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

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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 decision. 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 toposequence 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.

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 wide

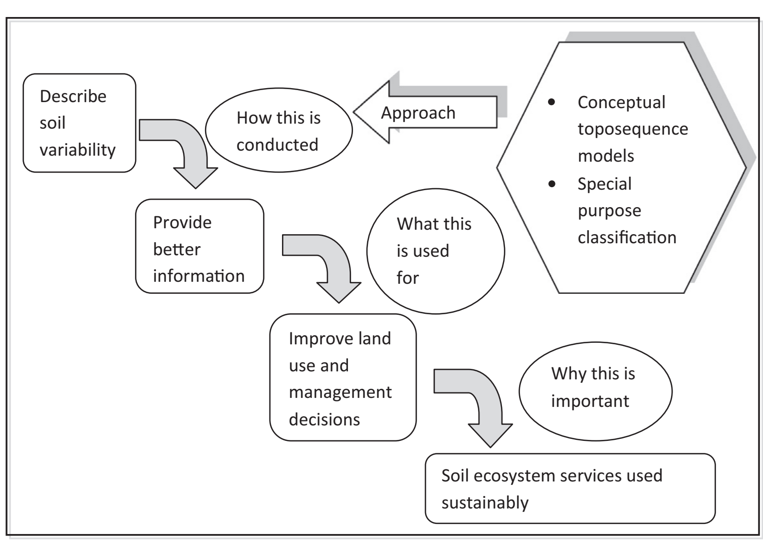

Fig. 1. How the approach links soil data, providing soil information to enhance soil ecosystem services.

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 Palehumult). 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

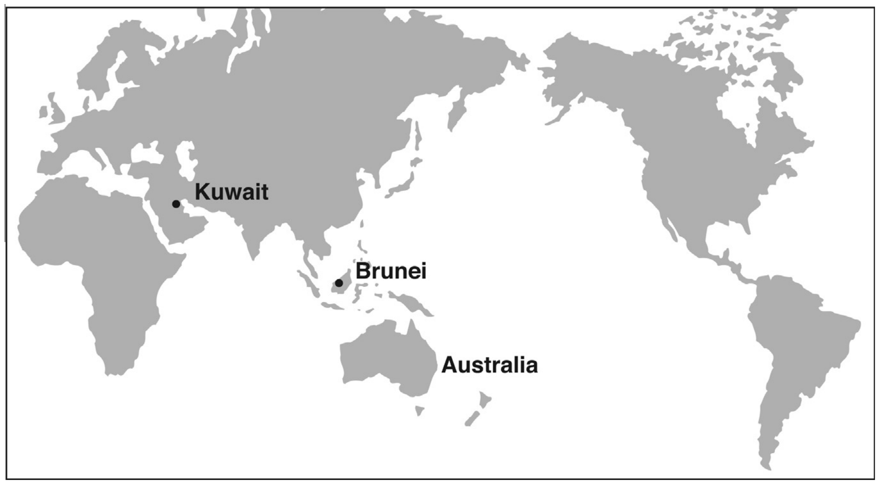

Fig. 2. Case study locations.

Table 1
List of case studies presented, which all have different objectives and occur in different locations with contrasting landscapes and climates.

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

Table 2
Case studies and the progression from legacy soil survey data to journal paper providing solutions.

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

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.

To complement the soil identification key, conceptual soil toposequence models presented the soil distribution and landscape position in a visual format that local land users understood (Fig. 3). Legacy soil survey information along with a widespread distribution of 172 soil sites from 35 traverses in 16 study areas provided a dataset to develop and test soil toposequence models and the soil identification key, both of which proved reliable and

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.

Diagnostic features for soil type	Soil type	Diagnostic features for soil subtype		Soil subtype	Soil taxonomy class
Does the upper 80 cm of soil consist of more than 40 cm of organic material (peat)? **No ↓ Yes →**	Organic soil (Saprist)	Does a sulfuric layer (pH < 3.5) occur within 50 cm of the soil surface? **No ↓ Yes →**	Sulfuric organic soil (Sulfosaprist) Does a mineral soil layer > 30 cm thick occur within 100 cm of the soil surface? **No ↓ Yes →**	Mineral sulfuric organic soil	Terric Sulfosaprist
			→	Sulfuric organic soil	Typic Sulfosaprist
		Does sulfidic material (pH > 3.5 which changes on ageing to pH < 3.5) occur within 100 cm of the soil surface? **No*** **Yes →**	Sulfidic organic soil (Sulfisaprist) Does a mineral soil layer > 30 cm thick occur within 100 cm of the soil surface? **No ↓ Yes →**	Mineral sulfidic organic soil	Terric Sulfisaprist
			→	Sulfidic organic soil	Typic Sulfisaprist
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 →**	Cracking clay soil (Aquert)	Does a sulfuric layer (pH < 3.5) or do sulfidic materials (pH > 3.5 which changes on ageing to pH < 3.5) occur within 100 cm of the soil surface? **No ↓ Yes →**	Poorly drained cracking clay soil (Aquert) Does sulfidic material occur within 100 cm of the soil surface? **No*** **Yes →**	Sulfidic poorly drained cracking clay soil	Sulfic Sulfaquert
		→	Poorly drained cracking clay soil (Aquert) Does a soil layer with pH < 4.5 occur within 50 cm of the soil surface? **No*** **Yes →**	Acid poorly drained cracking clay soil	Typic Dystraquert
Does a sulfuric layer (pH < 3.5) occur within 150 cm of the soil surface, AND is the subsoil uniformly grey coloured (poorly drained)? **No ↓ Yes →**	Sulfuric soil (Aquept)	Does the sulfuric layer occur within 50 cm of the soil surface? **No*** **Yes →**	Poorly drained sulfuric soil (Sulfaquept) Does a soft layer occur within 100 cm of the soil surface? **No ↓ Yes →**	Soft poorly drained sulfuric soil	Hydraquentic Sulfaquept
			→	Poorly drained sulfuric soil	Typic Sulfaquept
Does sulfidic material (pH > 3.5 which changes on ageing to pH < 3.5) occur within 100 cm of the soil surface, AND is the subsoil uniformly grey coloured (poorly drained)? **No ↓ Yes →**	Sulfidic soil (Aquent)	Does the sulfidic material occur within 50 cm of the soil surface? **No ↓ Yes →**	Poorly drained sulfidic soil (Sulfaquent) Does a soft clayey layer occur between 20 and 50 cm of the soil surface? **No ↓ Yes →**	Soft poorly drained sulfidic soil	Haplic Sulfaquent
			Does a buried organic layer (organic material covered by mineral soil) occur within 100 cm of the soil surface? **No*** **Yes →**	Organic poorly drained sulfidic soil	Thapto-Histic Sulfaquent
Ongoing decisions in key (not presented here)		→	Poorly drained moderately deep sulfidic soil (Aquent) Does a buried organic layer (organic material covered by mineral soil) occur within 125 cm of the soil surface? **No*** **Yes →**	Organic poorly drained moderately deep sulfidic soil	Sulfic Fluvaquent

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.

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

3.3. Kuwait case study (see [36])

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

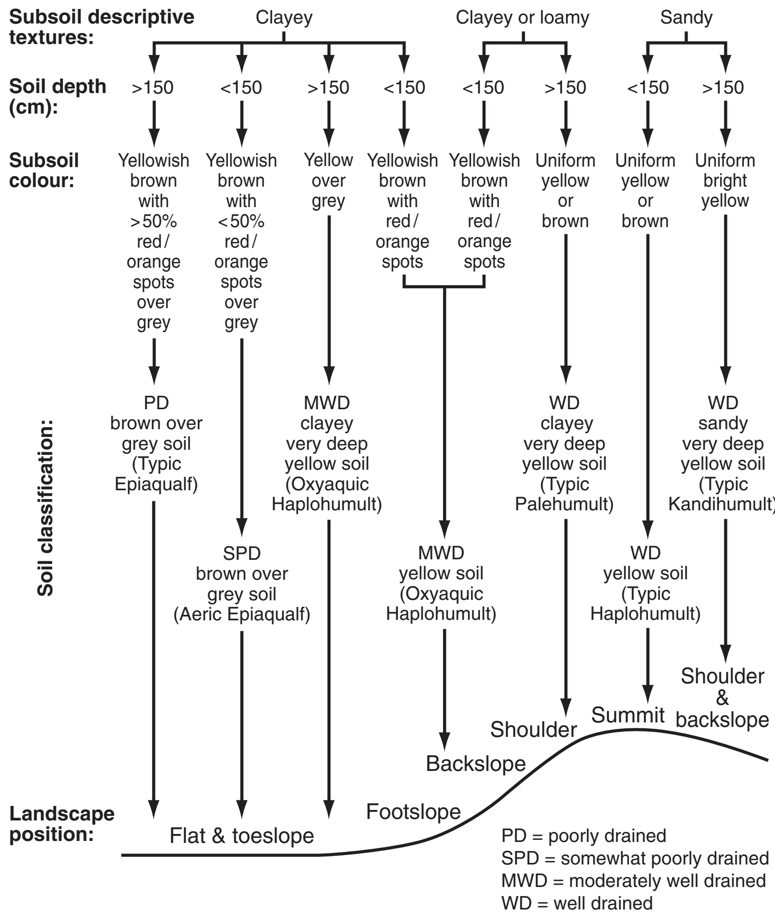

Fig. 3. Conceptual toposequence model showing landscape position and key soil identification features for the major soil types in Tutong District, Brunei. The soil classification provides the local descriptive soil name and the corresponding Soil Taxonomy class is bracketed (from [34]).

categories were named descriptively for ease of understanding by non-technical users, and were structured to align with the previously identified Soil Taxonomy classes to maintain linkages with the soil survey and other interpreted information.

To complement the soil identification key, conceptual soil toposequence models present the general soil distribution patterns in a visual format to aid understanding of spatial variation and soil type relationships (see [36]). The flexible approach was established so that it can be scaled with additional criteria as more knowledge is acquired about the relationship between soil types and vegetation communities during the revegetation program.

3.4. Australia case study (see [35])

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.

At a regional scale pedological, soil chemical and geomorphology data showed that acid sulfate soils with hypersulfidic (potential to acidify to $pH \leqslant 4$) 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).

4. Discussion

To deliver soil information a structured approach was presented that describes a framework (using conceptual toposequence models and soil identification keys) to convey soil data in a format that can be used and applied by non-soil scientists. The approach is generic, demonstrated by the case studies in different regions and land use problems. What is transferable and applicable is the framework, and for each new area the detail would have to be prepared by an experienced soil scientist. However, once prepared a larger audience of users can then apply the prepared information to assist with their land use decisions because the range of soil properties to recognise are limited and easy to identify, and the format of presentation is at a level of detail and language appropriate to their skills and knowledge.

Soil scientists with the experience to conduct this work are limited and cannot meet the demands for soil identification and interpretation, particularly if it was a one-on-one user basis, or even have time to promote the information in the soil survey reports.

Topography			
Landscape position	Hillslope	Terrace	Valley flat
Soil type	Yellow soils	Very deep yellow soils	Brown over grey soils
Suitable crops	Where slope <55% Grass species Fodder legume species adapted to wet areas	Cassava and sweet potato Grass species Fodder legume species adapted to wet areas	Rice Grass species adapted to wet areas Fodder legume species adapted to wet areas
Moderately suitable crops	Fodder legume species adapted to well drained conditions Where slope >55% Grass species Fodder legume species adapted to wet areas Where slope <65% All fruit crops assessed Where slope <55% Cassava and sweet potato Where slope <35% Leafy, fruit and root vegetables Groundnuts Soya and mung bean Maize Ginger and turmeric	Rice Leafy, fruit and root vegetables Groundnuts Soya and mung bean Maize Ginger and turmeric All fruit crops assessed Fodder legume species adapted to well drained conditions	Leafy, fruit and root vegetables Ginger and turmeric Grass species adapted to well drained conditions

Fig. 4. Summary of crop suitability presented according to soil type and topographic position for Temburong District, Brunei (from [34]).

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:

Table 4
Soil identification key for Kuwait, presented using a matrix with the presence of each soil feature required to determine the soil type (from [35].

Are gypsum soil features present?	Are calcium carbonate soil features present?	Are hardpan soil features present?	Soil type name (Approximate Soil Taxonomy Great Group)
Require all of the following: • 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) • Layer ⩾ 15 cm thick. • Not cemented. • Occurs within 100 cm of soil surface	Require all of the following: • 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) • Layer ⩾ 15 cm thick. • Not cemented. • Occurs within 100 cm of soil surface	Require all of the following: • Using an auger or shovel there is refusal to penetration due to hard layer (not coarse fragments) • Occurs within 100 cm of soil surface	
No	**Yes**	No	Calcareous soil (Haplocalcid)
No	**Yes**	**Yes**	Calcareous over a hardpan soil (Petrocalcid)
Yes	**Yes**	No	Calcareous over gypseous soil (Calcigypsid)
Yes	No	No	Gypseous soil (Haplogypsid)
Yes	No	**Yes**	Gypseous over a hardpan soil (Petrogypsid)
Yes	**Yes**	**Yes**	Gypseous and calcareous over a hardpan soil (Petrogypsid)
No	No	No	Deep sandy soil (Torripsamment)

- 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

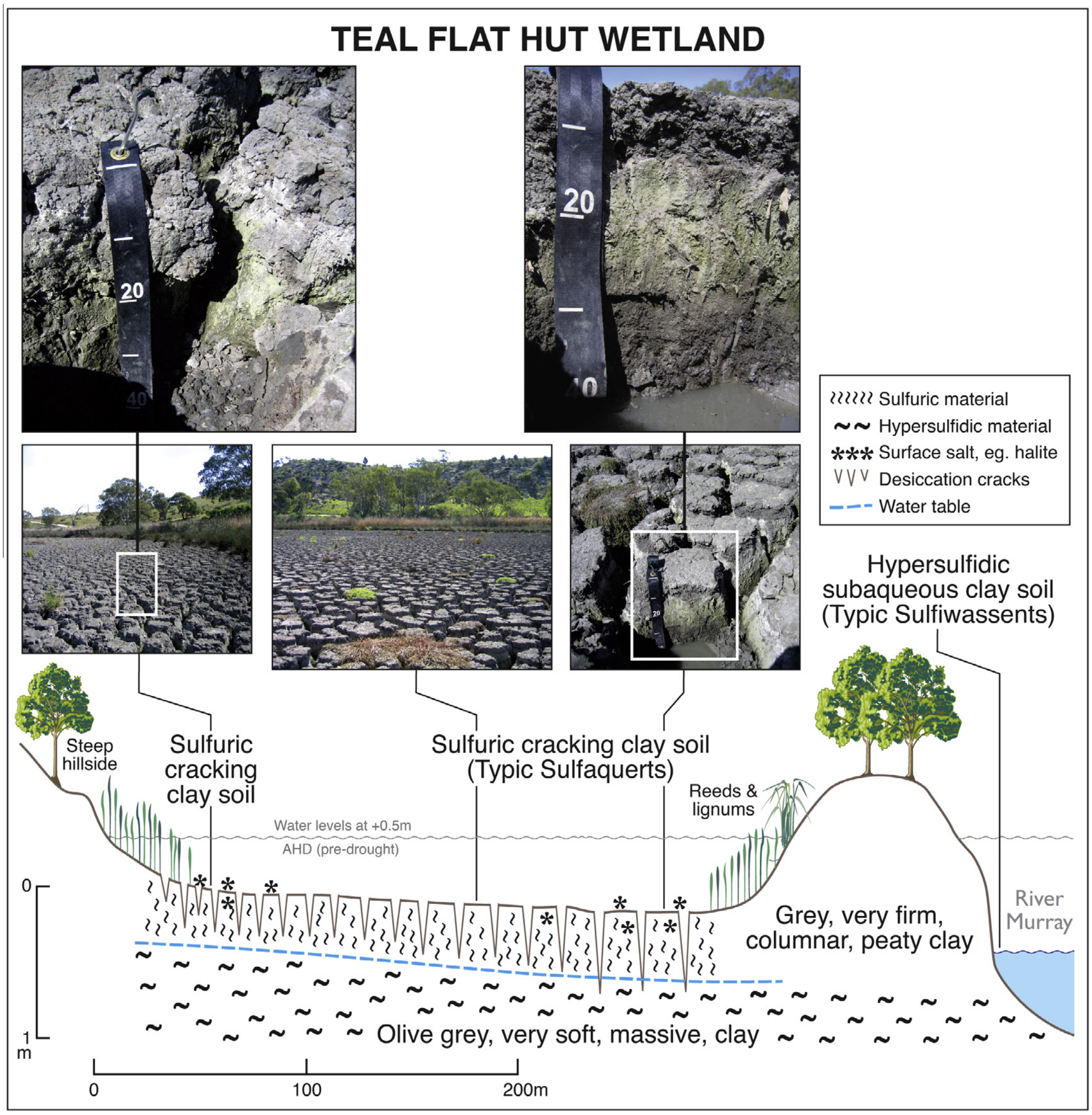

Fig. 5. Cross-section showing the distribution of acid sulfate soil materials at a local scale. The descriptive soil names are provided along with their approximate Soil Taxonomy class that is bracketed (from [36]. Photographs communicate location and soil characteristics.

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 measureable 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

Table 5
Soil survey stages of data development.

	Stage	Product	Data stage	Action
1.	Data	Soil survey	Legacy data gathering	Data collection
2.	Information	Soil reports, maps and appendices	Legacy data gathering	Consolidation using International and/or National soil classification, maps and map legends, laboratory data tables, map unit and soil descriptions
3.	Knowledge	Interpretation	*Legacy data elucidation*	Presented in user friendly format.Assessment against practical criteria
4.	Wisdom	Application	*Legacy data elucidation*	Derivation and identification of significance for specific question(s)

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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