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GRDC Southern Region scoping study: Available soil information to support prediction of PAWC

Output 3 Project CSP00210

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Acknowledgments

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Executive summary

Knowledge of the plant available water capacity ("PAWC") of soils on their farm can help growers and advisors improve the quality of yield forecasts that are used to inform management decisions including whether to sow or not (i.e. opportunity cropping), timing of sowing (and associated crop type and variety choice) and the input level of resources such as nitrogen fertiliser. Investment by GRDC, CSIRO and other collaborators has helped deliver a database ("APSoil") of more than 1,100 PAWC characterisations across the country. While most grain growing areas now have multiple PAWC characterisations, extrapolating the information to individual farm paddocks remains a challenge.

Project CSP00210 'Methods to predict plant available water capacity (PAWC)' will explore for the GRDC Northern Region, how to use available PAWC data and soil information to predict PAWC for locations of interest without a PAWC characterisation. It will also evaluate different approaches for prediction of PAWC. The most suitable predictive approach in a particular area may depend on the availability and reliability of the soil and landscape information as well as the complexity of the landscape. A scoping study reviewing available state-wide soil information that could be used for mapping PAWC to soil landscapes and predicting PAWC at the farm management scale was conducted for all three GRDC regions (Northern, Western and Southern).

This report reviews the available PAWC and soil data and other supporting information in the Southern Region. It also includes suggestions for possible case study areas where different predictive methods could be tested in the Southern Region.

The GRDC Southern Region has 375 PAWC characterisations, which are freely available online (https://www.apsim.info/Products/APSoil.aspx) and in the iPad application SoilMapp. Of these, 236 are located in SA, 117 in Victoria, and 22 in Tasmania. Their distribution coincides strongly with the main grain growing areas where the use of PAWC data is most relevant.

Over the years many soil and landscape surveys have been carried out within the GRDC Southern Region. However, apart from national soil mapping at a coarse scale (1:2M, generated in the 1960s and retrospectively correlated to Australian Soil Classification) there is no consistent soil mapping across the whole region. Each state has followed a different mapping approach that reflects their individual histories in terms of resource policy, institutional history and expertise. For example, SA embarked on a systematic mapping program (1970s-1990s) for the agricultural areas that created a seamless soil-landscape mapping coverage at 1:100,000-1:50,000 scale and now gives a powerful underpinning for contemporary land resources assessment work. In contrast, Victoria's and Tasmania's soil mapping history has been somewhat piecemeal, and characterised by numerous mapping campaigns covering discrete areas at different times, with mapping conducted using different thematic approaches and scales. Over time there have been projects to correlate mapping to remove border affects and/or harmonise mapping themes. In recent times digital soil mapping (DSM) using disaggregation approaches has been carried out to do this, and this approach indicates the way forward for further correlations to increase the level of inter-map consistency. Much of the mapping and soil point observations generated by the Southern Region states are freely available online via state data portals and in the Australian Soil Resource Information System in polygon or point formats, and/or as map scans and accompanying reports.

Soil and landscape surveys and associated geological and geophysics data can help build a conceptual model or narrative of soil landscape relationships within an area. This can in turn inform the extrapolation and prediction of PAWC. Details of the different soil and landscape surveys as well as geological and geophysics information can be found in Sections 3 to 5 and 8.

Digital soil mapping (DSM) is a modelling approach that produces digital grid based maps of soil and landscape attributes. The Soil and Landscape Grid of Australia (SLGA) provides consistent data across the GRDC Southern Region. It is publically available online and provides digital soil and landscape attribute predictions at a spatial resolution of 90 m x 90 m. The reliability of the predicted attributes may, however, vary within the Region and by attribute, so users need to gauge acceptable reliabilities on a case-by-case basis. By combining the DSM data for different soil and landscape attributes through statistical or so-called pedotransfer function models, PAWC could be predicted for the same grid cells. More information on DSM and associated terrain analysis information can be found in Sections 6 and 7.

A summary of the available data sources is provided below.

Data source	Summary	Section
PAWC characterisation data	Provides detailed and quality controlled PAWC data linked to key soil types/properties. As point data, there is little spatial context unless linked to other soil and landscape attributes. There are 375 (SA, 236; Victoria, 117; Tasmania, 22) records in the Southern Region. Data is publically available through the APSoil database here: https://www.apsim.info/Products/APSoil.aspx.	2
National mapping	The Australian Soil Classification (ASC) polygon mapping is available for all of the GRDC Southern Region at various scales. On-line access to ASC mapping is accessible for all of Australia through the SoilMapp iPad application as well as the Australian Soil Resource Information System http://www.asris.csiro.au/. It provides a composite of best available mapping from approximately 2012.	3.2
Soil profile data	National soil profile descriptions are also available to the public through the Australian Soil Resource Information System http://www.asris.csiro.au/. These records are a collection of soil profiles with accompanying detailed descriptions of site (e.g. landscape, relief), soil morphology, and physicochemical analyses. The types of soil profile data available through ASRIS vary, however. They range from soil profile data sourced from soil surveys and research projects, through to 'idealised' soil profile class descriptions and 'reference' profiles. The latter generally refer to a 'typical or 'best' description of a recognised soil type (P. Wilson, *pers. com.*, Wilson 5.04.18). Soil profile data may have application to support PAWC work, where soils of interest closely match. *SA soil profile data* The Soil Site SA portal (https://data.environment.sa.gov.au/Land /Data-Systems/Soil-Sites-SA/Pages/default.aspx) delivers >28,000 soil survey sites, including >1,000 characterisation sites. Soil survey data consist of site and soil profile descriptions, whereas characterisations sites having undergone detailed profile descriptions and laboratory analysis, and are selected because they are representative soils.	3.3

	Victorian soil profile data Victorian soil profile data is accessible via the Victorian Resources Online (http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/regionalprofile), where PDF documents are provided for 1:100,000 map sheets with the soil pit locations accessed on clickable maps. Information on soil description and management considerations is provided for most of the soil pits. A more general description of the main soils in each region is also provided. *Tasmanian soil profile data* Tasmanian soil sample site locations can be accessed through the Tasmanian Department of Primary Industries, Water and Environment LISTserver (https://maps.thelist.tas.gov.au/listmap/app/list/map). Within LISTmap soil site data are available via the 'Soil Sample Sites' layer. Associated soil sample reports for these sites are available via a link in the LIST mapping application. The LIST server recently moved to a new platform, and some functionality is still to be resolved.	
CSIRO land evaluations	CSIRO land evaluations include reports and maps documenting the systematic soil and land survey of Australia since the 1930s, http://www.publish.csiro.au/cr. These are in presented in a number of series, each with different land evaluation purposes and approaches. Some of the mapping is available on-line, although availability is piecemeal. Descriptions of soils and associations are generally detailed, and especially helped by conceptual landscape models is some cases. Mapping and investigation scales vary, typically from coarse scales (e.g. 1:1,000,000) to finer scales (e.g. 1:25,000). Scale of mapping and level of detail defines the utility of these maps for PAWC work. Potentially useful maps are listed in three tables, one for each state (SA, Table 3-1; Victoria, Table 3-2; Tasmania, Table 3-3), and print versions are accessible from CSIRO's library in Black Mountain, Canberra - or potentially from state archived and libraries.	3.4
South Australian soil landscape mapping	SA's soil mapping coverage is systematic across the agricultural areas, and the primary digital format is as polygons. The highest tier of mapping is land systems (1:250,000 scale), and the lowest, finest tier, soil landscape units (SLUs) (1:50,000-1:100,000 scales). Data is available online via the SA Nature Maps portal: http://spatialwebapps.environment.sa.gov.au/naturemaps. SLU polygons have numerous soil attributes associated, with types/classes/properties listed according to dominance. Data can be used for digital soil mapping, especially disaggregation methods supported by a good distribution of point (profile) data, which SA has undertaken (see Section 3.3). Scale of mapping and level of detail defines the utility of these maps for PAWC extrapolation and prediction.	4.1
Victorian soil landscape mapping	Victorian soil mapping is available from the data.vic portal (https://www.data.vic.gov.au/data/dataset?q=soil). Mapping themes include land systems (1:250,000 scale), soil types (ASC, harmonised from multiple surveys, presented at 1:0,000-1:250,000 scale range), land units (1:100,000 scale, not everywhere), and Victorian soil mapping series (1:100,000 scale, which presents soil properties at 6-standard depths to 2 m). Some of the map coverages of these themes is piecemeal, often drawing from - and harmonising - numerous legacy surveys.	4.2

Tasmanian soil landscape mapping	Tasmanian soil mapping is available through the Tasmanian Department of Primary Industries, Water and Environment *LIST server* (Land Information System Tasmania) (https://maps.thelist.tas.gov.au/listmap/app/list/map), including metadata. Soil maps of Tasmania include 1:100,000 reconnaissance soil maps and a number of more detailed soil surveys of smaller parts of agricultural land. Mapping is based on landforms, climate and geology with soil map units described in the accompanying reports. Reconnaissance maps are available for most of the GRDC's Southern subregions that fall within Tasmania. Information available in the more detailed map unit descriptions can provide some initial insights to inform PAWC predictions. In addition, field mapped and modelled land capability maps are available for all of the GRDC's Southern subregions that fall within Tasmania. These maps use the Tasmanian Land Capability Classification System (LCCS) to assess, classify and map land according to seven capability classes, which reflect the ability to support a range of crops on a long term sustainable basis. Evaluations are based on a number of limiting factors that are imposed on the land of interest, including erosion, soils, wetness and climate. The land is then evaluated based on potential crops, productivity, and ease of management and risk of degradation. Due to only showing the land capability classes, the land capability maps themselves have limited value for PAWC prediction. The accompanying reports can, however, provide useful insights into the geology, topography and geomorphology and soils of the area. This includes schematic soil-landscape diagrams that can be useful to build a soil-landscape narrative for extrapolation or generalisation of PAWC data.	4.3
Geological mapping	Geological maps can help users to understand soil forming conditions, and some Tertiary and Quaternary era mapping units may be useful for inferring PAWC properties. However, mapping tends to be of coarse scale (rarely finer than 1:100,000 scale), so may limit how it can support PAWC work. Information from geological mapping may provide some insights into landscape and soil similarities or dissimilarities (e.g. to compare a site of interest with existing PAWC characterisations). Access to maps varies, see Section 5.	5
Digital soil mapping	A suite of digital soil mapping products are available as part of the Soil Landscape Grid of Australia (SLGA). These datasets are available here: http://www.clw.csiro.au/aclep/soillandscapegrid/index.html. For SA and Tas, three SLGA soil attribute products are available, the national SLGA, the SA and Tas regional SLGA, and a merged national and SA/Tas regional product. The national and SA/Tas regional approaches developed simultaneously, not with the intention to duplicate the effort, but the assumption behind that certain methods were appropriate for specific regions of interest than others (Odgers et al., 2015). SLGA data may be used to create maps of new soil properties, or predict PAWC itself. Limitations for the data include the ground resolution, which at 90 m may be too coarse for some landscapes. That said, 30 m digital elevation data is available to the public via the Geosciences Australia portal, Elevation information System ('ELVIS' - http://www.ga.gov.au/elvis/#/), which will have significant impact on the level of local variability (consistent with finer mapping scales) that this data will support.	6
Terrain information	Terrain information can be used as a powerful predictor of soils and soil properties which are often strongly governed by land relief patterns. The principal dataset required for terrain analysis is a digital elevation model, of which the national version is accessible here: http://www.clw.csiro.au/aclep/soillandscapegrid/index.html. The 90 m ground resolution of this data may be too coarse to be of great value in some landscapes for PAWC work. This will change with access to 30 m data.	7

Gamma radiometrics data	Gamma radiometrics imagery represents the geochemistry of the land surface, which relates to strongly soil properties (i.e. clay content) and landscape history, including the age and weathering extent. These have baring on PAWC work, so in some conditions, the data could be of utility. National sources are found here: http://www.ga.gov.au/scientific-topics/disciplines/geophysics/radiometrics.	8.1
Mineralogy data	The clay minerals of kaolinite, illite and smectite have been mapped for the whole of Australia. These maps are available here: http://doi.org/10.4225/08/55DFFCA4715D8. Clay mineralogy has potential value in PAWC work as each type has different properties that relate to PAWC, particularly water storage and release properties. However, the ground resolution of 90 m may impact on utility.	8.2
Electromagnetic surveys	Electromagnetic surveys show soil conductivity in soil layers. Conductivity relates to clay mineralogy, water content and salinity. They are widely used in soil mapping and management unit delineation, and potentially for clay type and depth estimates – hence of potential value in PAWC work. Existing surveys tend to be for small areas and hardly any are in the public domain. However, instruments are widely available and convenient enough to use on a case-by-case basis, so are mentioned here for potential in PAWC work.	8.3

The overview of available data in Sections 2 to 8 of this report indicates that there is a variety of soil and landscape data that could support methodologies to predict PAWC at paddock scale. Almost all the data is freely available on-line and accessible to growers and advisors without any need for specialised GIS software or skills. On-line access is, however, through many different tools and applications, which complicates data integration. Experience has shown the task of accessing information to be challenging because at times each state has designed their data portals differently, and with different levels of intuition required to work them properly. Potential case studies in the Southern Region will need to consider this.

Another challenge is the scale at which the various maps and data are produced. For example, South Australia has generated a systematic and consistent series of soil maps at 1:50,000 or 1:100,000 scale at the lowest tier. Victoria's and Tasmania's soil mapping is more variable in scale. Some of the 'finest' scale mapping available may in fact be more consistent in terms of content with the coarser mapping scales that these maps were adapted from. In both cases, the most consistent baseline scale is 1:250,000 land system mapping, which means predictions need to be made with sparse data and associated high uncertainty needs to be considered.

Two main approaches for prediction of PAWC from the available data are:

1) use of SLGA/DSM to predict and map PAWC through the use of pedotransfer functions or statistical modelling techniques; and
2) use of soil landscape models tacitly held in soil reports and manuals to build a 'narrative' around expert soil landscape knowledge that can be interpreted to predict PAWC via extrapolation from known APSoil PAWC characterisations.

The first approach has the advantage that it can provide PAWC predictions at a 90 m resolution using the same approach everywhere. However, the uncertainty in digital soil attributes and models used in the predictions need to be considered and may not be sufficiently accurate everywhere.

Another downside of this approach is that the grower/advisor will get a predicted PAWC for a location, but will not have a way to validate this value.

The second approach requires that soil-landscape understanding relevant to the local area is transferred to the growers and advisors. This could take various forms that can be explored in the case studies. The variety of sources of soil landscape information, their variable level of detail, inconsistent approaches and different tools to access them also poses challenges and may mean that separate methodologies need to be developed for different areas/landscapes. The approach does, however, build on the knowledge already held by the grower/advisor and allows them to place the predicted PAWC value in context of other information.

Possible future case studies

For the GRDC Northern region project CSP00210 is funded to evaluate different methodologies for predicting PAWC from the available soil and landscape information. The data inventory for that region (Verburg et al., 2018) hence prepared for the next stage in the project, namely to select eight case study areas with different landscapes and varying types and amount of information.

This report includes suggestions for possible future case studies that could be of interest for the Southern region (Section 9). They allow the different approaches to be tested with the regional specific datasets available. The suggested case studies for the GRDC Southern Region include:

- South Australian mid-north, in the vicinity of Jamestown (Belalie Valley). The area covers an upland hilly landscape with generally regular soil patterns in toposequences. Soil salinity and sodicity are likely to be a factor to consider as a modifier of PAWC. Data is plentiful and on-ground expert knowledge is solid, and the area serve as a suitable candidate for comparing 'expert approximation of PAWC' and DSM approach using the national and SA DSM attributes.
- Victorian and South Australian Mallee. This case study allows testing of the use of the disaggregated land systems of the Central Mallee and Hopetoun in Victoria and comparison with the SA soil-landscape mapping and DSM.
- Use of Victorian land resource assessment mapping: This could be applied in the Corangamite catchment management region, which also has many detailed soil pit descriptions. May need to be confined to smaller areas within the cropping areas of the region to focus on a particular landscape.
- Tasmanian DSM interpretation: This is available for all of the cropping areas within Tasmania, but should probably focus on areas where there are existing APSoil characterisations (e.g. Devonport – Port Sorell or in Longford – Cressy).

1 Introduction

1.1 Context and aims

Knowledge of the plant available water capacity (PAWC) of soils on their farm can help growers and advisors improve the quality of yield forecasts. These could consist of rules of thumb or be assisted by tools like Yield Prophet®. The forecasts inform management decisions such as whether to sow, timing of sowing (and associated crop type and variety choice) and the input level of resources such as nitrogen fertiliser.

Past investments by GRDC and CSIRO have helped deliver a database (APSoil) of 1,100+ PAWC characterisations across the country that is freely available online (https://www.apsim.info/Products/APSoil.aspx) and through the iPad application SoilMapp. Other soil data resources are also becoming increasingly available for growers and advisors, which opens the way to soil specific management and digital agriculture.

The current project CSP00210 'Methods to predict plant available water capacity (PAWC)' (2017-2020) will research two current challenges for growers and advisors:

- How to estimate PAWC for different crops, given that most PAWC characterisations included in the database were determined for a single crop?
- How to use the available PAWC data and soil information to predict PAWC for the soils on farm where no APSoil characterisations are currently available?

To answer the first question, the project will review available rules of thumb for predicting PAWC for different crops, develop a predictive approach that incorporates an understanding of the effects of subsoil constraints on the crop's ability to extract soil water, and test this approach with new PAWC data obtained under a range of different crops.

The research planned for the second question consists of three stages: (i) a scoping study reviewing the available PAWC and soil information that could be used for mapping PAWC to soil landscapes and predict PAWC at the farm scale, (ii) proof-of-concept evaluating the suitability of different predictive approaches in case study areas that capture a range of landscapes and different levels of data availability, and (iii) validation of these approaches in select case studies. Stages two and three are currently only funded for the GRDC Northern Region. Scoping studies for the Western and Southern Regions were also carried out to help identify opportunities for similar work. This report documents the findings of the scoping study for the GRDC Southern Region.

1.2 Background

CSIRO, in collaboration with state agencies, catchment organisations, advisors and farmers has characterised more than 1,100 soils around Australia for their PAWC. Most of these PAWC characterisations used a field based method (Burk and Dalgliesh, 2013) to characterise the Drained Upper Limit (DUL; the amount of water a soil can hold against gravity) and the Crop Lower Limit (CLL; the amount of water remaining after a particular crop has extracted all the water available to it) (see Figure 1-1a).

The PAWC characterisations have been collated in a database ('APSoil') that can be accessed on-line (https://www.apsim.info/Portals/0/APSoil/APSRU-Australia-Soils.soils) and viewed spatially via Google Earth or the iPad SoilMapp application. Farmers and advisors use the PAWC information along with an assessment of soil water at sowing to gain an understanding of the amount of soil water that is available to the crop (PAW; Figure 1-1b). They use the information of PAW to forecast yield (through rules of thumb or application of tools like Yield Prophet®) and inform management decisions.

GRDC project CSP00170 (2013-2016) expanded the APSoil database by filling gaps in all three GRDC regions and held many farmer and advisor workshops to explain the concepts of PAWC and how this information can be used. With increased awareness around the value of knowing about plant available water and improving water use efficiency, the demand for PAWC characterisations continued to grow. Feedback at workshops organised by project CSP00170 identified that farmers and advisors found it a challenge to extrapolate from the point-based dataset to predict PAWC for soils on their farm. This has limited full exploitation of this resource for yield forecasting activities.

The PAWC depends on the soil's physical and chemical characteristics. In most cases soil properties are tightly linked to a soil's development and position in the landscape and these same aspects underpin soil and land resource surveys, so there is an opportunity to explore whether existing soil-landscape information can be used to assist with extrapolation of PAWC data or predict PAWC directly.

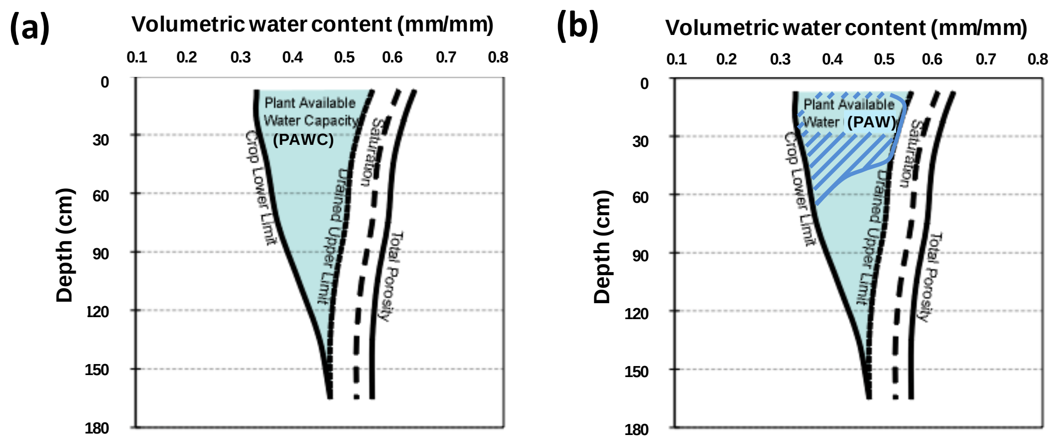


Figure 1-1. (a) The Plant Available Water Capacity (PAWC) is the total amount of water that a soil can store and release to different crops and is defined by its Drained Upper Limit (DUL) and its crop specific Crop Lower Limit (CLL); (b) Plant Available Water (PAW) represents the volume of water stored within the soil available to the plant at a point in time. It is defined by the difference between the current volumetric soil water content and the CLL.

Source: Verburg et al. (2016) GRDC Coonabarabran Update March 2016

The GRDC project CSP00170 informally developed ideas for an approach to use soil-landscape associations (available through state soil surveys in varying formats) to help interpret the PAWC characterisations and extrapolate across the landscape (Verburg et al., 2017; Verburg et al., 2015a; Verburg et al., 2015b). Preliminary concepts presented at workshops were well received and indicated an interest by farmers and advisors in the use of on-line soil information resources. More research is needed to determine the predictive power and spatial accuracy of the soil information currently available. Recent advances in digital elevation models (30m & 90m resolution DEM across Australia; Gallant et al., 2011) and their interpretation through terrain analysis as well as in geophysical techniques such as electromagnetic induction (EM), radiometrics (gamma) may provide opportunities to strengthen PAWC predictions.

Digital soil attribute mapping, such as the Soil and Landscape Grid of Australia (SLGA; Grundy et al., 2015) or other local efforts (refer to Section 6.4) provides another approach to spatially predict PAWC. Pedotransfer functions can be used to combine different soil attributes to predict PAWC at the same scale. While some work has been undertaken to develop the predictive approaches (pers. comm. Moore, Searle et al.), there has to-date been no testing of this approach at the farm scale.

1.3 Presentation of the available information

Brief descriptions of the available PAWC data and, soil and landscape information, their online access and their likely value for predictive purposes are provided in Sections 2 – 8. This is followed by a discussion on possible future work in Section 9.

Where possible the available data are presented on maps relative to the GRDC Southern Region sub-regions. We use the sub-region boundaries provided by Neil Clarke and Associates. These sub-regions are based on the 2016 Australian Statistical Area Level 2 (SA2) boundaries from the Australian Bureau of Statistics, which have been aggregated to define 6 sub-regions (Figure 1-2). Note, however, that the type, level and accuracy of soil information is not consistent within these sub-regions. They are, therefore, mainly included for ease of reference.

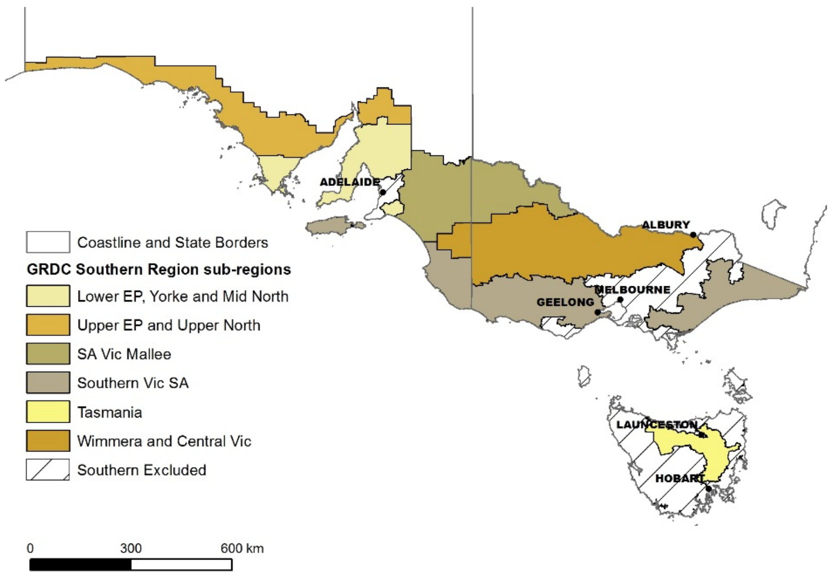


Figure 1-2. GRDC Southern Region sub-region boundaries.
Source: Neil Clarke and Associates (2017)

2 PAWC Characterisations

Characterisations of PAWC for more than 1,100 soils across Australia have now been collated in the APSoil database and are freely available to farmers, advisors and researchers. Of these, 375 are located in the GRDC Southern Region (Figure 2-1). The database software and data can be downloaded from https://www.apsim.info/Products/APSoil.aspx. The characterisations can also be downloaded in KMZ format for viewing in Google Earth (from the link above) or viewed directly in SoilMapp, an application for the iPad available from the Apple App store.

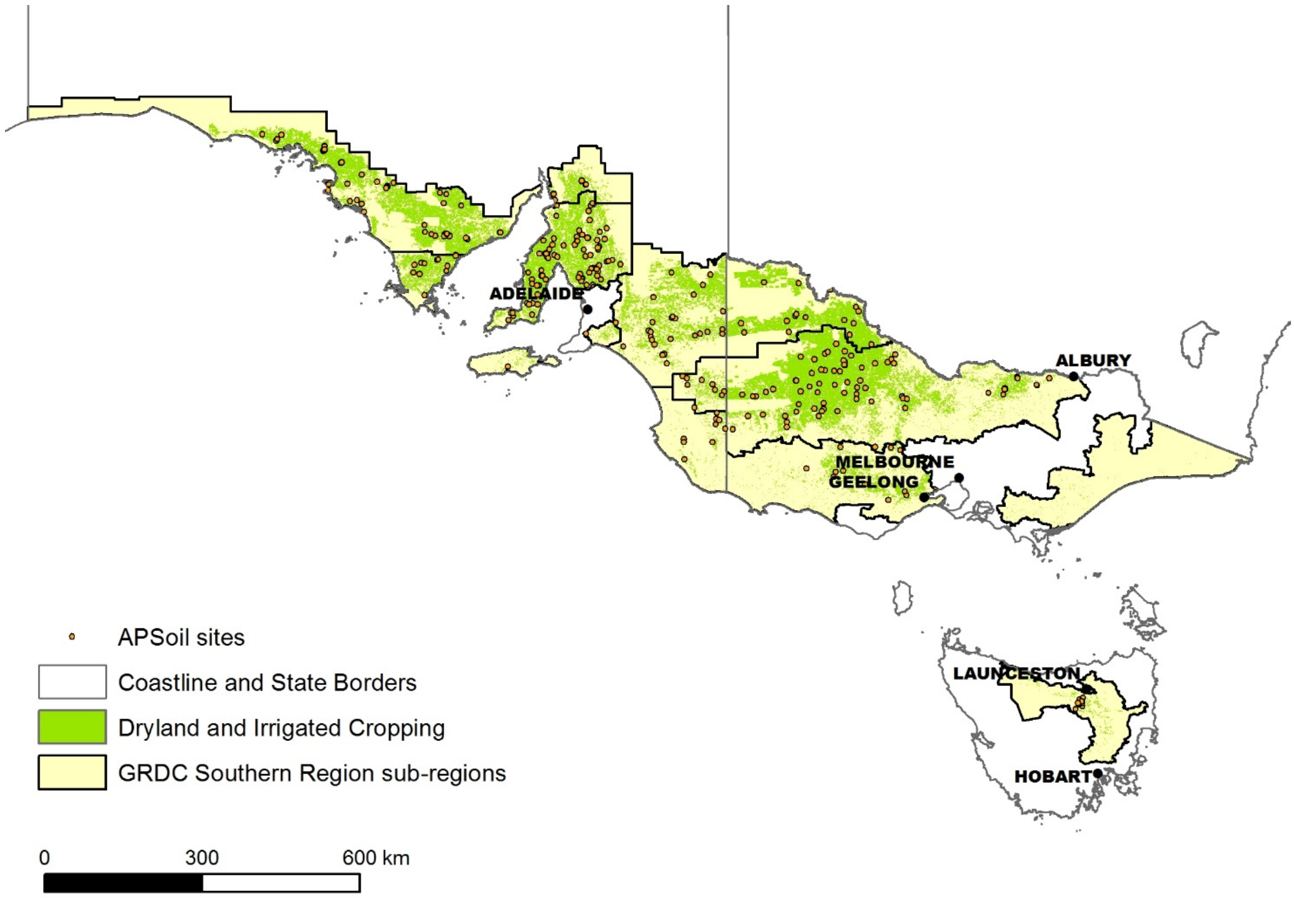


Figure 2-1. Locations of APSoil sites within the GRDC Southern Region. Dryland and irrigated cropping extents are from the May 2016 update of the Catchment Scale Land Use of Australia dataset.

In Google Earth the APSoil characterisation sites are marked by white circles with a green shovel symbol (Figure 2-2), with information about the PAWC profile appearing in a pop-up box if one clicks on a site (Figure 2-3a). The pop-up box also provides links to download the data in the APSoil database software or in spreadsheet format.

In SoilMapp the APSoil sites are represented by green dots (see Figure 2-3b). Tapping on the map results in a pop-up that allows one to 'discover' nearby APSoil sites or other soil (survey) characterisations. The discovery screens (see Figure 2-3c, d) then show the PAWC characterisation as well as any other soil physical or chemical analysis data and available descriptive information.

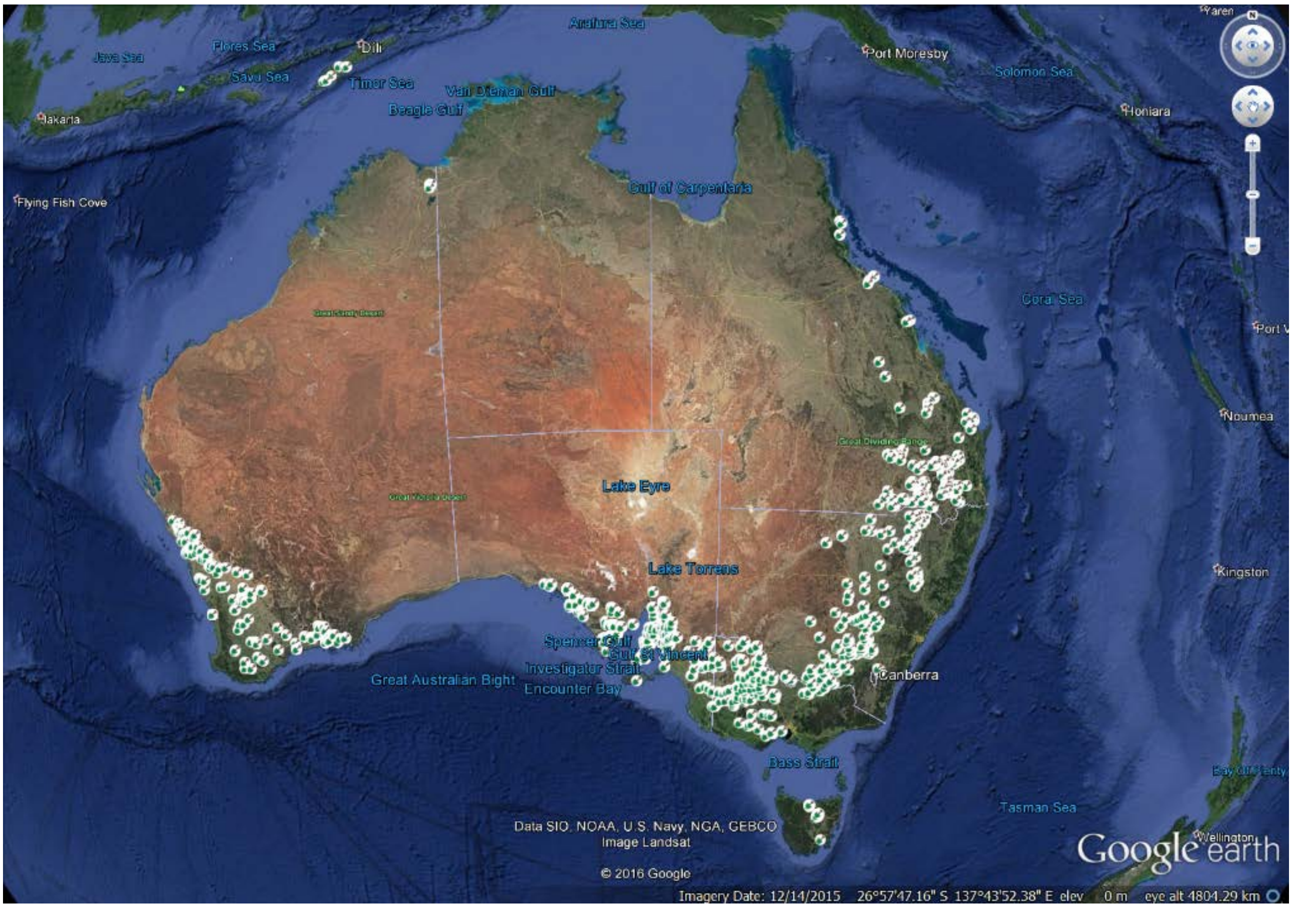


Figure 2-2. Access to geo-referenced soil PAWC characterisations of the APSoil database via Google Earth.

Most of the PAWC data included in the APSoil database have been obtained through the field methodology described in detail by Burk and Dalgliesh (2013). The database also includes some profiles where DUL and CLL have been derived from analysis of soil water measurements over time (e.g. monthly neutron moisture meter readings obtained in experimental trials). In addition it includes some profiles with estimated DUL and/or CLL (e.g. based on soil survey and/or laboratory data). A few projects have developed sets of 'generic soils' based on texture or soil classification, which are also made available through APSoil. While field measured profiles are mostly geo-referenced to the site of measurement (+/- accuracy of GPS unit), generic soils or those for which geo-referencing was not approved are identified with a regional town.

Apart from PAWC the characterisations also include a soil description, either based on texture or a (local) soil classification. In addition many include chemical and particle size data, especially those obtained in more recent projects. This supporting data will be important for extrapolation purposes, e.g. to compare the soil at a site of interest with that of an APSoil PAWC characterisation.

All GRDC Southern Region sub-regions contain a spread of APSoil PAWC characterisations (Figure 2-1). Most areas dominated by dryland cropping show a reasonably consistent spread of characterisation sites, broadly reflecting the intensity and productivity of dryland farming in the areas. A lower intensity of sites may reflect a lower level of local interest in farming tool uptake in the area, or difficulties in measuring PAWC using the conventional techniques, i.e. where the soils are stony. Most of the characterisations are in dryland cropping areas, and those found in areas not typically associated with dryland farming may indicate the location of past research projects.

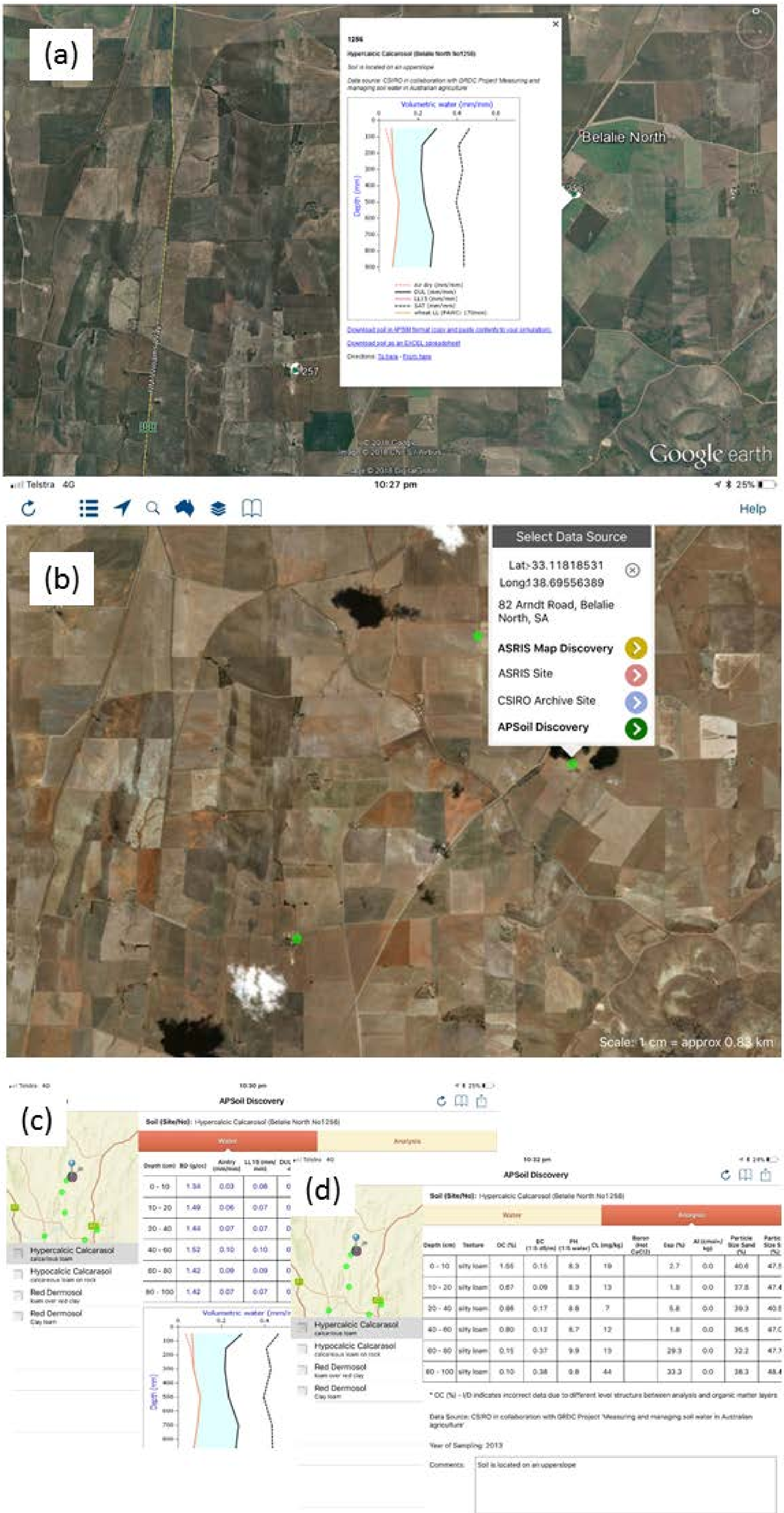


Figure 2-3. Access to geo-referenced soil PAWC characterisations of the APSoil database via (a) Google Earth and pop-up boxes and (b) SoilMapp; (c) and (d) APSoil discovery screens. The area is from the Midnorth, SA.

3 Soil surveys

This Section summarises Australian soil mapping and data potentially suitable for PAWC estimations. It discusses context and approaches to soil survey and mapping that have been followed by various land evaluation jurisdictions (national, State and Territory), the characteristics of the knowledge (expert, non-expert) and data that have been built out of these efforts, and the bearing that these may have on predictive PAWC work.

3.1 Soil classifications of Australia

Australian soils are distinctive compared to much of the world. Variability of Australian soils is particularly governed by the great age of the Australian landscape as a result of a prolonged period of tectonic stability, and the unique overprint of the continent’s past climates. For example, these combined factors give rise to soils that are often extremely well developed (e.g. strong texture contrasts, development of pans, nutrient poor), or are clay-rich, and/or have high salt content (sodicity, salinity). Knowledge of these characteristics is important for sustainable management of many Australian soils.

Soil classification provides a method for scientists and land managers to communicate important concepts about soils by providing a standardised framework for categorising and sharing soil knowledge. Given the distinctive character of Australian soils and their specific management needs, international soil classification frameworks have often proven to be deficient in the Australian context. Native classifications schemes will typically reflect local environments and soil development histories. A number of soil classification schemes have been developed to better cover the range of Australian soils and are summarised below. Chronologically, these classifications include: Great Soil Groups (GSG) developed in the mid-1900s and culminating with the publication of (Stace et al., 1968); the Factual Key for the recognition of Australian Soils refined during the 1960s and 1970s (Northcote, 1992), and finally; the Australian Soil Classification (ASC) that was developed during the 1980s and 1990s (Isbell and National Committee on Soil and Terrain, 2016). The development of each reflects the growing body of knowledge and supporting soil data, and the shifting needs of Australian classification and land management. Each classification remains valid in their own way, and the concepts underlying each has application in understanding PAWC whether for approximating predictions or correlation.

3.1.1 Great Soil Group (GSG)

The GSG classification is based on diagnostic morphological features as observed in the field from observations of land surface and soil profiles. Classification is based on concepts of soil genesis, and laboratory data is rarely required. The GSG is recognised as Australia’s rudimentary classification, as, for example, the underlying classification methodology does not cater well for class intergrades, i.e. different soils are sometimes allowed the same classification.

3.1.2 Factual Key for the recognition of Australian soils

The Factual Key represents a classification based on diagnostic morphology that at the highest 'division' features: texture contrast (duplex) soils; organic soils; uniform, and; gradational soils. Sub-divisions relate to, e.g. colour or texture, depending on the division. These is no consideration of soil genesis in the classification. The Factual Key is powerful in the sense that soil function is easily inferred from the classification. For example, readily inferred information that a soil profile is uniform in texture and clay-rich is valuable for PAWC inferences.

3.1.3 Australian Soil Classification (ASC)

The ASC is the latest and most widely used national soil classification, and it continues to evolve (http://www.clw.csiro.au/aclep/asc/). An underpinning concept behind ASC was to include soil attributes in the classification system that are of significance to land use and soil management, a limitation experienced with the use of GSG and the Factual Key (Isbell and CSIRO, 2016). Soil concepts are based on a hierarchical key with mutually exclusive criteria so that there can be no overlapping soil classes and classifications (cf. GSG). Development of the scheme has benefited from a vastly expanded national soil database compared to the previous soil classifications. In operation, classification is based on diagnostic soil characteristics designed to be detectable from observation in the field with only a limited reliance on laboratory data. Presently the ASC is based on 14 soil orders that refine at lower levels according to specific concepts. Importantly, the lowest level, family, provides information that may be very valuable in inferring PAWC from ASC, including profile depth, B horizon characteristics, stoniness etc.. However, classification to family level is rare in many soil databases.

3.2 National mapping

The Australian Soil Classification (ASC) mapping is available in digital format for all of the GRDC Regions (Figure 3-1). The most consistent national coverage is accessible though the online and publically available Australian Soil Resource Information System (ASRIS; http://www.asris.csiro.au/help.html#). A range of ASC data sets are available through ASRIS: one applies ASC soil orders based on dominance to the Atlas of Australian Soils (1:2M scale) soil mapping units (Northcote et al., 1960-1968); with others showing the various scales of regional and local mapping; and finally the 250 m ASC grid product, which assigns the dominant ASC from the best available underlying mapping to each grid cell (P. Wilson, *pers. com.*, Wilson 5.04.18).

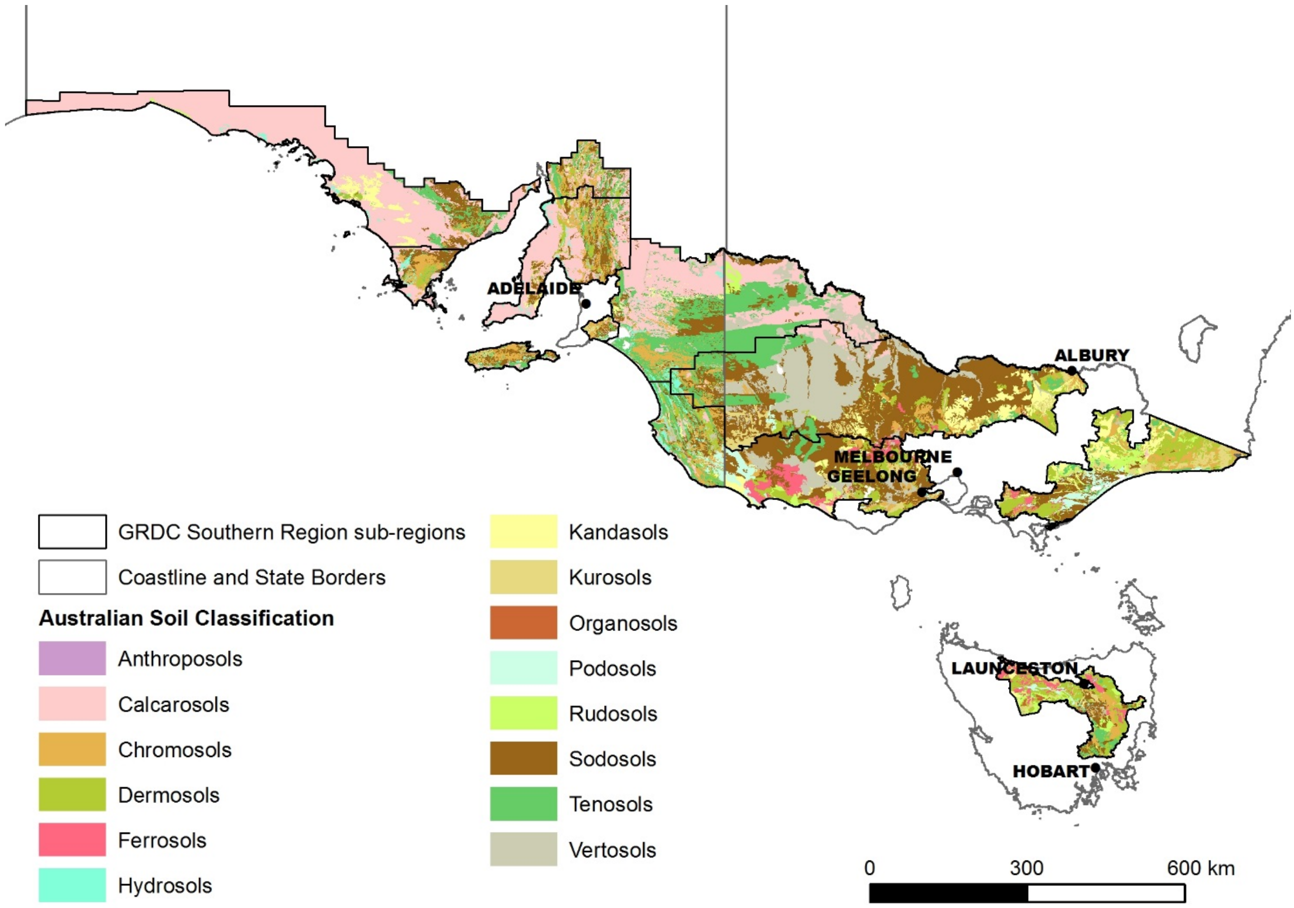


Figure 3-1. Australian Soil Classification within the GRDC Southern Region.

As discussed, ASC (Isbell and National Committee on Soil and Terrain, 2016) has been designed as a general purpose soil classification scheme (with some relevance to land use and soil management) that is based on soil profile diagnostic features (e.g. horizons) of what can be observed, rather than inferred. Where possible, classification is based on soil morphology, although at times laboratory data may be necessary for lower levels of classification. The scheme is hierarchical with 14 soil 'Orders' at the highest level, followed by 'Suborder', 'Great group', and 'Family'. Each criteria in the classification hierarchy varies (i.e. themes and thresholds) according to the ASC order.

Classification requires observation to no deeper than 2 m - so generally well within the soil depth typically associated with crop rooting depths, although observation to this depth is not always necessary for classification. As ASC draws heavily on soil morphology, it does lend itself to agriculture and understanding PAWC, especially if classification has been accomplished to the family level. This is because, depending on the order of the soil, components of family classification provides information on A1 horizon depth and texture, B horizon maximum (heaviest) texture and soil depth.

While direct prediction of PAWC is not possible, the family criteria may at times provide valuable guidance, especially when considered with the other classification criteria, for example the highest level, order. The ASC order Vertosol (ASC concept: clay rich throughout with shrink-swell properties) is often associated with a large PAWC (often >200 mm), unless crop rooting is constrained by e.g. sub-soil salinity. Clay rich versions of ASC orders Dermosols (ASC concept: structured B horizon and lacking a strong texture contrast between A and B horizons) and Kandosols (ASC concept: unstructured, massive B horizon and lacking a strong texture contrast between A and B horizons) can, however, also have relatively high PAWC (>180 mm). Lighter textured Dermosols and Kandosols as well as orders with strong texture contrast, e.g. Chromosols, Kurosols and Sodosols have generally lower PAWC, although with a wide range determined by actual texture. Furthermore, the low pH diagnostic of Kurosols, and the salinity and structural issues associated with Sodosols may further reduce PAWC due to hostile rooting conditions. Tenosols (ASC concept: weakly developed soil profile, often sandy and/or rocky, maybe shallow) or Calcarosols (ASC concept: rich in calcareous materials, often rubbly and/or shallow hardpan present) may often have lower PAWC values (e.g. <110 mm). Tenosols are often associated with crests and slopes of aeolian (wind-blown) dune landscapes e.g. south of the Gawler Ranges in South Australia, in cropping land adjacent to the Big Desert and Murray Sunset areas of South Australia and Victoria or among beach ridge series adjacent to the south east coast of South Australia. Tenosols are also be found as shallow soils on rock, e.g. some cropping areas south of Flinders Ranges of South Australia. Calcarosols are associated with high evaporation rates, limestone parent materials or aeolian sediments formed in combination with the higher water tables experienced during quaternary climate regimes. These factors promote the formation of alkaline soil materials that commonly include, shallow profiles, calcrete pans and segregations.

ASC classification mapping in polygon format is rare to levels below soil Order, and so is generally presented at this highest level of classification. Depending on the scale of mapping, polygon attribution may indicate multiple soil classes by areal proportion in each polygon. ASC to lower classification levels is constrained by the prohibitive intensity of survey effort required for most soil-landscapes.

Generally, ASC at low levels of classification (e.g. to Subgroup or Family level) in the hierarchy are restricted to individual profiles (sites). For example, Australian reference profiles as featured in soil reports tend to be classified typically to Family level because of the full descriptions and a comprehensive suite of accompanying analytical data.

On-line access to ASC mapping is available for all of Australia in the SoilMapp iPad application. It provides a composite of best available mapping from approximately 2012. ASC mapping localised for each state is also available through each of the states' data portals (SA, SA Nature Maps; Victoria, vic.data; Tasmania, LISTmap), although this particular mapping may reflect various jurisdictional nuances (so inconsistent in presentation and content) due to base data/mapping used, or the correlation methods.

The SoilMapp iPad application also includes a Map Discovery tool (Figure 3-2), which will list the soils (using ASC order or suborder) that are associated with the soil map unit identified by the location of interest. The soils listed here represent the dominant soil types identified at the time of the survey. The likelihood of the soil occurring at the location of interest is colour coded (high, medium and low). Additional information tabs provide general information on the Australian Soil Classification at the level of Soil Order (soil type tab), a description of the reference profile (from the originating survey), and summary data of the idealized soil. See the online wiki page for more information: https://confluence.csiro.au/display/soilmappdoc/SoilMapp+Home.

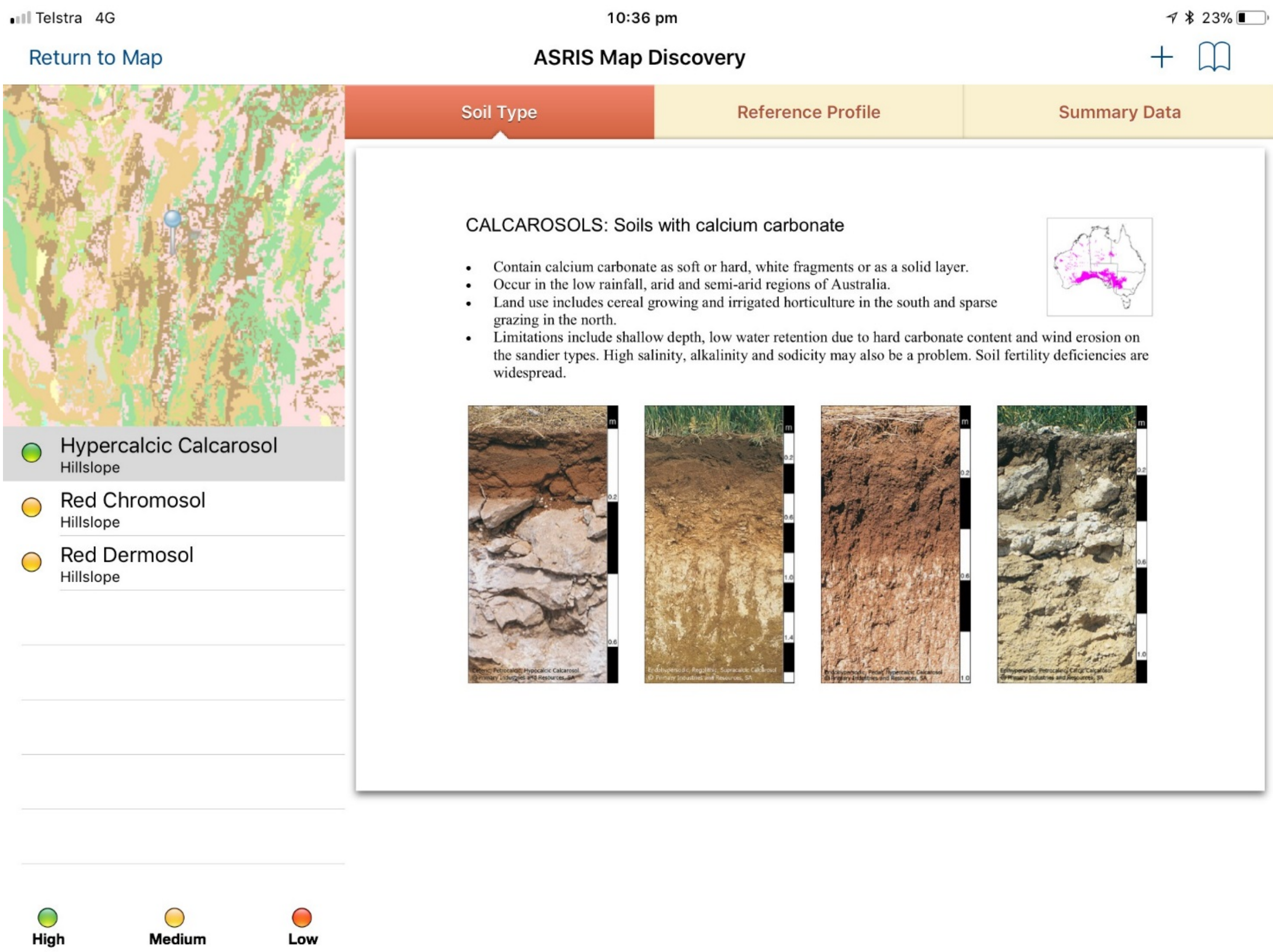


Figure 3-2. SoilMapp Map Discovery tool screen shot for a location in the Midnorth, SA.

3.3 Soil profile data

Soil mapping is based on soil observations and descriptions made *in situ* in the field. These often include accounts of relationships of the soil to the local landscape (relief, vegetation) and land surface features. Profile morphological descriptions are taken from soil pits and the exposed profile face, or from soil cores typically from hand augering or push tubes. Profile faces and cores also provide the means for sampling the soil. This is done at set depth increments, generally the case with agricultural surveys, or at increments corresponding to morphology, i.e. distinctive soil layers or 'horizons' in the soil profile. Depth of sampling depends on the objectives of the survey, for example agricultural sampling is rarely deeper than 1 m. The extent and detail of description and laboratory analyses accompanying the surveys are variable, and depend of the purpose and resources of the survey. In most cases the bare minimum are geographic coordinates to mark site locations and layer by layer morphological descriptions, while others may have a comprehensive suite of site, morphological, chemical, physical and mineralogical data.

Australian standards of description (National Committee on Soil and Terrain, 2009) and analysis (Littleboy, 2002; Rayment and Lyons, 2011) are followed by the agencies (e.g. CSIRO and State and Territories) tasked to do land and soil resource assessments to ensure national consistency in data. The standards make it possible for survey data to be compared and incorporated into other land and soil investigations, whether between surveys and across regions, jurisdictions or nationally.

Effort has been made by state governments independently to collate and curate land and soil records from various soil surveys and jurisdictions into a single, consistent online mapping platform. However, where existent, these platforms are state-specific and vary in their design, capability (e.g. provision and visualization of various data streams, or capacity to download metadata including soil profile data), and user friendliness.

In South Australia, the SA Nature Maps tool provides access to >1,000 soils characterisations sites http://spatialwebapps.environment.sa.gov.au/naturemaps and users may interactively click on each to provide a direct link to a PDF report (data sheet; Figure 3-3). As discussed in Section 3.5, each of these sites were selected as survey sites to be representative of important soils in the SA agricultural landscape, and soil pits excavated to enable thorough description and sampling. Reports contain a descriptive name with general description, site information (geographic coordinates, slope, parent material etc.) and a detailed layer-by-layer description of the soil profile generally to 150 cm where excavation was possible. Further information includes classification according to ASC (Isbell and National Committee on Soil and Terrain, 2016), and a summary of properties including drainage, fertility, pH, rooting depth, physical and chemical barriers to root growth, water holding capacity and other soil and farm management information. Layer-by-layer chemical data is also presented.

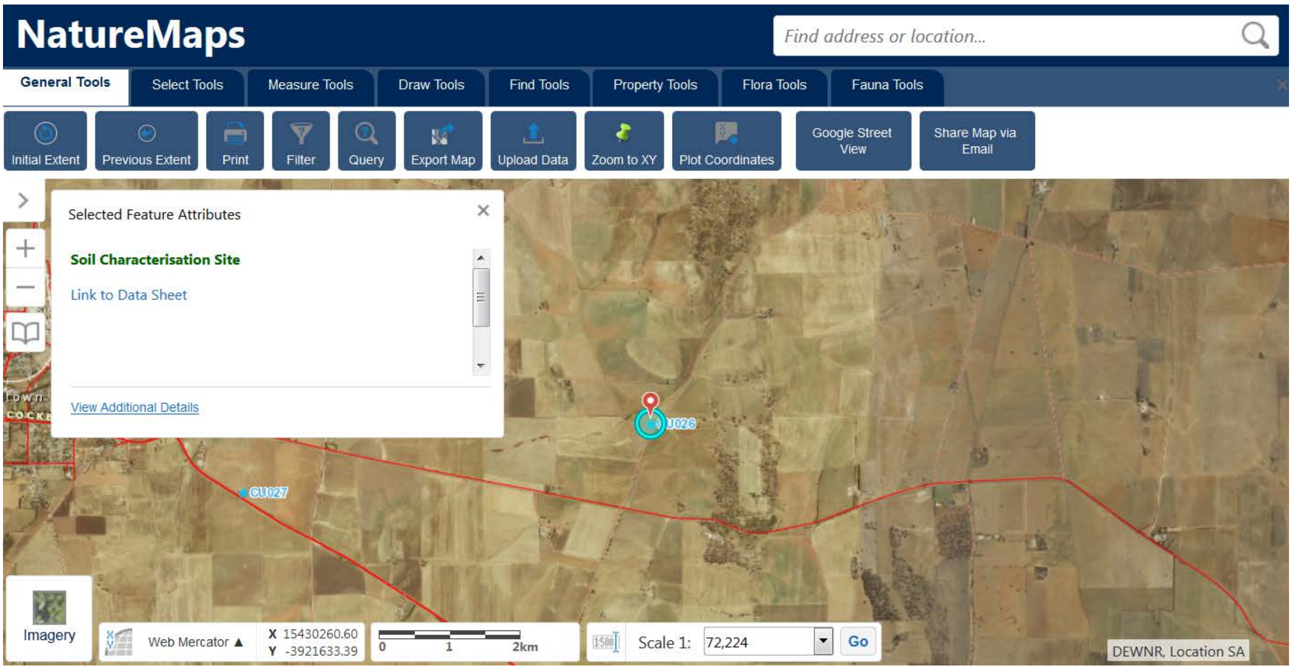


Figure 3-3. Framegrab of SA's NatureMaps access to data sheets for soil characterisation sites.

Soil profile data can also be obtained from Soil Site SA, which can be accessed here: https://data.environment.sa.gov.au/Land/Data-Systems/Soil-Sites-SA/Pages/default.aspx. Users may define their search (e.g. coordinates, interactively drawn box) to find the >28,000 soil sites, including >1,000 characterisation sites, and display site records, or download these as a file (csv format). The information contained in these files includes layer-by-layer data including horizon designations, texture, pans and other physical barriers, coarse fragments (abundance and type), texture, structure, and full chemistry suite for characterisations sites. In addition, site information including geographic location, landform and land use are given.

In Victoria the Victoria Resources Online portal provides access to a selection of soil pit descriptions for most of the catchment management regions (choose the region of interest on http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/regionalprofile, then choose the soil tab and the soil pit sites tab). High resolution PDF files are provided for 1:100,000 map sheets with the soil pit locations and they can also be accessed on clickable maps (Figure 3-4). On-line information on soil description and management considerations is provided for most of the soil pits. A more general description of the main soils in each region is also provided.

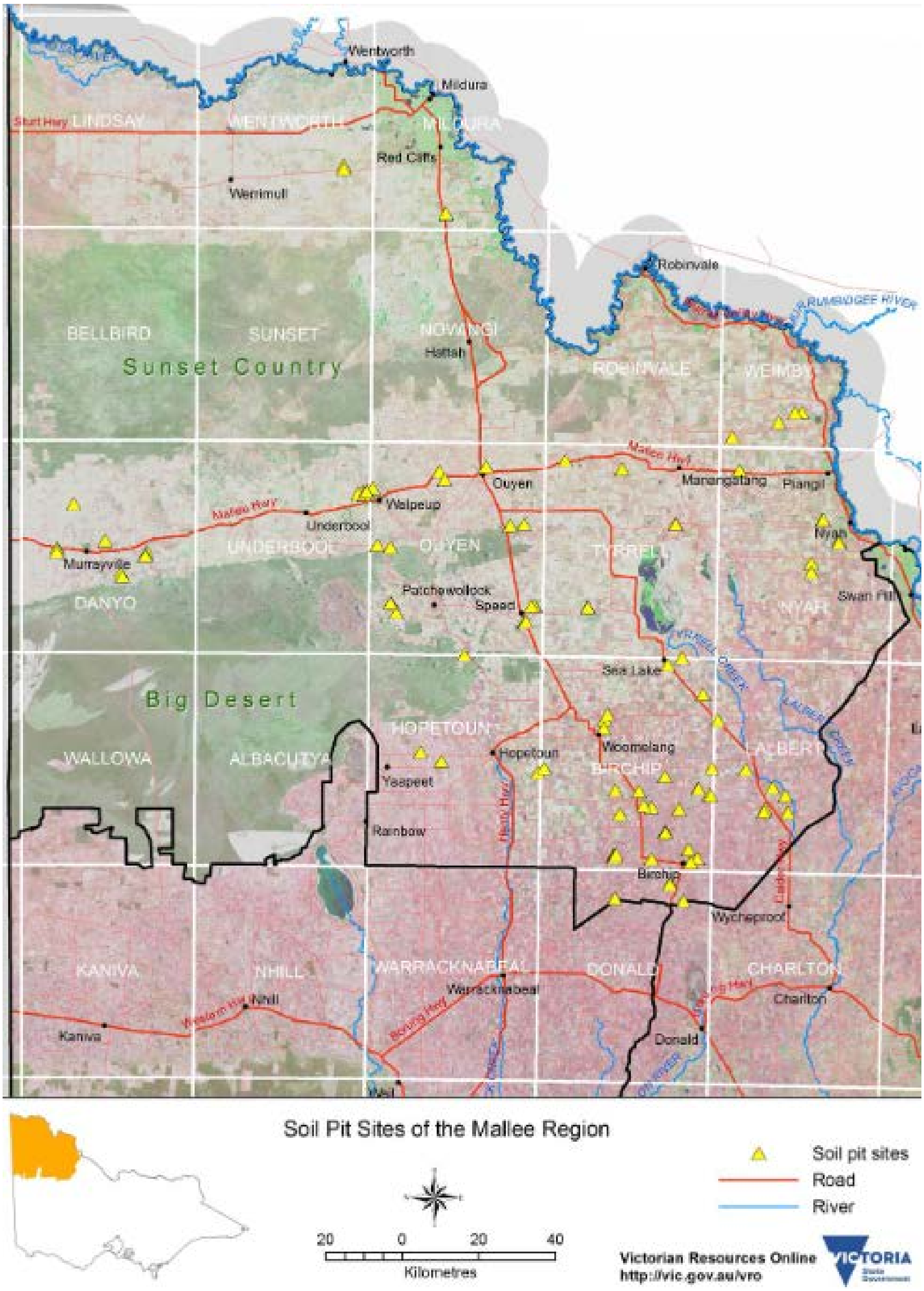


Figure 3-4. Mallee region soil pits as viewable in the Victoria Resources Online portal.

In Tasmania, soil sample site locations can be viewed through the Tasmanian Department of Primary Industries, Water and Environment LIST server (https://maps.thelist.tas.gov.au/listmap/app/list/map). Within LISTmap soil site data are available via the 'Soil Sample Sites' layer (Figure 3-5). Associated soil sample reports for these sites are available via a link in the LIST mapping application. It needs to be noted here, however, that the LIST server recently moved to a new platform, and not all of its functionalities are currently available (e.g. the link to the soil sample reports is currently broken). Resolving this is a work in progress.

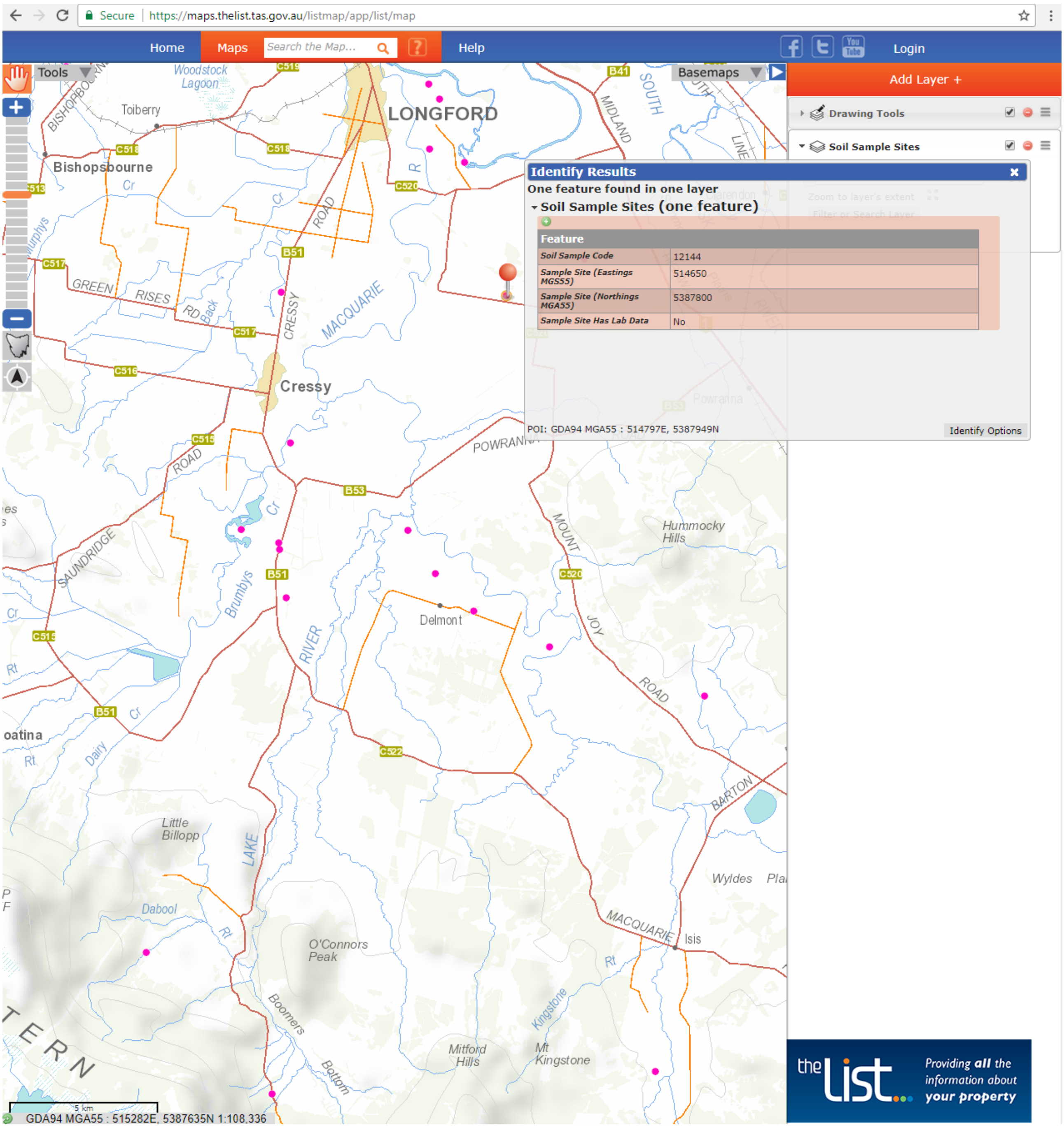


Figure 3-5. Framegrab of Tasmania's LISTserver access to soil sample site locations, close to the locality of Longford.

Depending on the survey purpose and resourcing, soil profile data may be useful for estimating PAWC from accompanying laboratory analytical data, especially clay %, EC and organic C used in conjunction with pedotransfer functions (in absence of DUL and CLL). However, while the profile data may predict PAWC reasonably well at the survey point, there remains the challenge of extrapolating the values to other soils in the area of interest, especially when the short range variability in the soil across the landscape is large. Map legends and reports as discussed in the following section (Section 3.4) may assist in this respect, or assist in correlations with known PAWC estimations (e.g. APSoil sites).

CSIRO through the auspices of the National Committee on Soil and Terrain maintains a national database of soil site records made publically available through the online Australian Soil Resource Information System (ASRIS, http://www.asris.csiro.au). ASRIS has a national overview and contains a collection of soil reference profile records developed by each of the State and Territory jurisdictions as part of their mapping programs (Figure 3-6). Reference profiles – sometimes also termed 'typic profiles' - are soil records selected to represent key soils and are accompanied by a full suite of descriptive and analytical data. These are presented under Level 7 *(Point Data); Reference Profiles* in the ASRIS data suite. As seen in Figure 3-6, the distribution of reference profile sites in the GRDC Southern Region is variable. In most of Victoria it is quite sparse, except in the Corangamite catchment management region and the southern part of the West Gippsland catchment management region. The denser distributions within South Australia and Tasmania are associated with strong and systematic land resource evaluation programs in agricultural areas.

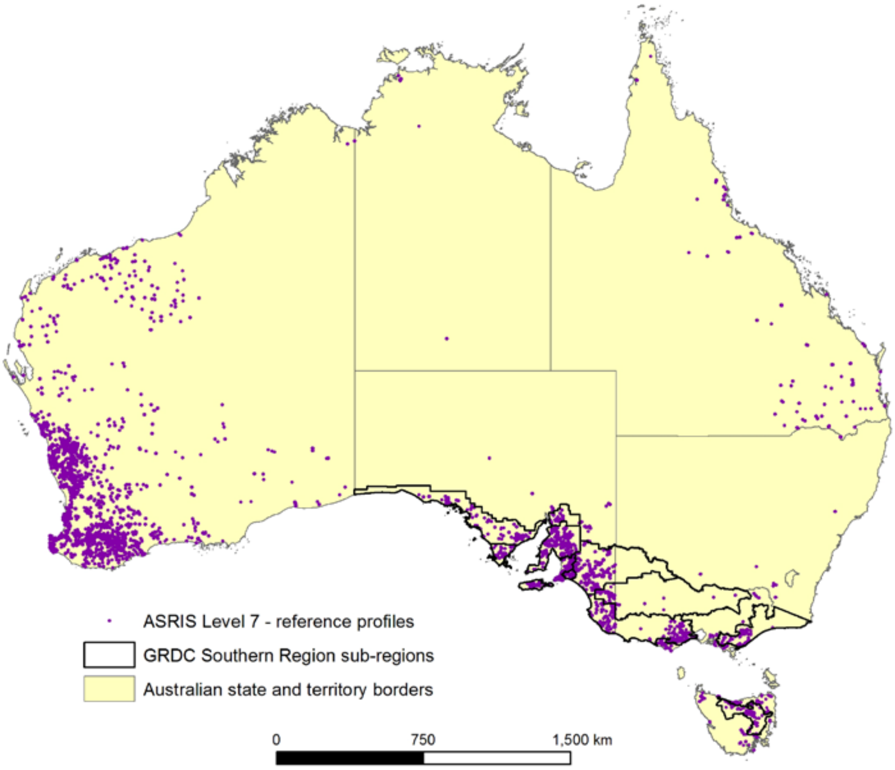


Figure 3-6. CSIRO's Australian Soil Resource Information System soil database interface showing distribution of national soil reference profile sites.

Level 7 Reference Profiles are also available online through CSIRO's GRDC-funded SoilMapp app available for iPad tablets (https://www.csiro.au/en/Research/AF/Areas/Sustainable-farming/Decision-support-tools/SoilMapp).

3.4 CSIRO land evaluations

Since 1929 CSIRO, and its forerunner the Council for Scientific and Industrial Research (CSIR), has been Australia's primary land resource assessment agency addressing national land resource priorities. Out of this has grown a strong legacy of work captured in a series of reports, here listed chronologically: *Soil Bulletins*, *Soil Publications* (1953-1972), *Soil and Land Use Series* (1949-1990) *Land Research Surveys* (1946-2010) and *Division of Soil Reports*.

These reports present various land research themes that are dominated by soil and land evaluations (surveys, mapping), examinations of specific soils and their constraints (e.g. salinisation, toxicities, etc.), and new analytical techniques. The reports document trends in soil science while also chronicling shifting Australian agricultural research needs, nation-building priorities and settlement patterns. They also document the evolution of Australian land evaluation methodology, commencing with ones drawing heavily on foreign approaches and culminating with the distinctive Australian methodology we have today and used by all government jurisdictions (covered in: Littleboy, 2002; McKenzie et al., 2008; National Committee on Soil and Terrain, 2009; Rayment and Lyons, 2011).

Historically the format of CSIRO land assessment mapping and reporting follows a two-tier hierarchical approach; the upper reporting tier units are normally distinguished by a repeating pattern of physiographic features, e.g. geology and terrain that themselves are an aggregation of repeating finer scale patterns (e.g. relief, natural vegetation) correlating with specific soil associations, types or properties – depending on scale. The scales and levels of aggregation are predetermined to suit the reporting objectives. Conventionally, the highest tier units are the ones that are mapped, while the concepts defining the lower tier soil units are presented in short form in map legends (e.g. landscape context and position, morphology, chemistry) and always fully explained in the body of the report. This includes narratives on broad physiographic settings, upper tier/lower tier unit relationships, soil formation, physical and chemical data trends, and possibly information on key constraints, etc. Reports present reference profiles deemed representative of soil units, and supported by field descriptions and measurements, photographs and laboratory data.

The following short discussion summarises the main characteristics of CSIRO's various land evaluation series, and highlights the utility typically contained in these that may assist PAWC predictions. This may involve specific soil attributes (e.g. especially clay content, clay mineralogy, EC, ESP) or the utility of descriptions and narratives contained in reports to guide soil correlations and select between alternative sources of PAWC data to use, e.g. profiles in APSoil.

Responding to inter-war years national priorities, many of the earliest land evaluation reports featured in the *Soil Bulletin* series covered small area (e.g. <1,000 ha) investigations to promote intensive agricultural developments (e.g. irrigation and horticulture). For example, many underpinned soldier-settler schemes. Methodologies were designed to address opportunities and constraints (e.g. salinity, slope) to land development, and results presented at scales consistent with local land planning needs, e.g. at fine scales, typically in the range 1:5,000 – 1:25,000. Typically map line work features upper tier 'soil series' with lower tier 'soil associations'. A soil series is typically based on parent material and age/soil stage of development, giving rise to soil associations identified from landscape position and other criteria like soil colour, texture, salinity, and segregations (carbonate, gypsum). Reporting includes reference profiles for soil association soils (e.g. Figure 3-7), and detailed discussions supported by morphological, chemical and physical data. Toposequence model diagrams are used to communicate terrain/soil relationships (e.g. Figure 3-8). While some measured values may have changed (e.g. pH, N) in the intervening years, Soil Bulletin maps and soil descriptions are likely to be at fine enough scale, and the soils described sufficiently well, to support contemporary correlations with PAWC, either for rudimentary estimations, or to make correlations to APSoil profiles.

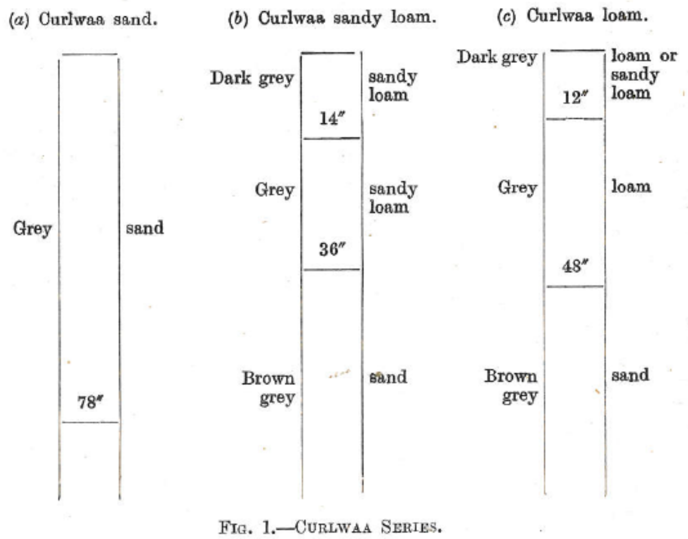


Figure 3-7. Soil profile morphologies of three soil associations comprising a soil series (Marshall and Walkley, 1937).

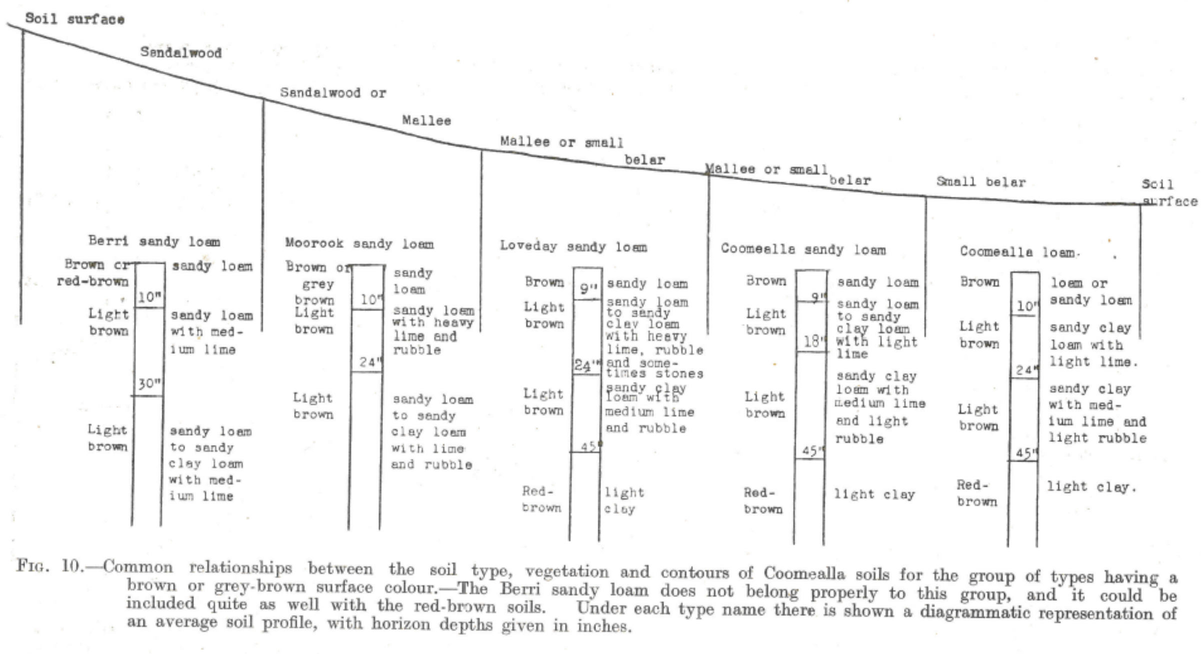


Figure 3-8. Use of slope position and natural vegetation to differentiate and communicate soil associations (Marshall and Walkley, 1937).

As national priorities shifted and new technologies became available (e.g. aerial photography), small area, intensive investigations gave way to large area, broader scale and more general land investigations. These were largely covered in the *Soil Publication* series. These broader-scale investigations (e.g. covering areas <100,000 km^2) followed a new integrated survey methodology (McKenzie et al., 2008) to address a broader suite of land development options (e.g. irrigation and dryland cropping, livestock), and were typically focussed on the frontiers of settled regions. Mapping matched the broad scale needs in terms of thematic content (e.g. mapped upper tier 'soil combination' units, containing lower tier sub-classes), with mapping scales in the range 1:250,000 – 1:1M.

Following this series, the *Land Research Surveys* series reported on large multi-disciplinary campaigns with pedologists, geologists, geomorphologists and botanists working together to undertake regional land resource assessments, typically over hundreds of thousands of hectares. Mapping scales are typically in the range 1:250,000 – 1:1M, and the soil mapping presented in the 'land system' style of mapping (Christian et al., 1960). The upper tier land system units comprise repeating patterns of geology and relief under comparable climate conditions, each containing a discrete set of lower tier soil associations consistent showing repeating patterns of vegetation and land facets. Soil and Land Use series campaigns were generally focussed on remote areas of tropical northern Australia and New Guinea, although a few reports cover parts of the GRDC Northern Region.

The coarse scale of mapping and the high level of soil and landscape aggregation typically contained in the *Soil Publications* and *Soil and Land Use* series of reports makes it unlikely that these can be particularly useful in supporting PAWC estimations, or guide correlations with APSoil soils. Moreover, most reports in these series' do not coincide with dryland cropping areas.

The final land evaluation reports in the CSIRO series, *Division of Soils Reports*, typically reverted to smaller area-type land evaluations, e.g. covering areas ~100,000 ha. These reports often addressed the potential to shift existing land uses to more intensive ones (e.g. dairy, sugarcane), or where current intensive practices where thought to potentially present a local environmental degradation threat like salinity or erosion. Soil mapping was typically published at scales of 1:50,000 or finer. Upper mapping tier units typically comprised 'soil series' (patterns of parent material, soil profile forms), which contained lower tier 'phases' or 'variants'. While it is likely that the scale and mapping themes may be sufficient at times to support PAWC work, these evaluations may not cover areas currently under dryland cropping.

The land evaluation reports worthy of investigation for supporting PAWC work in the Southern region are listed in Table 3-1 for SA, Table 3-2 for Victoria, and Table 3-3 for Tasmania. Readers will note that there can be significant overlap between CSIR/CSIRO land and soils surveys and those reported as state efforts. This is particularly in terms of custodianship of legacy material (reports and scanned maps) and subsequent value-addition/mapping evolution from earlier CSIR/CSIRO baseline data and mapping. This reflects to a great degree the extent of cross-pollination and collaborations in terms of developing and sharing land evaluation methodologies, field and laboratory efforts between CSIR/CSIRO and state land evaluation jurisdictions in Australia – especially in the formative era of Australian soil and land survey.

Table 3-1. CSIRO soil and land reports for South Australia with potential to support PAWC work in the GRDC Southern Region.

CSIR Bulletins	
42	A soil survey of Block E (Renmark) and Ral Ral (Chaffey) Irrigation Areas., 1929 / Taylor, J.K., England, H. N.
51	A soil survey of the swamps of the lower Murray River., 1931 / Taylor, J.K., Poole, H.G.
56	A soil survey of Blocks A, B, C, D, and F, Renmark Irrigation District, South Australia., 1932 / Marshall, T.J., Hooper, P.D.
62	A soil survey of the Cadell Irrigation Area, and New Era, South Australia., 1932 / Marshall, T.J.
76	A soil survey of the Hundreds of Laffer and Willalooka, South Australia., 1933 / Taylor, J.K.
86	A soil survey of the Berri, Cobdogla, Kingston, and Moorook Irrigation Areas, and the Lyrup Village District, South Australia., 1935 / Marshall, T. J., Hooper, P. D.
141	A soil survey of the Waikerie Irrigation Area, South Australia., 1941 / Herriot, R.I., Johnston, E.J.
142	A soil and land use survey of the Hundreds of Riddoch, Hindmarsh, Grey, Young and Nangwarry, County Grey, South Australia., 1941 / Smith, R., Stephens, C.G., Crocker, R.L., Butler, B.E.
188	A soil, land-use and erosion survey of part of County Victoria, South Australia., 1945 / Stephens, C.G., Herriot, R.I., Downes, R.G., Langford-Smith, T., Acock, A.M.
193	Post-Miocene climatic and geologic history and its significance in relation to the genesis of major soil types in South Australia., 1946 / Crocker, R.L.
CSIRO Bulletins	
233	A soil survey of the Hundred of Seddon, and part of the Hundred of MacGillivray, Kangaroo Island, SouthAustralia., 1948 / Northcote, K.H., Tucker, B.M.
266	The climate, geology, soils, and plant ecology of portion of the County of Buckinham (Ninety-Mile Plain), South Australia., 1951 / Coaldrake, J.E., Taylor, J.K., England, H.N., King, N.J.
Soil and Land Use Series	
2	A soil survey and land use potential of portion of the Hundred of Duncan, Kangaroo Island, South Australia., 1949 / Northcote, K.H.
6	Survey of soils, land use and soil erosion in the northern marginal lands, S.A., 1952 / Blackburn, G., Baker, R.M.
7	The soils of the Kingston-Avenue Drainage Area, South Australia., 1952 / Blackburn, G.
8	A survey of soils and land use in part of the Coonalpyn Downs, South Australia., 1953 / Blackburn, G., Litchfield, W.H., Jackson, E.A., Loveday, J.
13	Soils and land-use in the Barossa District, South Australia. Zone I. The Nuriootpa area., 1954 / Russell, J.S., Northcote, K.H., Wells, C.B.
14	The soils and potential land use of part of County Cardwell (Hundreds of Coombe and Richards) in the Coonalpyn Downs, South Australia., 1954 / Jackson, E.A., Litchfield, W.H.
22	Soils and land use in the Barossa district, South Australia. Part A. The Angaston - Springton area. Part B. The Tanunda Creek - Trial Hill area., 1957 / Northcote, K.H., de Mooy, C.J.
24	A study of the soils and some aspects of the hydrology at Yudnapinna Station, South Australia., 1958 / Jackson, E.A.
29	Soils and potential land use of the area around Lake Alexandrina and Lake Albert, South Australia., 1959 / de Mooy, C.J.
30	Soils and land use in the Barossa district, South Australia. The Greenock-Gomersal area., 1959 / Wells, C.B.
32	Soils and land use in the Barossa district, South Australia. The Tanunda - Williamstown area., 1959 / Northcote, K.H
33	The soils of County Grey, South Australia., 1959 / Blackburn, G.
34	The soils of the Tatiara district, South Australia. Hundreds of Tatiara and Wirrega, County Buckingham., 1959 / Blackburn, G.
45	The soils of Counties MacDonnell and Robe, South Australia., 1964 / Blackburn, G.
53	Soil survey of the Loxton Irrigation Area, South Australia., 1972 / Blackburn, G., Wright, D.A.

Soil Publications	
3	Soils of part of southern Flinders Ranges, South Australia., 1953 / Blackburn, G., Baker, R.M.
18	The soil landscapes of Australia., 1961 / Stephens, C.G.
22	Soil development associated with stranded beach ridges in south-east South Australia., 1965 / Blackburn, G., Bond, R.D., Clarke, A.R.P.
23	Geology, geomorphology, and soils of the south-western part of County Adelaide, South Australia., 1966 / Ward, W.T.
29	Geology, geomorphology, and soils of central County Hindmarsh (Mount Compass-Milang), South Australia., 1972 / Maud, R.R.
Division of Soils Reports	
37	Soil mapping in County Cardwell, South Australia 1933 - 1954. Notes and copy of a map prepared in the S.A. Department of Lands 1937., 1979 / Blackburn, G., Wright, D.A.
7/54	Soil survey of Martindale Estate, South Australia., 1954 / Mulcahy, M.J.
9/55	The laboratory examination of soils from Counties Macdonnell and Robe, South Australia., 1955 / Clarke, A.R.P.
4/57	The geochemistry of basaltic tuff and basalt and associated soils in the Mt. Burr area of S.E. Australia., 1957 / Tiller, K.G.
9/57	The laboratory examination of soils from Hundreds of Talunga and Part Para Wirra, County Adelaide, S.A., 1957 / Clarke, A.R.P.
8/59	Soils on the western slopes of the Mt. Lofty Range near Adelaide and Elizabeth, South Australia., 1960 / Litchfield, W.H.
4/61	Soils at Elizabeth, South Australia. The grid survey., 1961 / Wells, C.B.
2/63	Trace element concentrations in certain soils of the lower south east of South Australia., 1963 / Blackburn, G., Giles, J.B.
6/64	The laboratory examination of soils from the Hundreds of Tatiara and Wirrega, County Buckingham, South Australia., 1965 / Clarke, A.R.P.
7/64	A laboratory examination of soils of County Grey, South Australia., 1965 / Clarke, A.R.P.
78	A survey of the physical properties of wheatland soils in eastern Australia., 1985 / Forrest, J.A., Beatty, J., Hignett, C.T., Pickering, J.G., Williams, R.G.P.
107	Physical measurements on a red-brown earth at Kapunda., 1989 / Hignett, C.T.
Division of Soils Technical Papers	
33	Use of soil and land-system maps to provide soil information in Australia., 1978 / Beckett, P.H.T., Bie, S.W.
Others	
	The red-brown earths of South Australia., 1938 / Piper, C.S. - Transactions of the Royal Society of South Australia, 1938, Vol.621, pp.53-100
	Patterns in soil geography in and near Adelaide, South Australia., 1958 / Wells, C.B.
	Atlas of Australian Soils. Explanatory data for Sheet 1. Port Augusta - Adelaide - Hamilton area., 1960 / Northcote, K.H.
	Use of soil and land-system maps to provide soil information in Australia., 1978 / Beckett, P.H.T., Bie, S.W.

Table 3-2. CSIRO soil and land reports for Victoria with potential to support PAWC work in the GRDC Southern Region.

CSIR Bulletins	
45	A soil survey of the Woorinen Settlement, Swan Hill Irrigation District, Victoria., 1930 / Taylor, J.K., Penman, F.
52	The soils of Australia in relation to vegetation and climate., 1931 / Prescott, J.A.
73	A soil survey of the Nyah, Tresco, Tresco West, Kangaroo Lake (Vic.). and Goodnight(N.S.W.) Settlements., 1933 / Taylor, J.K., Penman, F., Marshall, T.J., Leeper, G.W.
123	A soil survey of the Merbein Irrigation District, Victoria., 1939 / Penman, F., Taylor, J.K., Hooper, P.D., Marshall, T.J.
125	A soil survey of part of the Kerang Irrigation District, Victoria., 1939 / Baldwin, J.G., Burville, G.H., Freedman, J.R.
128	An investigation of the problems of salt accumulation on a Mallee soil in the Murray Valley Irrigation Area., 1939 / Thomas, J.E.
133	A soil survey of the Mildura Irrigation Settlement, Victoria., 1940 / Penman, F., Hubble, G.D., Taylor, J.K., Hooper, P.D.
137	A soil survey of the Red Cliffs Irrigation District, Victoria., 1941 / Hubble, G.D., Crocker, R.L.
152	Soil survey of part of County Moira, Victoria. : including the parishes of Boosey, Cobram, Katamatite, Naringaningalook, Katunga, Yarroweyah, and Strathmerton, 1942 / Butler, B.E., Baldwin, J.G., Penman, F., Downes, R.G.
177	A soil map of Australia., 1944 / Prescott, J.A.
206	Pedogenesis following the dissection of laterite regions in southern Australia., 1946 / Stephens, C.G.
CSIRO Bulletins	
243	A soil, land-use and erosion survey of parts of the counties of Moira and Delatite, Victoria., 1949 / Downes, R.G.
Divisions of Soils reports	
1/65	Report on the suitability of certain lands in Counties Follett, Normanby and Dundas, Victoria, for plantations of Pinus radiata., 1965 / Stephens, C.G.
78	A survey of the physical properties of wheatland soils in eastern Australia., 1985 / Forrest, J.A., Beatty, J., Hignett, C.T., Pickering, J.G., Williams, R.G.P.
80	A summary listing of the archival soils collection of the Division of Soils, CSIRO, Adelaide., 1985 / Merry, R.H.
Soil and Land Use Series	
3	A survey of soils, land use and soil erosion in the Coleraine District, Victoria., 1949 / Blackburn, G., Leslie, T.I.
4	The soils of the western part of the Murray Valley Irrigation Area and their classification for irrigation., 1952 / Johnston, E.J.
17	A reconnaissance survey of the soils of the Shire of Kowree, Victoria., 1956 / Blackburn, G., Gibbons, F.R.
36	The soils of the Woorinen Settlement, Swan Hill Irrigation District, Victoria., 1960 / Churchward, H.M.
57	Geomorphology and soils of the Stratford - Bairnsdale Area, East Gippsland, Victoria., 1977 / Ward, W.T., Ward, W.T.
Soil Publications	
12	The characteristics and origins of soils in the Coleraine District, Victoria., 1958 / Blackburn, G., Leslie, T.I.
24	Soil development in relation to stranded beach ridges of County Lowan, Victoria., 1967 / Blackburn, G., Bond, R.D., Clarke, A.R.P.
Division of Soil Technical papers	
33	Use of soil and land-system maps to provide soil information in Australia., 1978 / Beckett, P.H.T., Bie, S.W.

Others	
	Atlas of Australian Soils. Explanatory data for Sheet 1. Port Augusta - Adelaide - Hamilton area., 1960 / Northcote, K.H.
	Atlas of Australian Soils. Explanatory data for Sheet 2. Melbourne - Tasmania area., 1962 / Northcote, K.H.
	Honeysuckle Creek Soil Mapping. 2009. Mark Glover and John Gallant CSIRO Land and Water Science Report 31/09
	Characterisation of nine soils down a salt-affected toposequence near Gatum on the Dundas tablelands in south-west Victoria. (application of a structural approach for constructing soil-water-landscape models) J.Brouwer and Fitzpatrick R. CSIRO Land and Water Technical Report 21/00 September 2000.
	The Physical, Chemical and Morphological Properties of soils in the Wheat-Belt of southern NSW and northern VIC. Geeves G.W, Cresswell H.P., Murphy B.W, Gessler P.E., Chartres C.J., Little I.P., and Bowman G.M. (1995) Department of Conservation and Land Management / CSIRO Aust. Division of soils occasional report

Table 3-3. CSIRO soil and land reports for Tasmania with potential to support PAWC work in the GRDC Southern Region.

CSIR Bulletins	
52	The Soils of Australia in Relation to Vegetation and Climate / by J.A. Prescott.
70	A soil survey of King Island., 1932 / Stephens, C.G., Hosking, J.S.
92	The apple-growing soils of Tasmania. Part 1. A general investigation of the soils. Part 2. A soil survey of part of the Huonville District., 1935 / Stephens, C.G., Taylor, J.K.
108	The basaltic soils of northern Tasmania., 1937 / Stephens, C.G.
139	The soils of Tasmania., 1941 / Stephens, C.G.
150	The soils of the Parishes of Longford, Cressy, and Lawrence, County Westmorland, Tasmania., 1942 / Stephens, C.G., Baldwin, J.G., Hosking, J.S.
204	A soil survey of part of Waterhouse Estate, County of Dorset, North-east Coast, Tasmania., 1946 / Hubble, G.D.
206	Pedogenesis following the dissection of laterite regions in southern Australia., 1946 / Stephens, C.G.
	Soil and Land Use Series
23	The soils of Flinders Island, Tasmania., 1957 / Dimmock, G.M.
26	The soils and some aspects of land use in the Burnie, Table Cape, and surrounding districts, north-west Tasmania., 1958 / Loveday, J., Farquhar, R.N.
	Soil Publications
8	The soils of Sorrell-Carlton-Copping area, south-east Tasmania, with special reference to the soils formed on basalt., 1957 / Loveday, J.
18	The soil landscapes of Australia., 1961 / Stephens, C.G.
	CSIRO Soils Technical Papers
33	Use of soil and land-system maps to provide soil information in Australia., 1978 / Beckett, P.H.T., Bie, S.W.
	Division of Soils Reports
2/57	Reconnaissance soil map of Tasmania. Sheet 75 - Brighton., 1957 / Dimmock, G.M.
2/58	Soils investigations at Frodsley Estate, Fingal, Tasmania., 1958 / Marshall, T.J., Hooper, P.D., Nicholls, K.D., Graley, A.M., Loveday, J., Honeysett, J.L., Piper, C.S., de Vries, M.P.C.
5/61	Reconnaissance soil map of Tasmania. Sheet 74 - Ellendale., 1961 / Dimmock, G.M.
5/61	Reconnaissance soil map of Tasmania. Sheet 75 - Ellendale., 1961 / Dimmock, G.M.
11/62	An examination of soil properties in relation to bitter pit in the apple variety Cleopatra in Tasmania., 1962 / Graley, A.M., Miezitis, E.
	Others
	Atlas of Australian Soils. Explanatory data for Sheet 2. Melbourne - Tasmania area., 1962 / Northcote, K.H.

3.5 South Australian soil mapping

The South Australian state soil and landscape mapping program has its origins in 1976, although the main activity occurred between 1986 and 2001. The main objectives of the program were to apply a systematic survey methodology to generate seamless soil and landscape mapping covering the 'inside country'. This is the southern portion of South Australia and closely matches with the dividing line between the areas where agriculture is viable (i.e. approximately >420 mm/yr rainfall zone) on freehold land and the drier pastoral areas to the north on leasehold land. The agricultural areas cover approximately 16 Mha (16% of the state), and all except for the municipal areas have been mapped. Mapping approach and outputs were principally designed to meet the needs of agriculture, land use planning, and natural resources management, while also allowing the outputs to be useable by as wider group of non-soil experts as possible, including farmers, advisors and land managers.

Higher rainfall areas where land use is generally more intensive, including the Adelaide Hills, lower Yorke and Eyre Peninsulas, mid-to-lower South East regions have been mapped at a base scale of 1:50,000, while the remaining, lower intensity use areas have been mapped at 1:100,000 scale.

Mapping products are presented in a number of scale tiers:

- Biophysical regions
- Biophysical subregions
- Land Zones
- Land Systems
- Land Types
- Soil Landscapes

The mapping program was designed around soil landscapes in which terrain and landform are central to interpreting soil patterns (Hudson, 1992). Referring to the above dot points, the lower three tiers (Land Systems, Land Types and Soil Landscapes) were the focus of the mapping program. The Land System mapping approach mirrors that developed by CSIRO (Sections 3.4 and 4) with mapping produced at a scale consistent with 1:250,000, and units delineated according to patterns of parent material, relief, vegetation, and in similar climate. Land Type mapping applies Land Systems as the map base, and delineates Land Types according to dominant landform, e.g. crests, slopes and alluvial zones. Soil Landscape Units (SLUs) represent the finest scale of soil mapping, and taking Land Type units as the base, delineating within these SLUs according to finer scale landscape patterns. Each Land System contains a discrete set of SLUs reflecting its distinctive set of biophysical conditions, e.g. parent material and relief patterns. Each SLU is potentially analogous to a soil association that contain soils with a distinctive range of properties. Accordingly, each SLU may contain numerous soils that classify differently, e.g. ASC (Section 3.1.3) and Soil Groups (see below). SLUs may be considered as the *fundamental* datasets emanating from the mapping program, as from this primary data source numerous secondary datasets have been generated.

In keeping with the objectives of the mapping program, soils have also been described according to a uniquely South Australian set of Soil Groups (of southern SA) and sub groups (Soil Types) that draw strongly in terms of naming on the most recognisable morphological features. The naming of units also applies non-technical terminology designed to assist non-soil experts to recognise and effectively communicate the soils. For example, the Soil Group 'Gradational Soils with Highly

Calcareous Lower Subsoil' (i.e. Group C) contains a number of Soil Types, including a 'gradational sandy loam' (i.e. C1) and a 'hard gradational clay loam' (i.e. C4). There are 15 Soil Groups and 61 Soil Types used. Soil Groups and Soil Types are fully described in the 430-page landmark publication "The Soils of Southern South Australia" (Hall et al., 2009), which is available in the public domain and can be downloaded in two sections:

- Part 1: https://data.environment.sa.gov.au/Content/Publications/Soils-of-SouthernSA-Part-1of2.pdf and
- Part 2: https://data.environment.sa.gov.au/Content/Publications/Soils-of-SouthernSA-Part-2of2.pdf.

By completion of the mapping program in 2001, >28,000 sites had been systematically described, of which >1,000 soil pits were sampled for laboratory morphological and chemical analyses. Soil pits were positioned in representative parts of landscapes to characterise 'typic soil profiles', and these are called 'Soil Characterisation Sites'.

3.6 Victorian soil mapping

Soil and landscape surveys and mapping in Victoria was essentially carried out in three phases. The first phase (1927-1943) of surveys conducted by the Victorian Government were done in collaboration with CSIR and were focussed on the development of irrigation districts along the Murray River. These districts sought to develop a range of horticultural industries. Key objectives included assessing the qualities of the soils, including limitations for irrigation (salinity, sodicity, waterlogging).

The next phase (1943-1975) was conducted by the state resources agency and addressed agricultural intensification and expansion. These surveys were completed at fine mapping scales and often addressed specific limitations to agriculture. Early ones were carried out in northern Victoria and central Gippsland. From 1944 survey methodology became more systematic with mapping published at a scale of 1:32,000 in 9 Technical Bulletins. These recognised >300 generalised soil types and the mapping relied on ~55,000 soil profile descriptions (some with laboratory data), and again, typically focussed on irrigation land uses. Other less intensive soils surveys were also conducted, some to address specific soil problems (e.g. irrigation), dryland agriculture, and research stations. This period also coincided with a broad land resources assessment program covering much of the Victoria's agricultural areas that commenced in 1954. These surveys were conducted under a land systems framework and provided an overview to assist in planning the most appropriate land development opportunities for agriculture. The outcomes of the program allowed that broad strategic overview to agricultural development while also highlighting the areas required for more intensive surveys, e.g. new schemes or areas of high value conservation. These latter surveys formed a patchwork across the state, and were generally mapped at fine scale (e.g. 1:10,000), and the mapping units were 'land components' and 'land units'.

Much of the Victorian Government mapping efforts were conducted post-1975, covering a total area >3 Mha and generally focussed on dryland agriculture surveys. The mapping methodology adapted in the 1980s to accommodate new opportunities from computing, e.g. GIS, remote sensing and digital terrain data. Many of the old maps were digitised and made available in digital formats. GIS methods were also applied using original mapping and expert knowledge as a baseline for addressing specific issues like drought affects, salinity and sodicity, and new secondary mapping issued. In the period 1970s-1980s some new surveys were conducted in conservation areas and adjacent areas where there were competing land use interests. These followed land system mapping approaches and maps were presented at 1:250,000 scale.

The distribution of many of the surveys are presented in Figure 3-9, noting that there are almost certainly others that have not been included.

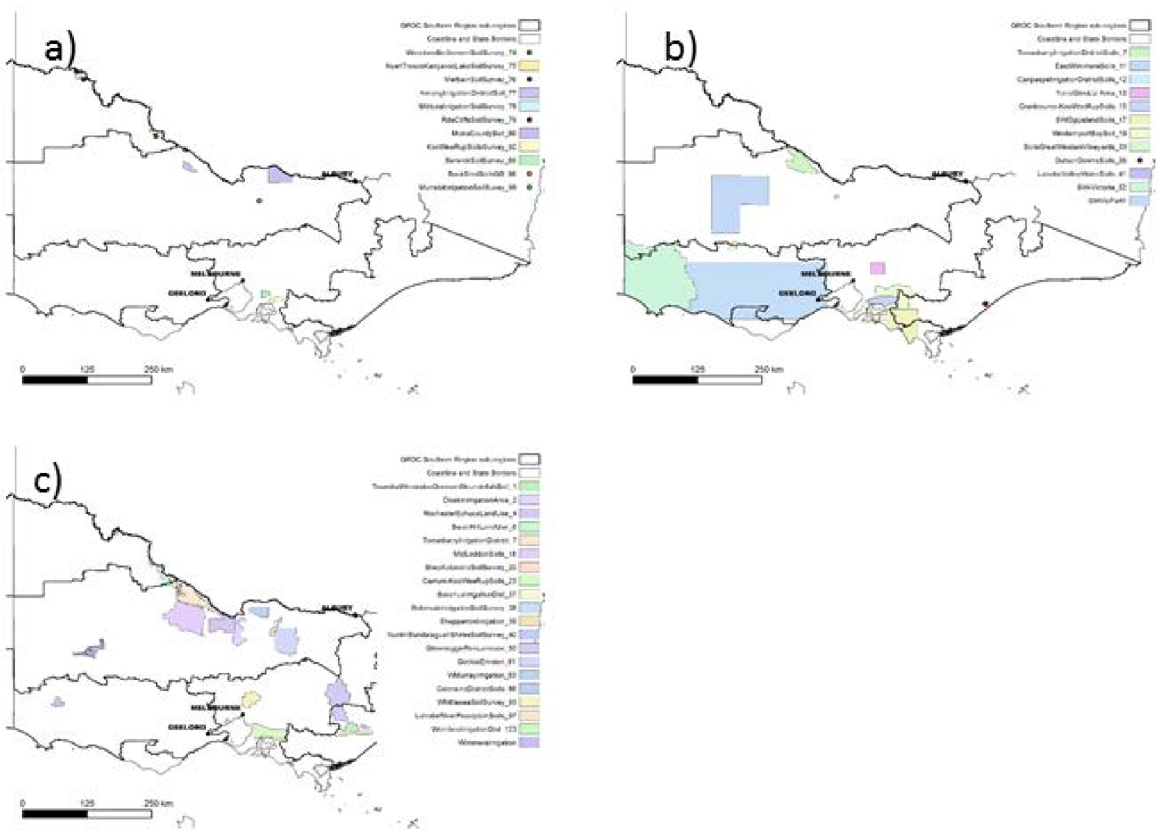


Figure 3-9. Distribution of Victorian surveys collated by era: a) 1928-1942; b) 1942-1975, and; c) after 1975-present.

3.7 Tasmanian soil mapping

Reconnaissance (small scale) soil maps and some more detailed (large scale) soil maps of agricultural land in Tasmania were conducted by the CSIRO Division of Soils, Adelaide over a 27 year period, between 1940 and 1967. These maps form the basis for the current understanding of the distribution of soils in Tasmania, and are based on landforms, geology and climate.

Because of inconsistencies in map units across different map sheets and outdated terminologies, and in conjunction with an increased demand for soil information, the Tasmanian Department of Primary Industries, Water and Environment together with the Natural Heritage Trust, initiated a project to correlate, update and reprint the reconnaissance scale soil maps and reports. Most of this effort was conducted between 1991 and 2001, and the majority of maps have now been updated and reprinted. Un-georeferenced, high-resolution pdf-versions of the maps are available through the Tasmanian Department of Primary Industries, Water and Environment website (http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/soil-maps-of-tasmania). Maps and associated metadata are also available through the Tasmanian Department of Primary Industries, Water and Environment LIST server (https://maps.thelist.tas.gov.au/listmap/app/list/map) (also refer to Section 4.3 for more details).

4 Online access to soil-landscape polygon mapping

As discussed in the preceding Section 3.3, Australian soil and land resource mapping has evolved since the 1930s into a distinctive methodology that reflects uniquely Australian soils and landscapes, and survey constraints (remoteness, field season etc.). Mapping and reporting often follows a 2-tier system in which the upper tier is mapped, and the soils within these units described in greater detail in terms of their properties and distributions. For example, the 'land system' style of mapping applies an upper tier units ('land systems') first described in Christian and Stewart (1953) comprising repeating patterns of geology and relief that each contain a discrete set of lower tier soil associations consistent with repeating patterns of vegetation and land facets. However, depending on the mapping scale and purpose, the concepts around defining upper and lower tier units may vary. For example, in finer scale mapping the upper tier mapping units may be developed around terrain concepts (e.g. hillslopes, alluvial areas) and soil associations within these distinguished by hillslope position or age of development are described in the lower tiers. While not mapped, lower tier soils may be attributed in GIS polygon data in terms of areal coverage or dominance in the mapping polygon.

4.1 South Australian soil landscape mapping

Outputs of the SA soil mapping program are in the public domain and ready available in various digital formats. For example, maps are available in GIS polygon format (including Google Earth kmz), as records (e.g. soil data and descriptions, point data GIS, see Section 3.3), and as documents and multimedia (e.g. reports, book). In addition to the *primary* soil and landscape attribute SLU mapping, the program has used these as base data to generate *secondary* maps often through combining ancillary data like terrain or expert knowledge using GIS modelling.

SA's soil and landscape maps can be viewed and downloaded via the SA Nature Maps portal (http://spatialwebapps.environment.sa.gov.au/naturemaps) In addition to state administrative, conservation, land cover, water and biophysical mapping themes, SA Nature Maps gives access to a comprehensive suite of soil and landscape maps and data. SA Nature Maps users may interactively set user-preferences, define base maps for viewing and zoom settings, define data searches and filters, and manage data download options.

The publication "The Soils of Southern South Australia" contains comprehensive information on SA's soils and mapping program, and is an invaluable resource for people wishing to learn about the state's agricultural soils, their formation, properties and distribution.

The following sections discuss the mapping data and information sources in further detail.

4.1.1 SA Nature maps

SA Nature Maps may be accessed here:
http://spatialwebapps.environment.sa.gov.au/naturemaps

Land System maps

Available in GIS polygon format and generated following methodologies described in Section 3.4 and elsewhere (Christian and Stewart, 1953; Christian et al., 1960). In SA Land Systems units are strongly governed by parent material and geology. The mapping scale approximates 1:250,000. Land System mapping contains 869 individually mapped units, see Figure 4-1.

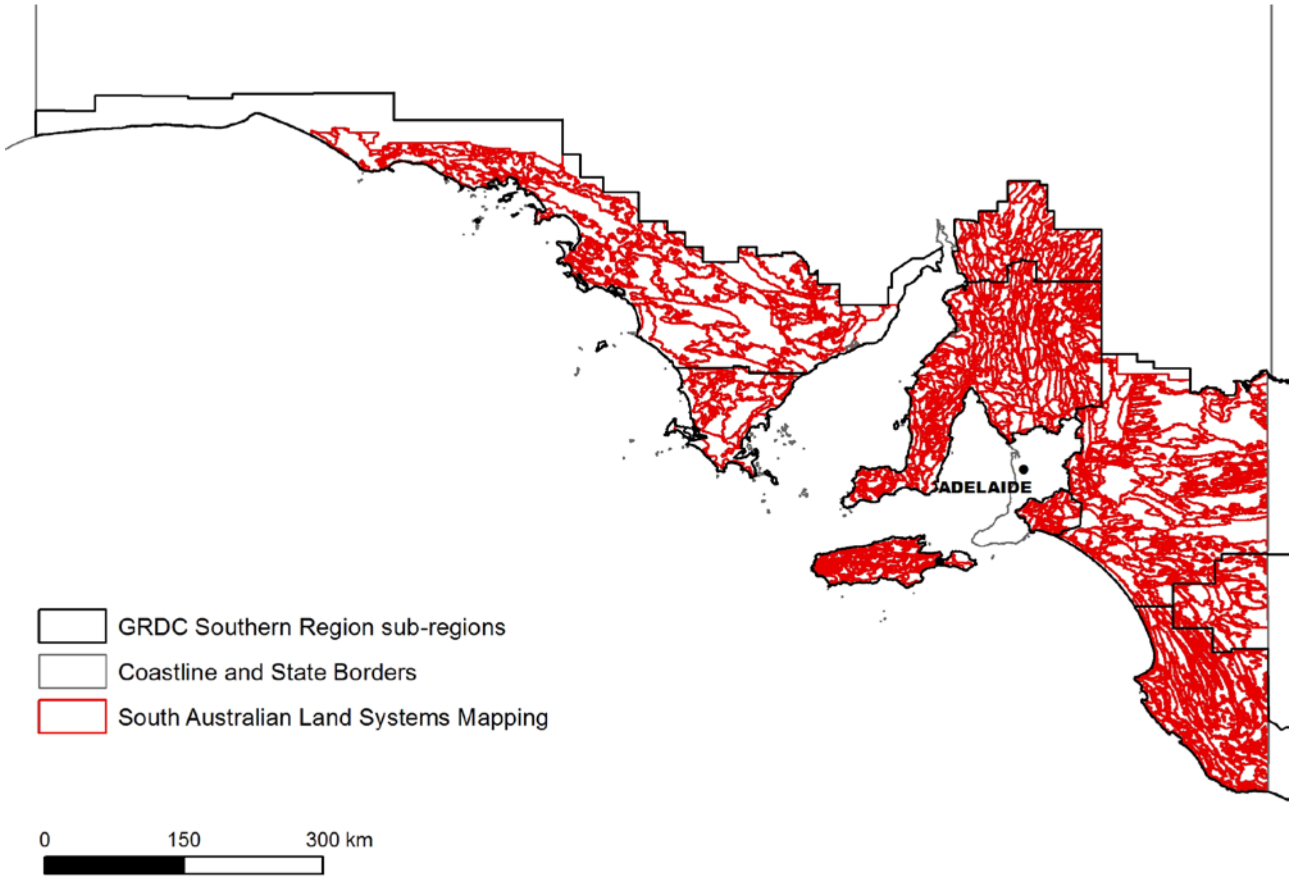


Figure 4-1. Extent and unit boundaries for SA's Land Systems mapping.

Land Type maps

Available in GIS polygon format, Land Types are essentially sub units of Land Systems differentiated from Land System units by broad relief patterns, i.e. crests and slope. The mapping scale approximates 1:250,000. Land Type mapping contains 4,479 individually mapped units.

Soil Landscape Unit maps (primary attribute maps)

Available in GIS polygon format, SLUs are essentially sub units of Land Types, and represent the fundamental map product of the mapping program. Units are differentiated by finer relief patterns, i.e. landscape facets and landscape position in upland landscapes, or parent material and soil forming processes in aeolian landscapes. Depending on the intensity of land use (related to rainfall), mapping scales vary from 1:100,000 in less intensive land use areas (generally dryland farming areas) or 1:50,000 in intensive land use areas (e.g. horticulture). Primary attributes held in a database and linked to the SLU polygons include soil physical data (e.g. texture, soil depth, pans and concretions, etc..), chemistry (e.g. EC, pH, nutrient status, carbonate content, ESP, organic matter, etc..), as well as site and landscape derived attribute classes (e.g. drainage, water holding capacity).

However, these attributes are not mapped *per se* within polygons, but link to a database in which the relative proportions of attribute value classes are presented in order of dominance. Users should note that visibility of SLU data is viewing zoom dependent in Nature Maps, and polygons may not be apparent at scales coarser than 1:144,448. SLU mapping contains 60,030 individually mapped units. The coverage of SA's SLU mapping is presented in Figure 4-2. Land system units, land type units and soil landscape units (SLUs) are compared in Figure 4-3.

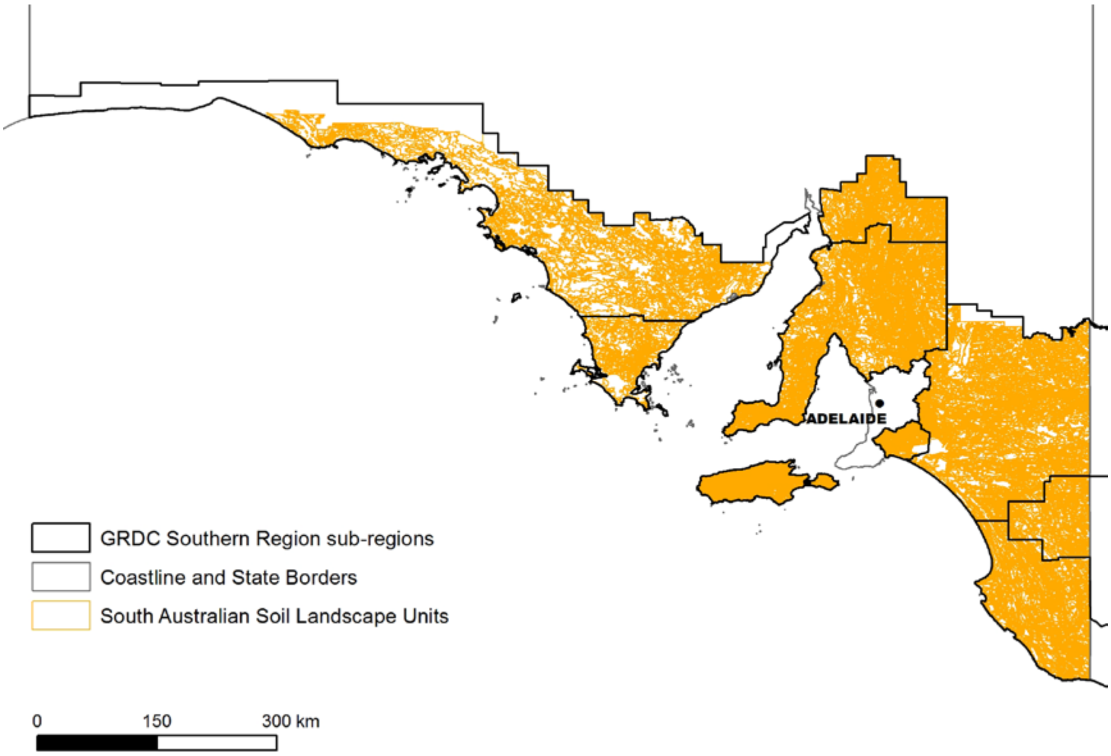


Figure 4-2. Extent and unit boundaries (mainly obscured) for SA's Soil Landscape Unit mapping.

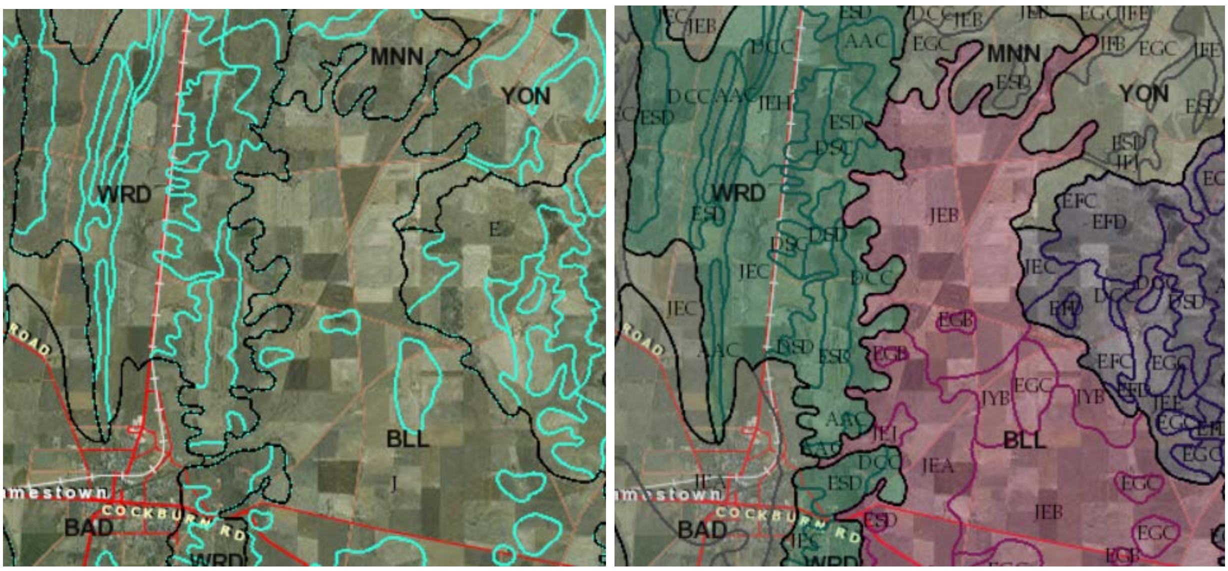


Figure 4-3. Screenshot SA Nature Maps with (a) Land-system units (black lines) with land type units (blue lines) near Jamestown SA, (b) Land-system units and within these soil landscape units.

Secondary attribute maps

As the primary mapping source, SLU mapping has enabled generation of a suite of secondary attribute maps through incorporation of ancillary datasets and/or expert knowledge (e.g. agronomic, soil conservation etc.) using GIS, and the resulting database of attributes linked to SLU polygon data. The suite of secondary attribute maps includes: land use potential, including field crops (e.g. wheat, oats, canola), horticulture crops, pasture etc., and; inherent fertility; erosion potential, and; soil surface attributes. Soil Groups and Soil Types are allocated to polygons according to dominance. However, also included in the suite of attributes with particular baring on PAWC are: soil salinity; soil moisture; boron toxicity; soil physical condition (depth to hardpan and rock, structure of subsoil and water repellence) and, soil chemistry, including acidity and alkalinity. The data is available in GIS polygon format.

4.1.2 The Soils of Southern South Australia

The book "Soils of Southern South Australia" (Hall et al., 2009) can be downloaded free of charge in two parts here: https://data.environment.sa.gov.au/Content/Publications/Soils-of-SouthernSA-Part-1of2.pdf and part 2 https://data.environment.sa.gov.au/Content/Publications/Soils-of-SouthernSA-Part-2of2.pdf.

The book contains a rich source of information on SA's farming soils presented in non-technical language to extend its reach, especially to non-soil expert farmers, adviser and land managers. It holds multiple soil and landscape maps, site and soil profile photographs, and profile data. The core of the book presents 16 sections each covering a Soil Group. Sections contain an overview of the Soil Group, including a map of distribution, summary of formation, and key management considerations - especially as these relate to farming. The Soil Group sections deal in turn with each constituent Soil Type (61 in total), including data and discussion on layer-by-layer soil morphology, formation processes, distribution in the Soil Group landscape, management considerations, and agricultural potential. Further information is given on key soil attributes such as inherent fertility, water holding capacity, drainage, erodibility, surface stoniness, surface and subsoil structural issues, and dryland and irrigation potential for the Soil Type. Notably, the sections contain for each Soil Type an annotated soil profile photograph showing likely cereal crop root growth patterns to illustrate rooting constraints, including soil chemistry (e.g. salinity, pH, toxicities) and physical barriers (e.g. rocky layers and pans), as shown by example in Figure 4-4. Information presented in this way presents farmers and advisors with an appreciation of possible modifiers to PAWC in any given Soil Type. Importantly, codes used for Soil Types in the book (e.g. as above, C4) can be linked to SLU polygon codes to allow cross-referencing between SLU polygons and book.

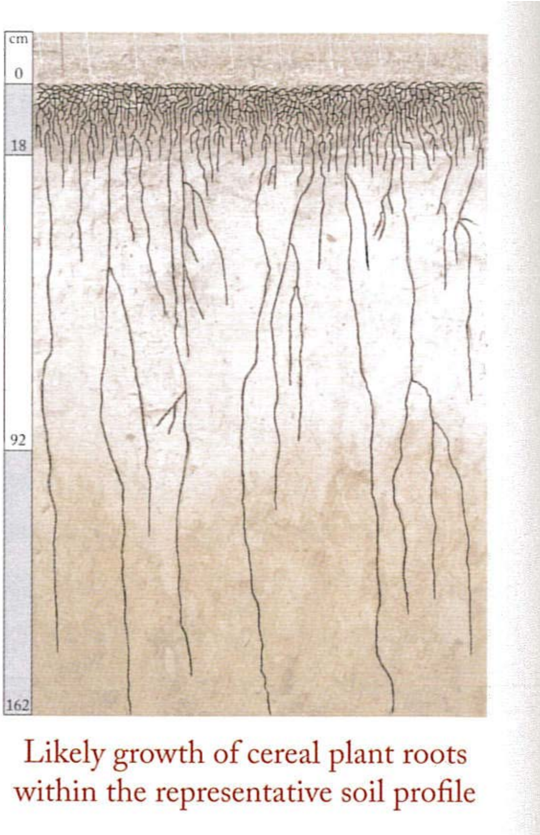


Figure 4-4. Illustration of likely cereal root exploration patterns for Soil Type (I1), Highly leached sand.

Source: Hall et al. (2009), p. 206.

4.2 Victorian soil landscape mapping

Soil mapping in GIS compatible formats may be downloaded through the Victorian data.vic online data portal. This includes the datasets listed in the following sections. The Victorian Government also provides public access to land and soil mapping and reports scanned from originals through the Victorian Resources Online portal (VRO) portal. These portals and data content they contain are discussed in further detail in the sections that follow.

4.2.1 data.vic

Victoria's land and soil mapping in GIS format (e.g. shape) are accessible via the link https://www.data.vic.gov.au/data/dataset?q=soil. Users are required to register, and once access is provided, instigate searches based on mapping theme, location, and data type (Figure 4-5). Once defined and dataset selected, users access an interactive interface to complete geographically-based data selections (e.g. government regions, postcodes, whole-of-state), which also involves defining desired data formats and projections, and once completed, data is downloaded.

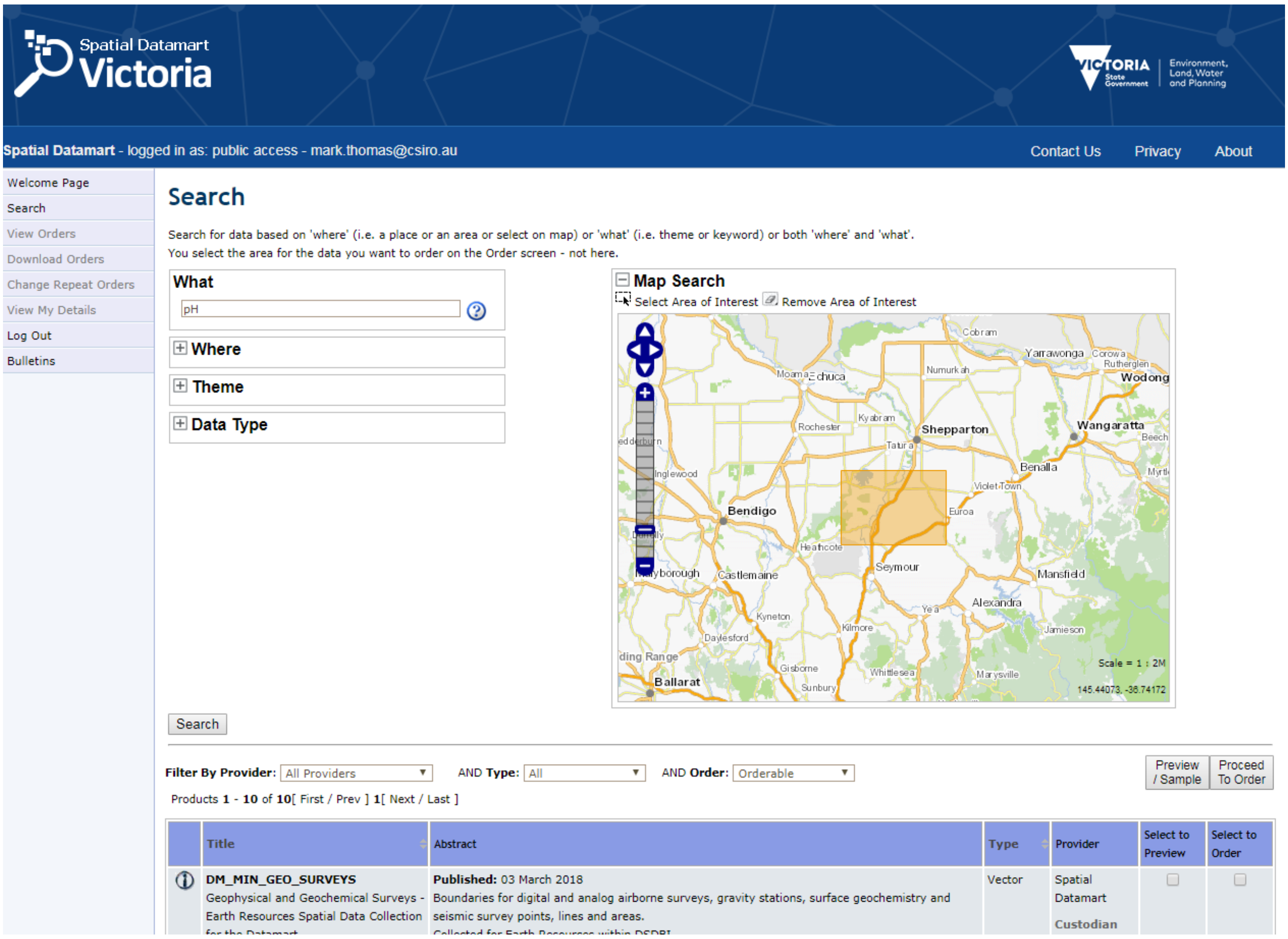


Figure 4-5. data.vic land and soil data search portal.

Land and soil datasets of main interest accessible through data.vic for PAWC include the following:

Victorian soil type mapping

The data is accessible in GIS shapefile format. The mapping is a collation of numerous surveys (see Section 3.6) consisting of 3,300 land units. As it is a harmonised product across numerous mapping scales (e.g. 1:10,000 to 1:250,000), and the units are attributed according to Australian Soil Classification (ASC; at Order and Suborder levels) by areal dominance. Particular effort has been applied to edge matching to harmonise across map borders. An index of mapping reliability accompanies the product. Given the variable intensity of underpinning soil surveys (and mapping scales), the mapping is more suited for strategic oversight-type applications, and care is necessary should the mapping be used for finer scale applications (e.g. farm of paddock scales).

Land units

Land units are mapped at 1:100,000 scale and each is defined in terms of soil-landforms. Descriptions contain attributes including dominant soil type, land capability, texture, sodicity and pH. At the mapping scales, land units are not able to be spatially explicit and hence represent a high level of aggregation. Land unit maps cover various regions of: North East Victoria, Corangamite, Wimmera, Glenelg-Hopkins, Goulburn Broken, and Gippsland.

Land systems

Land system mapping is available for the whole state, and map coverages consistent with the 1:250,000 scale national topographic mapping series.

Miscellaneous soil and land data

Data.vic lists a number of soil and land mapping themes, many of which have little thematic relevance for PAWC assessments. However, the themes that present the greatest opportunity include the following:

- The Victorian Soil mapping series is supplied at 1:100,000 scale six standard depths: 0-5, 5-15, 13-30, 30-60, 60-100 and 100-200 cm, aligning with the Soil and Landscape Grid of Australia (SLGA) and GlobalSoilMap standard depths. The mapped themes include pH, EC, % clay and soil organic carbon (%). The attributes were derived by DSM techniques (see Section 6.4.2), and the standard depth estimates using the spline algorithm (Bishop et al., 1999). The mapping has been aggregated to polygons according to median values for the soil properties for the polygons.
- Victorian Primary Production Landscapes (PLLs) divides the state into 6 region and 22 subregions. Units are defined from soil and landscape data, climate, and applying the experience of agronomists and land managers. Dominant soil types and important management issues are also considered in deriving the PLLs. Given the themes involved and level of information aggregation, PLL mapping is at a coarse mapping scale.
- The Victoria Geomorphology Framework (VGF) is a three-tier hierarchical framework classifying landforms and landscapes. Tier 1 comprises 8 divisions and approximates mapping scale in the range 1:1M-1:5M; Tier 2, has 35 categories and approximates mapping scales in the range 1:500,000-1:2M; and Tier 3, scales in the range 1:100,000-1:500,000. Many Tier 3 units are aggregations of land system and soil-landform mapping, hence are defined in strong accordance with landform and relief patterns. One of the purposes of VGF mapping is to provide a framework to align retrospective and future Victorian land and soil mapping programs and mapping products. For example, conceptually at least, Land unit mapping (or other similarly themed and executed mapping programs) would fall into Tier 3 – or even a Tier 4 if the mapping scale was fine enough.

The distribution of surveys and mapping of themes presented above are presented in Figure 4-6, noting that there are almost certainly others that have not been included in the figure.

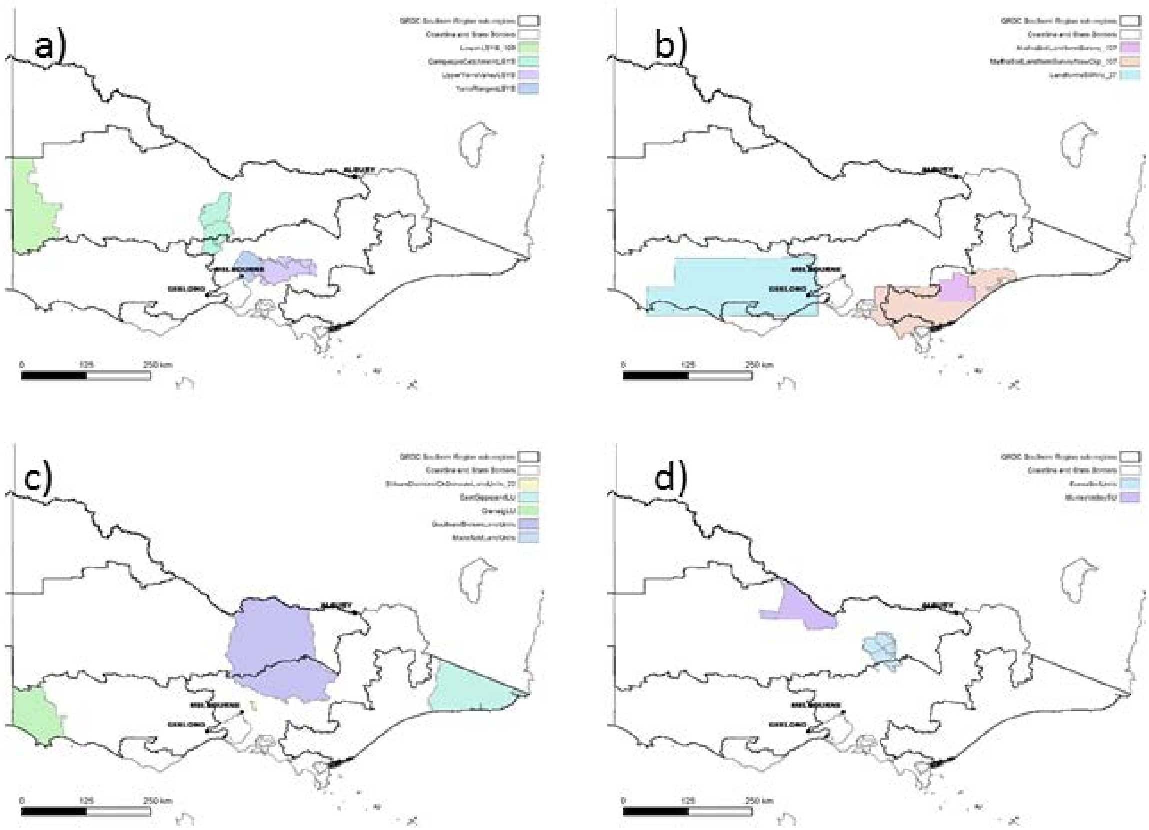


Figure 4-6. Distribution of Victorian surveys collated by mapping theme: a) Land Systems; b) Land Types; c) Land Units, and; d) Soil Units.

4.2.2 Victorian Resources Online

The Victorian Resources Online (VRO) is accessible via the link http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/sitemap. This facility presents numerous soil and land data and information, mainly in PDF format. These products include scanned maps and reports – many of which are historic. The site presents data products via two thematic portals, i.e. (i) soil and land theme or (ii) catchment management regions (Figure 4-7).

Soil and land themes likely to be the most valuable in terms of PAWC include landform, land use (land capability), soil, and land and water management. The 10 Victorian regions are Mallee, Wimmera, Glenelg-Hopkins, Corangamite, Port Phillip and Westernport, West Gippsland, East Gippsland, North East, Goulburn Broken and North Central. Each region has a homepage.

The following sections discuss the data and content for the key mapping themes, noting these data themes can also be accessed via the regional portals.

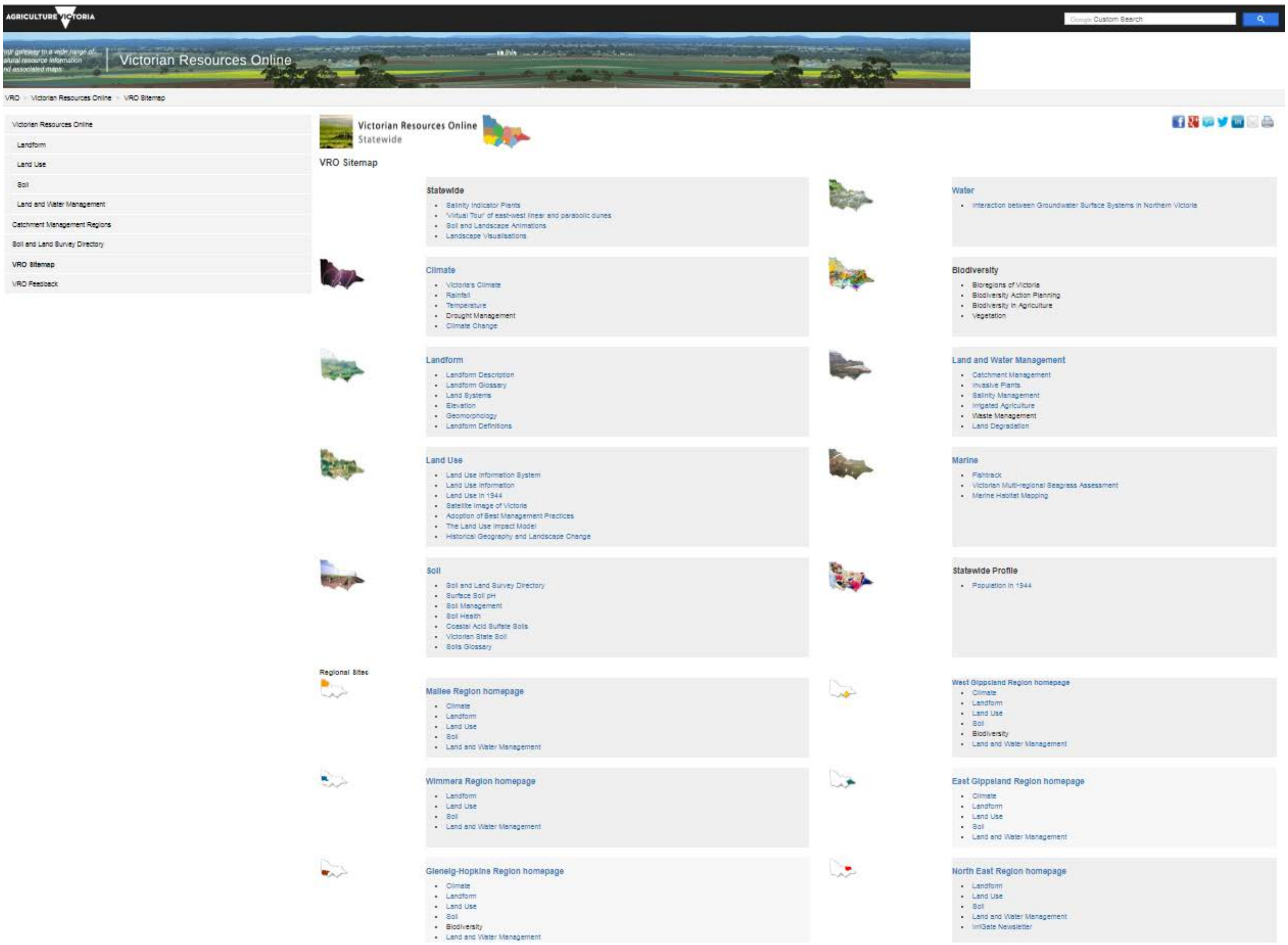


Figure 4-7. Victoria Resources Online portal.

Landform

Landform information captures the diversity of Victorian Land Systems, elevation, geomorphology and geology. The site points to references related to these themes for Victoria. All land systems reports are listed, including the 'enhanced Land Systems (V3)' mapping and information framework (currently incomplete for the state).

Soil

This section lists the key soil themes that have bearing on PAWC work, including land capability, soil health, soil pH, soil texture, and soil sodicity. For example, the land capability maps present land units based broadly on landscape and parent material, as this latter theme has significant impact on land use intensification opportunity.

Land and water management

The suite includes numerous and often disparate map and information themes, including catchment-wide hydrology or invasive plants, that would have little useful bearing on PAWC work due to theme and scale mismatch. However, in there it is possible that there could be some themes of value, including covering land degradation and land condition reports.

4.3 Tasmanian soil landscape mapping

For Tasmania two mapping types are available online, the *Reconnaissance soil maps* and the *Land capability mapping*.

Both mapping efforts are available digitally through the Tasmanian Department of Primary Industries, Water and Environment LIST server (Land Information System Tasmania) (https://maps.thelist.tas.gov.au/listmap/app/list/map), a GIS-based mapping tool that brings together a variety of land-based information, including soils and geology. LISTmap can be accessed through the web browser or via a mobile device, and enables the viewing and creation of personalised maps of Tasmania. Instructions of how to use LISTmap can be found here: http://listdata.thelist.tas.gov.au/public/outgoing/sif/listmaphelp.pdf. Youtube videos that explain its use and functionalities are also available: https://www.youtube.com/user/gsbclientserv. Metadata can also be downloaded through the LISTserver. The use of LISTmap is described in more detail under the 'Reconnaissance soil maps of Tasmania section'. LISTmap recently moved to a new platform, and some functionality is still to be resolved (e.g. for some maps only the spatial extent is currently shown).

Reconnaissance soil maps of Tasmania

Soil maps of Tasmania include 1:100,000 Reconnaissance maps and a number of more detailed soil surveys of smaller parts of agricultural land (refer to Section 3.7). Distribution and coverage of the maps is shown in Figure 4-8. Their mapping is based on landforms, climate and geology with soil map units described in the accompanying reports. High-resolution, un-georeferenced pdf versions of the Reconnaissance soil maps are available from: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/soil-maps-of-tasmania.

The revised Reconnaissance soil maps are also available digitally as clickable maps through the Tasmanian Department of Primary Industries, Parks, Water and Environment LIST server (https://maps.thelist.tas.gov.au/listmap/app/list/map). The other maps and detailed soil surveys are only available in print through the library. Associated soil survey reports are available in PDF format and can be made available upon request by contacting the Tasmanian Department of Primary Industries, Parks, Water and Environment (http://dpipwe.tas.gov.au/contact-us). The Department is currently, however, in the process, of making these reports available for download on its website.

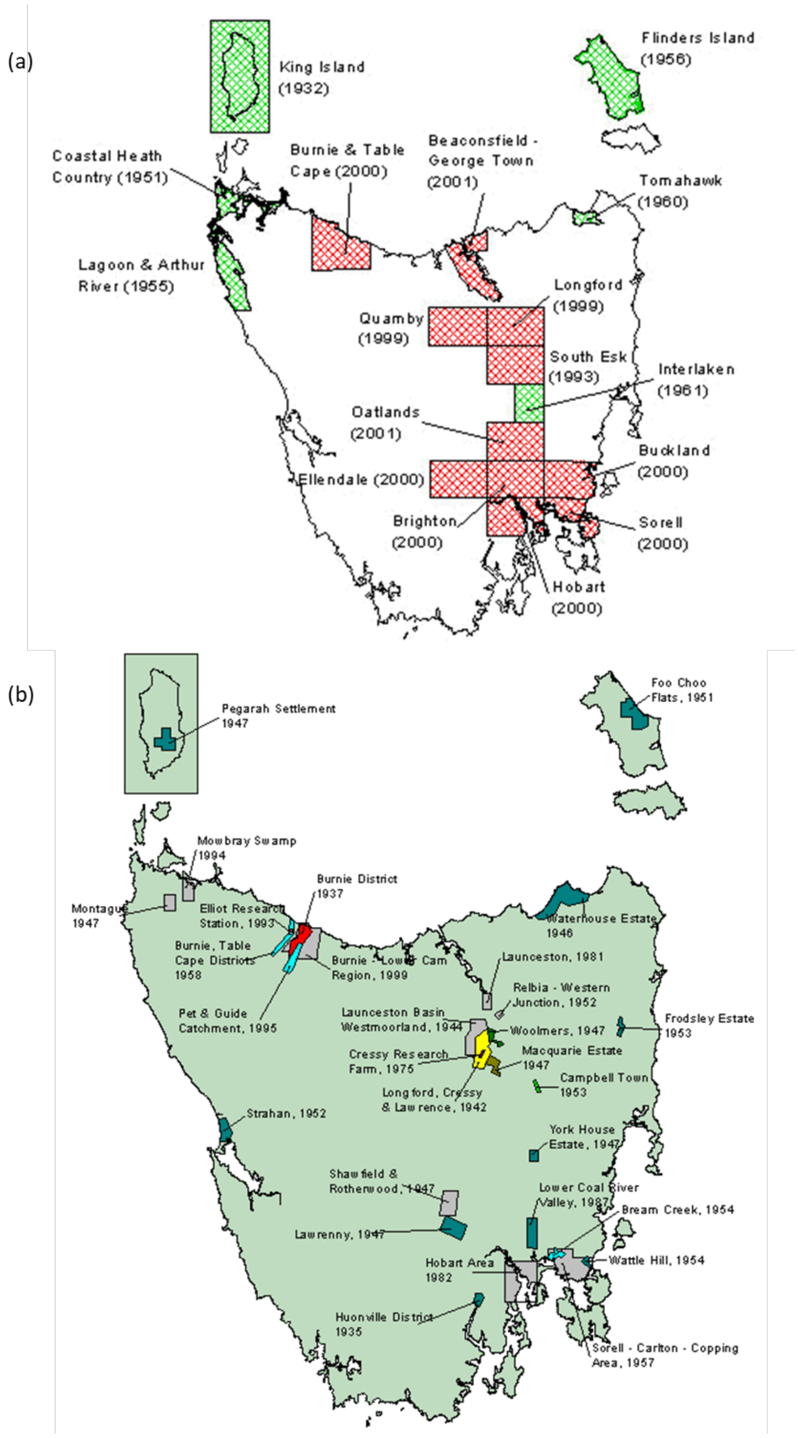


Figure 4-8. (a) Coverage of 1:100,000 scale soil reconnaissance maps in Tasmania; red hash indicates updated reconnaissance soil maps that are available online; (b) locations of more detailed soil surveys (source: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/soil-maps-of-tasmania).

In LISTmap, the 1:100,000 Reconnaissance soil maps are available as coloured polygons in a digital layer called ‘Soil Types’. Figure 4-9 shows an image of the LISTmap tool and the ‘Soil type’ layer, which can be displayed at varying transparency to help with navigating to areas of interest (Figure 4-9b). It needs to be noted here that one needs to zoom into this layer, as data are rendered scale dependently. Figure 4-9 also shows that relevant layers can be added to the mapping tool through the ‘Add layer’ icon, and that maps can be personalised through a range of drawing tools if desired (Figure 4-9b). The user can also navigate to a mapping unit of interest and open a Feature Info box that further explain this mapping unit. In the example shown in Figure 4-9c, the beige map unit was chosen. The Feature Info box shows it belongs to the Longford Reconnaissance soil map, and the Ca ‘Canola Association’ map unit. Information available in the more detailed map unit descriptions can then provide some initial insights to inform the PAWC predictions. For example, the Ca map unit belongs to the “soils of the basin sediments, river terraces or recent alluvium”, and is further described as “soils developed on alluvium on flat to gently undulating (0-3%) flood plains, valley flats and depressions”. Dominant soil types in ASC and Great Soil Group classifications systems are also provided, i.e. Vertosol and Black Earth, respectively.

Alternatively, the soil unit boundaries can be viewed in a layer called ‘Soil Boundaries’. Note that due to the migration of LISTmap to a new platform, the layer Soil 1:100,000 Reconnaissance Maps only indicates the spatial extent of the maps, not the soil units itself. The locations and spatial extent of the smaller, more detailed soil surveys are shown in the ‘Soil Local Area Maps’ layer.

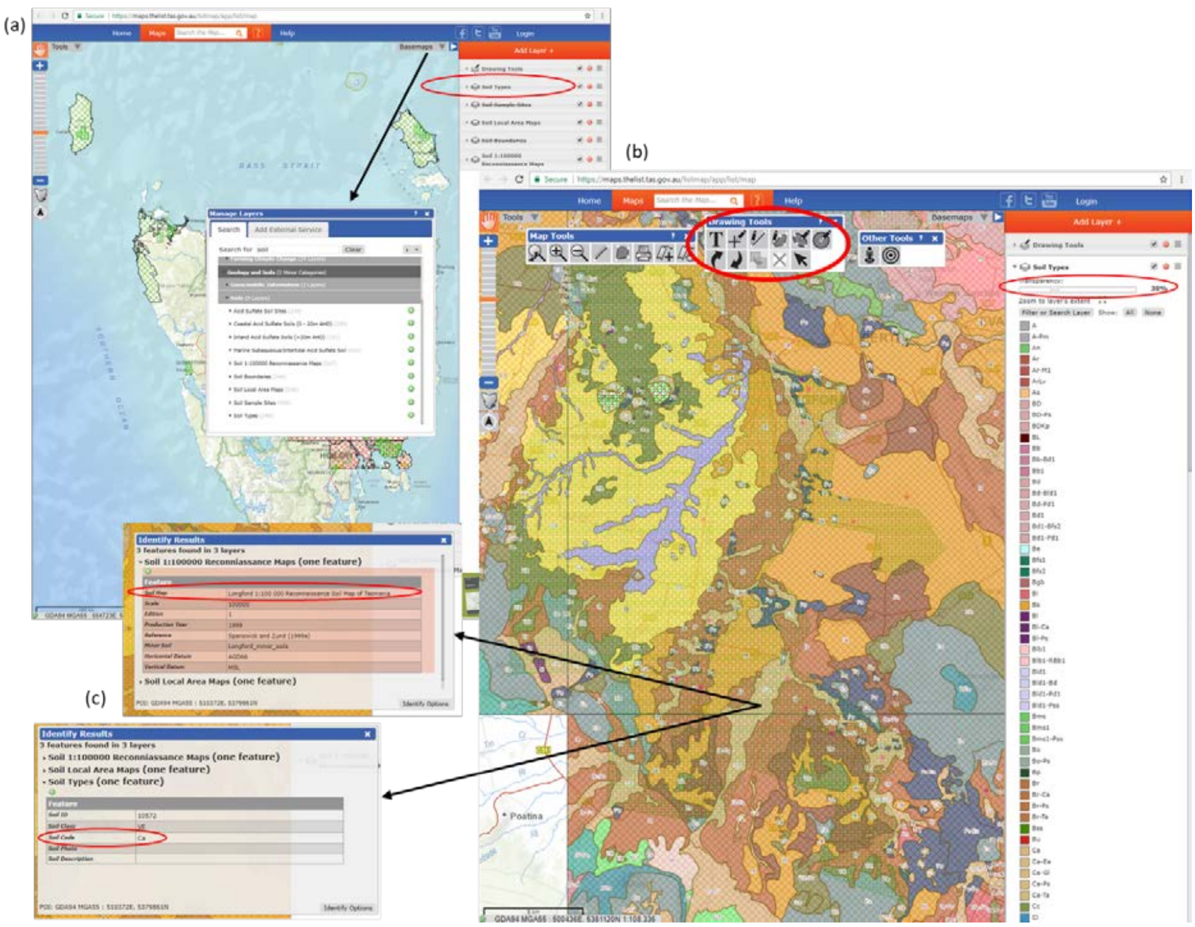


Figure 4-9. Framegrab of the LISTmap online mapping tool, showing soil types close to the locality of Longford.

Land capability mapping of Tasmania

Field mapped and modelled land capability maps cover all of the GRDC's Southern subregions that fall within Tasmania (Figure 4-10), and can be accessed through:

http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/land-capability/index-map-of-available-land-capability-maps

These maps use the Tasmanian Land Capability Classification System (LCCS) to assess, classify and map land according to seven capability classes, which reflect the ability to support a range of crops on a long term sustainable basis (Grose, 1999). Evaluations are based on a range of limiting factors that are imposed on the land of interest, including erosion, soils, wetness and climate.

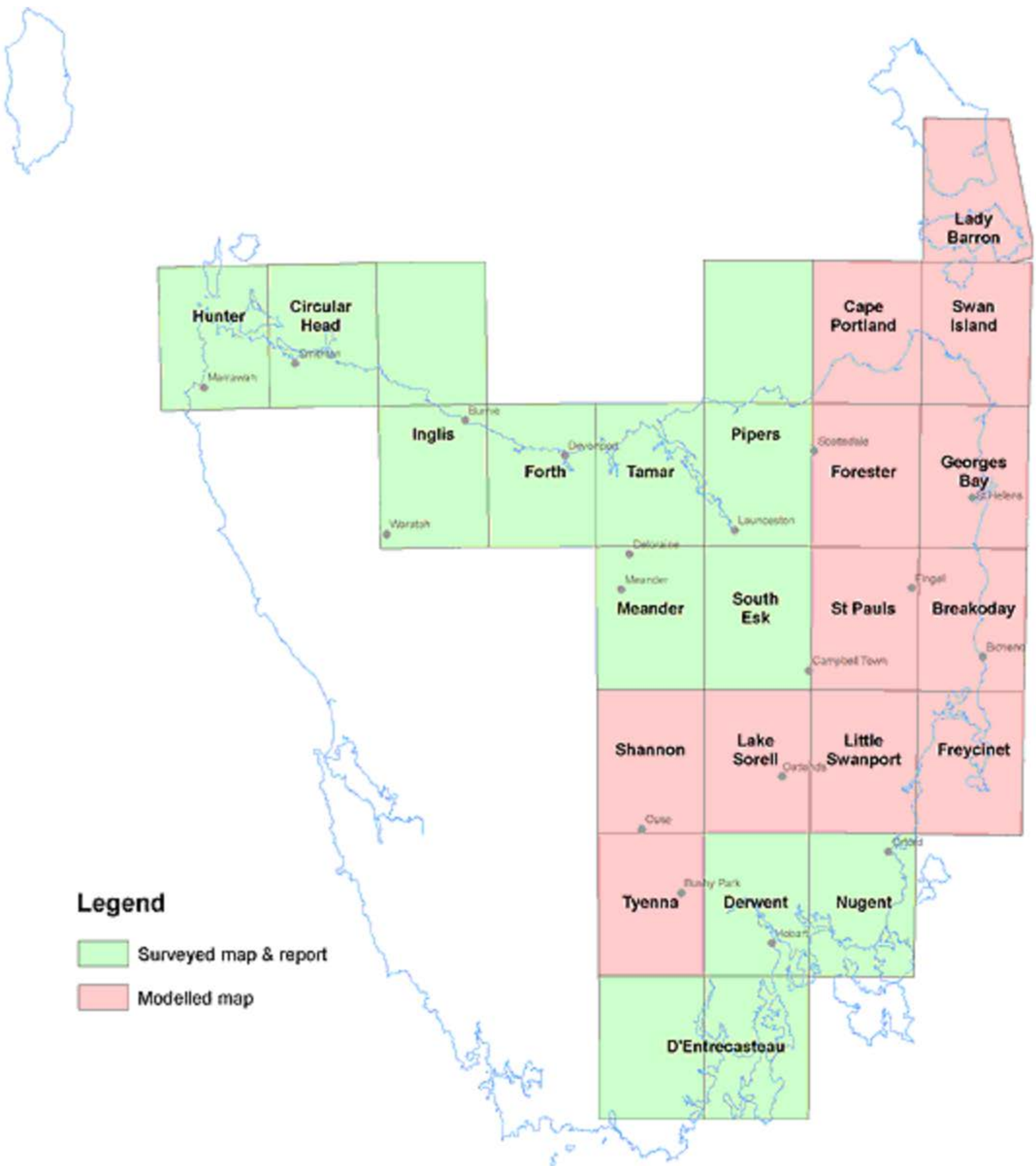


Figure 4-10. Availability of field mapped and modelled land capability maps for Tasmania. Green shows surveyed maps and reports; and pink shows modelled maps (source: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/land-capability/index-map-of-available-land-capability-maps).

The land is then evaluated based on potential crops, productivity, and ease of management and risk of degradation. Class 1 is the best land class and Class 7 the poorest. The field mapped land capability maps (un-georeferenced) and accompanying reports based on field survey techniques are available for download in PDF format through: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/land-capability/field-mapped-land-capability-maps-and-reports. Table 4-1 lists the field mapped land capability reports and maps with potential to support PAWC work in the GRDC Southern region.

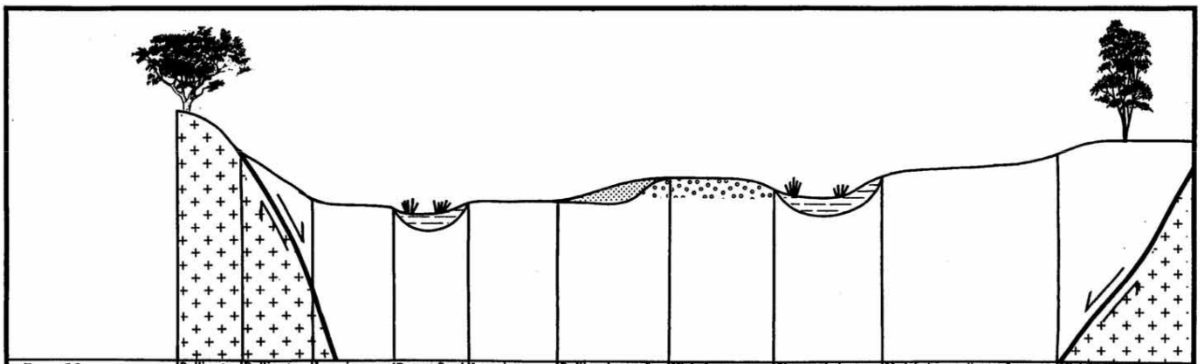
Table 4-1. Tasmanian Government land capability reports and maps with potential to support PAWC work in the GRDC Southern Region.

Year	Report Title
Tasmanian Land Capability Reports and Maps	
2000	Land Capability Survey of Tasmania. Derwent Report (1:100,000). / by R.A. Musk and R.C. Derose
1997	Land Capability Survey of Tasmania. Forth Report (1:100,000). / by R.M. Moreton and C.J. Grose
1999	Land Capability Survey of Tasmania. Inglis Report (1:100,000). / by R.M. Moreton
1993	Land Capability Survey of Tasmania. Meander Report (1:100,000). / by K.E. Noble
2001	Land Capability Survey of Tasmania. Nugent Report (1:100,000). / by R.C. Derose and D.J. Todd
1990	Land Capability Survey of Tasmania. Pipers Report (1:100,000). / by K.E. Noble
1996	Land Capability Survey of Tasmania. South Esk Report (1:100,000). / by C.J. Grose and R.M. Moreton
1992	Land Capability Survey of Tasmania. Tamar Report (1:100,000). / by K.E. Noble

For the seven regions in Tasmania that fall within the GRDC Southern Region (i.e. Forester, St Pauls, Breakday, Little Swanport, Lake Sorell, Shannon, Tyenna), only modelled land capability maps (1:100,000 scale) are available, which were generated through computer modelling using available digital information and rules for capability. A report detailing the modelling process and its limitations, including a summary of the land classes found on each modelled map sheet is currently in preparation. High-resolution un-georeferenced PDF versions of the modelled maps are downloadable through the Tasmanian Department of Primary Industries, Parks, Water and Environment website: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/land-capability/modelled-land-capability-maps.

The land capability mapping into 7 classes is also available in Tasmania's online GIS-based mapping tool ListMap under the Farming layers (https://maps.thelist.tas.gov.au/listmap/app/list/map), including metadata.

Due to only showing the land capability classes, the land capability maps themselves probably have limited value for PAWC prediction. The accompanying reports can, however, provide useful insights into the geology, topography and geomorphology and soils of the area. This includes schematic soil-landscape diagrams that can be useful to build a soil-landscape narrative for extrapolation or generalisation of PAWC data. See e.g. Figure 4-11 for an example of a north-south cross section of a landscape within the South Esk Land Capability report.



Landform	Rolling to steep land	Rolling to steep land	Low river terrace (Brumby surface)	Recent flood plain	Low river terrace (Brumby surface)	Rolling dunes of low relief	High river terrace (Brickendon surface)	Sinuous drainage lines	Undulating gradients often below Woodstock surface	High level erosion surface (Woodstock surface)
Geology	Jurassic dolerite	Permian tillite	Quaternary alluvium	Quaternary alluvium (silts and clays)	Quaternary alluvium	Windblown sand	Tertiary clays with Quartz gravels	Quaternary alluvium (silts and clays)	Tertiary clays	Tertiary clays
Soils	Eastfield assoc.	Miller assoc.	Brumby assoc.	Canola assoc.	Brumby assoc.	Panshanger assoc.	Brickendon assoc.	Kinburn asssoc.	Cressy assoc.	Woodstock assoc.
Slope	Gentle to moderate 5-40%	Undulating to steep 10-60%	Flat to gently undulating 0-3%	Flat to gently undulating 0-3%	Flat to gently undulating 0-3%	Gently undulating to rolling 3-20%	Flat to gently undulating 0-5%	Flat to sloping 0-5%	Gently undulating to undulating 3-10%	Flat to undulating 0-10%
Limitations	- Stoniness - Rock outcrops - Gradient	- Soils - Stoniness	- Soils - Sodicity - Seasonal wetness	- Flooding - Sodicity - Wetness	- Soils - Sodicity - Seasonal wetness	- Soils - Erosion	- Stoniness - Soils - Seasonal wetness	- Wetness	- Drainage soils	- Stoniness - Soils
Land capability class	5,6	4,5,6	4,5	4,5	4,5	4,5	4	4	3	4,5,6

Figure 4-11. Example of a soil-landscape diagram in the South Esk Land Capability Report (source: http://dpipwe.tas.gov.au/Documents/Land_Cap_Report_South-Esk.pdf).

5 Geological Mapping

In many situations underlying geology strongly influences soil formation (parent material, see discussion in Section 3.3) as it determines factors such as resistance to weathering, terrain and relief patterns, and the geochemical/mineralogical building blocks of the soil. As such geological mapping provides important physiographic information used in understanding and mapping soils, and helps in making inferences on soil. Geological maps informed the soil-landscape mapping presented in Section 4.

Lithological records associated with Quaternary and some Tertiary mapping units may provide a general level of information on mineralogy and soil texture, hence directly relating to soil properties. However, geological mapping is rarely provided at scales finer than 1:100,000, and so likely to be limited in terms of direct relevance to PAWC work. Where soil-landscape mapping is not available or limited in useful content, geological mapping may, however, provide some insights into landscape and soil similarities or dissimilarities.

The following sections provide information regarding public access to geological mapping by the South Australian, Victorian, and Tasmanian sources.

5.1 South Australia

The Department of Primary Industries SA (PIRSA) maintains the state's catalogue of geological mapping. The data is accessible through the online SARIG data portal https://map.sarig.sa.gov.au/ and the geological data accessed by clicking on the *geoscientific* portal. Under this option there are numerous geology maps available, of which surface geology is likely to be the most informative for PAWC work. (At this portal users will note availability of soils data, although it is recommended that soils data instead be accessed via the Nature Maps described in Section 4.1.1 as the dedicated state soil and land data portal that contains the full suite of data.) Key themes include surface geology, which reveals access to geological mapping varying in scale from 1:7M-1:100,000. Each scale category lists unit map symbology, age, boundaries, labels and structure. These layers are turned on and off with a satellite image base map (Figure 5-1). Data searches can be initiated based on location, or selected interactively by drawing a box of the area of interest. Selected map themes may be downloaded in various polygonal formats (e.g. shape, kmz), and the order compiled as a zip file. Users will note that other data themes under the geoscientific portal include elevation (DTM) and regolith, although the latter may reflect ad hoc surveys and hence distribution is piecemeal.

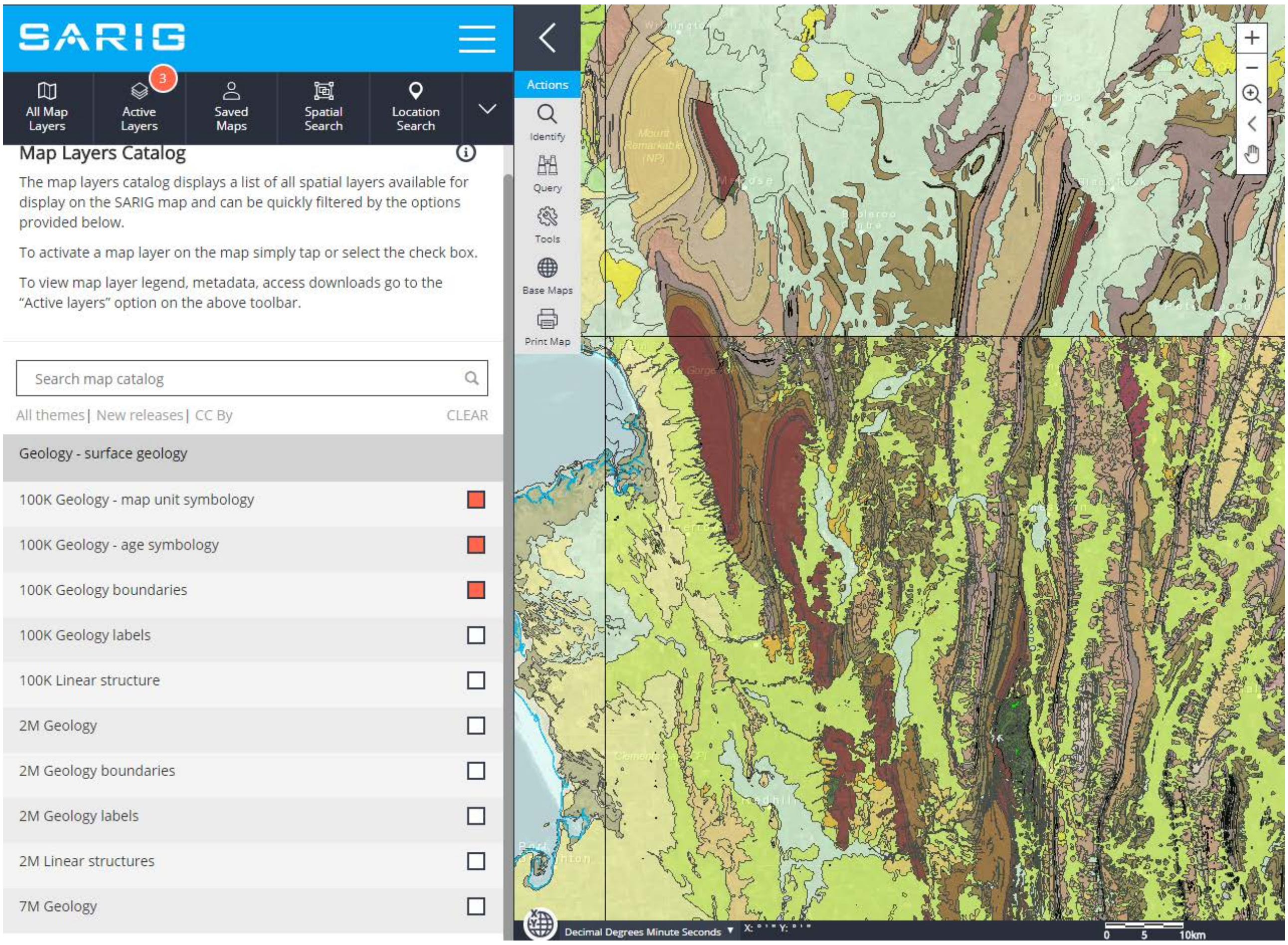


Figure 5-1. SA's SARIG data search for 1:100,000 scale surface geology covering areas of the Midnorth. Note differences in apparent mapping intensity at map borders, with more intensive mapping in the more intensive land use areas.

5.2 Victoria

Geological mapping is for Victoria is made available through the data.vic portal, as described in Section 4.2.1. What is likely to be the most useful geological data for use in PAWC work includes polygonal outcropping/sub-cropping geological rock units and boundaries separating rock units. Geological features (e.g. fault or dyke) are included in the mapping where the feature forms a boundary to rock units. Data have typically been captured to align to the national 1:100,000 map sheet framework. The intensity of geological survey allows a mapped scale equivalence of 1:25,000, although mapping is supplied at a printed scale equivalent to 1:50,000. Reference to Figure 5-2 shows the Victorian 1:50,000 scale geological features to be presently incomplete for the state.

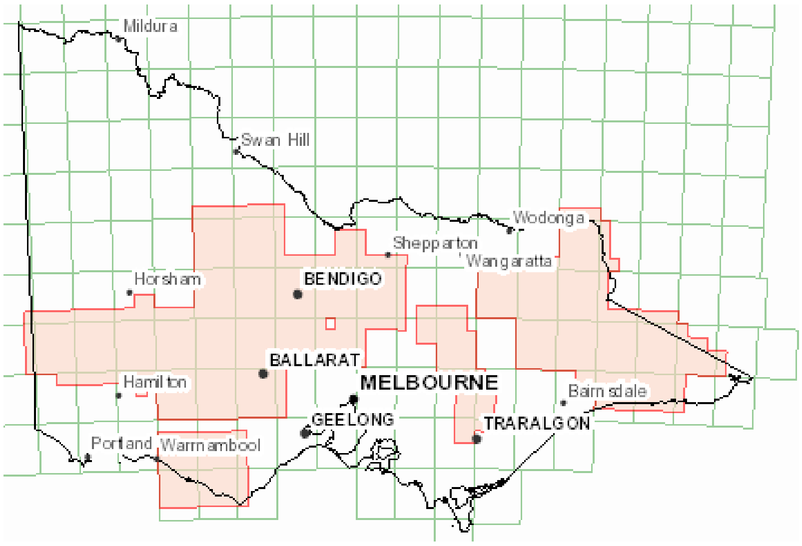


Figure 5-2. Extent of Victorian geological features mapping (1:50,000 scale), generally designed to align to the national 1:100,000 scale topographic mapping framework.

5.3 Tasmania

Geological mapping for Tasmania is managed by Mineral Resources Tasmania and is available via their data access portal http://www.mrt.tas.gov.au/portal/digital-geological-atlas-1-25000-scale-series. This data includes a 1:25,000 scale geological mapping series, which given its scale, may be useful for the interpolation of soil properties including PAWC, especially where an absence of higher quality soil mapping exists. Geological structures are mapped in conjunction with geological units and are grouped on the basis of geological age and lithology.

Individual 1:25,000 scale maps and reports can be accessed using two methods by selecting an appropriate map from Figure 5-3 below and then download in various formats.

1. as PDF format maps and reports with full legend intact present per sheet
2. as geo .tif or .ECW formats which are georeferenced (GDA – MGA Zone 55)

An example of the PDF map from the Deloraine 1:25,000 geological sheet is shown in Figure 5-4. Alternatively, the whole contiguous series at 1:25,000 can be downloaded in shape file format, as a ZIP file, for direct GIS input through

http://www.mrt.tas.gov.au/webdoc2/app/standalone/disclaimer?url=http://www.mrt.tas.gov.au/mrtdoc/public_files/geol_25.zip. A report with the data directory is included.

Geoscientific maps at smaller scales are also available via the Mineral Resources Tasmania site http://www.mrt.tas.gov.au/portal/geological-maps.

Geological maps at a scale of 1:25,000 are also available through LISTmap (refer to Section 4.3) under the Geology layers (https://maps.thelist.tas.gov.au/listmap/app/list/map).

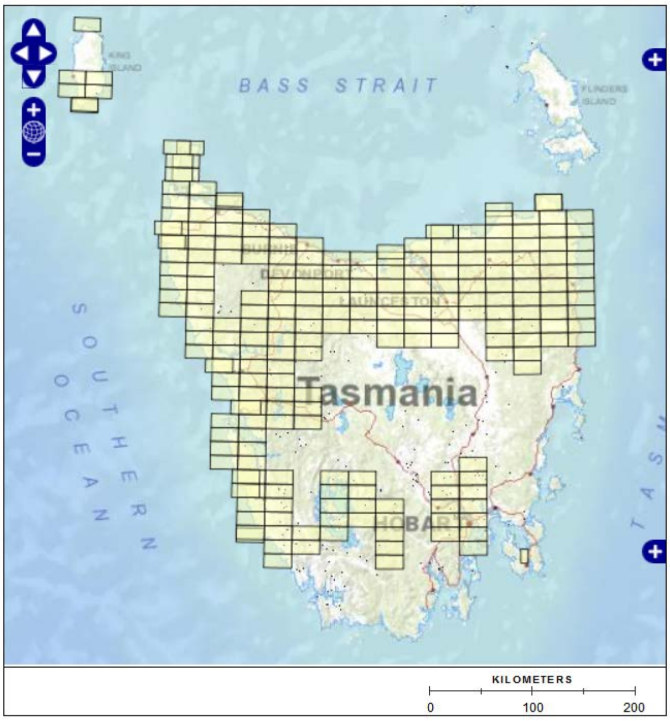


Figure 5-3. Mineral Resources Tasmania 1:25 000 geological atlas sheet index.

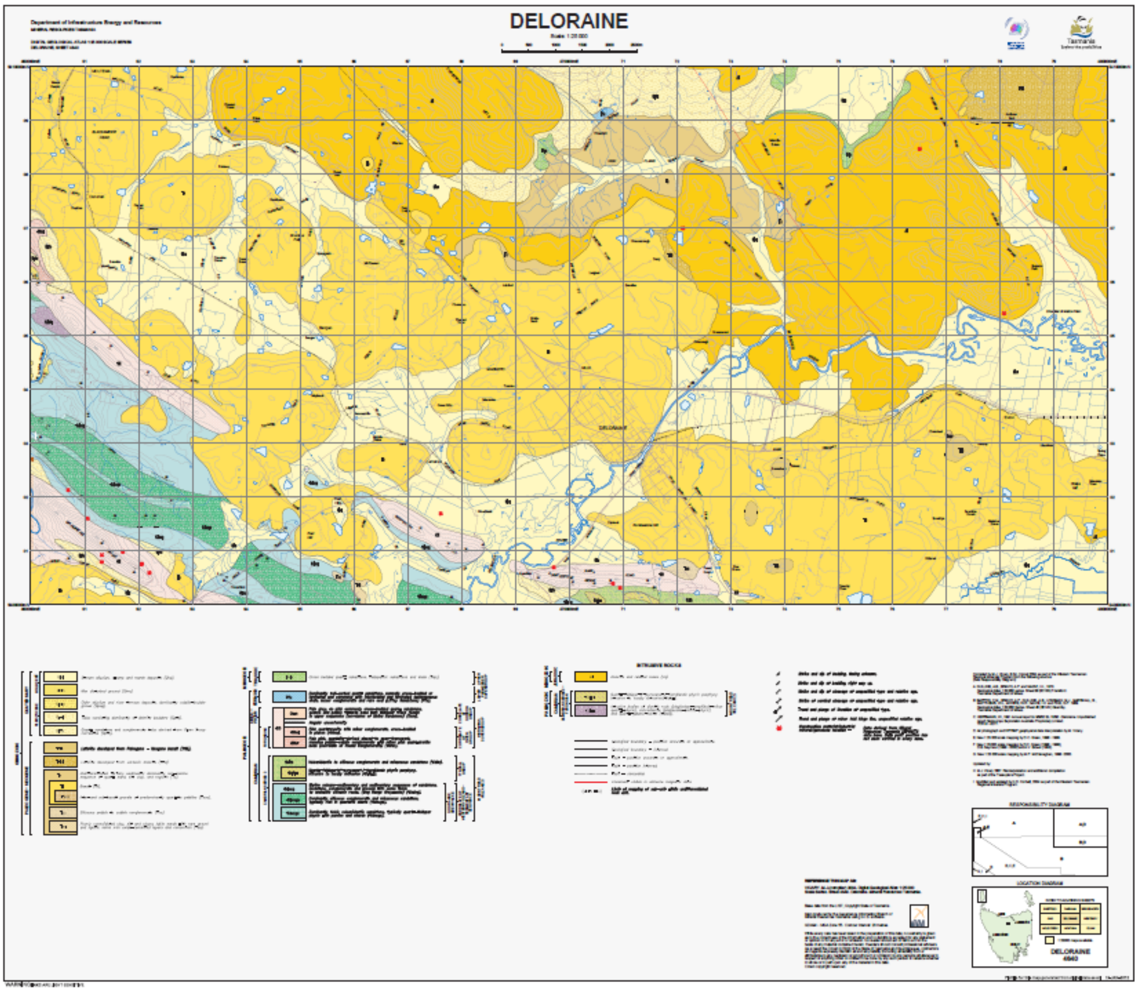


Figure 5-4. Deloraine 1:2500 Geological Sheet.

6 Digital soil mapping information

6.1 Introduction

Digital soil mapping (DSM) is a modern analogue of traditional soil mapping approaches that has co-evolved with gains in computing power, adoption of statistical methods, and increased access to predictor datasets, or *covariates* - particularly in Australia as underscored by Bui (2007) with routine access to reliable climate, remote sensing, digital elevation models (DEMs, and derived terrain attributes), and gamma radiometrics (mineralogy, landscape evolution). DSM outputs include maps of soil attributes (or soil types) created as geographic information system (GIS) gridded data, which represent natural patterns of soil changes across the landscape. DSM also allows production of companion mapping reliability maps that show where the soil attribute maps are more or less reliable so that on-ground or modelling users can make objective decisions on how best to use the data. Comprehensive texts on DSM are presented elsewhere for readers to follow (e.g. Grunwald, 2006; Hengl and Reuter, 2009; McBratney et al., 2003).

Many of the DSM modelling approaches used today rely on statistical models that establish environmental correlation between soil observations/data at points and spatially extensive covariates (McKenzie and Ryan, 1999). Some of the best performing models use data mining and machine learning to capture spatial distribution of soil properties without prior assumptions about the form of the complex relations between soils and covariates (Jenny, 1941; McBratney et al., 2003).

DSM models can be expressed as statistically-based rules representing the relationship between (i) soil data at the sampling site and (ii) the geographic intersection with the covariates. Multiple, co-registered covariates in raster file format are used in environmental correlation - effectively in a stack of raster[1] covariates (predictors), as represented in Figure 6-1. The soil attribute to be mapped is predicted at an unsampled location where particular data characteristics of the covariates in the stack estimate, through the rules, the soil attribute value at that point. This process of rule–to-covariate matching progresses through the whole area of interest (grid stack area) to compile the complete final soil map. In essence the environmental correlation approach is a digital analogue of the traditional soil mapping method, which relies on experts to build models (rules) from patterns of relief, drainage or vegetation, i.e. soil covariates (Hudson, 1992). In the DSM analogue, the ‘expert’ is represented by the statistical modelling process.

[1] Raster files comprise a continuous array of regular sized grid cells (pixels) that represent the variable values.

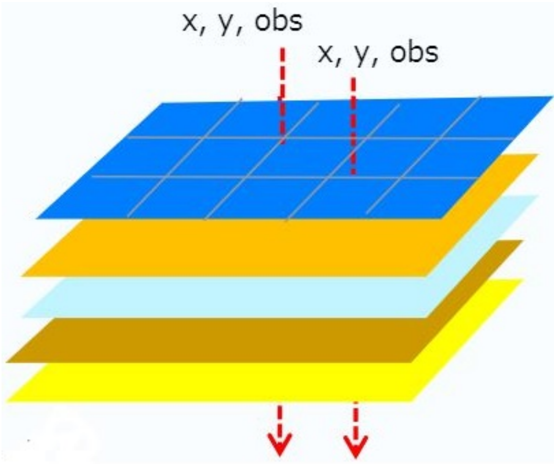


Figure 6-1. DSM models built from the spatial intersection of observations and covariates.

A major benefit of DSM compared to traditional soil mapping is that it is possible to statistically quantify and map the reliability - termed *uncertainty* - associated with the soil attribute prediction at each grid cell. Additionally, DSM also allows mapping approaches to be consistent so that there is no methodological or operator bias, and users of the mapped outputs can be confident that all areas in the output are systematically comparable. Furthermore, this makes updating maps a straightforward process once new soil observations or better covariates become available.

6.2 Soil and Landscape Grid of Australia

The Soil and Landscape Grid of Australia (SLGA) represents the culmination of a national effort to create a set of DSM soil attribute rasters (Grundy et al., 2015; Rossel et al., 2015). For South Australia (SA) and Tasmania, three SLGA soil attribute products are available, the national SLGA, the SA and Tasmanian regional SLGA, and an integrated version at the national scale of the national SLGA and the SA/Tasmanian regional effort which was merged on a pixel-by-pixel basis, where the map with the lowest uncertainty (highest reliability) was used. In the next couple of paragraphs, the national SLGA and SA/Tasmanian regional SLGA mapping approach are briefly explained and illustrated below. These two approaches developed simultaneously, not with the intention to duplicate the effort, but the assumption that certain methods may be more appropriate for specific regions of interest than others (Odgers et al., 2015). Each of the SLGA soil attributes of national and SA and Tasmanian regional products have been created using DSM approaches fine-tuned to reflect the availability of supporting data and the experience of the mapper.

The national SLGA DSM approach relies on environmental correlation (McKenzie and Ryan, 1999). The soil data (site data and spectroscopic estimates of soil properties) used to generate the national SLGA soil attributes have been gleaned from national and State/Territory soil and landscape databases with locations shown in Figure 6.2, and the covariates were collated into a central database specifically for the SLGA. Many of the landscape covariates used in the national SLGA DSM approach were developed through terrain analysis using the national DEM. These and other terrain analysis attributes are available through SLGA (see Section 7 and Table 7-1). Soil-property estimates were based on a Cubist-kriging approach (Viscarra Rossel et al. 2015).

The Tasmanian regional SLGA DSM approach also relies on environmental correlation (McKenzie and Ryan, 1999). Different to the national product, Tasmanian regional soil attribute maps were derived using datasets held by the Tasmanian Department of Primary Industries, Parks, Water and Environment Soils Database, including state-specific derived covariates. Soil attribute maps were generated at 80-m resolution, based on a Cubist regression tree data mining approach (Kidd et al., 2015b). An updated version of this product will soon be available at 30 m resolution (proposed date of availability: June 30th 2018) through the Tasmanian Department of Primary Industries, Water and Environment LIST server (https://maps.thelist.tas.gov.au/listmap/app/list/map); a resolution more appropriate for paddock-scale decision making.

The SA regional SLGA soil attributes have been created using a different DSM approach, namely spatial disaggregation of polygon soil maps. In a first DSM step, legacy polygon soil maps (collected at 1:50,000 and 1:100,000 mapping scale) were spatially disaggregated using the DSMART algorithm (Odgers et al., 2014b), to produce a set of soil-class probability rasters. In a second DSM step, the PROPR algorithm (Odgers et al., 2015) was used to map soil-attributes and their associated uncertainties (90% prediction interval), using reference soil property data and the in the first step produced soil-class probability rasters. Estimates were then calculated as the weighted mean of the reference soil-property values, where the weights resembled the probabilities of the relevant soil classes. SA regional SLGA rasters are available at ~90 m (3-arc second) resolution.

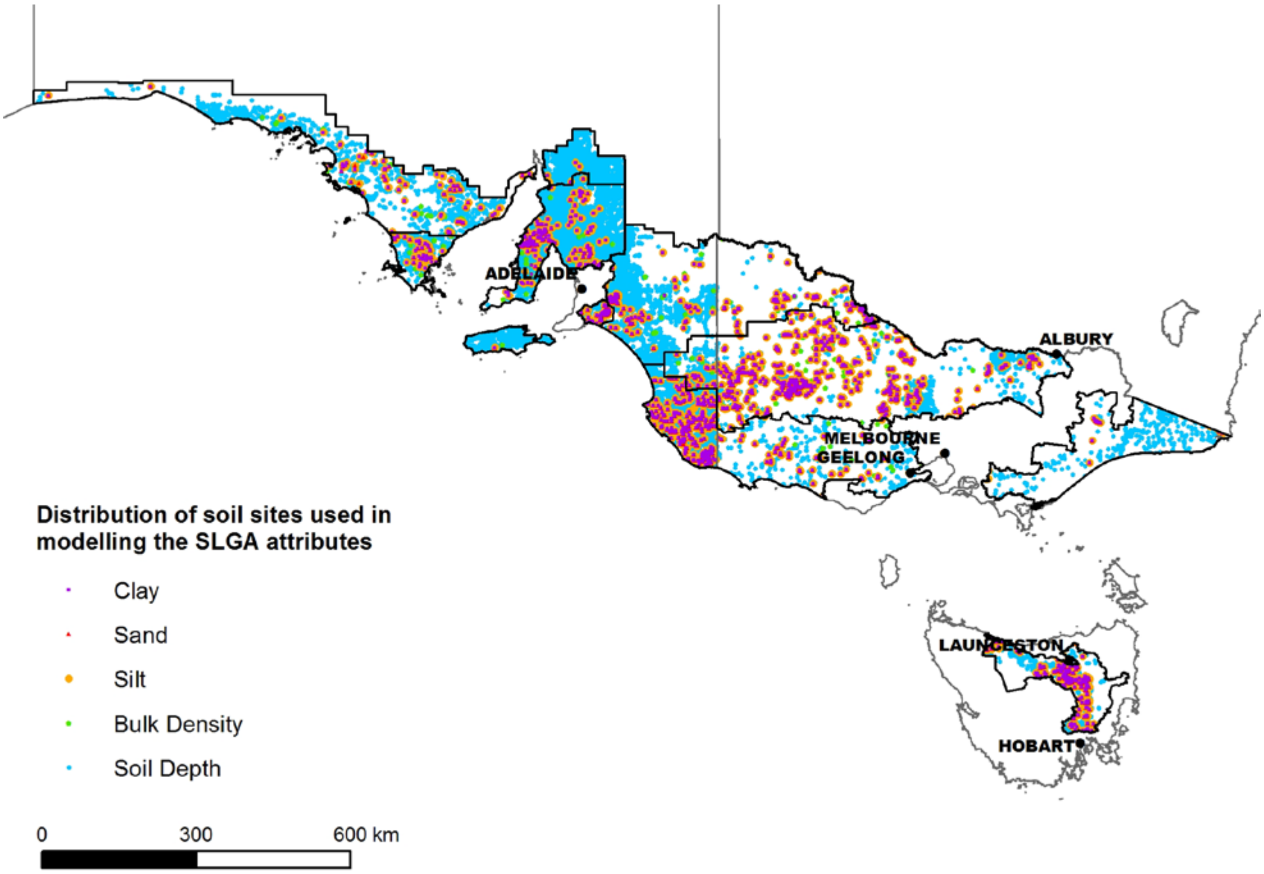


Figure 6-2. Distribution of soil records within the GRDC Southern Region which were used in SLGA attribute mapping. Note that many sites contributed information to the modelling of more than one attribute.

The soil attributes available as national and SA and Tasmanian regional SLGA rasters are listed in Table 6-1. Each attribute has been selected because they are functionally important for agricultural and land assessment needs, and supplied at specific depth increments, namely 0 - 0.05, 0.05 - 0.15, 0.15 - 0.30, 0.30 - 0.60, 0.60 - 1.00 and 1.00 - 2.00 m. As such, the specifications (attributes and formats) of SLGA align closely to that of GlobalSoilMap (GlobalSoilMap Science Committee, 2011; Hartemink et al., 2010).

Figure 6-3 shows various SLGA national sol maps for an area near Jamestown, SA. The figure includes clay (a), sand (b), silt (c), available water capacity (d), and bulk density (e) for the 5-15 cm depth layer. Depth of soil (f) represents the A & B horizons depth. The impact of local relief on soil properties is apparent.

Each SLGA soil attribute file is supplied with companion reliability maps and a set of mapping reliability statistics (e.g. R^2, RMSE). The reliability maps represent the 90% confidence interval of the prediction (difference between 5th and 95th percentiles). Users of these maps can assess which areas in the maps are weaker or stronger than others, and decide the confidence they can put into using the data in certain areas. It is assumed that if available the regional SLGA soil attribute mapping may be more appropriate, when compared to the national SLGA approach. The SA regional equivalent to Figure 6-3 is presented in Figure 6-4, indicating that the two approaches result in mapped outputs that vary to various degrees depending on the theme and location.

Figure 6-5 and Figure 6-6 show the SLGA coverage derived from the national and the regional approaches for clay % (5 - 15 cm) and 90% confidence intervals, respectively. The gap for Victoria in Figure 6-6 reflects that the regional mapping exercise has not been done to date for that state.

SLGA datasets can be drawn from:

http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html.

The SLGA data can also be viewed in Google Earth (download a KML file from the SLGA website: http://www.clw.csiro.au/aclep/soilandlandscapegrid/), or using the Soil and Landscape Grid Viewer tool accessible from the SLGA website (http://www.asris.csiro.au/viewer/TERN/). The Google Earth option only shows the soil and landscape attributes, whereas the viewer also allows the 5th and 95th percentiles to be viewed. All SLGA datasets are also available from the CSIRO Data Access Portal (https://data.csiro.au/dap).

Table 6-1. Soil and Landscape Grid of Australia soil attributes.

NATIONAL SLGA SOIL ATTRIBUTES	
Sand (%)	20-µm – 2-mm mass fraction of the <2-mm soil material determined using the pipette method.
Silt (%)	2 – 20-µm mass fraction of the <2-mm soil material determined using the pipette method.
Clay (%)	<2-µm mass fraction of the <2-mm soil material determined using the pipette method.
Bulk density (g/cm^3)	Bulk density of the whole soil (including coarse fragments) in mass per unit volume by a method equivalent to the core method.
Available Water Capacity (%)	Available water capacity (gravimetric) computed for each of the specified depth increments.
Organic Carbon (%)	Mass fraction of carbon by weight in the <2-mm soil material as determined by dry combustion at 900°C.
pH	pH of 1 : 5 soil/0.01M calcium chloride extract.
Effective Cation Exchange Capacity (mEq/100g)	Cations extracted using BaCl2 plus exchangeable H+ Al.
Total Phosphorus (%)	Mass fraction of total phosphorus in the soil by weight.
Total Nitrogen (%)	Mass fraction of total nitrogen in the soil by weight.
Depth of soil (cm)	Depth of soil profile (A and B horizons).

TASMANIAN REGIONAL SLGA SOIL ATTRIBUTES	
Sand (%)	20-µm – 2-mm mass fraction of the <2-mm soil material determined using the pipette method.
Silt (%)	2 – 20-µm mass fraction of the <2-mm soil material determined using the pipette method.
Clay (%)	<2-µm mass fraction of the <2-mm soil material determined using the pipette method.
Bulk density – whole earth (g/cm^3)	Bulk density of the whole soil (including coarse fragments) in mass per unit volume by a method equivalent to the core method.
Coarse fragments (>2 mm)	>2-mm mass fraction.
Organic carbon (%)	Mass fraction of carbon by weight in the <2-mm soil material as determined by dry combustion at 900°C.

SOUTH AUSTRALIA REGIONAL SLGA SOIL ATTRIBUTES	
Sand (%)	Based on spatially disaggregated soil classes using PROPR.
Slit (%)	Based on spatially disaggregated soil classes using PROPR.
Clay (%)	Based on spatially disaggregated soil classes using PROPR.
Bulk density – whole earth (g/cm^3)	Based on spatially disaggregated soil classes using PROPR.
Coarse fragments	Based on spatially disaggregated soil classes using PROPR.
Available water capacity	Based on spatially disaggregated soil classes using PROPR.
Electrical conductivity	Based on spatially disaggregated soil classes using PROPR.
Cation exchange capacity	Based on spatially disaggregated soil classes using PROPR.
pH ($CaCl_2$)	Based on spatially disaggregated soil classes using PROPR.
Organic carbon (%)	Based on spatially disaggregated soil classes using PROPR.

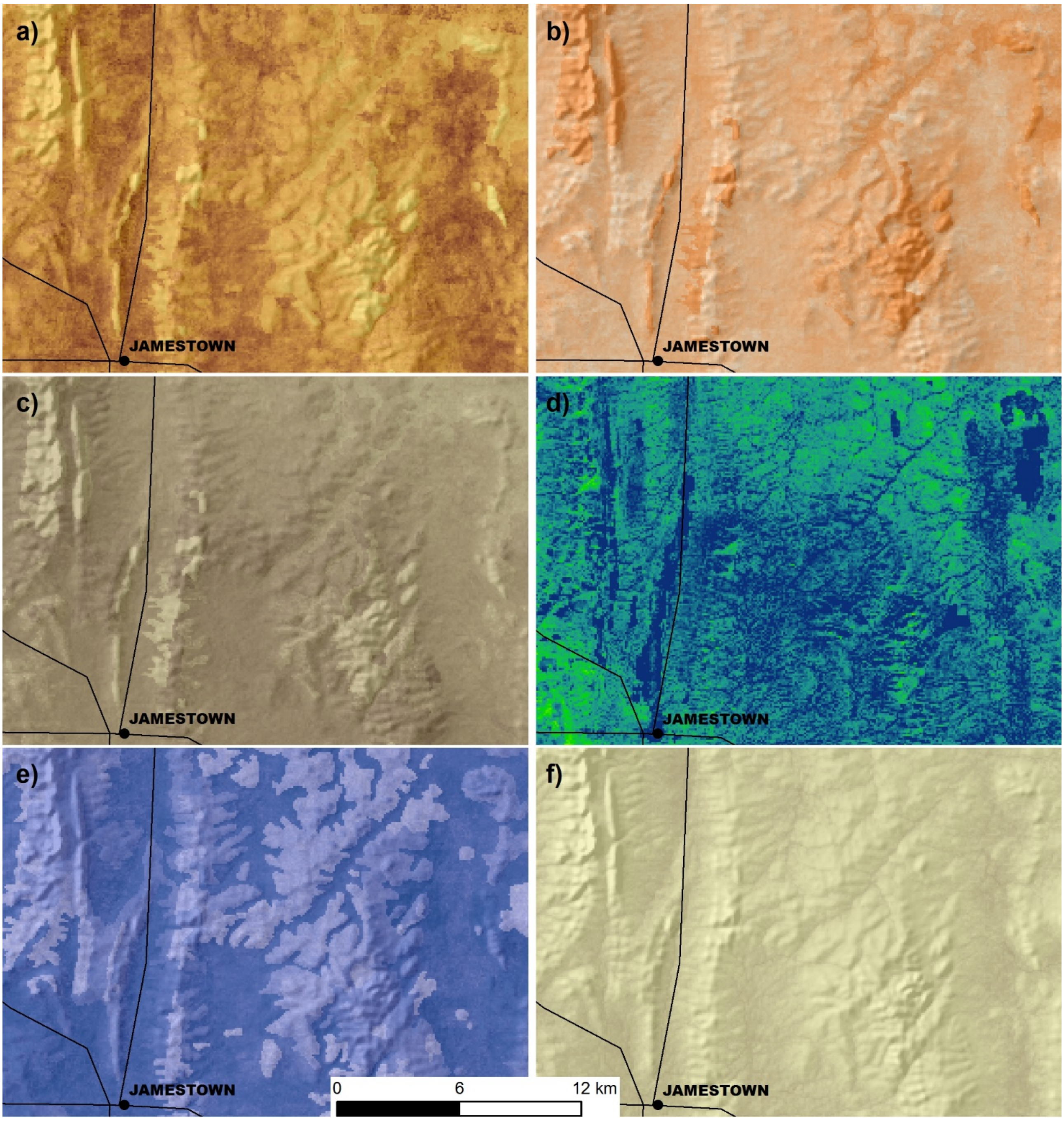


Figure 6-3. Examples of national SLGA soil attributes at 5-15 cm depth near Jamestown, SA. a) Clay % (yellow, max – brown, min), b) Sand % (pale orange, max - dark orange, min), c) Silt % (dark brown, max – pale brown, min), d) Available water capacity % (blue, max - brown, min), e) Bulk density gcm^{-3} (dark blue, max – light blue, min), f) Depth of soil m (dark brown, max – pale brown, min). A semi-transparent hillshade accentuates local relief.

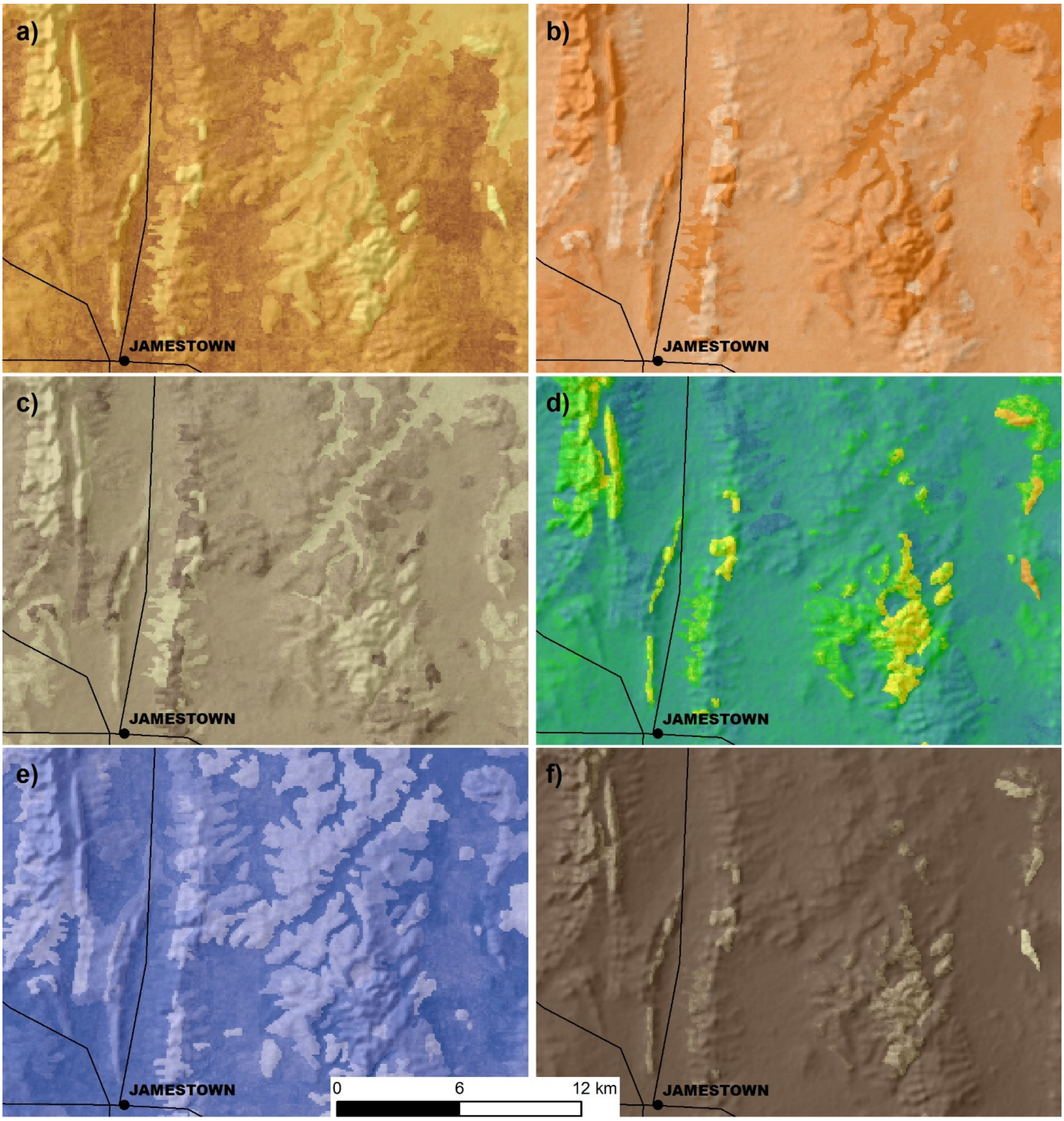


Figure 6-4. Example of the Regional South Australian SLGA soil attributes at 5-15 cm depth near Jamestown, SA. a) Clay % (yellow, max – brown, min), b) Sand % (pale orange, max - dark orange, min), c) Silt % (dark brown, max – pale brown, min), d) Available water capacity % (blue, max - brown, min), e) Bulk density gcm^{-3} (dark blue, max – light blue, min), f) Depth of soil m (dark brown, max – pale brown, min). A semi-transparent hillshade accentuates local relief.

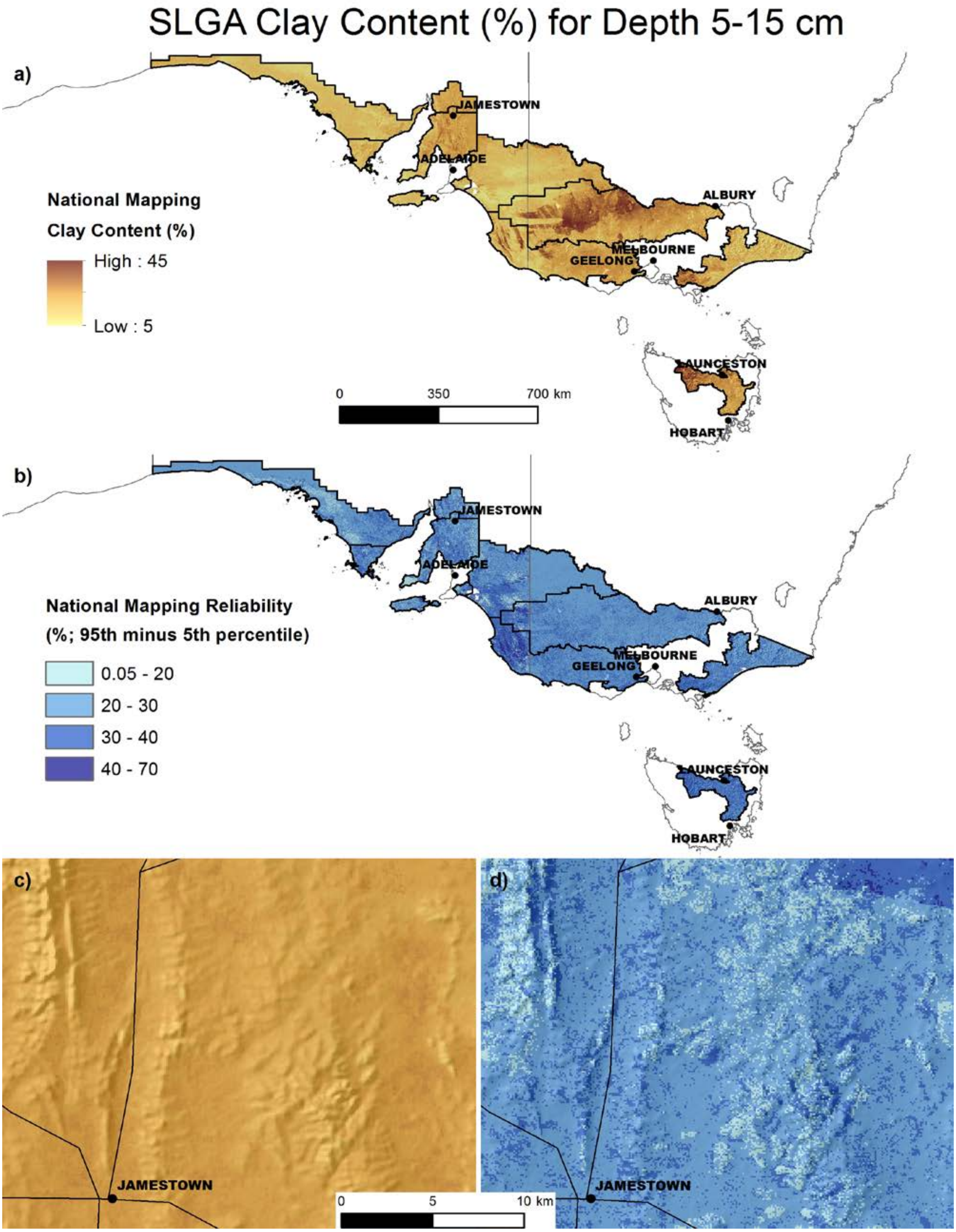


Figure 6-5. Examples of SLGA National mapping for clay % at 5-15 cm depth for a) the whole GRDC Southern Region and c) an area near Jamestown SA, and b), d) the associated 90% reliability range. The soil attributes in a) to d) are semi-transparent to allow the hillshade underneath to show local relief.

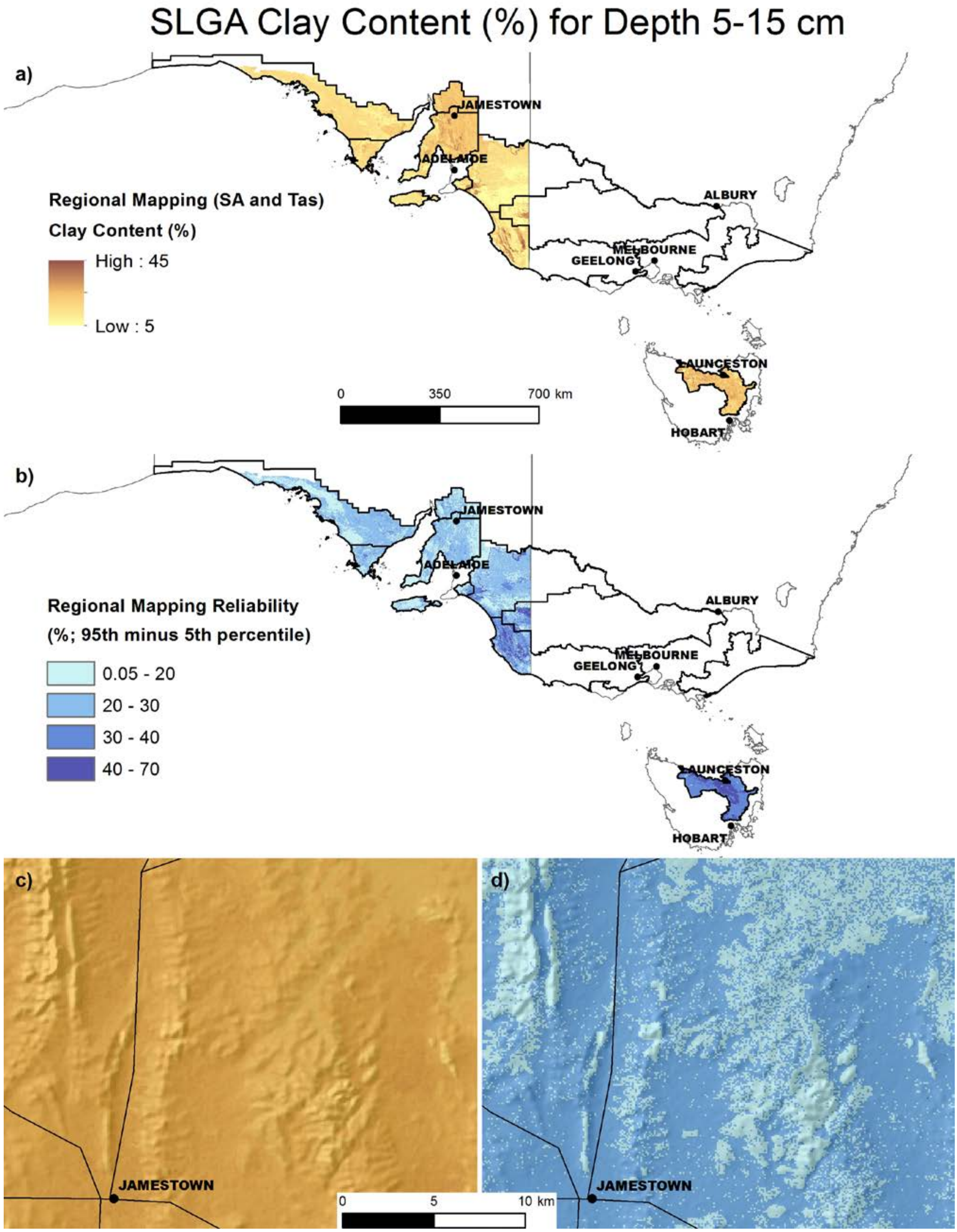


Figure 6-6. Examples of SA Regional SLGA Mapping for clay % at 5-15 cm depth for a) the whole GRDC Southern Region and c) an area near Jamestown SA, and b), d) the associated 90% reliability range. The soil attributes in a) to d) are semi-transparent to allow the hillshade underneath to show local relief.

6.3 Prediction PAWC using SLGA attributes

The soil attributes contained in the SLGA can be used to derive spatial sets of estimated soil physical and chemical properties that can together be used to initialize the APSIM-SoilWat, APSIM-SoilN and APSIM-Plant models. This is still work-in-progress (Moore et al. unpublished), but envisages a web service that allows property prediction for any given location. As the APSIM-SoilWat model uses the crop lower limit (CLL) and drained upper limit (DUL), this means the same prediction can be used to spatially predict PAWC at the same 90 m resolution as the SLGA.

The methodology relies on the use of pedotransfer functions that predict more difficult to measure soil characteristics from basic soil properties. The draft methodology uses a pedotransfer function based on % sand, % silt and % clay from Minasny et al. (1999) for prediction of CLL. The prediction of DUL uses the predicted CLL and the AWC (the water held in the soil between its field capacity and '15 bar' permanent wilting point) attribute. The existing SLGA AWC soil attribute product could be used here, but would require further evaluation given that the units (gravimetric or volumetric) vary between the different SLGA datasets (Grundy et al. 2015) and that the analysis by Viscarra Rossel et al. (2015) suggested that it explained only around 30% of the total variation.

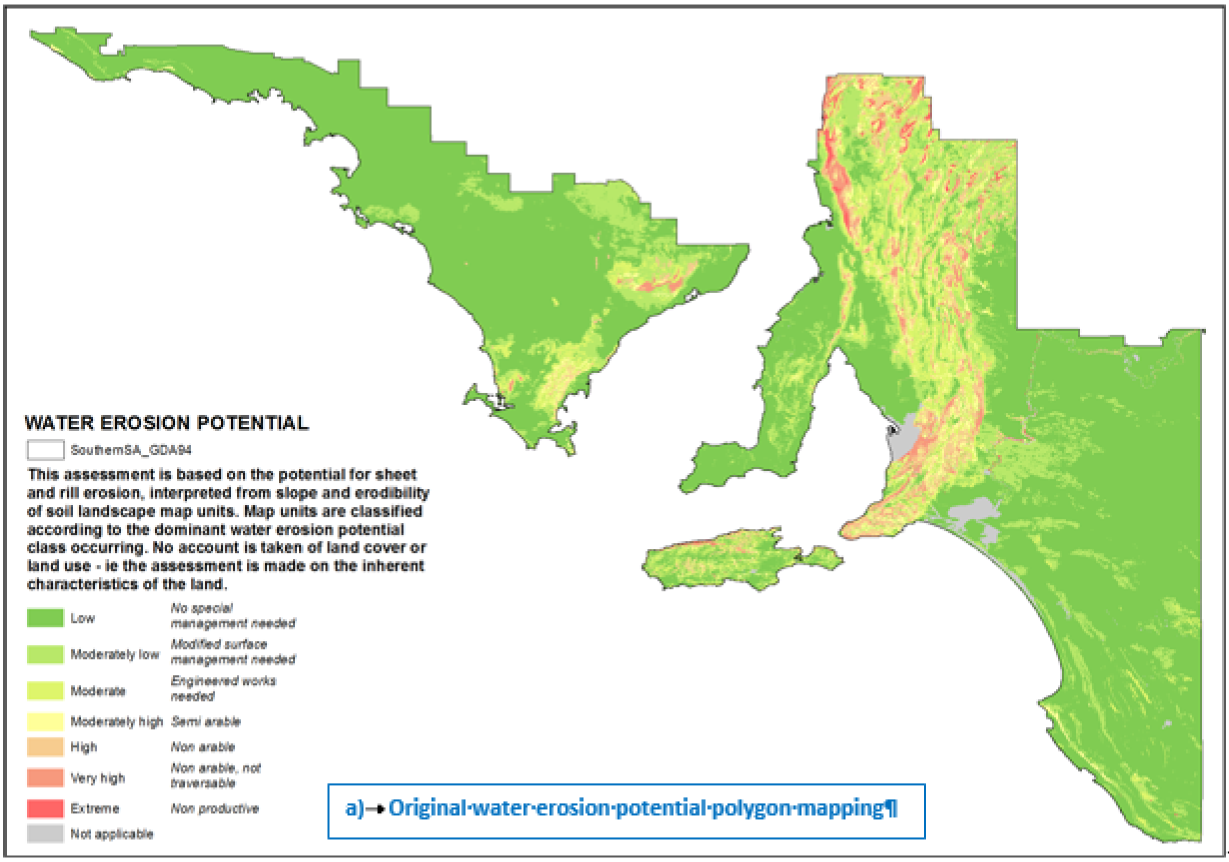
Other pedotransfer functions could be explored. While attractive because it allows mapping of predicted PAWC, the methods require testing at the paddock scale to evaluate the impacts of uncertainty in the predicted SLGA attributes that are used in the pedotransfer functions.

6.4 Other local digital soil mapping

The following sections describe local (i.e. other than national) DSM projects. The ones highlighted are selected because data is in the local domain (i.e. created by state agencies) and have large and consistent enough coverage to be relevant to PAWC projects covering a large enough spread of each state's dryland cropping area.

6.4.1 South Australia

As briefly mentioned in Section 4.1.1, the extent, consistency and quality of underpinning data of SLU polygon mapping enables a baseline (primary) dataset to apply DSM approaches to create secondary soil attribute mapping. For example, DSM methods allow the creation of spatially explicit (rasterized) information/data products that polygonal data cannot provide; as discussed elsewhere, many soil attributes reported in state polygonal data are given on only a dominance or ranking basis. That is to say, in the absence of soil reports, soil unit polygons in themselves lack any capacity to show *where exactly* any soil attribute, e.g. pH is high or low in the area covered by map unit. One DSM example for SA involves the spatial disaggregation ('DSMART' algorithm, Odgers et al., 2014a) of SLU polygons to estimate within-polygon distributions of water erosion potential across the agricultural areas of SA (C. Liddicoat, *pers. com.*, Liddicoat 12.03.18), as shown in Figure 6-7 that compares the spatial outputs of water erosion risk as presented through SLU polygons (categorical) compared with that as spatially explicit raster data (numeric) estimated using DSMART.



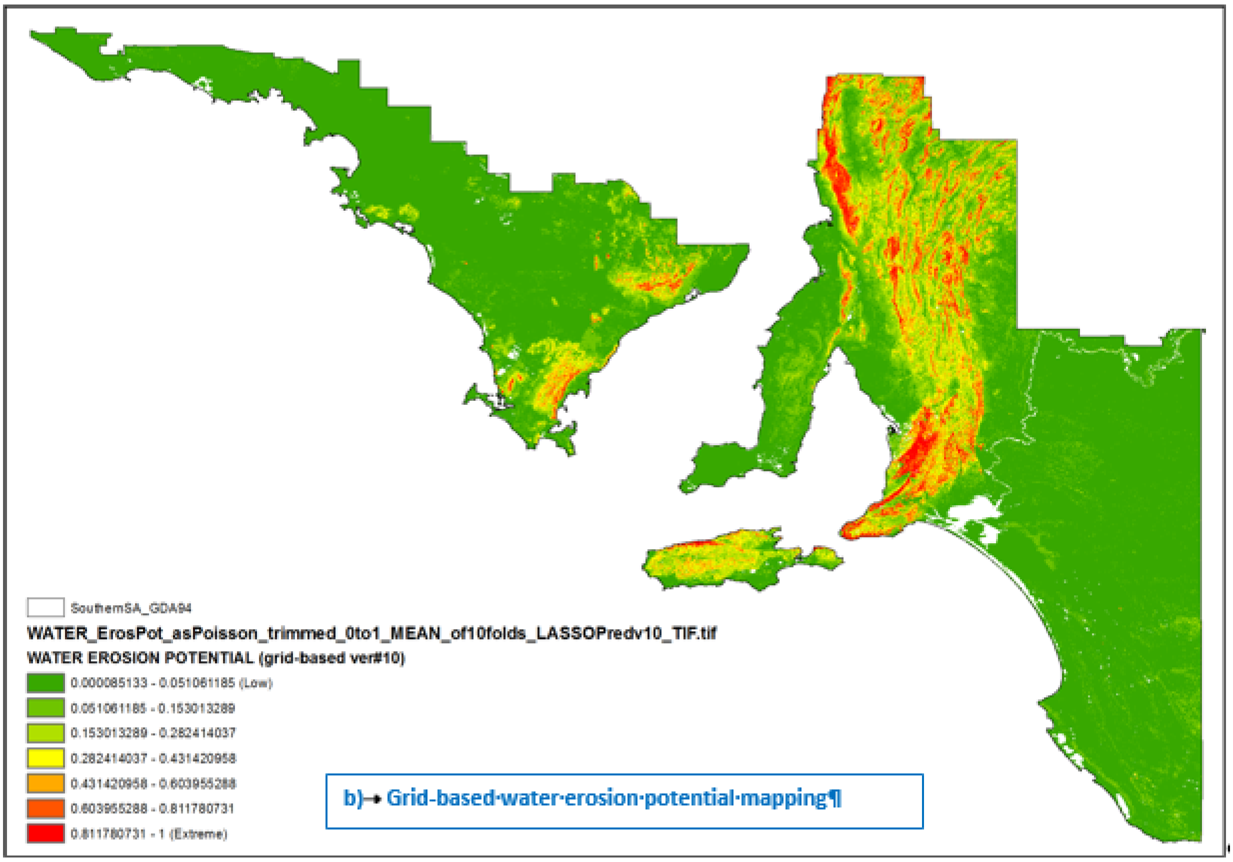


Figure 6-7. Map presentation of water erosion potential for SA agricultural areas as derived by SLU polygonal data (plate a)) and raster derived by spatial disaggregation using the DSMART algorithm (plate b)). Source: C. Liddicoat, pers. com., 19.03.18.

SA's contribution to the SLGA soil attributes are presented in Liddicoat et al. (2015) using DSMART; the paper shows an example of the work done in SA through describing the DSMART method to achieve the mapped estimation of carbon stock distribution at 90 m using SLGA products as covariates.

These examples illustrate the opportunities to use DSM to estimate numerous secondary attribute maps using underpinning SLU data.

6.4.2 Victoria

The Victorian Government has undertaken a DSM project to predict soil property attributes for the state through estimation by a conditional piecewise linear regression approach implemented in the Cubist algorithm (www.rulequest.com). The methodology uses available soil attribute data to 'train' the algorithm to predict soil properties elsewhere through the use of covariates (see Section 6.1 above). Predictions of various soil properties have been generated for various standard depths (0-5, 5-15, 13-30, 30-60, 60-100 and 100-200 cm) using a spline function (Bishop et al., 1999). The depths align with SLGA and GlobalSoilMap standard depths. The mapped data [(Version 1.0 of the Victorian Digital Soil Map (VicDSMv1)] is available via the data.vic portal here https://www.data.vic.gov.au/data/dataset/victorian-soil-ph-mapping-vicdsmv1. The full suite of data maps generated includes:

- pH (water and CaCl)
- Clay %
- Silt %
- Fine and coarse sand %
- Field capacity % (proxy for DUL)
- Wilting point % (proxy of CLL)
- AWHC %
- Bulk density
- Total organic carbon %

All maps are supplied as a raster file at a ground resolution of ~100 m. In addition, all maps are accompanied by reliability maps (90% confidence intervals) and summary statistics for each estimated attribute. A full report of the methods used in the project remains unpublished for now.

6.4.3 Tasmania

Tasmanian soil drainage assessment

Digital soil mapping was used to produce a soil drainage index to inform land suitability modelling in Tasmania (refer to the Tasmanian Enterprise Suitability Toolkit). A continuous soil drainage index was predicted spatially using expert field drainage estimates at ~930 sites in conjunction with various terrain-based and remotely sensed covariates, based on a regression-tree spatial modelling approach (Kidd et al., 2014). Prediction uncertainty was assessed using a K-fold cross validation technique. Diagnostics indicated that the root mean square error was consistently within 1 drainage unit, which provides reasonable spatial prediction accuracy (source:

https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?detailRecordUID=da5735ae-e560-405b-b470-af0d7a0158db).

The grid surface delineating soil drainage classes (very poor, poor, imperfect, moderately well, well, rapid) at a spatial resolution of 80 m (Figure 6-8), is available in Tasmania's online GIS-based mapping tool ListMap under the Farming layers (https://maps.thelist.tas.gov.au/listmap/app/list/map).

The soil drainage assessment is a valuable DSM effort that can be used to inform on PAWC, as it summarises likely soil and site drainage occurring across the landscape.

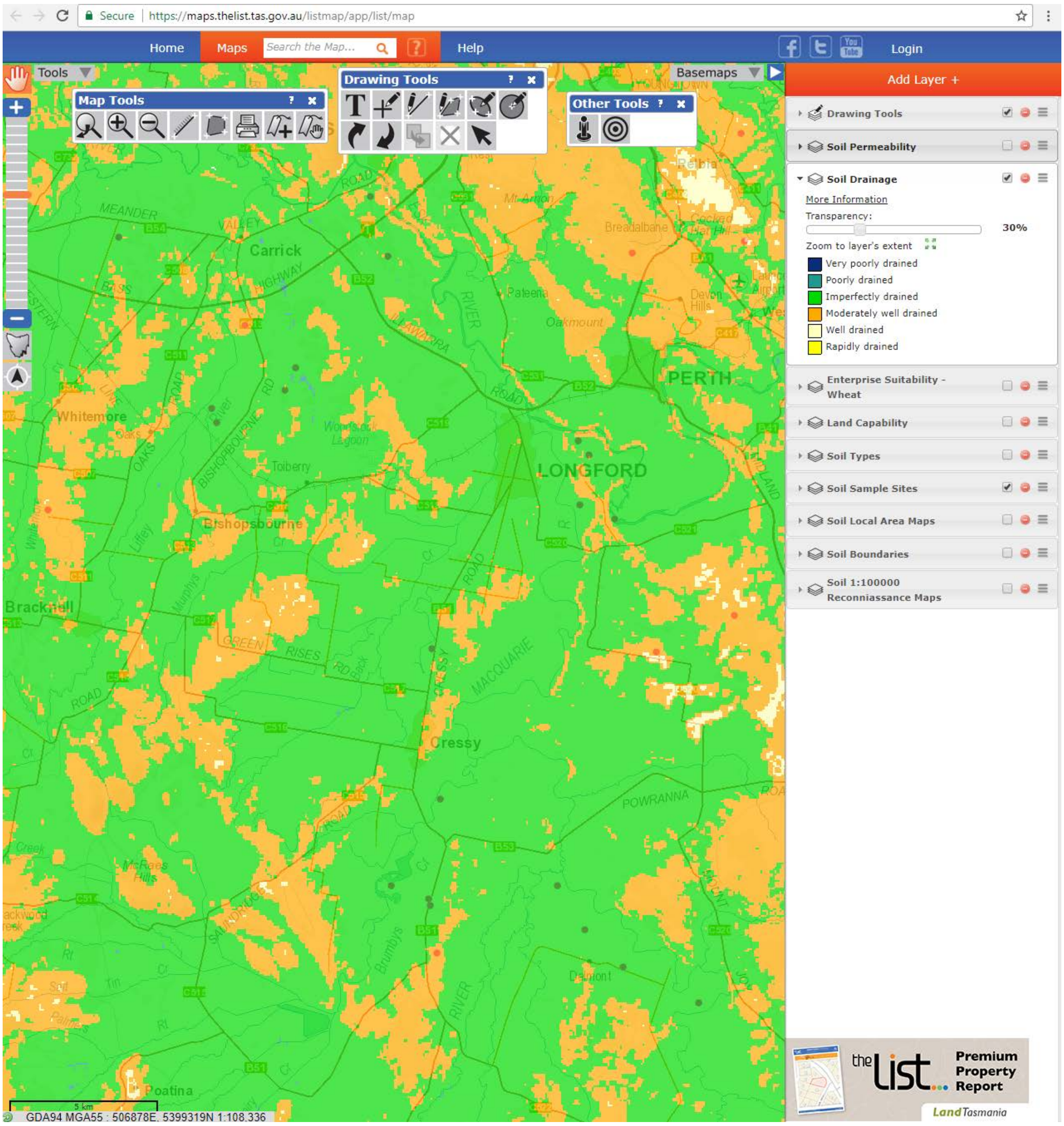


Figure 6-8. Framegrab of the LISTmap online mapping tool, showing soil drainage assessment close to the locality of Longford.

Tasmanian soil permeability

The Tasmanian soil permeability assessment was derived as part of the digital soil maps described in Kidd et al. (2015b), using regression tree interpolation. Soil permeability is controlled by the ability of a soil to transmit water through the least permeable layer in the soil, and can be inferred from soil attributes such as texture and porosity. Prediction uncertainty was assessed using a K-fold cross validation technique. Diagnostics indicated that the root mean square error was consistently within 1 permeability unit, which provides reasonable spatial prediction accuracy (source: https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?detailRecordUID=0766dcff-c489-4c4d-949e-2e1c609054b5).

The grid surface delineating soil permeability classes (very slow, slow, moderate, high) at a spatial resolution of 80 m (Figure 6-9), is available in Tasmania's online GIS-based mapping tool ListMap under the Farming layers (https://maps.thelist.tas.gov.au/listmap/app/list/map).

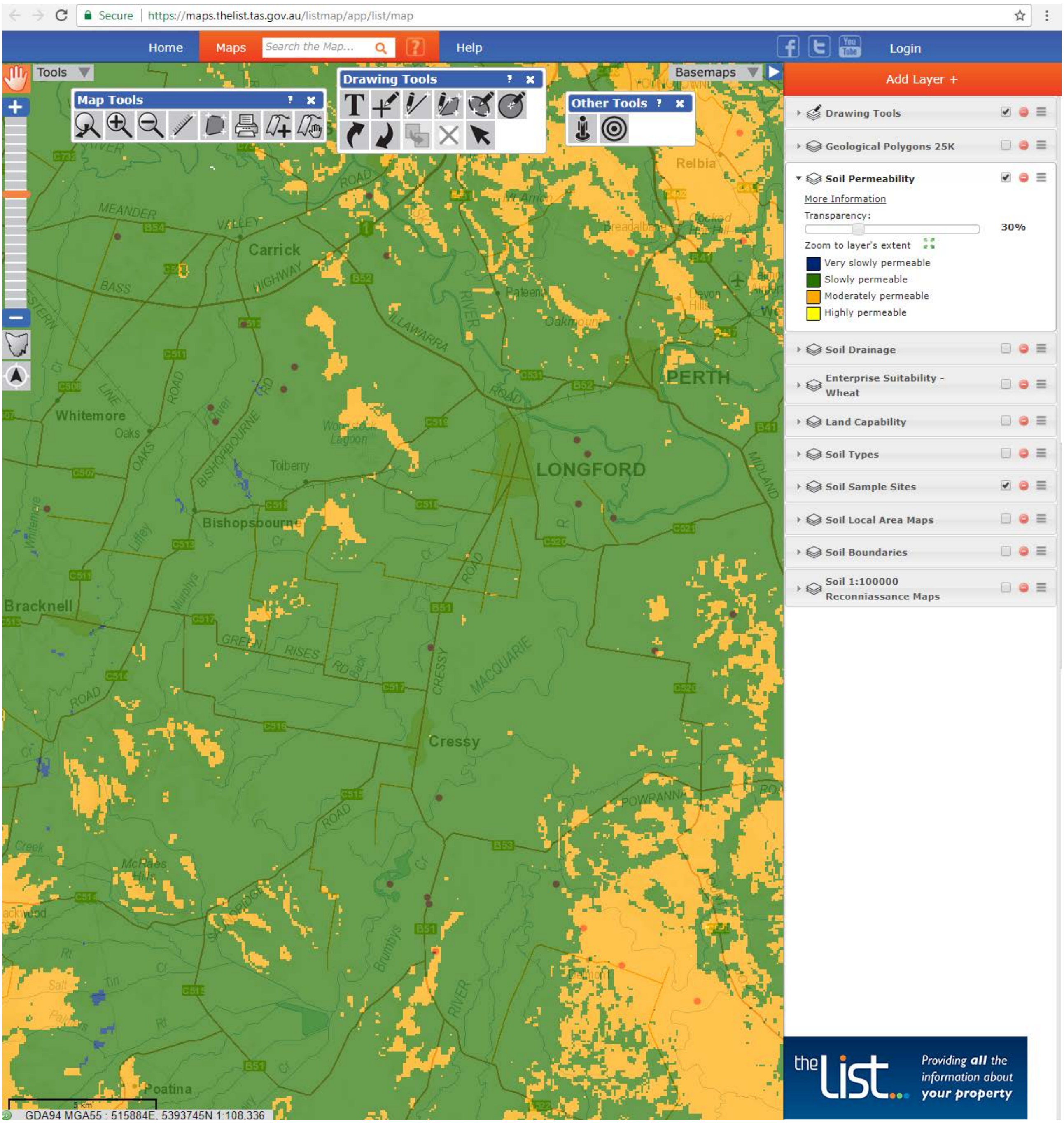


Figure 6-9. Framegrab of the LISTmap online mapping tool, showing soil permeability classes close to the locality of Longford.

Tasmanian Enterprise Suitability Toolkit

The Tasmanian Enterprise Suitability Assessment was driven by newly commissioned irrigation schemes, in support of government agricultural expansion policy. Digital soil mapping products were used to assess the agricultural land suitability for a total of 20 different crops (Kidd et al., 2015a). The model included comprehensive soil, climate and terrain parameters to rate the suitability of the land, based on a set of rules available through: http://dpipwe.tas.gov.au/agriculture/investing-in-irrigation/enterprise-suitability-toolkit/enterprise-suitability-maps. This effort was piloted in the 20,000 ha irrigation district in the Meander Valley Region, and subsequently tested further at 30 m mapping resolution. The Tasmanian Government extended this Enterprise Suitability Assessment state-wide as part of the 'Water for Profit' program, with areas outside the original pilot program, mapped at 80 m resolution. More information is available through: http://dpipwe.tas.gov.au/agriculture/investing-in-irrigation/enterprise-suitability-toolkit.

The Enterprise Suitability Assessment (classes: well suited, unsuitable, suitable, marginally suitable) is available in Tasmania's online GIS-based mapping tool ListMap under the Farming layers (https://maps.thelist.tas.gov.au/listmap/app/list/map). Figure 6-10 shows an example of the Enterprise Suitability Assessment for wheat.

The suitability assessment informs whether climatic and land characteristics are favourable to yield crops at their 'best performance'. The rule set underlying the suitability assessment can also be used to identify possible constraints, which then in turn helps with PAWC assessments. In this regard, the Enterprise Suitability Toolkit is currently undergoing updates to include enterprise suitability mapping with available soil constraints, including recommendations for managing those. In addition, this assessment will soon be available at 30 m resolution (proposed date of availability: June 30th 2018); a resolution more appropriate for paddock-scale decision making.

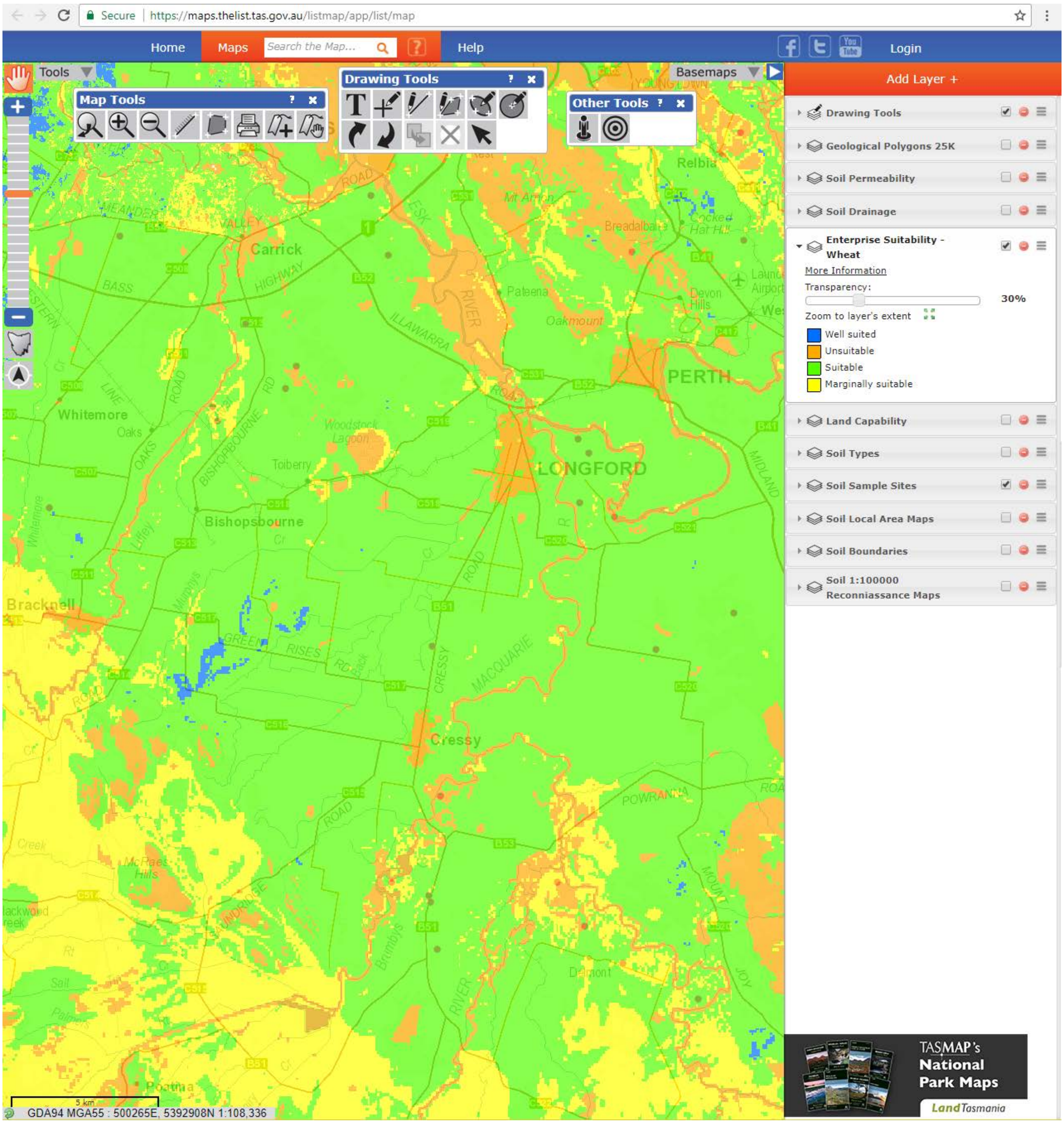


Figure 6-10. Framegrab of the LISTmap online mapping tool, showing enterprise suitability classes for wheat close to the locality of Longford.

7 Terrain information

Traditionally knowledge of terrain information has always been important in mapping soils and their properties (Grunwald, 2006; Hudson, 1992; McKenzie et al., 2008). The value of terrain is highlighted in Jenny's (1941) factors of soil formation, which recognises that the following factors act and interact to explain how the soil has been formed, and the reasons for the properties that the soil shows:

- parent material/geology
- relief (terrain)
- biological processes
- climate
- time

Depending on the size of area of interest, each can dominate over other factors to explain properties. For example, climate is more meaningful at the continental/sub-continental scale, whereas geology and relief is probably more meaningful at finer, sub-regional scale that users will use for local or farm planning.

The following sections discuss the role of terrain, and more particularly quantitative digital approaches of investigation - terrain analysis - commonly used in contemporary land and soil resource assessment. Special emphasis is given to how these may contribute to new knowledge or data relating to PAWC.

7.1 Terrain analysis

Terrain analysis uses computer-based algorithms to analyse digital elevation models (DEMs) to derive terrain shape and landform over the area of interest and has an established track record in quantitative land and soil assessments. DEMs are geographic information system (GIS)-compatible files in a variety of formats, including vectors (i.e. contour lines) and raster grids. The remaining discussion centres on raster gridded DEMs. DEMs display the continuous variation in elevation across the ground footprint of the file. The spatial dimension (resolution) of grid cells equates to physical dimensions on the ground (e.g. 10 x 10 m; 10 m^2) and the grid cell value represents the average elevation of the grid cell's footprint.

Compared to coarser resolution DEMs (e.g. 100 x 100 m), finer resolution ones (10 x 10 m) are capable of representing smaller and finer ground features that would otherwise be 'hidden' in the 100 x 100 m example. DEM grid cells also have a vertical 'resolution', so if fine (e.g. sub-metre) they are also capable of showing finer ground feature details. Terrain analysis on coarser resolution DEMs require less computational power so there is sometimes an operational trade-off between detail of analysis and computational requirements. Australia has in the public domain national DEM datasets at 1 arc second (~30 m) and 3 arc second (~90 m) resolutions (Figure 7.1). These are accessible from Geoscience Australia (http://www.ga.gov.au/data-pubs).

The following section provides a brief discussion on the influence of terrain on soil properties and describes important digital terrain attributes from terrain analysis that are useful in inferring or predicting soil properties.

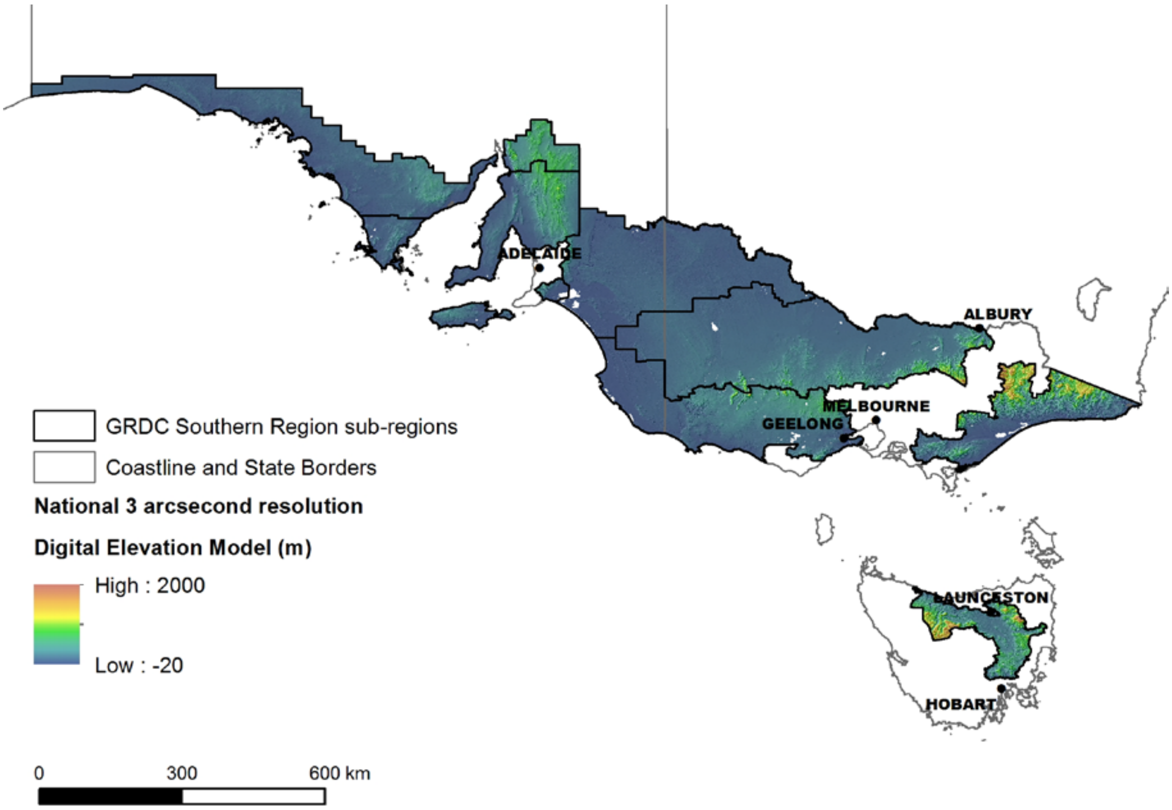


Figure 7-1. National 3 arc second resolution DEM within the GRDC Southern Region, with 3 arc second resolution hillshade underneath.

7.2 Landforms and soil properties

Landforms, which are characterised by patterns of relief, often exist in a series of nested or hierarchical scales. For example, coarse scale patterns (e.g. ridges and valleys, ~>100 m horizontal dimension) contain medium scale patterns (e.g. depressions and hillocks, ~100 to 10 m), and within these, finer still, microrelief patterns (e.g. furrows, hollows and mounds, ~<10 m). The patterns are governed by an interplay of multiple factors operating over all these scales. Amongst the most important, the players include:

- parent material; governing the strength or rock and rates of weathering
- gravity (a function of slope); potential energy to move soil material, water and solutes down hill
- rainfall intensity/plant soil protection; rates of soil erosion.

The relief patterns expressed at any one point in a landscape represent the culmination of process that have gone before, particularly related to climatic and tectonic shifts. Relief patterns influence soil properties according to how soil matter, water and solute flows are channelled, dissipated or restricted. Relationships between relief patterns and soil properties are typically tight and result in ordered, sequential and predictable soil patterns, i.e. toposequences. A toposequence can be exemplified by a conceptual erosional/depositional hillslope (i.e. ridge to valley bottom, ~1,500 m) situated on metasediments.

The conceptual example provided in the discussion below draws from observation from a South Australian upland hillslope (Thomas et al., 2009a; Thomas et al., 2009b). This hillslope has shallow soil on the steep ridge/upper slope because the rate of soil removal through erosion and dissolution exceeds the rate of addition through *in situ* bedrock weathering. The soil has regular bedrock outcropping and is stony, which combined with the shallow profile leads to a very restricted capacity to store water. High rates of water throughflows in the shoulder slope helps dissolves clay minerals and leachate/nutrients are moved downslope. These upper-most soils are not suitable for dryland cropping.

In the mid slopes the soil is deeper, as rates of soil addition (*in situ* weathering, and material received from upslope) and loss (erosion, leaching) are quite well balanced. The soil may be somewhat leached because of moderate rates of water throughflows in downhill open depressions, although salts may have accumulated in soils located in slightly elevated (perched) positions because of flanking throughflow patterns. The soils are generally favourable for dryland cropping, although erosion needs to be managed.

On the lower slopes where gradient is low to flat, soils are deep to very deep because upslope and *in situ* weathering additions exceed soil losses. This means that water storage capacity is large in these soils and nutrient status is good. These soils may even undergo *in situ* changes in clay mineralogy or form new clay particles due to favourable conditions, including moisture persistence coupled with leachate/salts received from upslope. However, the apparently favourable growing conditions are off-set by salts causing salinity and/or sodicity resulting in poor soil structure, waterlogging and salt toxicity in places, which reduces the plant available water capacity by restricting root growth. The structural problems caused by sodicity means that salts persist. Waterlogging is likely to be a significant problem in these soils in wet years as salinity is in dry years, so the soils need to be carefully managed at all times. Upstream alluvial deposits from periodic flooding may have a rejuvenating effect on these soils, especially with addition of nutrient rich sediments.

7.3 Terrain attributes

While there are numerous ways in which terrain analysis can provide landscape or terrain attributes to support digital soil mapping (see Grunwald, 2006; Hengl and MacMillan, 2009; Wilson and Gallant, 2000), a few of them have proven consistently useful in many Australian land and soil evaluations:

- Topographic Wetness Index (TWI, Beven and Kirkby, 1979)
- Multi-resolution Valley Bottom Index (MrVBF, Gallant and Dowling, 2003)
- Slope
- Curvature (plan and profile)
- Prescott Index (PI)
- Topographic Position Index (TPI)
- Hillshade

These terrain attributes are either widely accessible from public databases (e.g. Table 7-1 showing the suite of attributes available nationally associated with the SLGA) or are readily computed through various terrain analysis options, including the R statistical platform (R Core Team, 2014) and GIS (e.g. ESRI or QGIS). Below we discuss these attributes in more detail, along with an illustration of each of them in an area near Jamestown SA in Figure 7-2.

Table 7-1. Soil and Landscape Grid of Australia landscape attributes.

Slope (%)	Slope measures the inclination of the land surface from the horizontal.
Slope (%) Median 300m Radius	The median slope within a 300 m radius representing the typical slope in the local landscape.
Slope Relief Classification	Slope relief landform pattern classification based on Speight (2009).
Aspect	Aspect measures the direction in which a land surface slope faces. The direction is expressed in degrees from north.
Relief 1000m Radius	The elevation range measures the full range of elevations within a 1000m circular radius and can be used as a representation of local relief.
Relief 300m Radius	The elevation range measures the full range of elevations within a 300m circular radius and can be used as a representation of local relief.
Topographic Wetness Index	TWI estimates the relative wetness within moist catchments, but is more commonly used as a measure of position on the slope with larger values indicating a lower slope position.
Topographic Position Index	Topographic Position Index (TPI) is a topographic position classification identifying upper, middle and lower parts of the landscape.
Partial Contributing Area	Contributing area in m^2 computed using multiple flow directions on hillslopes and ANUDEM-derived flow directions in channels.
MrVBF	MrVBF is a topographic index designed to identify areas of deposited material at a range of scales based on the observations that valley bottoms are low and flat relative to their surroundings and that large valley bottoms are flatter than smaller ones.
Plan Curvature	Plan (or contour) curvature is the rate of change of aspect (across the slope) and represents topographic convergence or divergence.
Profile Curvature	Profile curvature is the rate of change of potential gradient down a flow line and represents the changes in flow velocity down a slope.
Prescott Index	The Prescott Index is a measure of water balance that is sensitive to regional climate and local topography and has proven to be a useful in soil mapping both to stratify study areas for sampling and as a quantitative predictor of soil properties.
SRAD Net Radiation January	Mean monthly solar radiation was modelled across Australia using topography from the 1 second resolution SRTM-derived DEM-S and climatic and land surface data.
SRAD Net Radiation July	Mean monthly solar radiation was modelled across Australia using topography from the 1 second resolution SRTM-derived DEM-S and climatic and land surface data.
SRAD Total Shortwave Sloping Surface January	Mean monthly solar radiation was modelled across Australia using topography from the 1 second resolution SRTM-derived DEM-S and climatic and land surface data.
SRAD Total Shortwave Sloping Surf July	Mean monthly solar radiation was modelled across Australia using topography from the 1 second resolution SRTM-derived DEM-S and climatic and land surface data.

7.3.1 TWI

This is an index that describes the tendency for cells to accumulate water. The inputs include the specific catchment area and the local slope angle. Water transmissivity and infiltration are considered to be constant in the analysis. TWI differentiates patterns and intensity of water accumulation from non-water accumulation areas in the landscape. As such, ridges and summits that are divergent landforms that shed water (are drier), while downslope open depressions (convergent) and valley bottoms accumulate water (wetter areas, surface and throughflows). TWI is not effective in extensive flat landscapes. Figure 7-2a shows an example of TWI at 3 arc second resolution for an area near Jamestown, SA.

7.3.2 MrVBF

This is an index that partitions landscapes into the erosional and depositional areas. It operates at a range of scales and on the premise that valley bottoms (depositional) are flat and low relative to the surrounding areas, and that the lowest, flatter areas are the largest valley systems in the area of investigation with values approaching 1. These areas are likely to have deep soils so with a greater capacity to store water. Conversely, elevated, rounded features in the area of investigation correspond to summits and ridges. Index values for these relief types approach zero, and as they are likely to be shallower, have a lower capacity to store water. Figure 7-2b shows an example of MrVBF at 3 arc second resolution for an area near Jamestown, SA.

7.3.3 Slope

Slope is the measure of inclination of the ground surface, and so is relatable to the gravitational potential. It helps to infer the intensity of downslope movement of solid matter and water and solute throughflow. Gravitational intensity is greatest where slope is steepest, so steep areas in the landscape can generally be expected to coincide with erosional areas, whereas flat or low gradient areas are depositional. Figure 7-2c shows an example of Percent Slope at 3 arc second resolution for an area near Jamestown, SA.

7.3.4 Curvature

This relates to the convexity or concavity of the land surface. Convex areas represent divergent, shedding zones, hence are likely to be erosional (drier, shallower soils), whereas concave areas are convergent, hence likely to accumulate soil and water, and so likely to be depositional zones. Plan curvature is the curvature in a horizontal plane (i.e. looking down vertically from above) where concavity denotes open depressions or lines of drainage going down the slope, hence are typically wetter, accumulating zones, whereas convex landforms are divergent and water- and material-shedding (e.g. ridges and summits). Profile curvature addresses the cross-sectional curvature of the hillslope, hence the gradient down a flow line. Profile convexity indicates parts of hillslopes where flows accelerate, so are likely to be erosional and water shedding due to high gravity potential, whereas profile concavity highlights the areas were flows decelerate, hence are accumulating zones. Figure 7-2d and Figure 7-2e respectively show examples of plan and profile curvature at 3 arc second resolution for an area near Jamestown, SA.

7.3.5 Prescott Index

The Prescott Index is functionally an index of soil leaching (Prescott, 1950). This takes into account long-term annual rainfall and annual evaporation rates from national climatic data. Leaching soils are associated with places where rainfall exceeds evaporation, so these soils may have lower nutrient status and be acidic. Conversely, where evaporation exceeds rainfall, soils tend not to be leached and so are likely to retain salts in the profile, are possibly alkaline, and commonly rich in carbonates and gypsum. In calcareous soils the effective soil depth and water storage capacity may be hampered if the calcrete is abundant, e.g. rocky or as a near surface continuous hardpan. If the index is used in the form originally proposed by Prescott (1950) it is most suited for use on a continental or sub-continental scale because climate is the key driver. However a recent adaptation presented in Gallant and Austin (2015) incorporates a topographic aspect modifier to assimilate the effects of incident solar radiation. This emulates the effect of differential heating/drying on north and south-facing slopes over daily and annual cycles, and the cumulative effect that these differences impose on soil development even within small areas. Figure 7-2f shows an example of Prescott Index at 3 arc second resolution for an area near Jamestown, SA.

7.3.6 Topographic position index

TPI is used to indicate position in the landscape, e.g. ridge, slope, plain and valley bottoms (Weiss, 2017). The algorithm operates by analysing the elevation of each and every pixel relative to all others in a predetermined radius, hence a short radius shows relative position over a short range in the landscape to highlight fine scale landscape features, e.g. open depressions and rises. Conversely a longer range radius highlights coarser landscape features like hills, mountains and valley bottoms. As such TPI is most effective when using a radius that highlights landscape features fitting the objectives of the work, and finding this radius is typically an iterative undertaking. Figure 7-2g shows an example of TPI at 3 arc second resolution for an area near Jamestown, SA.

7.3.7 Hillshade

Hillshade is a DEM-derived grey scale simulation of sun shadows to show relief patterns across landscapes. In itself hillshade has no soil-predictive power, but when arranged with terrain analysis it combines powerfully to give experts a synoptic view of the landscape. Arrangement of files is done in GIS by overlaying a semi-transparent terrain analysis data layer over the hillshade. The shading accentuates local relief in a synoptic view of the landscape to explain patterns in the underlying terrain analysis. For example, if overlaid on TWI, hillshade relief shadows help to explain water flows and accumulation in the landscape. Figure 7-2h shows an example of a hillshade at 3 arc second resolution for an area near Jamestown, SA.

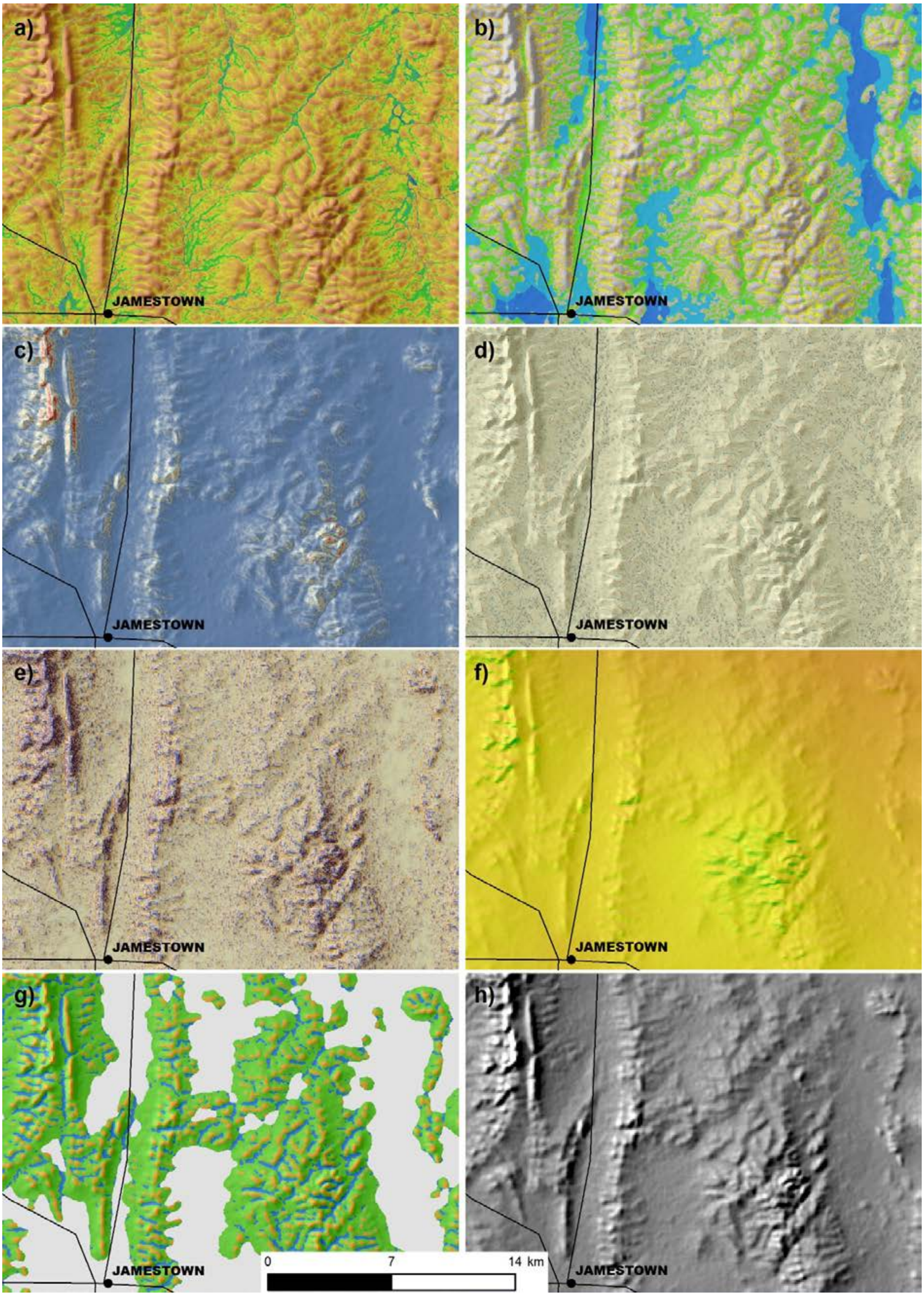


Figure 7-2. Examples of terrain attributes at 1 arc second resolution near Jamestown SA. a) Topographic Wetness Index (min 5 – orange, max 19 – blue), b) MrVBF (min 1 – orange, max 5 – dark blue, 0 – grey), c) Percent slope (min 1 – blue, max 48 – red), d) Plan curvature (min -2 – blue, max 5 – brown), e) Profile curvature (min -0.008 –orange, max 0.01 – purple), f) Prescott Index (min 0.3 – orange, max 0.8 – blue), g) Topographic Position Index (lower slope – blue, mid-slope – green, upper slope – orange), h) Hillshade. 1:5 M scale roads (black lines) provide context. The terrain attributes in a) to g) are semi-transparent to allow the hillshade underneath to show local relief.

7.4 Disaggregating land systems using terrain analysis

Recognising that the land system mapping at 1:250,000 can only provide broad-scale information about landform components and not spatially identify individual landforms in the landscape, Hopley and Robinson (2009) undertook a study to apply terrain analysis using a 10 m DEM to disaggregate the Central Mallee and Hopetoun Land Systems. Using a combination of DEM applied rules, including the MrVBF index (e.g. Figure 7-2b), they delineated the landform components. As factors that affect PAWC, like clay% and subsoil constraints, are often linked with landscape position, this type of terrain analysis may have potential to contribute to interpretation or prediction of PAWC.

7.5 Dryland farming landscapes and scale of investigation

Basing dryland agricultural land resource investigations on hillslopes is a common strategy (McKenzie et al., 2008). It allows soil investigations to be bedded around toposequences and the convenience of well-established soil forming links in relief to soil properties (Hudson, 1992). Furthermore, the hillslope scale of investigation is consistent with the level of information suitable for on-farm planning in many Australian dryland farming landscapes. For example, soils of a toposequence in many Australian hillslopes are consistent enough in their soil properties/capabilities to be large enough (e.g. ±500 ha) to be managed as individual paddocks.

While there is no 'best' grid ground resolution for supporting terrain analysis for hillslope land assessments because of the nested scales of processes simultaneously at play (see above) in the landscape, there is evidence to suggest that resolutions in the range of 5 to 10 m form a good compromise (Hengl, 2006; Hengl and Reuter, 2009). However, some Australian experience (e.g. Kidd et al., 2012; Kidd et al., 2014; Thomas et al., 2015) shows that the routinely available ~30 m resolution DEM remains very capable of performing well and supplying information at suitable mapping reliability and ground detail for Australian conditions.

The forgoing discussion suggests that the suite of SLGA terrain attributes and soil attribute data available at ~90 m resolution would be too coarse to be effective for predicting soil water/depth related attributes for many Australian dryland farming landscapes (also refer to Figure 7-3). However, this should be tested on a case by case basis before dismissing the SLGA suite.

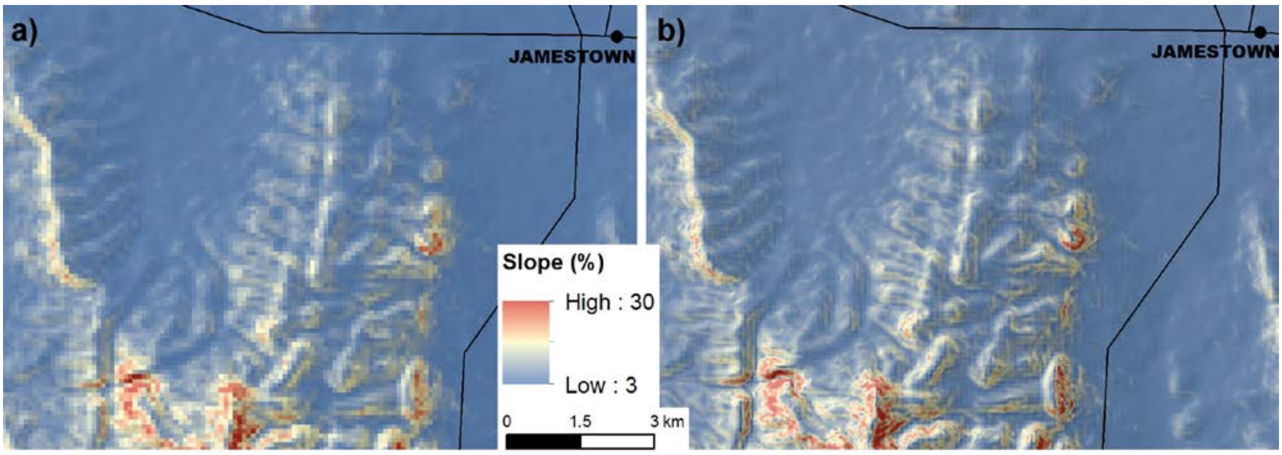


Figure 7-3. Examples of terrain attribute slope (%) at 3-arc second resolution (a) and 1 arc second resolution (b) near Jamestown SA. It can be seen readily that the 1 arc second product shows a lot more detail.

In summary, terrain information can be a potent source of data to support assessments of PAWC and changes in the landscape. The various terrain products viewed together provide a powerful synoptic view of the landscape as a whole, and when combined, provide strong clues about the water accumulation and soil depth patterns.

8 Geophysics

The following sections discuss the gridded datasets that are readily available for public use in Australia, and by-and-large have a track record in mapping soil properties and are likely to have bearing on soil depth. These cover gamma radiometrics and mineralogy (and supporting data sources). Finally, brief mention is made of electromagnetic surveys. While this geophysics data is also available for some regions derived by aircraft, such data is not considered sufficiently valuable in PAWC-type work due to the coarse depth resolution, i.e. surface depth increments are typically no better than 5 m.

8.1 Gamma radiometric data

In terms of Jenny's factors of soil formation (Jenny, 1941) discussed in the preceding section, gamma radiometrics ('radiometrics') relate strongest to parent material because it provides a measure of natural emissions of radiation in the surface 0.3 m of soil from elemental potassium (K), thorium (Th) and uranium (U) (Minty, 1997). Radiometric data can essentially be treated as geochemical maps. The radiometric elemental responses show the geochemistry of parent material and evidence of landscape evolution, and the possible relationships to soil depth. Strong potassium (K) signals are associated with fresh felsic igneous rock (e.g. granites), so depending on local lithology, may be associated with shallow or rocky soils and their weathering products such as illite clays. Potassium is a relatively mobile element, and tends to be most common in younger soils, becoming increasingly sparse in deeply weathered landscapes where most mobile forms have already been leached. Thorium (Th) is also commonly associated with felsic igneous rocks, but is concentrated in resistant minerals that tend to remain stable and weathered very slowly. This leads to higher concentrations of Thorium in very weathered (ancient, Cenozoic) soils, and has a strong association with iron oxides and bauxitic material. Strong Th signals are commonly associated with residual landscapes that, because of their antiquity, tend to be highly leached and nutrient-poor. These soils may also be deep because the landscape has been stable for a considerable amount of time. Uranium (U) is often associated with certain minerals that are sometimes abundant in granite, and may be readily leached by alkaline or acidic conditions to be transferred in solution through the landscape in groundwater and precipitated (e.g. in carbonates). Inferences on soil depth from U are difficult and landscape context is necessary to assist interpretation.

The Weathering Intensity Index (WII) draws heavily on the gamma radiometric signals of K, Th and U, and incorporates terrain analysis to add landscape evolution context (Wilford, 2012). High index values show where soils are stable, ancient and highly weathered (deep), while medium values indicate fresher and potentially deep to moderately deep soils and may be associated with fresh Quaternary deposits. Low index values are likely to indicate areas that have signals from fresher bedrock (i.e. recent, unweathered bedrock), and possibly the location of shallow or skeletal soils. WII has been shown to be a powerful predictor of soil depth (depth to bedrock) in Australia (Wilford and Thomas, 2012; Wilford et al., 2016).

The radiometric data for Australia is available from Geoscience Australia http://www.ga.gov.au/scientific-topics/disciplines/geophysics/radiometrics

While gamma radiometric data do not allow estimations of PAWC directly, their spatial variability informs on the soils present which can in turn support PAWC estimations. For example, high K signals on crests and ridges are likely to be indicative of shallow soils where bedrock is close. Given the freshness of weathering, the soil is likely to contain a larger proportion of coarser soil fraction. Combined, PAWC in these situations are likely to be small. However, strong K signals in lowlands/plains are likely to be associated with smectitic clay mineralogy (see next section) in Quaternary alluvial soils, hence the soils likely to be deep and clay-rich, hence a large PAWC. Equally, strong Th in high landscape positions are likely to be deep, kaolinitic (see next section) and nutrient deficient. Predominantly textures are likely to be coarser through the profile, so PAWCs are likely to be moderate.

8.2 Mineralogy

Clay minerals are important in influencing the properties of soils, including permeability and fertility. The dominant soil mineralogy is indicative of soil forming conditions, including the age, and related, fertility, dominant soil moisture conditions, and parent material. Soil colour is strongly governed by dominant mineralogy, hence the colour of the soil may offer insights into the property of a soil (Bigham and Ciolkosz, 1993). The relative abundances of kaolinite, illite and smectite have been mapped for Australian soils at a ground resolution of ~90 m (3 arc second) for the surface (0 - 0.2 m) and in the subsoil (0.6- 0.8 m), using methods described in Viscarra Rossel (2011). The mapping is available from CSIRO's data access portal (DAP; http://doi.org/10.4225/08/55DFFCA4715D8).

The structure of clay particles dominates the property of soils. While kaolinite, illite and smectite share similar basic building blocks, their arrangement in terms of how the particles layer vary, which in significant differences in terms of water retention and nutrient status.

Kaolinite occurs in a range of climates and dominates in deeply weathered, leached soils, generally associated with upper landscape positions. The advanced stages of weathering means that kaolinite is often associated with a high content of coarser textured particles left in situ (e.g. quartzite). The stacking of particles means there is low capacity to store and release water, and the associated lack of shrink-swell behaviour means that the structure becomes massive, very closely packed with little pore space to store water or air, creating hostile rooting conditions; PAWCs tend to be low. Kaoline soils have low fertility status, partially due to their highly leached status, and inability to attract and release nutrients in the soil matrix. These soils tend to be light grey coloured.

Illite is present in varied landscapes and may be representative of colder, more arid climates, but may also be present in warmer and wetter soil environments. The structural arrangement of illite means that the soils have a moderate capacity to hold and release water and nutrients, hence illite-rich soils tend to have moderate PAWC values.

Smectite is often an authigenic mineral formed from the weathering of basalt, but it also occurs on sediments and calcareous substrates. It occurs predominantly in drier climates and in landscapes with low relief, and is typically associated with the lowest part of landscapes. Smectitic clays are notable for their shrink-swell characteristics and their high fertility. Shrink-swell means that they have the capacity to attract, store and release water and nutrients, resulting in soils with high PAWC and nutrient status. The physical soil conditions created by wetting-drying/shrink-swell cycles means that the smectitic soils are often well structured, creating favourable conditions for root establishment. Smectitic soils tend to be dark in colour and have high PAWC.

The proportions of these minerals in soils may therefore be a useful guide to predicting PAWC (especially when patterns are viewed in land relief context; Section 7.3.7), allowing crude predictions - especially if soil depth is known. However, the 90 m resolution of mapping remains coarse for on-farm estimations.

8.3 Ground electromagnetics

Electromagnetic (EM) instruments emit an electrical signal into the ground and measure the response. The difference in magnitude of the response and amplitude shifts indicate intrinsic soil properties governed by the dialectic (conductive) properties of the soil (e.g. Doolittle and Brevik, 2014; McNeill, 1980). Weakest responses are associated with dry and sandy soils, whereas strongest responses are associated with wet and clay-rich soils. Saline conditions also show very strong responses (McKenzie et al., 1997; Williams and Baker, 1982). EM instruments tend to be hand-held or mounted on vehicles (quad bikes, utility vehicles) and response data and GPS positioning are recorded simultaneously. Large areas can be covered quickly and conductivity maps easily generated using GIS. Commonly used systems in the agricultural setting in Australia are the Geonics EM38 and EM31 systems, although there are others available. Each system is designed to measure at different ground depths, for example the EM38's response is dominated by the <1.5 m soil profile, and the EM31, the <8 m profile. EM survey services are widely available in Australia through agricultural advisors and geophysical survey consultants.

Ground EM surveys have a track record in identifying and mapping texture transitions in the landscape (i.e. toposequences) and identification of management zones relating to soil type from conductivity (texture, moisture, salinity) transitions (e.g. Hedley et al., 2004; James et al., 2003). Given these soil properties relate to clay contents, the fine scale of EM survey that is possible has strong utility in defining conductivity zones (i.e. clay contents and depth) that can assist in PAWC investigations and possibly predictions – especially if responses are calibrated and ground-truthed to clay type and depth.

9 Possible future case studies

For the GRDC Northern Region a similar data inventory was prepared for the next stage in the project, namely to evaluate in detail the different methodologies for predicting PAWC from available information in eight case study areas. It would be of similar value to carry out a few select case studies within the GRDC Southern Region to evaluate the regional specific information resources to predict PAWC in dryland landscapes. A number of suggestions are briefly outlined below. The basis for case study selection is included, although the final locations and priority of work would be determined in consultation with GRDC, and on-ground experts (e.g. state soil mapping agencies, land managers, farmers and advisors).

9.1 Midnorth, SA

This area is approximately 15 km south of Jamestown in the Belalie Valley (see Figure 9-1). It is a productive landscape with good coverage of APSoil sites over much of the region, although as shown in Figure 9-1, there is only one site in the valley (record 608). The area covers an upland landscape with regular soil patterns in a generally regular toposequence (crest: Vertosols/Dermosol, Chromosols; valley bottom: Sodosols/Vertosols). Soil salinity and sodicity are likely to be factors to consider as modifiers of PAWC. Soil-landscape data is plentiful and expert knowledge is strong (e.g. Thomas et al., 2007; Thomas et al., 2009a; Thomas et al., 2009b) and there a progressive farming and farm advisor community. It could offer a comparison between ‘expert approximation of PAWC’ using the soil-landscape polygon narrative approach and DSM approaches based on the SLGA national DSM as well as the SA specific DSM.

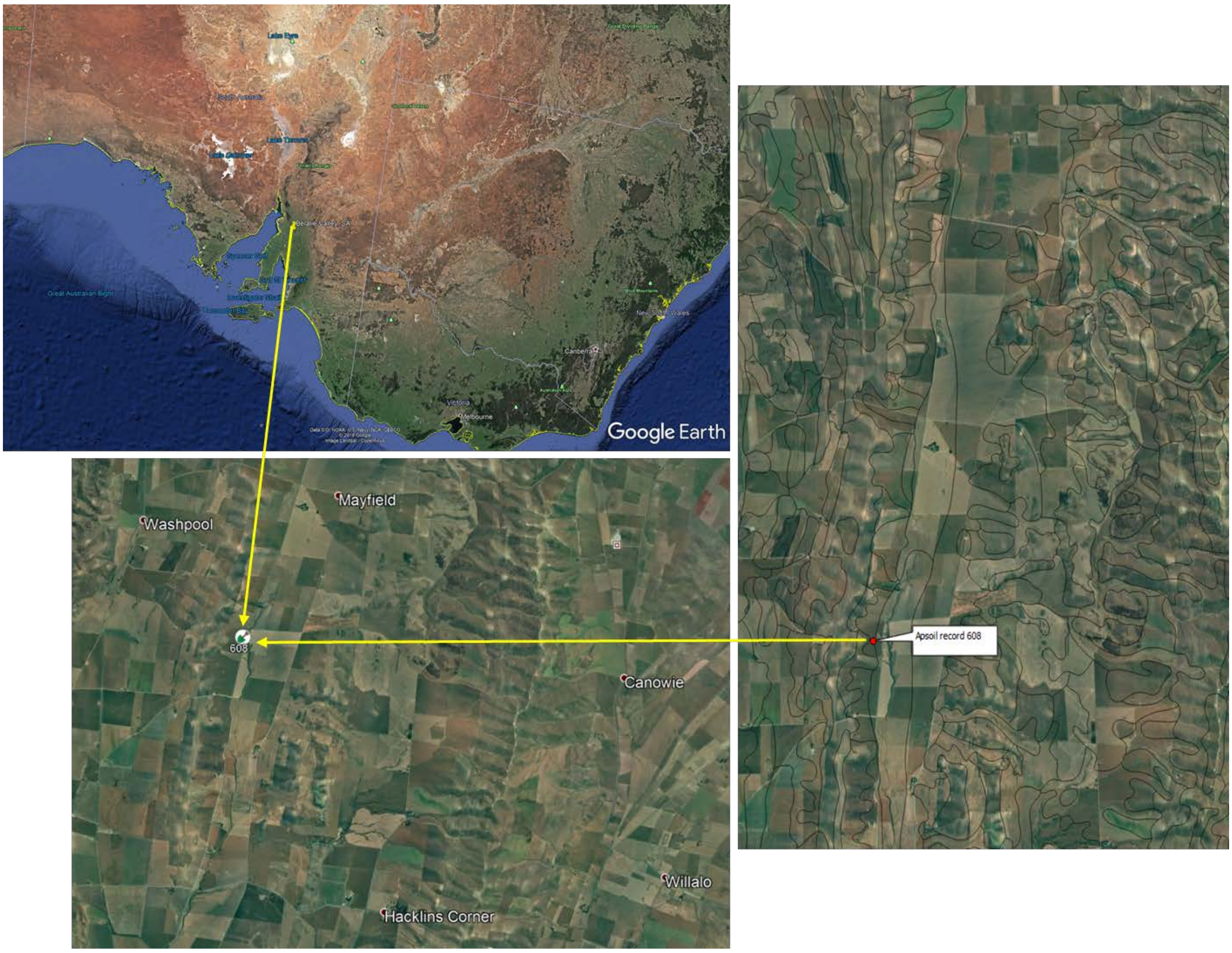


Figure 9-1. Belalie Valley in the Midnorth of SA, with state SLU mapping overlaid.

9.2 Mallee, Victoria and SA

The Mallee landscape is dominated by aeolian soil forming processes with deep sandy soils on dune crests grading downslope to heavier clay loams in the swales. PAWC is strongly linked to soil texture in these environments, as illustrated in Figure 9-2.

Subsoil constraints such as sodicity and salinity are a common feature in some swales where restricted drainage moderate crop lower limit. Understanding these constraints will require a considered approach when assessing spatial extrapolation of PAWC. Terrain attributes (e.g. MrVBF) may assist interpretation of some subsoil constraints.

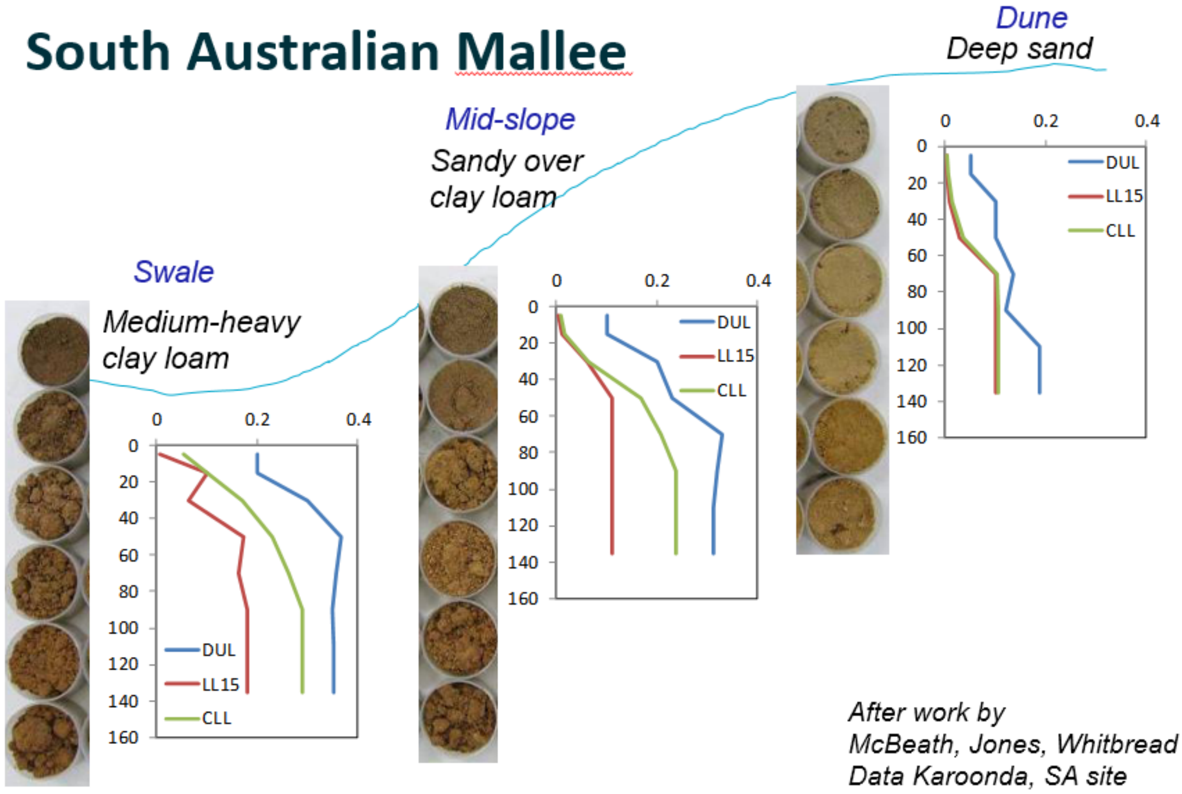


Figure 9-2. A conceptual frame-work for PAWC distribution in South Australian Mallee soils. Source: presentation by McBeath, Jones and Whitbread - Karoonda SA

As the Mallee landscape crosses the SA-Victorian border a case study would allow evaluation of a range of different soil-landscape resources for PAWC prediction. The case study would consider the area of the Central Mallee and Hopetoun Land Systems within the Mallee catchment region of Victoria in an approximate area delineated by Figure 9-3.

Soil and landscape data is relatively rich and there are numerous PAWC characterisations in both South Australia and Victoria. In the Central Mallee and Hopetoun Land Systems of the Mallee Catchment Region of Victoria terrain analysis using the digital elevation model (Hopley and Robinson, 2009) has allowed disaggregation of the landscape into landform components. With texture and subsoil constraints often linked to slope position it would be interesting to evaluate if this disaggregation can capture differences in PAWC. The case study would also allow comparison with DSM approaches based on both the (SLGA) national Victorian and the SLGA South Australian attribute mapping. Aspects of such a study in the Victorian Mallee may also be transferable to similar soil landscapes in Western Australia.

Figure 9-3. An approximate location for Central Victorian Mallee Study area.

9.3 Corangamite, Victoria

This is a high rainfall area in an in-situ weathered basalt dominated landscape. Toposequences are dominated by Ferrosols, Dermosols, Chromosols and Sodosol. There are relatively few APSoil sites in this area (see Figure 9-4) as high in-season rain may refill plant available water in some seasons; however future utility of PAWC information may increase with changed climate scenarios. Soil landform and geomorphology mapping (Figure 9-5) is available at potentially useful mapping scales along with some detailed soil pit descriptions. Soil hydraulic properties are strongly influenced by columnar jointing (probably sodic), weathering processes of parent material and drainage. These factors in combination with high rainfall may also confound PAWC estimations.

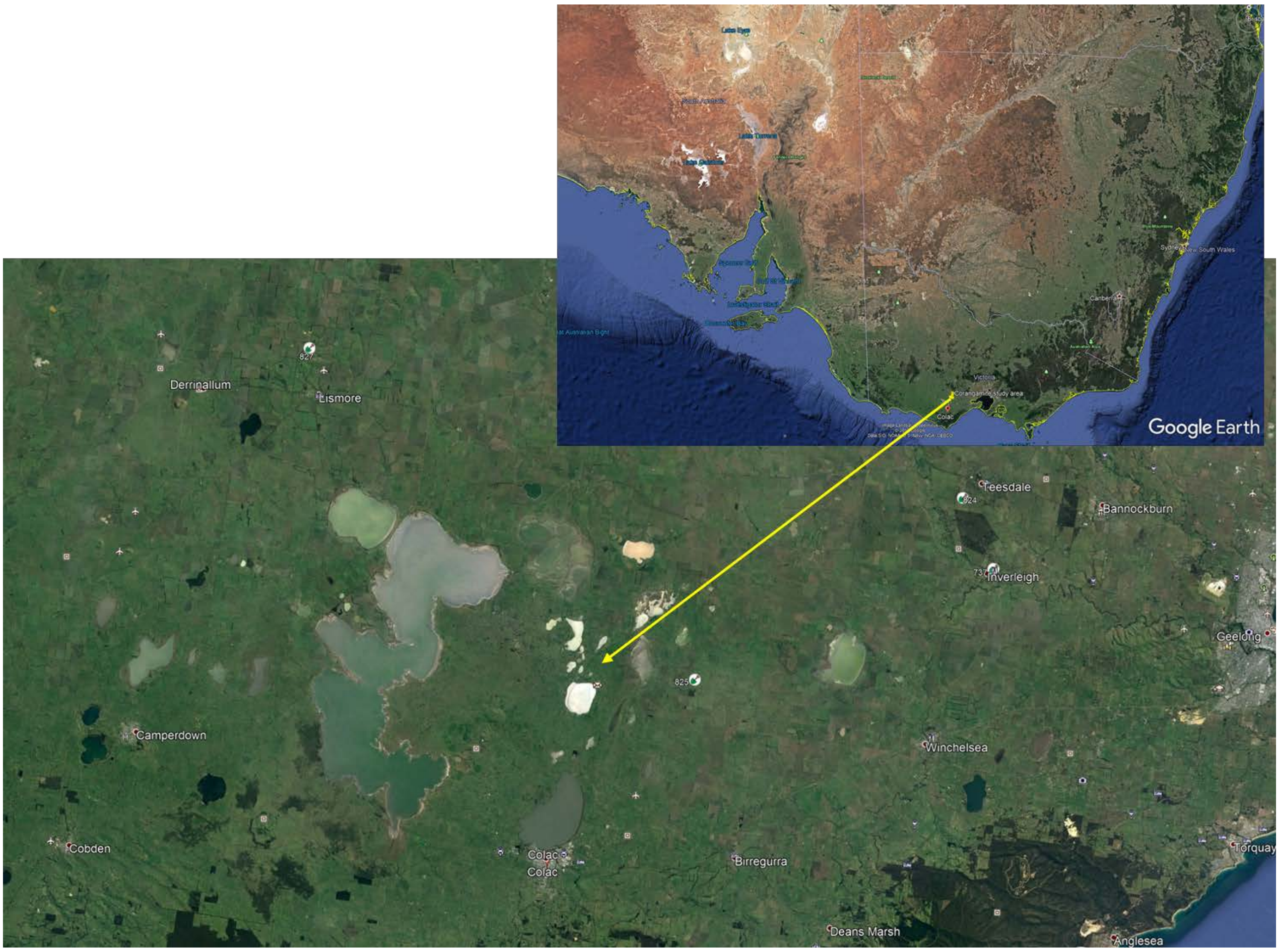


Figure 9-4. Potential Corangamite study area in Victoria.

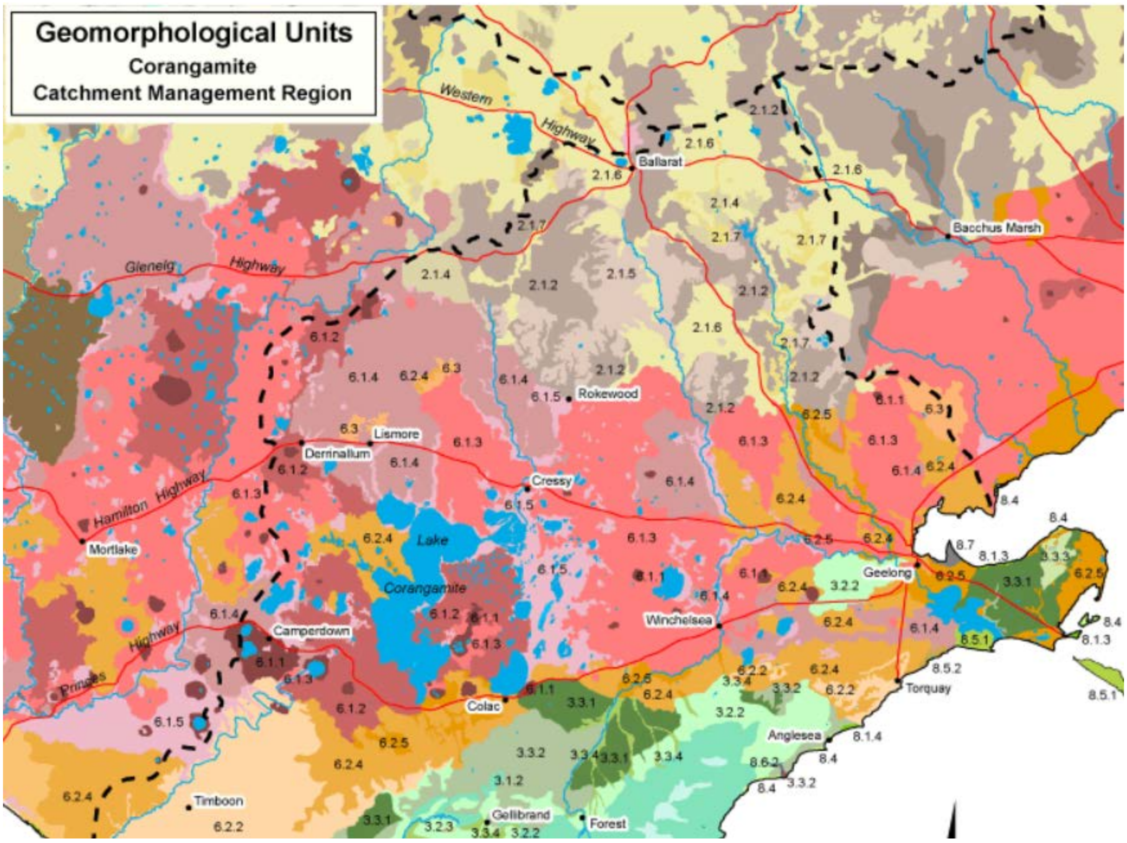


Figure 9-5 Geomorphological unit mapping for the Corangamite area in Victoria

9.4 Midlands, Tasmania

Quality digital soil mapping data is available for much of the Tasmanian cropping area. Current growers and advisors are actively using these data to plan different farming systems whilst assessing cropping limitations e.g. frost frequency and cold air drainage. Traditional soil mapping is available at reconnaissance level in many areas as is 1:25,000 scale geological mapping, and both may provide assistance when predicting PAWC. There are relatively few (21) APSoil characterisations located in two clusters one between Devonport and Port Sorell and the other in the Longford-Cressy districts (Figure 9-6). These areas might provide improved validation options. Alternatively, a study area selected with no characterisations may prove the value of the quality DSM approach. Further exploration of the case study can be undertaken and facilitated by the Department of Primary Industries, Parks, Water and Environment, who has developed a network of growers and advisors from their recent mapping activities.

Figure 9-6. Potential area for location of a Tasmanian case study, which contains 13 APSoil characterisations. Launceston is in the north east of the area.

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