authorship

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Chapter 6

Regional distribution of acid sulfate soils in wetlands during severe drought along the Lower River Murray, South Australia: A synthesis to support management

This chapter provides an understanding of acid sulfate soil distribution for a large regional area of wetlands associated with the River Murray in South Australia, how to recognise these soils and their likely distribution. The use of conceptual toposequence models (at a regional and local scale) and soil identification to assist with identifying areas that require monitoring and management to maintain river water quality.

Data reported here comes from work conducted during my PhD studies where I: (a) conducted all the detailed soil survey investigations in 80 wetlands, and (b) was the project and field team leader responsible for conducting soil assessment, interpretation of data and reporting to the client. Reinterpretation of this work for the thesis was first prepared and presented as refereed poster papers at two conferences: (i) 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia; and (ii) Joint Australian and New Zealand Soils Conference ‘Soil solutions for diverse landscapes’ 2-7 December 2012, Hobart, Australia (see Appendix for conference papers). The study was expanded and published in Geoderma Regional. This paper is presented in the following pages.

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Chapter 7

Synthesis, research outcomes, future work and conclusions

This thesis has investigated the application of user-friendly special purpose soil classification systems in the form of soil identification keys and conceptual toposequence models to identify soil types and their distribution in a wide range of landscapes. This final chapter brings together the findings from the previous case studies Chapters 2 to 6, describes the generic approach, the benefits, limitations, and possible improvements. The philosophy underpinning the approach is also presented.

The findings from this thesis study were published in GeoResJ Special Issue Title: Rescuing Legacy Data for Future Science. This paper is presented in the following pages.

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Soil survey data rescued by means of user friendly soil identification keys and toposquence models to deliver soil information for improved land management

G.J. Grealish a,⇑, R.W. Fitzpatrick a,b, J.L. Hutson c

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ABSTRACT

In many countries there is a large source of soil survey information that could be used to guide land management decisions. This soil information is commonly undervalued and underused, because it is usually not in a user-friendly format that non-soil specialists who generally make land management decisions can readily apply, nor are soil specialists always immediately available to conduct the interpretation required.

The aim of this work was to develop an approach to convey soil survey information by means of special-purpose soil classifications and conceptual toposquence models in order to improve land management decisions. The approach: (i) salvages and reinterprets valuable soil survey legacy data from the plethora of detailed published soil survey technical reports and their numerous appendices of quantitative and qualitative data, and (ii) delivers complex or intricate soil survey information to non-soil specialists using a vocabulary and diagrams that they can understand and have available to apply when they need it.

To illustrate the wide applicability of this approach, case studies were conducted in three different parts of the world – Kuwait, Brunei, and Australia, each of which exhibit vastly different landscapes, climates, soil types and land use problems. Pedologists distilled published soil survey information and identified a limited set of soil properties related to landscape position which enabled non-soil specialists to determine soil types by following user-friendly approach and format. This provides a wider audience with information about soils, rather than always relying on a limited number of soil specialists to conduct the work.

The details provided in the case studies are applicable for the local area that they were prepared for. However, the structured approach developed and used is applicable to other locations throughout the world outside of: (i) Brunei, especially in tropical landscapes, (ii) Kuwait, especially in arid and semi-arid landscapes and (iii) Australian winter rainfall landscapes, especially in Mediterranean landscapes – in order to establish similar local classifications and conceptual models.

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1. Introduction

In many countries legacy soil survey data comprise a plethora of large published soil survey technical reports with numerous maps, soil and map unit descriptions, analytical data and appendices of qualitative and quantitative data. These are valuable sources of soil information to help guide land management decisions, but are commonly undervalued and underused.

Construction of the soil survey reports and maps is not an explicit process, particularly with regard to describing soil variation [11,45]. Therefore disaggregation cannot be easily automated and requires the skills of an experienced soil surveyor to conduct in the first instance and place in a framework that others can understand and use.

The link between soil information and good decisions about land use and management needs to be improved. On the world stage, most soil survey data are more than thirty years old and may not be in a form applicable to answer current questions; also, many of those who have the ability to apply and interpret the data are being pensioned off [21].

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1.1. Soil information is important

Soils provide vital ecosystem services that support human needs for food, fibre, fuel and water [17,19,20], e.g., soils shelter seeds, provide physical support for plants, moderate the water cycle, and retain and deliver nutrients to plants. Soil information is traditionally associated with food and fibre production, but can also be applied to a number of other important ecosystem services that affect the quality of human life. These include water quality, the carbon cycle and locating sources of building and road construction materials, all of which require improved understanding of the distribution and properties of soil types. Soil knowledge can contribute and provide an effective linking role for sustainable development and land related issues [7].

Human activities on landscapes need to be carefully planned and managed. Inefficient and inappropriate use of soil resources increases the risk of land degradation and reduces future opportunities. Land degradation includes irreversible deterioration of soil quality through intensification of soil acidity, salinity, soil structure and loss of soil organic matter and biodiversity [58]. Total land area is fixed and our finite soil resources need to be optimally used and managed to sustain current capacity and to meet future demand from the projected increasing human population [24]. Climate change is also likely to stress agricultural land areas through droughts and more intense rain storms [12]. Good management decisions require correct and understandable soil information for a location; confusing and inappropriate data can lead to suboptimal practices. Uncertainty about appropriate management arises because soils are highly variable both spatially (horizontally and vertically) and temporally [4,5,59].

1.2. How soil information is used

Land management decisions are generally made by non-soil specialists who require soil data to be evaluated and presented by soil experts in an interpreted or user-friendly format. However there is a growing shortage of trained pedologists, the people who have the skill and experience to reinterpret legacy soil survey data or to obtain new data [21,3,53]. Therefore approaches need to be developed to provide soil information in a form that a wider audience can understand and apply without the need for re-interpretation by soil specialists for each specific application.

Soil information as a commodity does not have value unless it is interpreted and applied to a particular question to support a decision. Knowledge of soil helps the site-specific management of agricultural inputs, such as seed rate, fertiliser, agrochemicals and irrigation. Soil knowledge also improves selection of appropriate crop types, land uses, infrastructure development or environmental management requirements. This in turn helps increase profitability of crop production, improves product quality, protects the environment, and promotes the best use of natural resources. Drohan et al. [22] suggests that soil information delivery and education must use modern information delivery techniques, coupled with simple landscape-based presentations of interpreted data.

Digital soil mapping is a developing area of research that has accelerated significantly in recent years due to advances in information technologies [49] and offers the potential to map soil properties from broad to detailed scales [37]. Digital soil mapping uses numerical models to spatially predict variations of soil properties based on soil and environmental related information [42]. However, this method of mapping has rarely been used for routine production mapping or addressing land management questions; it is still very much used in a research setting to improve data acquisition, the development of analytical tools and processes that could be applied. The technologies are not readily available or affordable, and the skills required to use it are not yet widespread [16]. However, in time this will become a very important part of the soil surveyor’s tool kit and approach.

While digital soil mapping offers much promise, it does not provide a solution for the current issue that requires immediate delivery of soil data, or to deal with historical soil survey reports where primary data is not necessarily available or to deal with reinterpretation and applying it to land management decisions.

1.3. Delivery of soil survey data

The aim of this work was to deliver soil information to improve land management by developing an approach and framework to convey soil survey information by means of special-purpose soil classifications and conceptual toposequence models.

This approach bridges the gap between complex or intricate technical soil survey information and provides it in a user-friendly format for non-soil specialists, by using vocabulary and diagrams that they can understand and apply. The soil information is delivered in a way that is directly applicable to pressing land use decisions, affordable, and readily available to be used by a wider audience and soil professionals. This may be interpreted and applied to a particular question to support a decision. Knowledge of soil helps the site-specific management of agricultural inputs, such as seed rate, fertiliser, agrochemicals and irrigation. Soil knowledge also improves selection of appropriate crop types, land uses, infrastructure development or environmental management requirements. This in turn helps increase profitability of crop production, improves product quality, protects the environment, and promotes the best use of natural resources. Drohan et al. [22] suggests that soil information delivery and education must use modern information delivery techniques, coupled with simple landscape-based presentations of interpreted data.

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audience, thereby encouraging sustainable use of soil ecosystem services (Fig. 1).

2. Method – presenting the approach

The approach presented provides a framework which builds on recognised and proven soil survey tools, namely conceptual soil toposequence models and special-purpose soil classifications [25,33], but developed to address current decision maker requirements. The process requires an experienced soil surveyor to acquire and interpret conventional soil data and then distill and represent the information. This interpretation process needs to be conducted for each local area, but the framework and format for presentation of information demonstrated here could be replicated elsewhere for new local areas.

2.1. Conceptual soil toposequence models

The soil toposequence model is based on the catena concept, which comes from the Latin word “catena”, which means chain. Milne [46] developed this concept in central Uganda to describe the close relationship between a sequence of soils in different positions in the landscape, which he likened to “a chain of soils linked by topography”. Several soil scientists have since expanded this concept to more strongly emphasise pedogenic processes, drainage, erosion, sediment transport and hydrogeology (e.g., [10,54,55]). A soil toposequence describes a soil association that can be defined in terms of topography, but does not necessarily imply the more strictly defined process-based linkage of a soil catena. Fritsch and Fitzpatrick [27] used conceptual toposequence models to provide a better understanding of soil-regolith processes and then used them to explain causes of land degradation. Conceptual two-dimensional toposequence models provide the ability to present a variety of soil, regolith, water movement, and soil property changes in one diagram that can communicate complicated information in a form that assists land management decisions [26]. It is this explicit presentation, which also includes the depiction of soil profiles as simple diagrams illustrating different layers or processes with inclusion of colour photographs (e.g., [38]) that adds value to an initial understanding of soil variation.

The soil surveyor constructs conceptual toposequence models using information from the survey reports and maps, and from limited field investigations. To do this the soil maps and accompanying descriptions in the map legend, map unit descriptions and soil report need to be interpreted and understood. These maps are based on the mental models that the original soil surveyor created to relate observable features and measurable soil properties to a landscape position [45], however these mental models are often only intuitively understood and rarely explicitly presented [11,45]. Therefore soil survey experience is required to evaluate and interpret the soil reports and maps enabling the construction of a conceptual toposequence from the available information.

A farmer’s understanding of soil variation is also strongly influenced by terrain, so reasonable agreement is likely [2]. While soil survey maps and map legends provide information on how soils vary across an area, they are often not understood except by soil specialists. Soil toposequence models can be used to graphically convey information about soil variation in a form that non-soil experts, such as farmers, can understand and apply.

2.2. Special-purpose soil classifications

Soil classification systems provide methods for ordering soils into groups with similar properties that facilitates transfer of knowledge about the soil and land management performance (e.g., [23,25,59,61]). Soil Taxonomy [51,52] and the World Reference Base [60] are general purpose technical based soil classification systems used to communicate soil information internationally.

For local users, national and international classifications such as Soil Taxonomy have limitations that include reliance on laboratory analyses and the use of specialized terminology and language to classify and name soils [22,25]. To improve the impact of soil survey data, the knowledge and ability of local land users need to be taken into account [50]. Linking soil data and extension of the information could be achieved by synthesizing soil survey data into simplified non technical language and/or diagrams [13,14]. Presenting soil information in the form of a simplified soil key allows local, nontechnical users to identify soils using their own language and should improve the uptake and use of soil data [25].

To achieve this, a local soil identification key that is complementary to and maintains the same technical classification sequence was constructed in plain language. This required the soil surveyor to identify the soil types of interest, then to determine a few easily recognisable soil features (such as soil depth, soil colour, and colour patterns) that, when ordered in a soil key would uniquely identify each of the soil types. A collection of plain language soil names was developed to correspond with the formal international and/or national soil class names to provide assistance in understanding the general nature of the soil types and provide more meaning for local users (e.g., very deep yellow soil); than the international Soil Taxonomy classification (e.g., Oxyaquic Paleudult). The soil key was trialled, tested and refined by conducting field training with local farmers and other potential users.

2.3. Approach demonstrated through case studies

The approach was demonstrated through case studies conducted in three different parts of the world, namely in Kuwait, Brunei and Australia (Fig. 2), each of which exhibit vastly different landscapes, climates, soil types and land use problems (Table 1). Each case study was driven by specific local demands to contribute to on-going projects tackling difficult environmental problems involving highly complex soil issues, all with different objectives that have a direct impact on significant current and future investment decisions.

3. Results

All of the case studies reinterpret large legacy soil survey reports, maps and data sets, and present information in a form conducive to answer specific questions (Table 1). The details of how the approach has provided the information can be found in the journal papers listed in Table 2. A summary of the case studies follows.

3.1. Brunei acid sulfate soil case study (see [32])

A diverse range of acid sulfate soils occur in Negara Brunei Darussalam on the inland flat areas that are important agricultural lands. Prior to this study there was no information on the nature and occurrence of these acid sulfate soils that present significant management challenges for both agriculture and protection of the environment.

Interpretation of legacy soil survey data supported by limited field investigations and laboratory data conducted in eight areas of the Brunei-Muara District and four areas of the Belait District identified, characterised and classified eleven acid soil types according to Soil Taxonomy Classification (Table 3). Because the use of Soil Taxonomy requires considerable expertise and experience, a local soil identification key was developed based on the presence or absence of a few easily observed soil properties (soil colour, pH, depth, texture, and consistence) that were able to
uniquely identify these soil types. Plain language soil subtype names were assigned to assist Brunei users with the description and recognition of the range of acid sulfate soils (Table 3).

Conceptual soil hydro-toposequence models in the form of cross-sections were constructed to explain the spatial heterogeneity of: (i) the features of acid sulfate soils (e.g., organic-rich materials/peats, clays, sands, cracks and jarosite-rich mottles), sulfidic material and sulfuric horizons, (ii) pyrite shale outcrops and (iii) soil subtype names and linking with the corresponding formal Soil Taxonomy classification. These toposequence models (see referenced case study) provide guidance to local users on different soil relationships, both with each other and the landscape, as well as another form of information to provide confidence that they have identified the correct soil type.

3.2. Brunei hill soil case study (see [34])

The Brunei hill soil case study translated soil survey information into a form suitable for a non-specialist audience. Soil Taxonomy was first used to characterise the major soil types and then to assist end users, a complementary special-purpose soil classification was developed in the form of a soil identification key using plain language terms in English (Fig. 3) that were also translated into Malay [29,30]. A few easily recognised soil features such as depth, colour and texture were used to categorise soils to match the recognised Soil Taxonomy classes.

Fig. 2. Case study locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Delivery objective</th>
<th>Legacy soil survey data</th>
<th>Journal paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brunei</td>
<td>Minimise impact on environment</td>
<td>For the entire country [39]. For selected areas [6,28,56,57]</td>
<td>[32]. Acid sulphate soil characterization in Negara Brunei Darussalam: a case study to inform management decisions</td>
</tr>
<tr>
<td>Brunei</td>
<td>Improve food security</td>
<td>For the entire country [39]. For selected areas [6,28,56,57]</td>
<td>[34]. Assisting nonsoil specialists to identify soil types for land management: an approach using a soil identification key and toposequence models</td>
</tr>
<tr>
<td>Kuwait</td>
<td>Mitigate land degradation</td>
<td>For the entire country and selected areas at greater detail [41]</td>
<td>[36]. Assisting non-soil experts to identify soil types for land management, to support restoration of arid rangeland native vegetation in Kuwait</td>
</tr>
<tr>
<td>Australia</td>
<td>Maintain water quality</td>
<td>For 71 wetlands below Lock 1 [31]</td>
<td>[35]. Regional distribution of acid sulfate soils in wetlands during severe drought along the Lower River Murray, South Australia: A synthesis to support management</td>
</tr>
</tbody>
</table>

Table 1

List of case studies presented, which all have different objectives and occur in different locations with contrasting landscapes and climates.

<table>
<thead>
<tr>
<th>Delivery objective</th>
<th>Location</th>
<th>Landscape Climate</th>
<th>Information is used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimise impact on environment</td>
<td>Brunei</td>
<td>Flat Tropical</td>
<td>Recognition of acid sulfate soils for the first time here, allows options for management to be prepared</td>
</tr>
<tr>
<td>Improve food security</td>
<td>Brunei</td>
<td>Hill slopes Tropical</td>
<td>Recognition of soil types to guide suitable crop selection and their management</td>
</tr>
<tr>
<td>Mitigate land degradation</td>
<td>Kuwait</td>
<td>Desert Tropical</td>
<td>Rangeland restoration by targeting vegetation communities to soil types to improve success</td>
</tr>
<tr>
<td>Maintain water quality</td>
<td>Australia</td>
<td>Wetlands Mediterranean</td>
<td>Distribution of acid sulfate soil to assist with wetland management, particularly during drought</td>
</tr>
</tbody>
</table>

Table 2

Case studies and the progression from legacy soil survey data to journal paper providing solutions.
Table 3
A portion of the Brunei soil identification key for the acid sulfate soils (modified from [28]). That shows the descriptive plain language soil subtype name and technical Soil Taxonomy class.

<table>
<thead>
<tr>
<th>Diagnostic features for soil type</th>
<th>Soil type</th>
<th>Diagnostic features for soil subtype</th>
<th>Soil subtype</th>
<th>Soil taxonomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)? No ↑ Yes →</td>
<td>Organic soil (Saprast)</td>
<td>Does a sulfuric layer (pH &lt; 3.5) occur within 50 cm of the soil surface? No ↑ Yes →</td>
<td>Sulfuric organic soil (Sulfosaprist)</td>
<td>Terric Sulfosaprist</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does a sulfuric layer (pH &lt; 3.5) or do sulfidic materials (pH &gt; 3.5 which changes on ageing to pH &lt; 3.5) occur within 100 cm of the soil surface? No ↑ Yes →</td>
<td>Sulfidic organic soil (Sulfisaprist)</td>
<td>Terric Sulfisaprist</td>
</tr>
<tr>
<td>Does the soil develop cracks at the surface OR in a clay layer within 100 cm of the soil surface OR have slickensides (polished and grooved surfaces between soil aggregates), AND is the subsoil uniformly grey coloured (poorly drained or very poorly drained)? No ↑ Yes →</td>
<td>Cracking clay soil (Aquert)</td>
<td>Does a sulfuric layer (pH &lt; 3.5) or do sulfidic materials (pH &gt; 3.5 which changes on ageing to pH &lt; 3.5) occur within 100 cm of the soil surface? No ↑ Yes →</td>
<td>Poorly drained cracking clay soil (Aquert)</td>
<td>Sulfic Sulfasquept</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does the soil develop cracks at the surface OR have slickensides (polished and grooved surfaces between soil aggregates), AND is the subsoil uniformly grey coloured (poorly drained or very poorly drained)? No ↑ Yes →</td>
<td>Poorly drained cracking clay soil (Aquert)</td>
<td>Acid poorly drained cracking clay soil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does a sulfuric layer (pH &lt; 3.5) occur within 150 cm of the soil surface, AND is the subsoil uniformly grey coloured (poorly drained)? No ↑ Yes →</td>
<td>Poorly drained sulfuric soil (Sulfasquept)</td>
<td>Sulfic Sulfisaprist</td>
</tr>
<tr>
<td>Does a sulfuric layer (pH &lt; 3.5) occur within 100 cm of the soil surface, AND is the subsoil uniformly grey coloured (poorly drained? No ↑ Yes →</td>
<td>Sulfuric soil (Aquept)</td>
<td>Does the sulfuric layer occur within 50 cm of the soil surface? No ↑ Yes →</td>
<td>Soft poorly drained sulfuric soil</td>
<td>Hydraulentic Sulfasquept</td>
</tr>
<tr>
<td>Does sulfidic material (pH &gt; 3.5 which changes on ageing to pH &lt; 3.5) occur within 100 cm of the soil surface, AND is the subsoil uniformly grey coloured (poorly drained)? No ↑ Yes →</td>
<td>Sulfordic soil (Aquert)</td>
<td>Does the sulfidic material occur within 50 cm of the soil surface? No ↑ Yes →</td>
<td>Soft poorly drained sulfidic soil</td>
<td>Haplic Sulfasquept</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does a buried organic layer (organic material covered by mineral soil) occur within 100 cm of the soil surface? No ↑ Yes →</td>
<td>Organic poorly drained sulfidic soil</td>
<td>Thapto-Histic Sulfasquept</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Does a buried organic layer (organic material covered by mineral soil) occur within 125 cm of the soil surface? No ↑ Yes →</td>
<td>Organic poorly drained moderately deep sulfidic soil</td>
<td>Sulfic Fluvaquentic</td>
</tr>
</tbody>
</table>

Note: A No* indicates to restart the key or consider that a new soil has been identified that is not classified in the identification key.


The approach supports the restoration of Kuwait rangelands, where there is a need to assist revegetation success by removing uncertainty about soil conditions and matching revegetation communities to soil type. Legacy data from soil survey reports were available for reinterpretation. The soil identification key was developed in a matrix form, and allowed soil types to be determined by the presence or absence of three recognisable soil features that generally typify arid zone soils worldwide, i.e., hardpan, gypsum and calcium carbonate (Table 4). The soil type

robust. Toposequence and soil type were then linked to crop suitability providing management guidance (Fig. 4).

3.3. Kuwait case study (see [36])
Acid sulfate soil materials, if disturbed or influenced by lowering water levels, have serious environmental impacts, that include harm to ecosystems and leaching of acidity and metals into water bodies. Low river flows from 2007 to 2010 due to an unprecedented drought resulted in 71 wetlands along 210 km of the River Murray below Lock 1 in South Australia becoming dry, exposing normally permanent subaqueous wetland soils, which in some instances caused severe soil and water acidification. The aim of this study was to provide an understanding of the nature and distribution of acid sulfate soils for hazard assessment and to guide management. Substantial legacy soil survey and acid sulfate soil data from multiple studies were consolidated, interpreted, and described in a regional and local context. Fig. 5 shows a conceptual toposequence for the distribution of soils at a local scale in one of the wetlands, with the descriptive soil names and corresponding formal Soil Taxonomy classes in brackets.

4. Discussion

At a regional scale pedological, soil chemical and geomorphology data showed that acid sulfate soils with hypersulfidic (potential to acidify to pH ≤ 4) and sulfuric (pH < 4) materials with higher acidification hazard were more dominant in downstream wetlands. A trend observed in chromium-reducible sulfur data was suggested to be linked to regional fluvial erosion and deposition processes because the transition coincides with the river landscape changing from a linear gorge valley upstream to downstream open flood plain areas (see [35] for figures).
This approach does not diminish the soil specialist skills or existence, but does allow them to disseminate the available soil information by providing many users with the tools for them to identify soil types. Knowledge embed in the soil survey reports, that probably otherwise would not have been considered by local users, has been made available.

4.1. Conceptual toposequence models

Toposequence models are a proven concept that have successfully assisted with providing understanding for various soil related questions, e.g., soil formation (e.g., [40,15,54], water movement (e.g., [18,8,9,43,44,47], soil-regolith process [27] and land degradation [25]. The topographic position of soil profiles is a key attribute collected by soil surveyors and is an important component of other environment data collections such as geology, vegetation type and hydrology. We have used conceptual toposequence models to more clearly convey soil distribution (e.g., Figs. 3 and 5), and also provide a link between soil information and land management (e.g., Fig. 4).

Findings from our case studies indicate that soil toposequence models applied to current land management decisions can be:

- Integrating for simple and complex data sets and processes.
- Able to show spatial (vertical and horizontal) changes.
- Linked with maps to provide three-dimensional variation.
- Scale independent.
- Flexible and easy to update with new information.
- Used to mimic what people see in a landscape.
- Able to convey information as a figure that is visual and easily understood.
- Potentially able to extrapolate using digital datasets through digital soil mapping processes.
- Applicable to different climates and landscapes.
- Customised to present information specific to a problem or enquiry.
- Extrapolated with confidence over an area using terrain information, either visually or by using digital elevation models and other remotely sensed data.

4.2. Special-purpose soil classification

Soil classification systems provide the rigour necessary for ordering and scientifically naming soils, which facilitates transfer of knowledge about soils and crop performance on similarly classified soils. While general-purpose international soil classifications such as Soil Taxonomy are readily understood by soil surveyors, they are often impossible to use and mean little to non-soil specialists; therefore special-purpose soil classification systems for an area provide a means for local land users to identify soils and the key attributes that distinguish the soil types.

Special-purpose soil identification keys were developed and presented in two forms: (i) a bifurcating approach with yes or no answers leading to the next question until a result is reached (Brunei case studies), and (ii) as a matrix where a collection of yes or no answers to questions provided a result (Kuwait case study). Both worked equally well. The matrix approach works best when there are fewer questions, e.g., the Kuwait case study with three questions (Table 4). The bifurcating approach was better suited when there are more options, and worked well for land users when it involved simple yes or no questions to progress through the key, reducing and simplifying the decision process (Table 3).

Findings from our case studies indicate the benefits of applying local special-purpose soil classification keys to current land management decisions include:
Benefits of this information included:

- Soil survey information in a user-friendly non-technical framework.
- Information to current problems confirmed the value of presenting

Table 4

<table>
<thead>
<tr>
<th>Are gypsum soil features present?</th>
<th>Are calcium carbonate soil features present?</th>
<th>Are hardpan soil features present?</th>
<th>Soil type name (Approximate Soil Taxonomy Great Group)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require all of the following:</td>
<td>Require all of the following:</td>
<td>Require all of the following:</td>
<td></td>
</tr>
<tr>
<td>• Gypsum identified – where there are any white or opaque (gypsum) crystals visible (if necessary cheque with field EC test where reading is about 2 dS/m)</td>
<td>• Calcium carbonate identified where there are 5% or more visible white soft masses or nodules (if necessary cheque with field HCl test, where fizz will be a strong or violent reaction)</td>
<td>• Using an auger or shovel there is refusal to penetration due to hard layer (not coarse fragments)</td>
<td>Calculcareous soil (Haplocalcid)</td>
</tr>
<tr>
<td>• Not cemented.</td>
<td>• Not cemented.</td>
<td>• Occurs within 100 cm of soil surface</td>
<td>Calculcareous over a hardpan soil (Petrocalcid)</td>
</tr>
<tr>
<td>• Occurs within 100 cm of soil surface</td>
<td>• Occurs within 100 cm of soil surface</td>
<td></td>
<td>Calculcareous over gypsum soil (Calcigypsid)</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Gypseous soil (Haplogypsid)</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Gypseous over a hardpan soil (Petrogypsid)</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Gypseous and calcareous over a hardpan soil (Petrogypsid)</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Deep sandy soil (Torripsamment)</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

- An approximate correlation between the key and national/international soil classifications provides linkage with technical soil data and interpretations.
- Use of descriptive common plain language allows non-specialist to more easily understand and apply to determine soil types.
- Readily updateable for the area of interest as new soil types or further separations of soil types are required.
- Limiting to a few easily recognisable soil properties makes it practical and affordable for people to use.

4.3. Immediate uptake of information

For the case studies described, rapid application of the soil information to current problems confirmed the value of presenting soil survey information in a user-friendly non-technical framework. Benefits of this information included:

- **Brunei acid sulfate soils** [32] – Farmers growing vegetables on these soils now understand the source of acidity, and the need to manage the water table and minimise soil disturbance to avoid oxidising the sulfidic subsoil materials. Additionally, methods of identifying and locating these hazardous soils were requested by local researchers investigating fish kills in an adjacent estuary.

- **Brunei hill slope soil identification** [34] – Agricultural advisors used the classification system to identify soils and provide crop and soil management information to farmers. Additionally, requests were received from agencies in other countries (including Iranian University, Philippines Bureau of Soil and Water, and Abu Dhabi Environment Agency) for further information on the approach and possible application to their environments.

- **Kuwait desert restoration** [36] – Soil information can now more easily be included in planning. The approach could be regularly updated during the implementation of the revegetation program, as monitoring data on plant performance becomes available to improve targeting of plants and seeds to soil.

- **Australia River Murray and adjacent wetland acid sulfate soils** [35] – Soil information was used during the so-called ‘Millennium drought’ by Federal and State Government agencies to prioritise wetlands and prepare management plans. Although that immediate issue has passed, the data is now being applied to plan management strategies for future drought events.

The case studies have shown that the approach not only addresses decision issues for the traditional area of agriculture (e.g., Brunei case studies), but also provides soil information applicable to broader environmental concerns e.g., hazardous soils (Brunei and Australia acid sulfate soil case studies), land degradation (Kuwait and Australia case studies), restoration and revegetation (Kuwait case study) and water quality (Australia case study).

4.4. Study outcomes

The approach has successfully delivered soil information as demonstrated by the case studies because it has addressed the following:

- **Communication** – The soil identification keys use plain language and simple words that most people recognise, but retain sufficient rigour to identify different soil types for the area of interest. By not using complex scientific words, the Brunei soil key could be translated into Malay, thus improving its utility for non English speakers.

- **Dissemination** – The technical information in the soil survey reports was understandable to a select group of trained soil scientist. Without these soil specialists the information would not be used. This approach provides a framework that connects the data now with a larger audience of decision makers in a
format for their local area that they can understand and apply, now and in the future, as demonstrated by the examples of information uptake listed above. Preparation of simple manuals and information notes as was done in Brunei, both in hardcopy and online, ensures longer term availability. It should be acknowledge that in some locations, land users do not have access to the internet and online systems or even the ability to afford or use them. Therefore simple hardcopy fact sheets remain valuable.

- **Scale** – mapping was not an output, hence map scale was not considered. The conceptual toposequence models were scale independent, showing the relationship of soil types to each other and their location in the landscape. Non-technical users could more easily relate to these diagrams because they mimicked the real landscape (rather than maps), thus providing confidence in recognition of soil type locations and a cheque on the soil type determined by the soil identification key.

- **Identification** – with limited training non-soil specialists could readily recognise observable soil features such as colour, texture and depth, and determine easily measurable features such as pH and electrical conductivity. This enabled them to answer the identification key questions to determine soil type without requiring understanding and application of more complex soil morphology descriptions and analytical data.

- **Technology transfer** – the strength of the approach was that soil types were correlated to the specialist national or international taxonomic classifications, providing the ability to transfer and apply known technologies, practices and soil behaviour knowledge from the same taxonomically classified soils elsewhere in the region.

- **Timely** – a key issue was to address the immediate requirements for communicating soil information. This was achieved by reworking legacy soil survey data, using proven soil surveyor tools (toposequence models and soil classification systems), formatted to address current needs. The approach is explicit and can be updated or expanded as new information about the soils and land use is acquired.

### 4.5. Stages of soil information delivery

The goal was not to have as much data as possible, but to identify the data set required for a decision, obtain it and organise it in a way...
that relates to the problem to be addressed. The stages leading up to delivery of solutions based on soil survey data can be summarised using the DIKW pyramid [1] as presented in Table 5.

Stages 1, 2, and 3 are well understood and documented in the literature, stage 4 to a lesser degree. The approach presented provides links between stages 1, 2 and 3. The success of stage 4 depends on how the soil information is subsequently used by the decision maker.

4.6. Future work recommendations

**Develop an application to operate on computers, tablets or mobile phones.** An app linking interactive toposequence information and a soil identification key for an area would be useful. Even in remote rural locations mobile phone communication is common. The application could be downloaded by farmers, and easily updated as more information becomes available, providing flexibility and adaptability compared with static paper outputs. Guidance in the form of soil and management information could be attached to the soil type results, supported with tabular information and graphics.

**Determine what type and level of information a decision maker requires.** How do users deal with complex uncertainty? Throughout the case study work it was clear that there was little or no documented information on how decision makers use and apply soil information, and in particular, how they incorporate uncertainty. Is soil information used, for example, to maximise benefits or minimise the likelihood of negative outcomes? Users of information have different risk thresholds and therefore information requirements, e.g., a farmer’s decision criteria are very different to those of a land-use planner or policy maker. All have different levels of training and capability of interpreting data. Soil information likely contributes only a portion of the information required to make a decision, as there will be a number of other factors to consider. Decision makers often have conflicting goals and values and will tend to view analyses from their own perspective [48]. An improved understanding of their needs and expectations would aid in determining the level and format of soil information to be delivered.

**Support digital soil mapping.** Digital soil mapping is the next major tool to assist with mapping soil properties [37]. The increase in technology has led to the development of new standards as well as data acquisition and processing tools; however it is important that the invaluable information and knowledge that a soil surveyor has about a soil landscape or that is contained in legacy reports not be neglected. This approach provides a method for presenting the conceptual models and organising of soils used in traditional soil survey, as well as understanding to assist with verifying digital soil mapping outputs.

5. Conclusions

An approach has been presented to: (i) salvage and reinterpret valuable legacy soil survey data from the plethora of large published soil survey reports for future science, and (ii) deliver complex or intricate soil survey information to non-soil specialists using vocabulary and diagrams that they understand. This was achieved by re-interpreting soil survey data in the form of special-purpose soil classifications and conceptual toposequence models for the areas of interest. The derived soil types, correlated to formal soil classifications, allow technical soil property data to be applied to land suitability evaluations and environmental problems.

Adoption of the information to answer real current questions confirms the value of presenting soil survey information in a user-friendly format that a non-soil specialist audience can understand.

The approach developed and used is applicable to other locations throughout the world outside of: (i) Brunei, especially in tropical landscapes, (ii) Kuwait, especially in arid and semi-arid landscapes and (iii) Australian winter rainfall landscapes, especially in Mediterranean landscapes – in order to establish similar local classifications and conceptual models.

The approach does not diminish the need for pedologists to conduct soil survey investigations using general-purpose international and national soil classifications. Instead it enables a wider non-soil specialist audience to take advantage of soil information in a format that enables them to incorporate soil information in their decision-making and better understand soils in their local area or discipline.

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Conference Papers

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Chapter 2:
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