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GRDC Northern 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 Northern Region that could be used for mapping PAWC to soil landscapes and predict PAWC at the farm management scale. This supports the selection of the eight case study areas.

The GRDC Northern Region has 404 PAWC characterisations, which are freely available online (https://www.apsim.info/Products/APSoil.aspx) and in the iPad application SoilMapp. They are located in the grain growing areas of all the GRDC sub-regions and mostly associated with dryland cropping, where the concept of PAWC is most relevant.

Over the years many soil and landscape surveys have been carried out within the GRDC Northern Region. There is, however, no mapping that is consistent across the region, or even within the two states (Queensland and NSW). Apart from the national mapping using the Australian Soil Classification, which is at a very broad scale within the GRDC Northern Region, the soil and landscape surveys all cover smaller areas within these states. They have also been carried out at different scales and for different purposes. Many of these surveys are, however, freely available on-line through two state based tools. The soil profile data that underpin these surveys, as well as those collected for other purposes are also available. Geological surveys and a variety of geophysics data can also be accessed from other online sources.

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 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 Northern 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 404 records in the Northern 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 sub-regions within NSW and Queensland 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. The NSW eSpade tool (http://www.environment.nsw.gov.au/eSpade2Webapp) provides ASC at soil order level for a revised 2017 map.	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. *NSW soil profile data:* NSW soil profile data are accessible via the NSW eSpade tool (http://www.environment.nsw.gov.au/eSpade2Webapp). The NSW database also contains soil profile data from a variety of other projects with a mix of soil profile descriptions and/or soil data at select depths. *Old soil profile data:* Queensland soil profile data are accessible through Queensland Globe (https://qldglobe.information.qld.gov.au/). Similarly to NSW, the Qld database also contains soil profile data from a variety of other projects.	3.3
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 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.	3.4

Qld soils mapping	A variety of soil surveys for the Queensland part of the GRDC Northern Region are available via https://data.qld.gov.au/dataset/soils-series. The distribution is piecemeal and each survey has been conducted for different purposes and mapped at different scales. Scale of mapping and level of detail defines the utility of these maps for PAWC extrapolation and prediction.	3.5
NSW soil landscape mapping	For the NSW part of the GRDC Northern Region, seventeen 1:100,000 and six 1:250,000 soil-landscape maps are available through the NSW eSpade tool (http://www.environment.nsw.gov.au/eSpade2Webapp). In addition, there are three unpublished 1:250,000 soil-landscape maps. Soil-landscape maps provide an understanding of different soil types in relation to landscape position and parent material, which can inform extrapolation and prediction of PAWC in conjunction with existing PAWC characterisations. Mapping approaches vary between maps, except for those carried out by the same group of surveyors. Utility for PAWC prediction may hence vary by map sheet.	4.1.1
NSW soil and land resource mapping	The NSW soil and land resource maps are also available through eSpade and form an enhancement of the Soil Landscape mapping to create seamless datasets across six catchment areas; four of which are within the GRDC Northern Region. This includes new mapping for the Moree Plains. Use of this information source for PAWC mapping is similar to that of soil-landscape mapping.	4.1.2
NSW hydrogeological landscapes mapping	The NSW hydrological landscape mapping is also available through eSpade. This mapping describes the soil, rocks, climate and landforms that influence salinity in a given area, and provides salinity management options for specific parts of the landscape. While the reports include some reference to soil-landscape units and soil types found within the hydrogeological landscape, it does not appear useful for PAWC interpretation, except where landscape diagrams within the reports can help explain the landscape or provide insights into subsoil constraints driven by salinity or sodicity.	4.1.3
NSW land systems mapping	NSW eSpade also provides access to land systems mapping for Western NSW, but most of the coverage falls outside the cropping zone. Land systems are areas or groups of areas throughout which there is a recurring pattern of topography, soils and vegetation.	4.1.4
Qld land resource area mapping	Land Resource Area (LRA) mapping in Queensland is similar to the NSW Soil Landscape Mapping and the NSW Soil and Land Resource Mapping. It is accessible via Queensland Globe (https://qldglobe.information.qld.gov.au/). The scale of mapping ranges from 1:100,000 to 1:500,000, and so LRA mapping may vary significantly in terms of mapping concepts, and the level of spatial information regarding the distribution of soils that may be gleaned from them. Utility for PAWC prediction may vary accordingly. The detailed LRA for the Central Darling Downs may provide opportunity to link PAWC prediction and select APSoil PAWC profiles to the local soil types described in its manual.	4.2.1
Qld land systems mapping	Mapping scales vary between 1:70,000 scale and 1:500,000, although most are mapped at a scale of 1:250,000. Many of the mapping scales and soil information that the reports contain will be too coarse for PAWC estimations and correlations, but utility in absence of other information is to be explored. Maps are available via Queensland Globe and the associated data portal.	4.2.2

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 NSW and Queensland, the SLGA national soil attribute product is available. 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. However, as discussed above, this will change with new opportunities for 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
Qld 3D mineral mapping	The ASTER satellite collects land surface reflectance data in wavebands that are suitable for mineral investigation (see above). The Queensland data are available here: http://doi.org/10.4225/08/59068b8b07cf6. Areas of coverage and ground resolution may limit the value in PAWC work.	8.3
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.	8.4

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. This will be considered in the case studies of the project.

Another challenge is the scale at which the various maps and data are produced. Very little of the NSW and Queensland data is produced at a scale less than 1:100 000 and much of it is at a scale of 1:250 000. This 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.

Selection of case study areas

The data inventory presented in this report prepared for the next stage in the project, namely to evaluate in detail the different methodologies for predicting PAWC from the available information in eight case study areas within the GRDC Northern Region: Young and Harden granodiorite hill country NSW, Central West NSW (west of Condobolin), Macquarie-Bogan flood plains NSW, Liverpool Plains NSW, northern half of the Moree plains NSW, Central Darling Downs Qld, Murilla-Tara-Chinchilla area Qld and Central Highlands Qld. The selected case study areas reflect areas with different types of landscapes and different levels or type of soil and landscape information available. Details of the case study areas and the rationale for their selection are outlined in Section 9.

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 Northern 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.

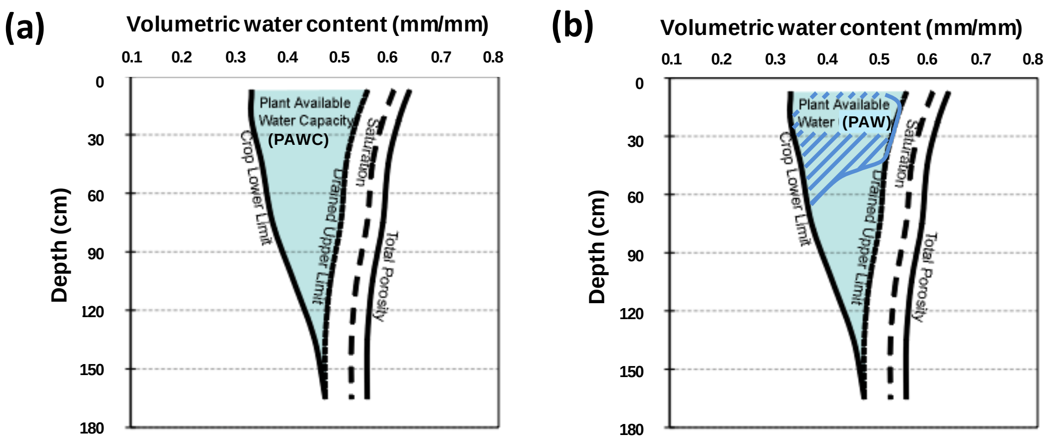

Figure 1.1. (a) The Plant Available Water Capacity (PAWC) is the total amount of water that a soil can store and release to different crops and is defined by its Drained Upper Limit (DUL) and its crop specific Crop Lower Limit (CLL); (b) Plant Available Water (PAW) represents the volume of water stored 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. (2016a) 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 (e.g. terraGIS; Huang et al., 2017) 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 Northern 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 11 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.

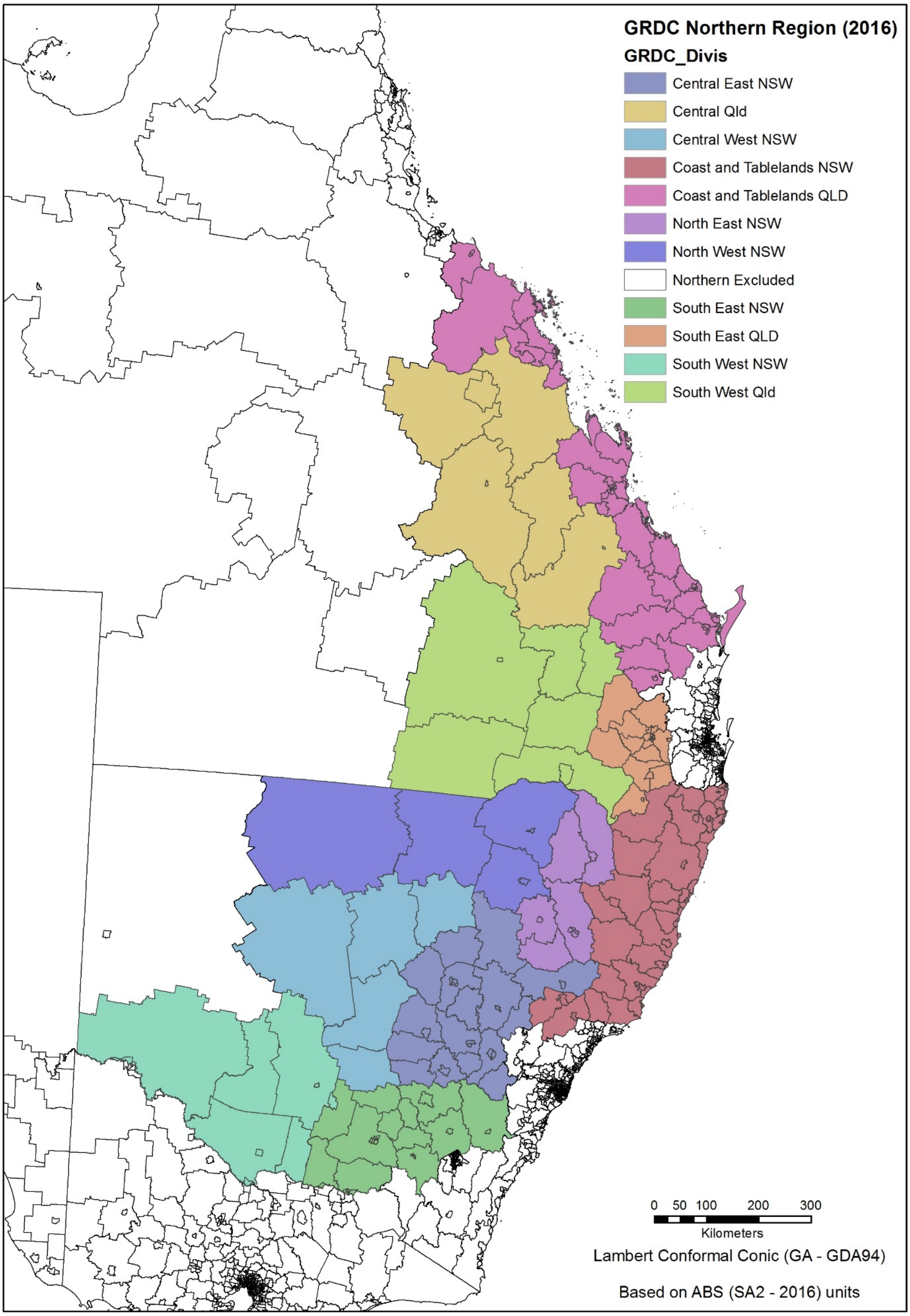

Figure 1.2. GRDC Northern Region sub-region boundaries.

Source: McMillan et al. (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, 404 are located in the GRDC Northern 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.

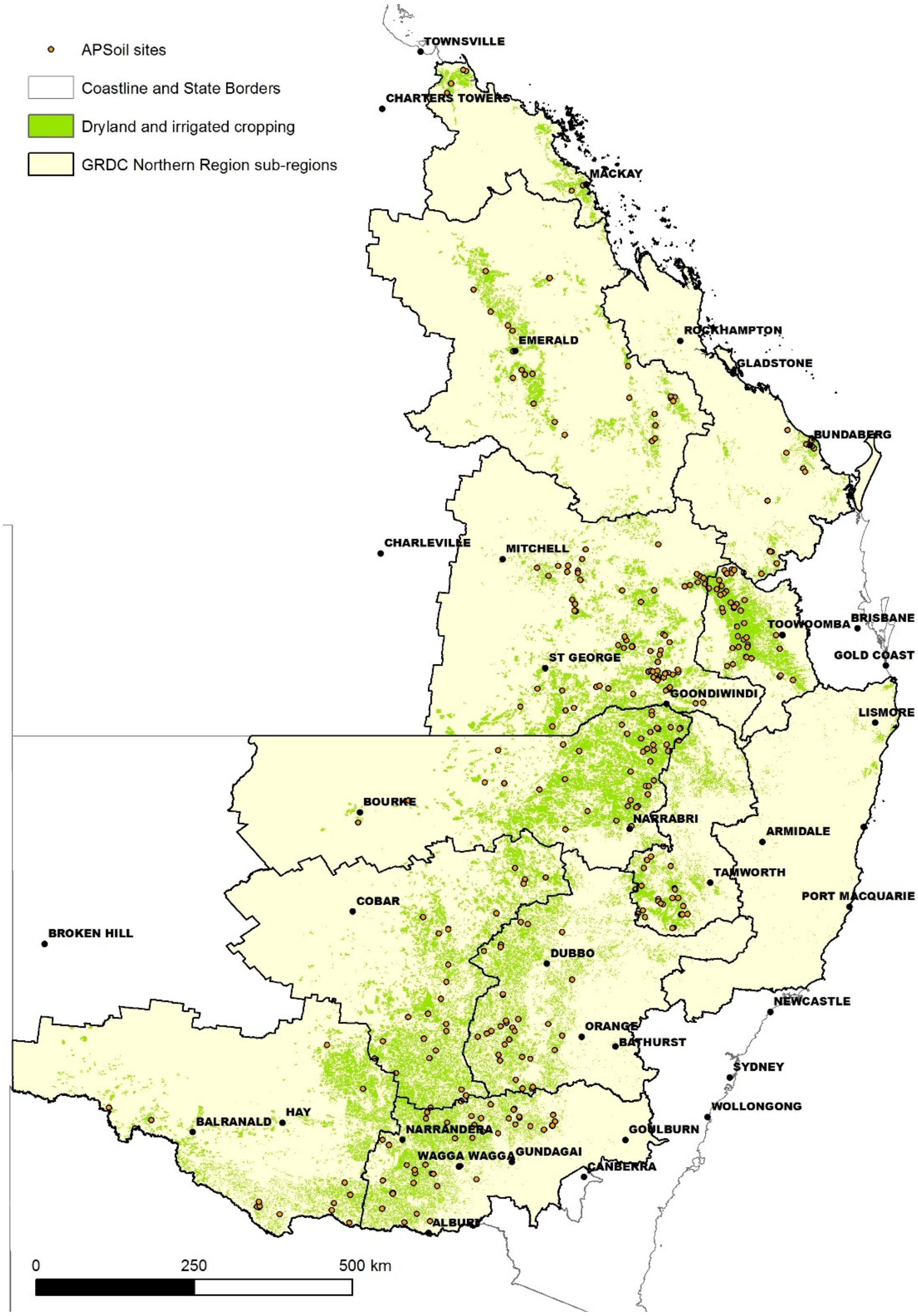

Figure 2.1. Locations of APSoil sites within the GRDC Northern Region. Dryland and irrigated cropping extents are from the May 2016 update of the Catchment Scale Land Use of Australia dataset.

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.

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 Northern Region sub-regions except the 'Coast and tablelands NSW' region have multiple APSoil PAWC characterisations. The distribution of PAWC characterisations within the sub-regions appears uneven in Figure 2.1, but relates to the characterisations being associated with grain growing areas within these sub-regions. Most of the characterisations are in dryland cropping areas.

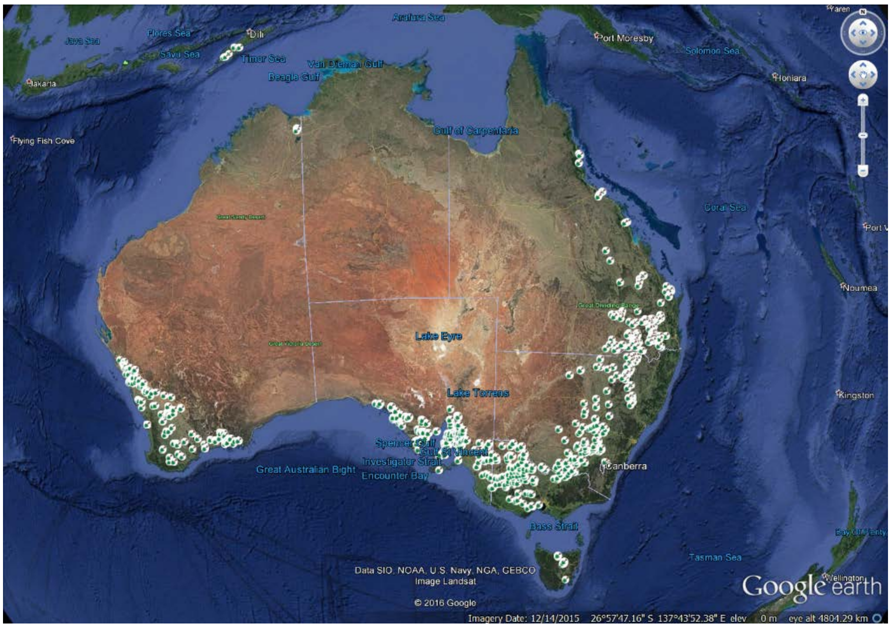

Figure 2.2. Access to geo-referenced soil PAWC characterisations of the APSoil database via Google Earth.

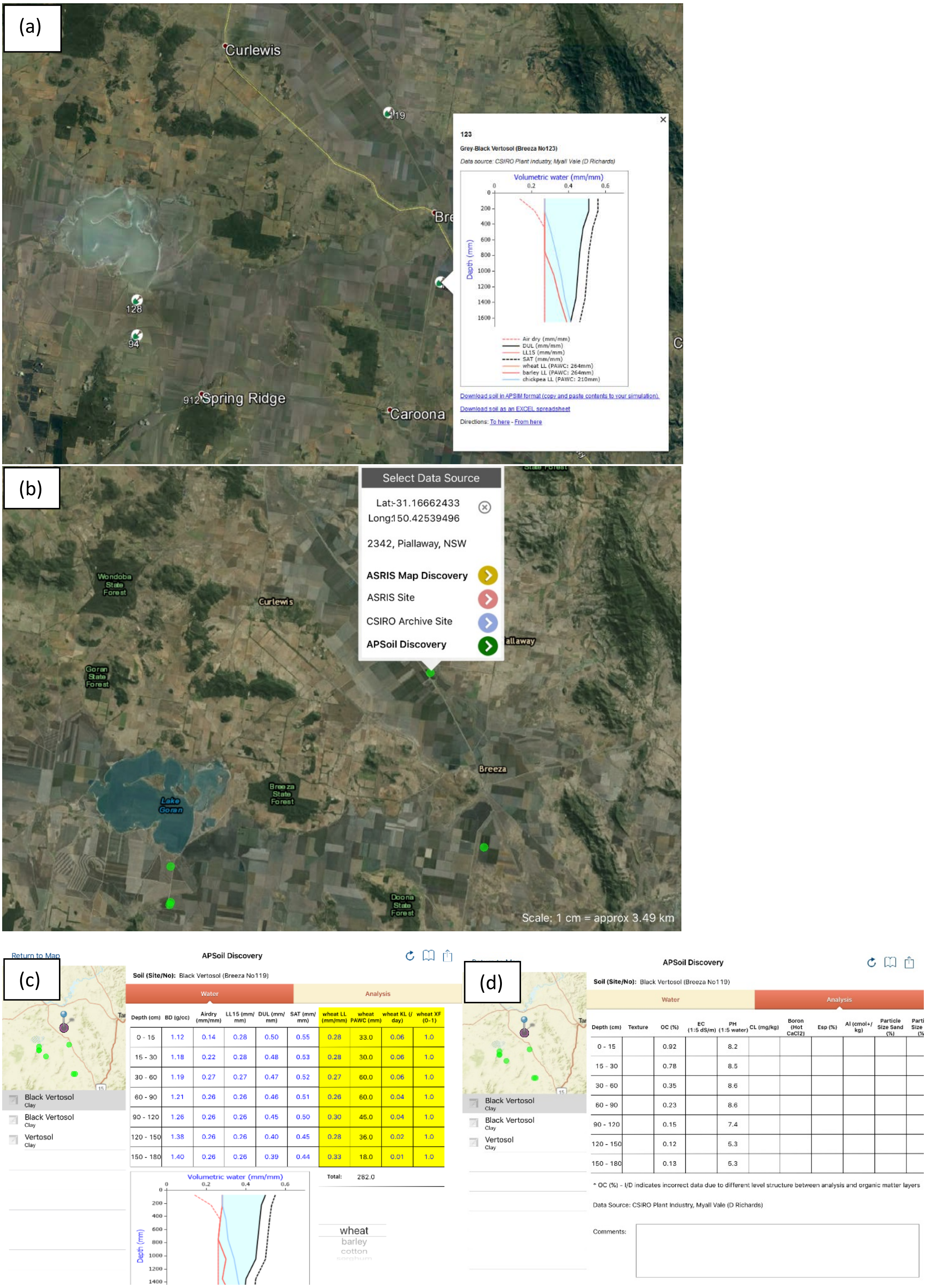

Figure 2.3. Access to geo-referenced soil PAWC characterisations of the APSoil database via (a) Google Earth and pop-up boxes and (b) SoilMapp; (c) and (d) APSoil discovery screens.

Source: Verburg et al. (2017)

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

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).

The NSW data are from the ASC Soil Type Map of NSW (October 2017 update) from the NSW Office of Environment and Heritage, while the Queensland data are the Queensland Soil Surveys – ASRIS Compilation (2017) from the Queensland Department of Science, Information Technology and Innovation.

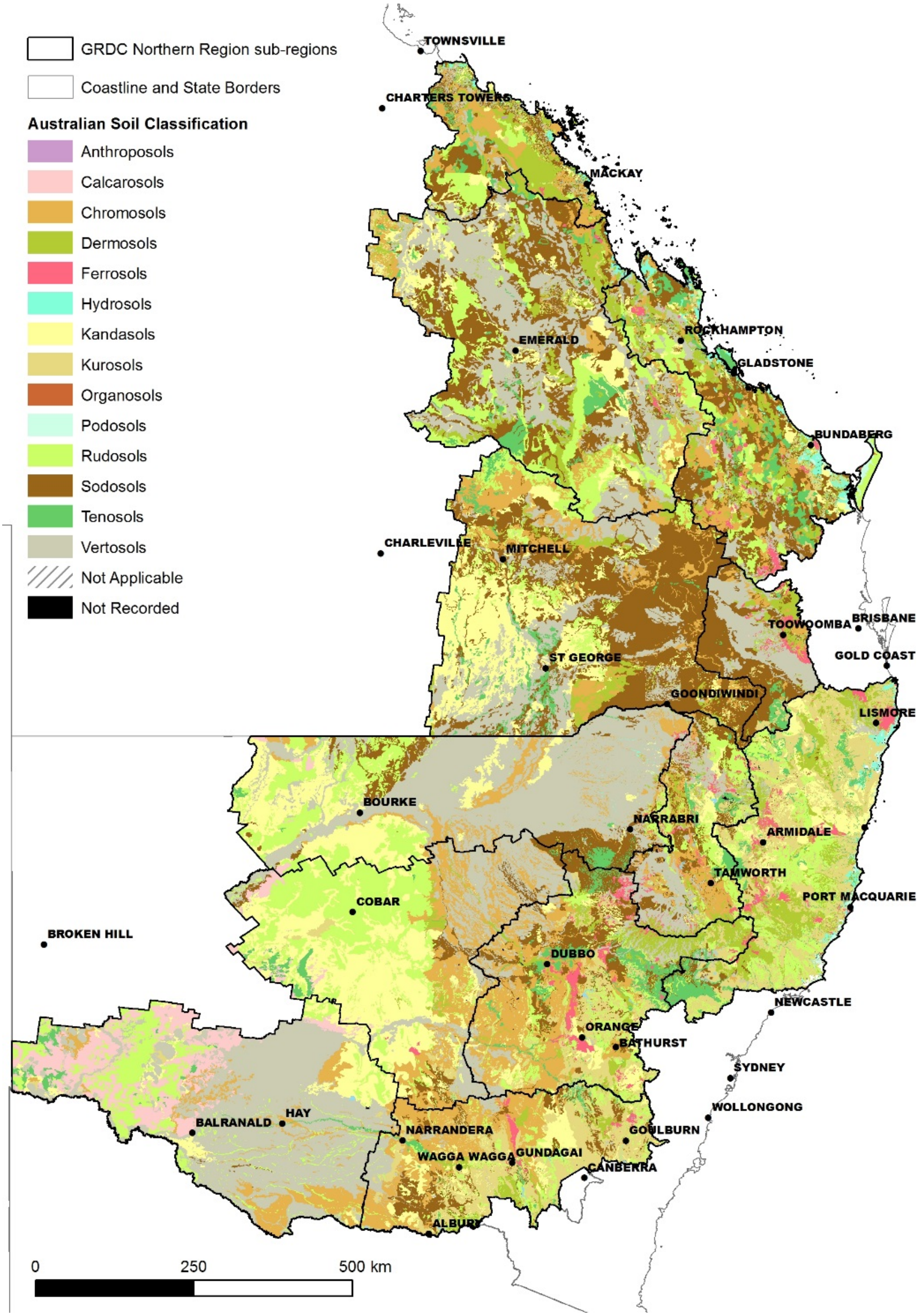

Figure 3.1. Australian Soil Classification within the GRDC Northern Region.

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). However, these ASC orders are more common in the Western and Southern GRDC regions.

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. The NSW eSpade tool (http://www.environment.nsw.gov.au/eSpade2Webapp) provides ASC at soil order level for a revised 2017 map. The NSW eSpade tool also provides mapping using an older classification of Great

Soil Groups, whereas the Queensland Globe tool (https://qldglobe.information.qld.gov.au/) provides access to mapping of the Atlas of Australia using the earlier Northcote (1979) Factual Key classification.

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.

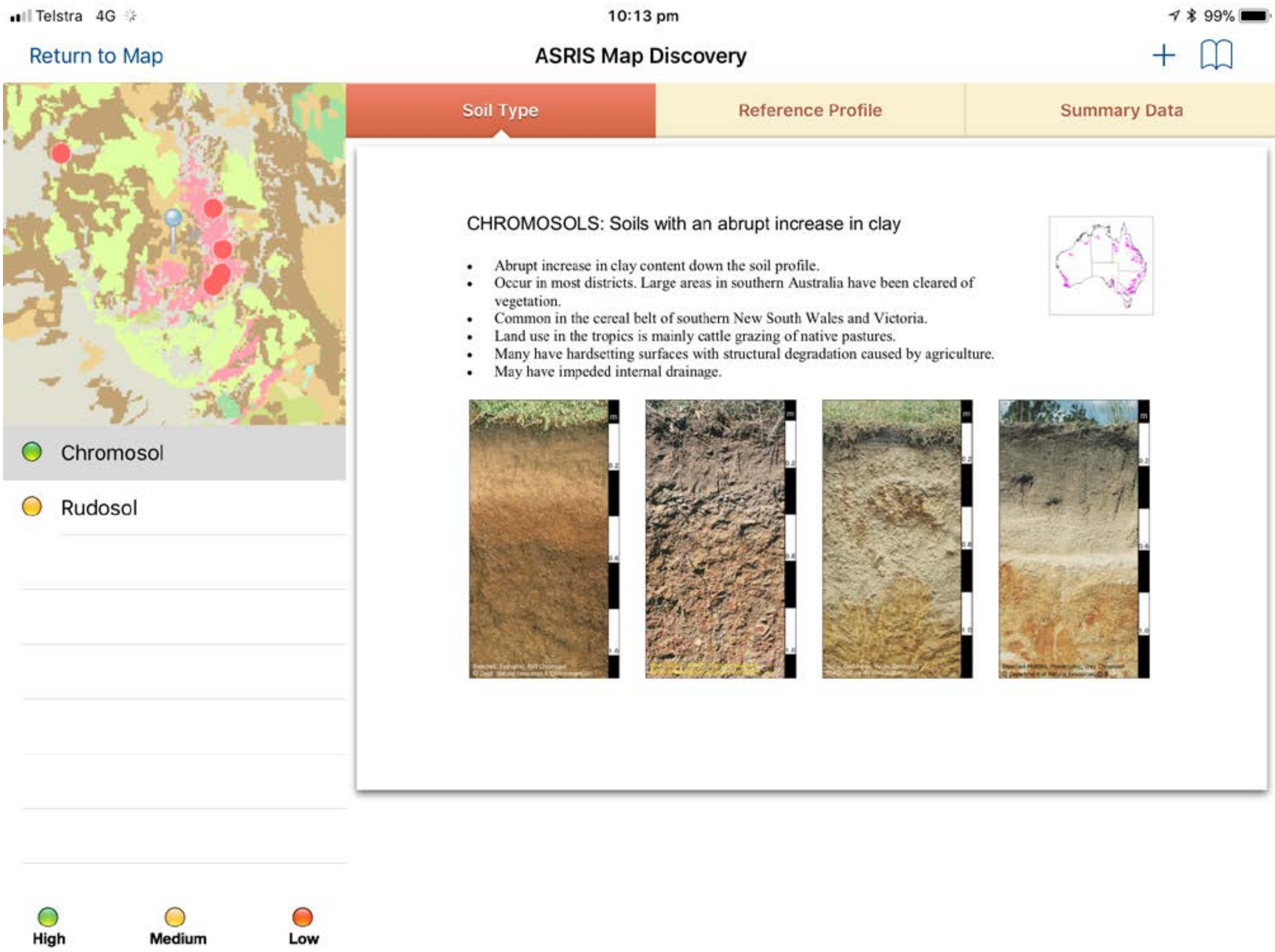

Figure 3.2. SoilMapp Map Discovery tool screen shot for a location west of Kingaroy, Qld.

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.

For example, in NSW these soil profile data have been placed in the public domain via the online "eSpade" tool (http://www.environment.nsw.gov.au/eSpade2Webapp; User guide: http://www.environment.nsw.gov.au/research-and-publications/publications-search/espade-user-manual).

The user interface shown in Figure 3.3 allows users to centre on an area of interest and geographically display the soil profiles that are available there. Users may click on the site icon to reveal a number of reports detailing site and profile descriptions, and laboratory data, depending on the information requirements of the user. The reports include a soil technical report, soil essentials report, and soil profile report.

The soil records presented in the eSpade user interface are also accessible directly from NSW's soil database, the Soil and land Information System (SALIS) (http://www.environment.nsw.gov.au/salis5app/main/account/login). Users with accounts may download the soil records contained in SALIS, for example, in GIS compatible formats for their own use.

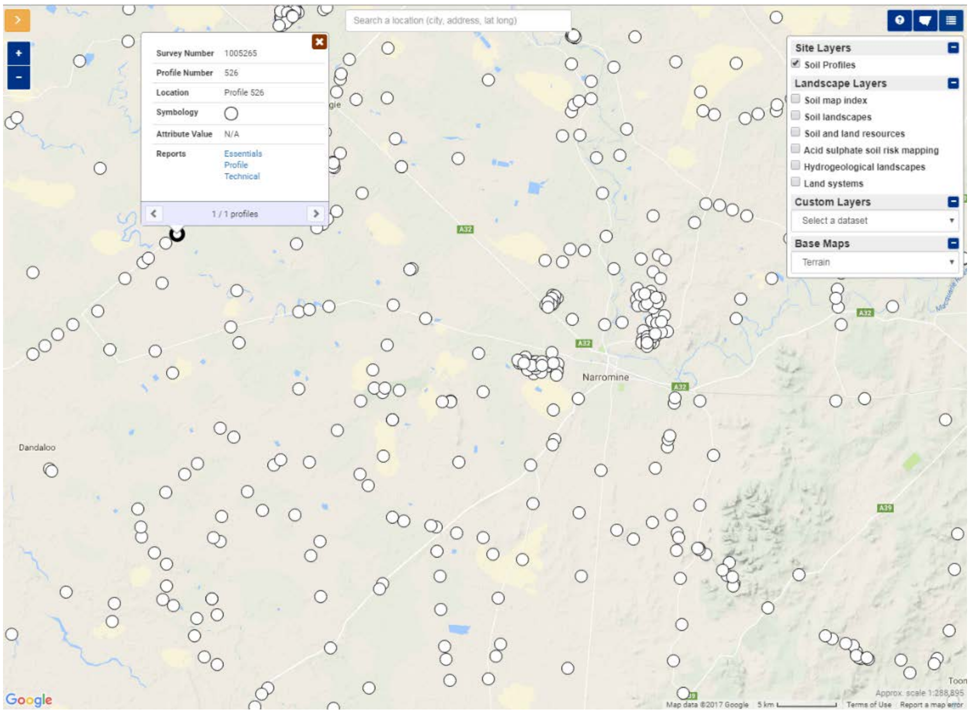

Figure 3.3. Framegrab of NSW's "eSpade" soil database interface showing distribution of soil sampling sites and preliminary record interface.

Queensland's online equivalent of eSpade is "Queensland Globe" (https://qldglobe.information.qld.gov.au/). Queensland Globe provides users with a geographic interface (Figure 3.4) and the ability to centre on an area of interest to display soil survey sites. The initial click on the survey site using the selection tool reveals record metadata, and a link to the full report that is downloadable.

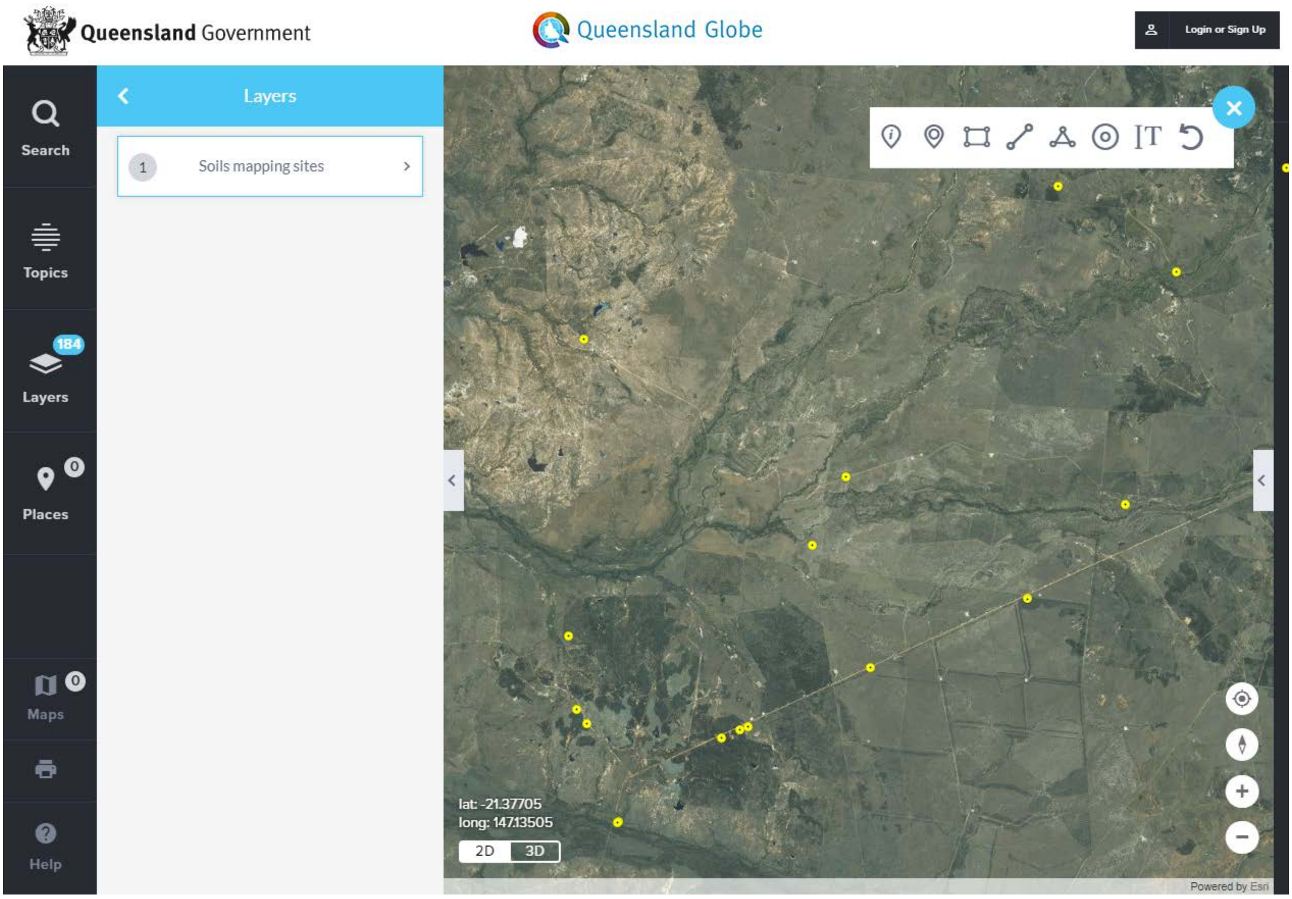

Figure 3.4. Framegrab of Queensland's "Queensland Globe" soil database interface showing distribution of soil sampling sites and preliminary record interface.

The underlying soil record database, the Soil and Land Information (SALI) is also publically available via the State government website (https://www.qld.gov.au/environment/land/soil/soil-data/mapping), and may be downloaded in GIS compatible formats. The distribution of SALI sites is presented in Figure 3.6.

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).

In Queensland soil profile data is considerably denser in the coastal regions (Figure 3.6). Within the inland grain growing areas there are, however, a few areas that have been intensively sampled. These are associated with fine scale soil surveys (see Section 3.4).

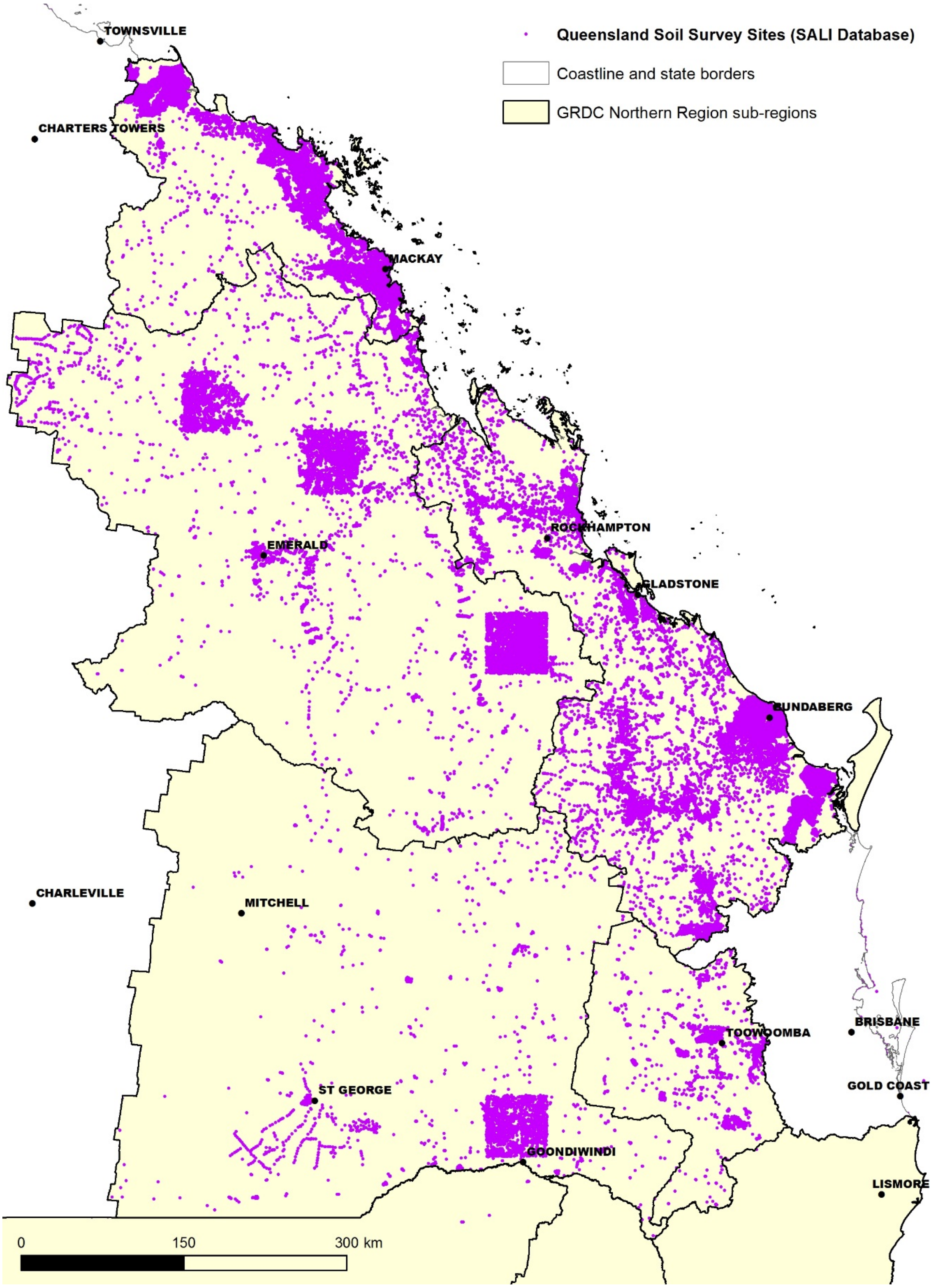

Figure 3.5. Distribution of Queensland's Soil and Land Information (SALI) database soil records within the GRDC Northern Region.

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 3.7). 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 3.7, the distribution of reference profile sites in the GRDC Northern Region is sparse. Dense distributions are strongly associated with jurisdictions that have a history of strong and systematic land resource evaluation programs in agricultural areas, as experienced in Western Australia and South Australia.

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).

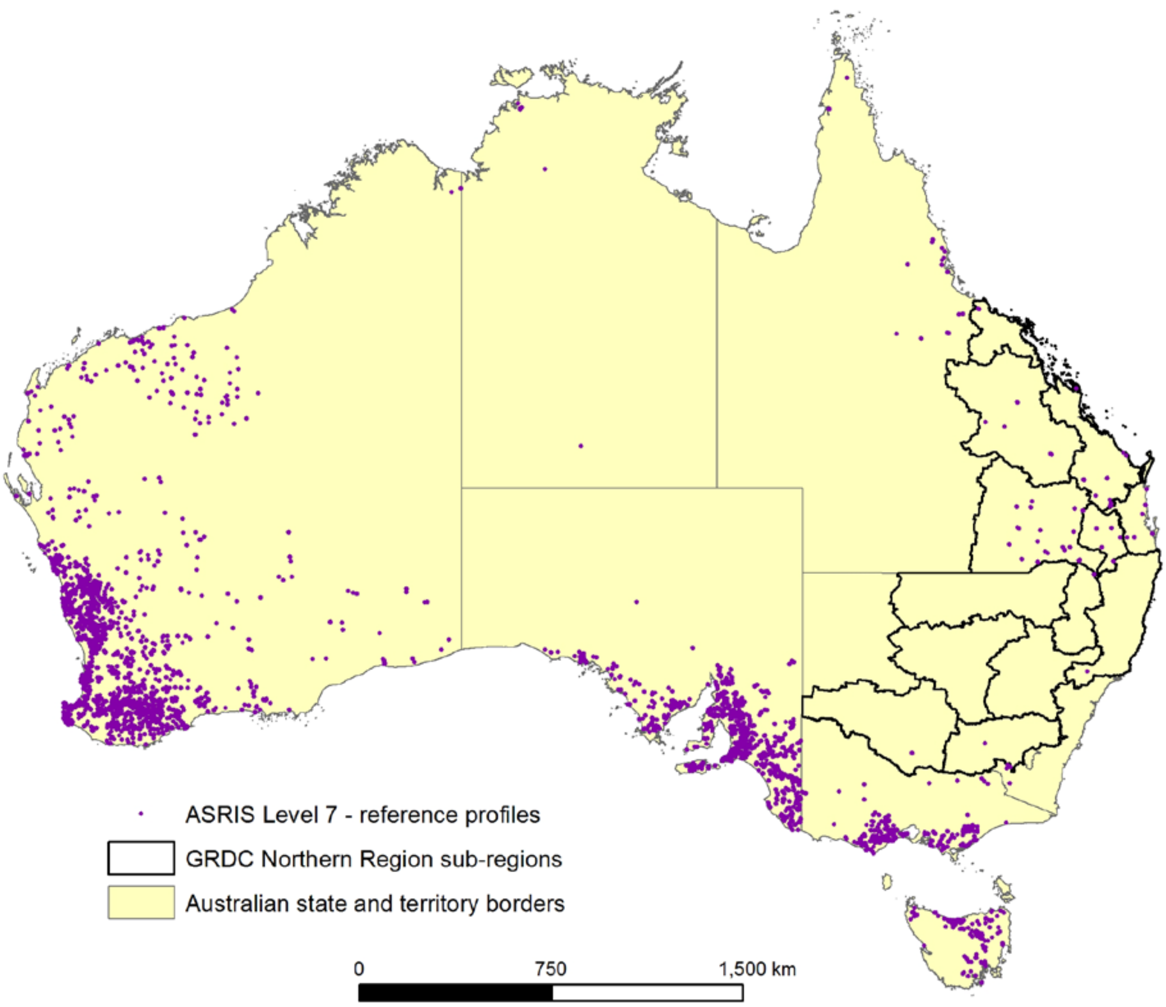

Figure 3.6. CSIRO’s Australian Soil Resource Information System soil database interface showing distribution of national soil reference profile sites.

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 3.8), and detailed discussions supported by morphological, chemical and physical data. Toposequence model cartoons are used to communicate terrain/soil relationships (e.g. Figure 3.9). 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.

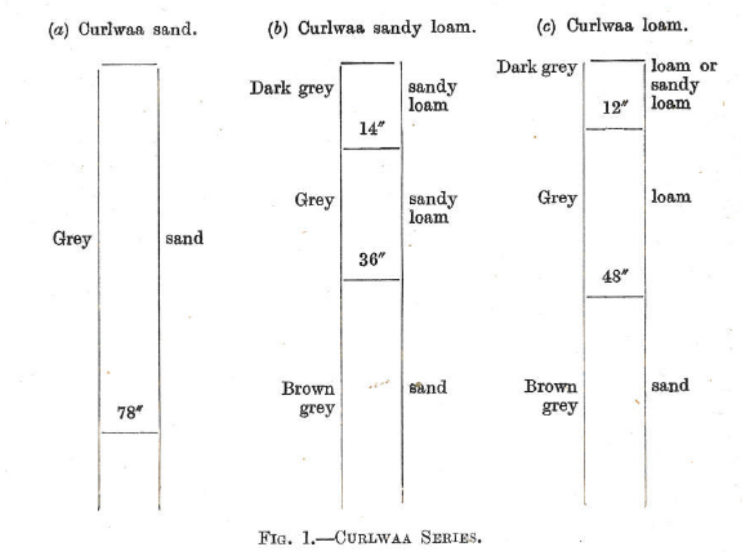

Figure 3.7. Soil profile morphologies of three soil associations comprising a soil series (Marshall and Walkley, 1937).

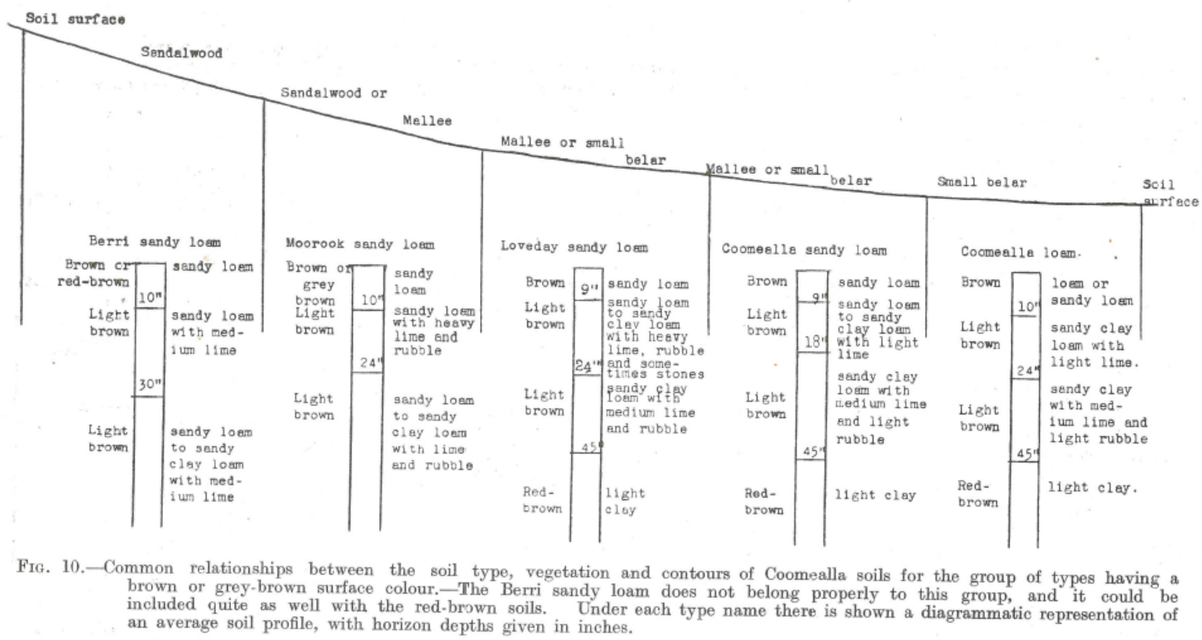

Figure 3.8. Use of slope position and natural vegetation to differentiate and communicate soil associations (Marshall and Walkley, 1937).

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, e.g. "General Report on the Lands of the Hunter Valley" and a series of reports on the Queensland Brigalow regions.

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 Northern region are listed in Table 3.1. 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 with potential to support PAWC work in the GRDC Northern Region.

Series	Report Title
Soil Bulletin	
73	A Soil survey of the Nyah, Tresco, Tresco West, Kangaroo Lake (Vic.), and Goodnight (N.S.W.) settlements / by J.K. Taylor
74	Observations on soil moisture and water tables in an irrigated soil at Griffith, N.S.W / by E. S. West
107	A soil survey of the Coomealla, Wentworth (Curlwaa) and Pomona irrigation settlements, N.S.W / by T. J. Marshall and A. Walkley
162	The soil and land-use survey of the Wakool Irrigation District, New South Wales / by R. Smith, R.I. Herriot, and E.J. Johnston
189	Soils of the Berriquin Irrigation District, N.S.W. / by R. Smith
259	The morphology and evolution of the soils of "Pine Lodge" estate, New South Wales / by E.J. Johnston
264	A pedological study of the soils occurring at Coomealla, New South Wales / by K.H. Northcote
289	A soil survey of the horticultural soils in the Murrumbidgee Irrigation Areas, New South Wales (2nd Ed) / by J. K. Taylor, B.E. Butler, P.D. Hooper
Soils and land use series	
1	The soils and horticultural potential of portion of the Coomealla irrigation area, New South Wales / by K.H. Northcote and E.W. Boehm
5	Soils of Deniboota Irrigation District and their classification for irrigation / by E.J. Johnston
9	Soils of the Abermusden Irrigation Area, New South Wales / by B.E. Butler and R. Brewer
11	A survey of soils, and some aspects of soil fertility, in the Lismore District, New South Wales / by K.D. Nicholls, J.D. Colwell and B.M. Tucker
18	Jernargo extension of the Berriquin Irrigation District, New South Wales / by H.M. Churchward and S.F. Flint
19	The soils of the East Murrakool district, New South Wales, and their relation to land use under irrigation / by H.M. Churchward
27	The soils and land use of the Denimein Irrigation District, New South Wales
28	Soils and land use in the Toowoomba Area, Darling Downs, Queensland / by C.H. Thompson and G.G. Beckmann
37	Soils and land use in the Kurrawa area, Darling Downs, Queensland / by G.G. Beckmann, C.H. Thompson
38	A reconnaissance of the soils and land use of part of the South Coast of New South Wales / by P.H. Walker
39	The soils of the Lower Murrakool District, New South Wales / by H.M. Churchward
40	Soils of the southern portion of the Murrumbidgee Irrigation Areas / D.C. Van Dijk
43	Soils and vegetation of the Brigalow lands, eastern Australia / by R.F. Isbell
44	A reconnaissance of soils in the Kempsey district, N.S.W / by P.H. Walker
46	Soils and land use in the Dorrigo-Ebor-Tyringham area, New South Wales / by W.M. McArthur
47	Soils of portion of the Coleambally Irrigation Area, N.S.W. / by T. Talsma
48	Soils of the East Bald Hill area, Collinsville district, North Queensland / by R.F. Isbell
56	The soils of the Central Burnett Area, Queensland / by G.D. Hubble, G.G. Beckmann
62	Soils of the southern Lockyer Valley, Queensland / by G.G. Beckmann and I.P. Little

Soil Publications	
1	Pedology of the Deniboota Irrigation District, New South Wales / by E. J. Johnston.
2	Pedology of part of the Upper Hunter Valley, New South Wales / by R. Brewer and B.E. Butler.
4	The soils of the Macquarie Region, New South Wales / by R.G. Downes and J.R. Sleeman.
5	Mineralogical examination of a yellow podzolic soil formed on granodiorite / by R. Brewer.
7	Pedology and chemistry of the basaltic soils of the Lismore District, N.S.W / by K.D. Nicolls and B.M. Tucker.
10	Depositional systems of the riverine plain of south-eastern Australia in relation to soils / by B. E. Butler.
11	Principles of soil distribution in the Griffith-Yenda district, New South Wales / by D.C. van Dijk.
14	Periodic phenomena in landscapes as a basis for soil studies / by B.E. Butler
21	The soils of the Central Portion of the New England Region, New South Wales / by R.W. Jessup.
28	Groundsurfaces of the Wagga Wagga region, New South Wales / by J. A. Beattie.
CSIRO Soils Technical paper	
28	Red basaltic soils in North Queensland / by Isbell R.F., P.J. Stephenson, G.G. Murtha, G.P. Gillman
30	Some properties of red, yellow and grey massive earths in North Queensland / by R.F. Isbell
33	Use of soil and land-system maps to provide soil information in Australia / P.H.T Beckett, S.W. Bie
34	Brown basaltic soils in North Queensland / by R.F. Isbell
CSIRO Soils Divisional Report	
5/57	Soil survey of the C.S.I.R.O. experimental farm, Samford, Queensland / by G.G. Beckmann
1/60	The laboratory examination of soils from the Toowoomba and Kurrawa areas, Darling Downs, Queensland / by R. Reeve, G.G. Beckmann, C.H. Thompson
7/61	Soil and climatic data for the Brigalow lands, Eastern Australia / by R. Reeve, R.F. Isbell, G.D. Hubble
17	The soils on three major rock types in the Upper Brisbane Valley, Southeastern Queensland / by G.G. Murtha
25	Reconnaissance study of dark subsoil bands in the Condamine-Balonne Valley, south-east Queensland / by D.C. van Dijk
47	Salt and soil reaction patterns in the Tara Brigalow lands, South-east Queensland / by D.C. van Dijk
53	Texture differentiation in soils on hillslopes, south-eastern Queensland / by C.H. Thompson and T.R. Paton
60	Morphology and particle-size characteristics of the red, yellow and grey earths and associated soils of the Torrens Creek area, central North Queensland / R.J. Coventry and D.E.R. Fett
78	A Survey of the physical properties of wheatland soils in eastern Australia / J.A. Forrest
83	Soils of the Wycanna Woodland Experiment Centre, Talwood, South Maranoa Region, Queensland / by D.J. Ross
106	Hydrology of small catchments at the Narayen Research Station and the effects of land use change / by R.E. Prebble and G.B. Stirk
117	Soils of the lower Macquarie Valley, New South Wales / by N.J. McKenzie
121	Application of continuous methods of soil classification and land suitability assessment in the lower Namoi Valley / by J. Triantafilis, A.B. McBratney

Land Research Surveys	
8	General report on the lands of the Hunter Valley / by R. Story, A.D. Tweedie, R.H.M. van de Graaf and R.W. Galloway
18	Lands of the Nogoa–Belyando Area, Queensland / by R.H. Gunn, E.A. Fitzpatrick, L. Pedley and R.W. Galloway
19	Lands of the Isaac–Comet Area, Queensland / by R. Story, E.A. Fitzpatrick, R.H. Gunn and R.W. Galloway
21	Lands of the Dawson–Fitzroy Area, Queensland / by N.H. Speck, R.L. Wright, F.C. Sweeney, I.B. Wilson, E.A. Fitzpatrick, H.A. Nix, R.H. Gunn and R.A. Perry
34	Lands of the Balonne–Maranoa Area, Queensland / by R.W. Galloway, R.H. Gunn, J.D. Kalma, K.D. Cocks and L. Pedley
39	Land Units of the Fitzroy Region, Queensland / by H.A. Nix and R.H. Gunn
Other	
	Atlas of Australian soils : explanatory data for sheet 3 Sydney-Canberra-Bourke-Armidale area / by K.H. Northcote
	Atlas of Australian soils : explanatory data for sheet 4 Brisbane-Charleville-Rockhampton-Clermont area / by K.H. Northcote

3.5 Qld Soils Mapping

The Queensland Government Soils Series data and metadata are available from https://data.qld.gov.au/dataset/soils-series and shown in Figure 3.10. As seen, the distribution is piecemeal and each survey has been conducted for different purposes and mapped at different scales. Some of these surveys correspond with reports mentioned in Section 3.3. Soil and landscape concepts underpinning what is termed soil series are likely to vary accordingly. Scales range from 1:5 000 over small areas (e.g. 5 ha) up to 1:250 000 over 22,000 km^2. The distribution of soil series mapping is limited in Queensland's dryland cropping areas (Figure 3.10), and whether useful for PAWC estimations or correlations in the areas that are mapped will be dependent on the scale of mapping and the concepts behind the soil series mapping.

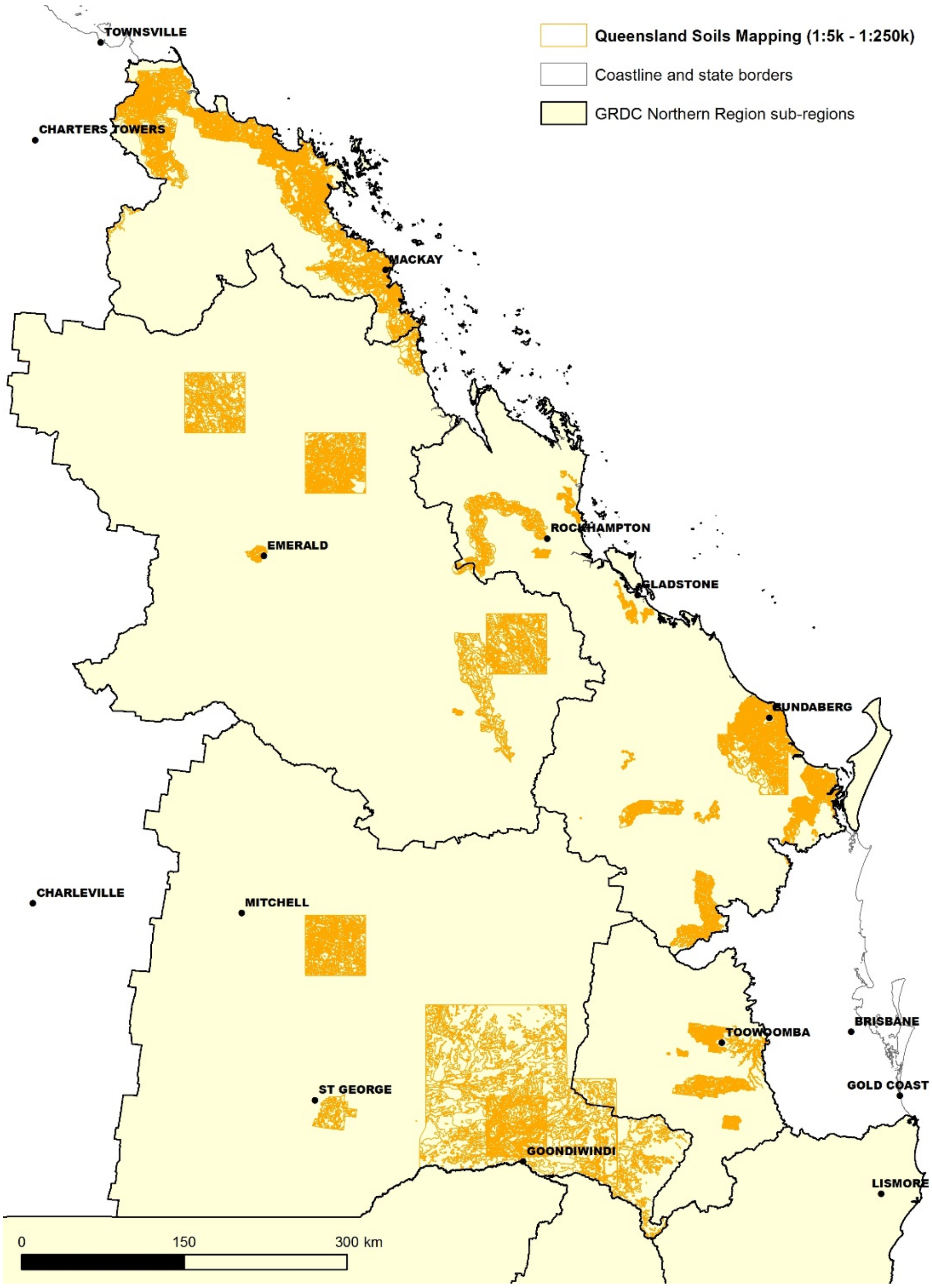

Figure 3.9. Queensland Soil Series mapping within the GRDC Northern Region.

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 NSW soil and land mapping

For NSW, a variety of mapping types are available, with most maps viewable and accessible through eSpade (http://www.environment.nsw.gov.au/eSpade2Webapp). The suite of land and soil mapping products for NSW include:

- Soil Landscapes Mapping
- Soil and Land Resource Mapping
- Hydrogeological Landscapes Mapping
- Land Systems Mapping

4.1.1 NSW Soil landscape mapping

The NSW Soil Landscape Mapping viewable in NSW eSpade is a compilation of 39 soil landscape maps covering central and eastern NSW, with extents aligning with the standard 1:100 000 or 1:250 000 topographic map sheets. Of these, seventeen 1:100 000 maps and six 1:250 000 maps are within the identified GRDC Northern Region sub-regions (Figure 4.1). In addition there are three unpublished soil-landscape maps covering the 1:250 000 sheets of Narromine, Nyngan and Walgett. The data and metadata of the published maps and accompanying reports (where available), can be downloaded from http://www.environment.nsw.gov.au/topics/land-and-soil/soil-data/soil-maps.

The information and mapping approach is not seamless but is discrete to each individual map sheet area. The exceptions to this are the 1:100 000 maps in the Liverpool Plains area (by Rob Banks) and the three unpublished 1:250 000 maps in the Central West catchment (by team including Brent Forbes, David Duncan, Brian Murphy, Neroli Brennan and Andrew Wooldridge), where approaches and soil-landscape mapping units do extend across map boundaries so that the line work is seamless at map edges and there are no border effects.

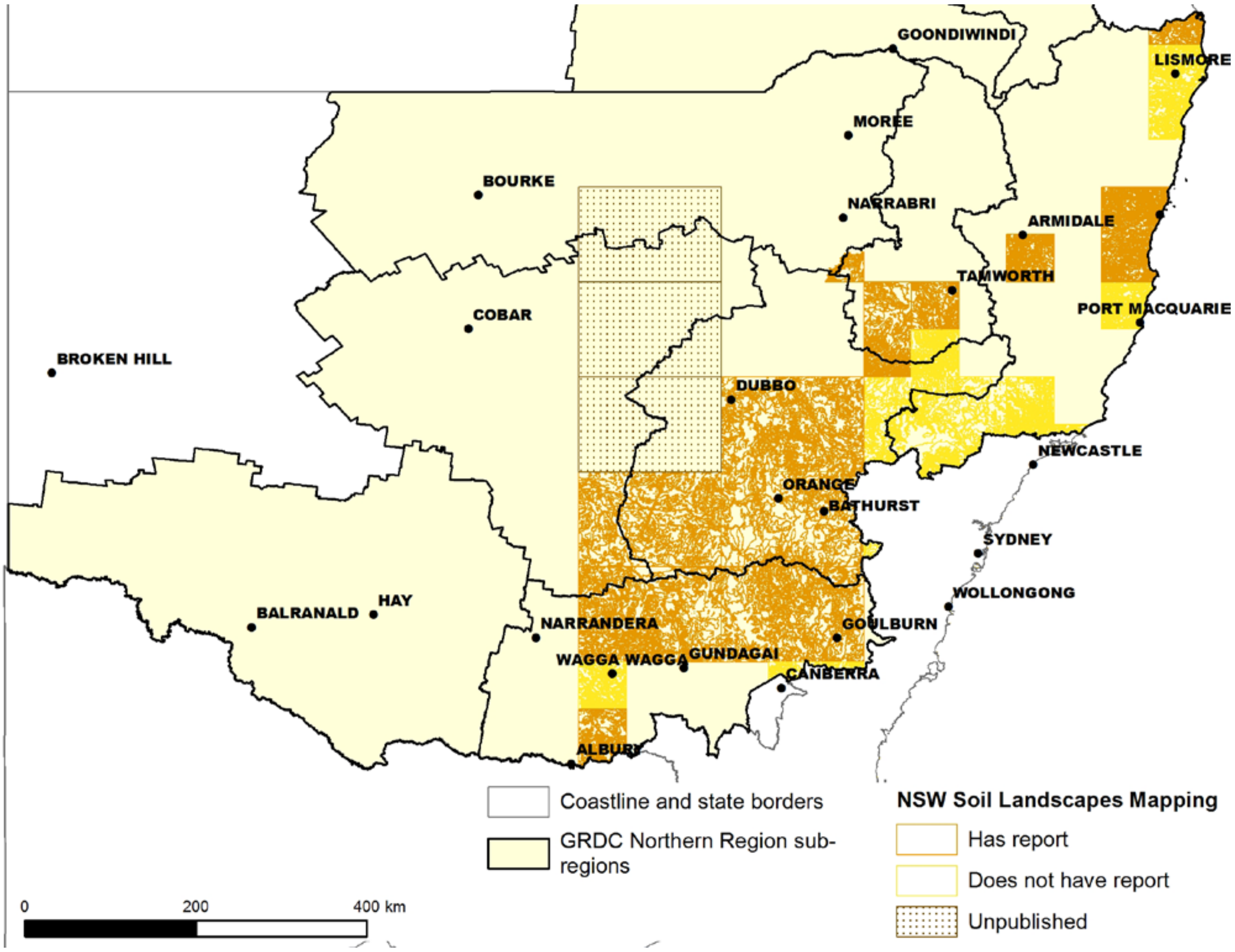

Figure 4.1. NSW Soil Landscape Mapping within the GRDC Northern Region. Unpublished datasets exist for the Narromine, Nyngan and Walgett 1:250,000 map sheets.

At 1:100 000 or 1: 250 000 it is in most landscapes not feasible to map individual soil types (G. et al., 2001). The NSW soil landscape maps, therefore focus on repeating patterns of soil to map soil landscapes. These are defined using a definition of Northcote (1978) as areas of land that “have recognisable and specifiable topographies and soils, that are capable of presentation on maps, and can be described by concise statements” (Edye et al., 2001; Goldrick et al., 2001; Murphy et al., 2001). Soils and the landscape have similar factors of formation (Murphy et al., 2001) and this close association allows both soil and landscape characteristics to be integrated into a single soil-landscape unit (Edye et al., 2001).

The approach to the soil landscape mapping in NSW differs by map sheet, except where the same authors were involved with multiple map sheets. All maps have in common, however, that the accompanying reports include for each soil-landscape unit a description of the landscape, geology, topography, (native) vegetation, land use and dominant soil types. The latter are often presented in a diagram/cross section of the landscape. In addition the reports comment on degradation issues, soil and landscape limitations, including fertility, salinity, sodicity, alkalinity, permeability and hazards such as erodibility or flooding.

As the information on soil types is not mapped, but contained in the descriptions of the soil-landscape units, the soil landscape maps cannot be used to map PAWC. The information can, however, still be used to predict PAWC at a site or to extrapolate from known APSoil PAWC sites using the soil-landscape understanding contained in the combination of map and accompanying report. The *Glovebox guide to Soil of the Macquarie-Bogan Flood Plain* (Hulme, 2003) , the land management manuals accompanying some of the land resource area mappings in Queensland (e.g. Central Darling Downs Land Management Manual; Harris et al., 1999) and several *Soil Specific Management Guidelines for Sugarcane Production* in different sugarcane growing areas from northern NSW to northern Queensland (e.g. Wood et al 2003) are based on the same concept. The mapping units identify the soil-landscape units. Soils within these are identified by their position in the landscape and/or visible properties, with their characteristics, features and management issues described to assist the growers and advisors.

GRDC Project CSP00170 used the NSW soil landscape maps to identify the locations for new APSoil sites (Liverpool Plains and Macquarie-Bogan Flood Plain) and to summarise the obtained PAWC data in an attempt to provide some initial generalisations (Verburg et al. 2017). While this work requires further testing, the PAWC profiles were found to match the soil descriptions (e.g. texture and subsoil constraints) of the soil landscape units well. Some soil landscape units with multiple APSoil PAWC characterisations also demonstrated good consistency between the different PAWC profiles, whereas others showed variability that could be explained by different levels of subsoil constraints (see e.g. Figure 4.2).

In another study (Verburg et al., 2015a; Verburg et al., 2015b) the soil-landscape diagram contained in the soil-landscape unit description was used to explain to local growers and advisors the soil forming factors leading to the different soil types and the implications for both PAWC and soil chemical properties. This was found to correlate well with the farmer’s management experience (Figure 4.3).

These approaches that use the soil landscape mapping and unit information to build a narrative for growers and advisors or provides generalised PAWC profiles for different positions within a landscape will be tested further in the current GRDC project.

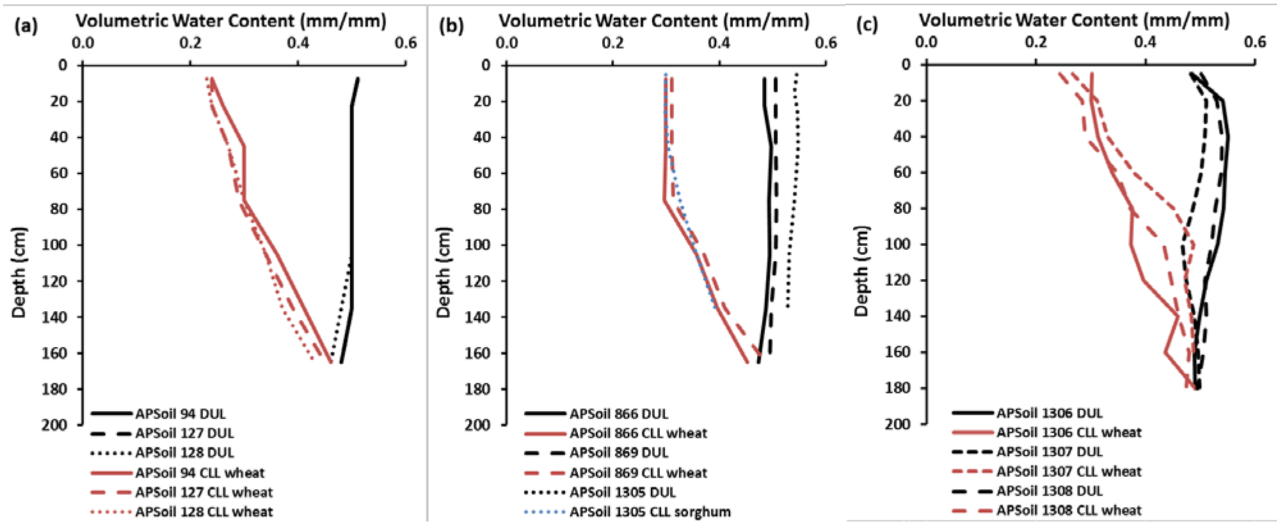

Figure 4.2. APSoil PAWC profiles in select soil-landscape units (SLUs) within the Liverpool Plains; (a) Nooje SLU, (b) Conadilly SLU (southern area between sand hills), and (c) effect of subsoil salinity on variability in PAWC within Yarraman SLU. Based on data presented in Verburg et al. (2017).

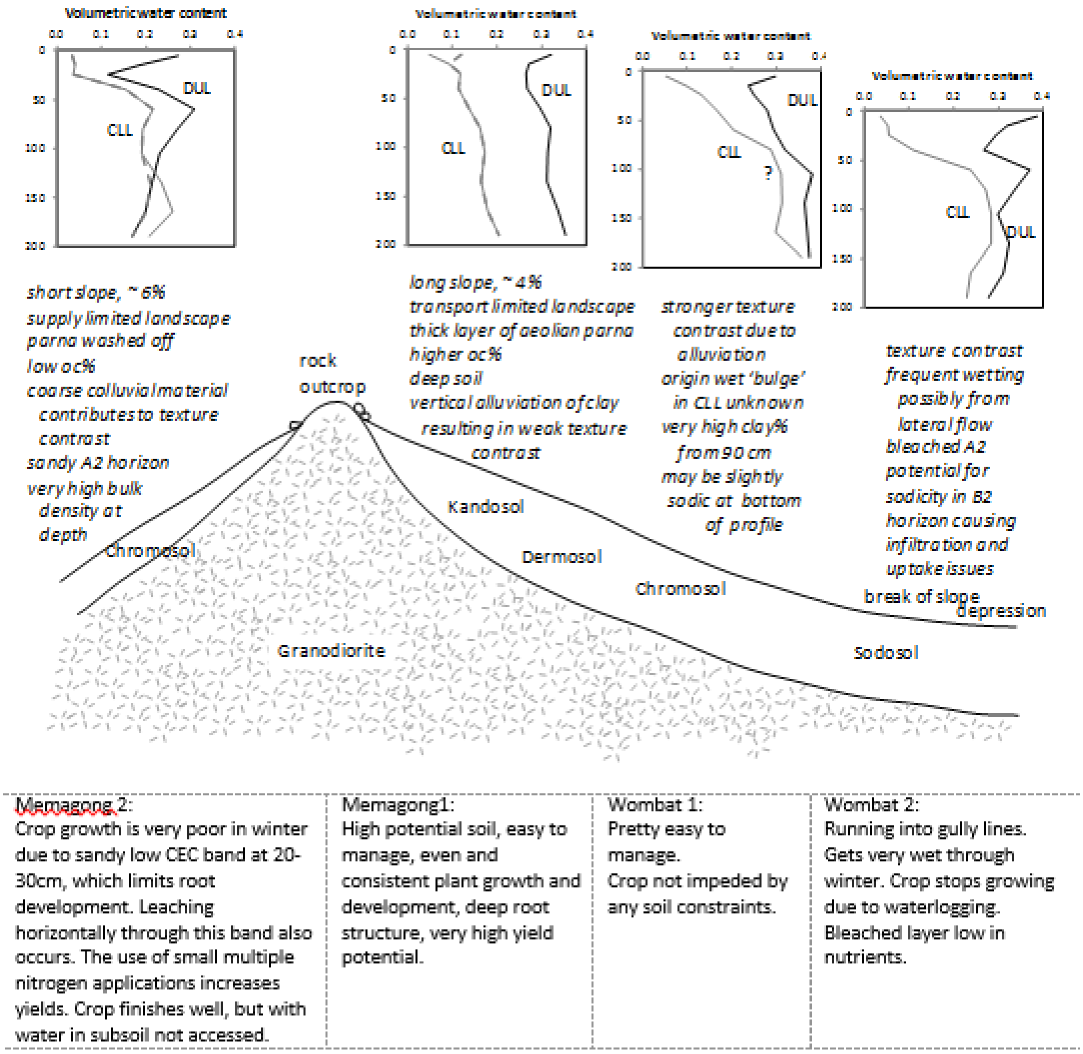

Figure 4.3. Schematic linking four different PAWC profiles, associated chemistry and their management implications to relative slope positions in the Young granodiorite hills.

Source: Verburg et al. (2015a) GRDC Wagga Wagga Update February 2015

4.1.2 NSW Soil and Land Resource Mapping

The NSW Soil and Land Resources mapping viewable through NSW eSpade is an enhancement of the Soil Landscape mapping to create seamless datasets across six catchment areas, four of which are within the GRDC Northern Region (Figure 4.4): the Murray Catchment, the Moree Plains, the Liverpool Plains catchment and the Merriwa Plateau, although the latter has little cropping. The data and a brief description of each mapping area is available from http://www.environment.nsw.gov.au/topics/land-and-soil/soil-data/soil-maps.

As with the NSW soil landscape mapping in Section 4.1, each soil and land resource unit is an inventory of soil and landscape information with relatively uniform land management requirements, allowing major soil and landscape qualities and constraints to be identified. Soils are described using the Australian Soil Classification and the Great Soil Groups systems. In parts of Liverpool Plains where both soil landscape mapping and soil and land resource mapping are available, the mapping units and their naming are the same. The accompanying report for each mapping unit of the soil and land resource mapping also draws on that of the matching soil landscape unit, but tends to be a bit briefer and does not include the landscape diagram.

The value of the soil and land resource mapping for PAWC extrapolation and prediction is mainly in the areas where the soil-landscape maps are not available: the western part of the Liverpool Plains, the Moree Plains and the Murray catchment on the border with Victoria. Although without landscape diagrams, interpretation of relative position of different soil types within the mapping units may be more difficult.

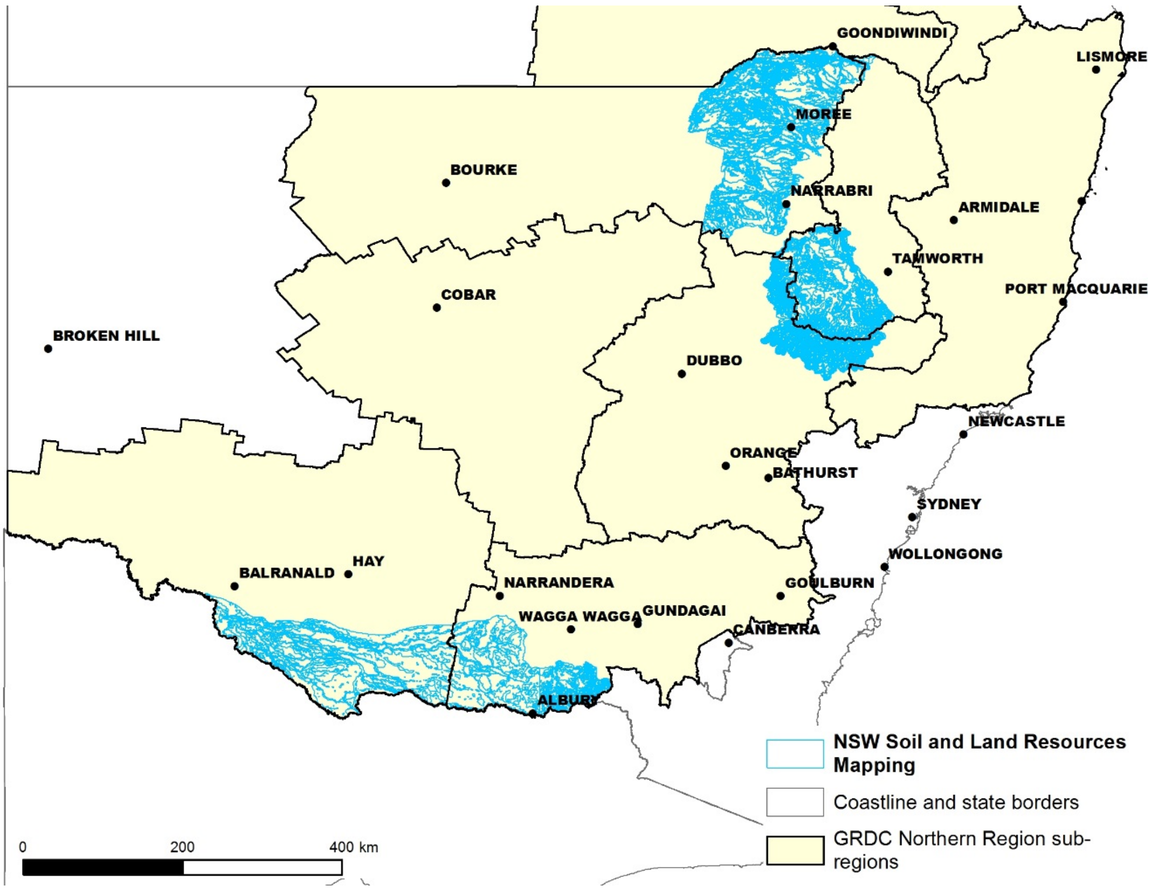

Figure 4.4. NSW Soil and Land Resource Mapping within the GRDC Northern Region. Data are within the Murray Catchment, Moree Plains, Liverpool Plains and Merriwa Plateau.

4.1.3 NSW Hydrogeological Landscapes Mapping

A third type of landscape mapping provided in NSW eSpade is the NSW hydrogeological landscape mapping. A hydrogeological landscape describes the soil, rocks, climate and landforms that influence salinity in a given area, and provides salinity management options for specific parts of the landscape. A hydrogeological landscape unit defines areas of similar salt stores and pathways for salt movement. See http://www.environment.nsw.gov.au/topics/land-and-soil/soil-degradation/salinity/salinity-locations-and-mapping. The current extent of this mapping within the GRDC Northern region is shown in Figure 4.5. The large area covered by the Central West catchment would be of most interest.

In some places the mapping of hydrogeological landscapes draws on the soil-landscape information, but the boundaries of the units differ. The hydrogeological landscapes tend to group some soil landscape units, e.g. the back plains and associated meander plains and include parts of nearby soil-landscape units where they relate to salt movement.

While the reports include some reference to soil-landscape units and soil types found within the hydrogeological landscape, it does not appear useful for PAWC interpretation, except where landscape diagrams within the reports can help explain the landscape or provide insights into subsoil constraints driven by salinity or sodicity. Maps of salinity and sodicity hazards are also available.

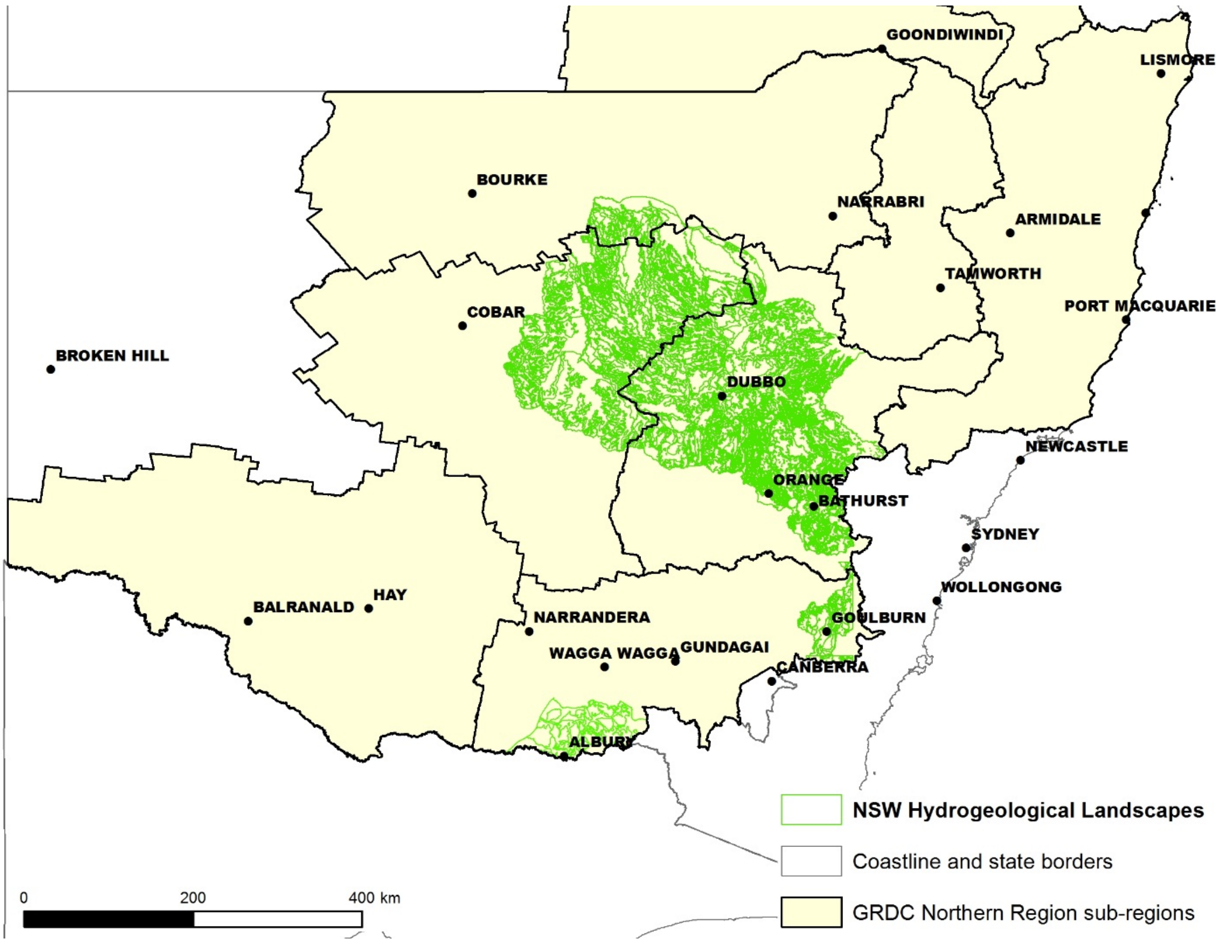

Figure 4.5. NSW Hydrogeological Landscapes Mapping within the GRDC Northern Region.

4.1.4 NSW Land Systems Mapping

Land systems are areas or groups of areas throughout which there is a recurring pattern of topography, soils and vegetation. NSW eSpade provides access to mapping of 251 land systems for Western NSW (Figure 4.6). The mapping and accompanying reports provide soil and land resource information suitable to assist in broad scale land-use planning and land management. The land systems were mapped at a scale of 1:250,000 scale. Data and metadata are available from: http://data.environment.nsw.gov.au/dataset/land-systems-of-western-new-south-wales0f783

The coverage of this mapping is mostly outside the cropping zone, except the western edge of the cropping zone west of Walgett, west of Nyngan and northwest of Condobolin.

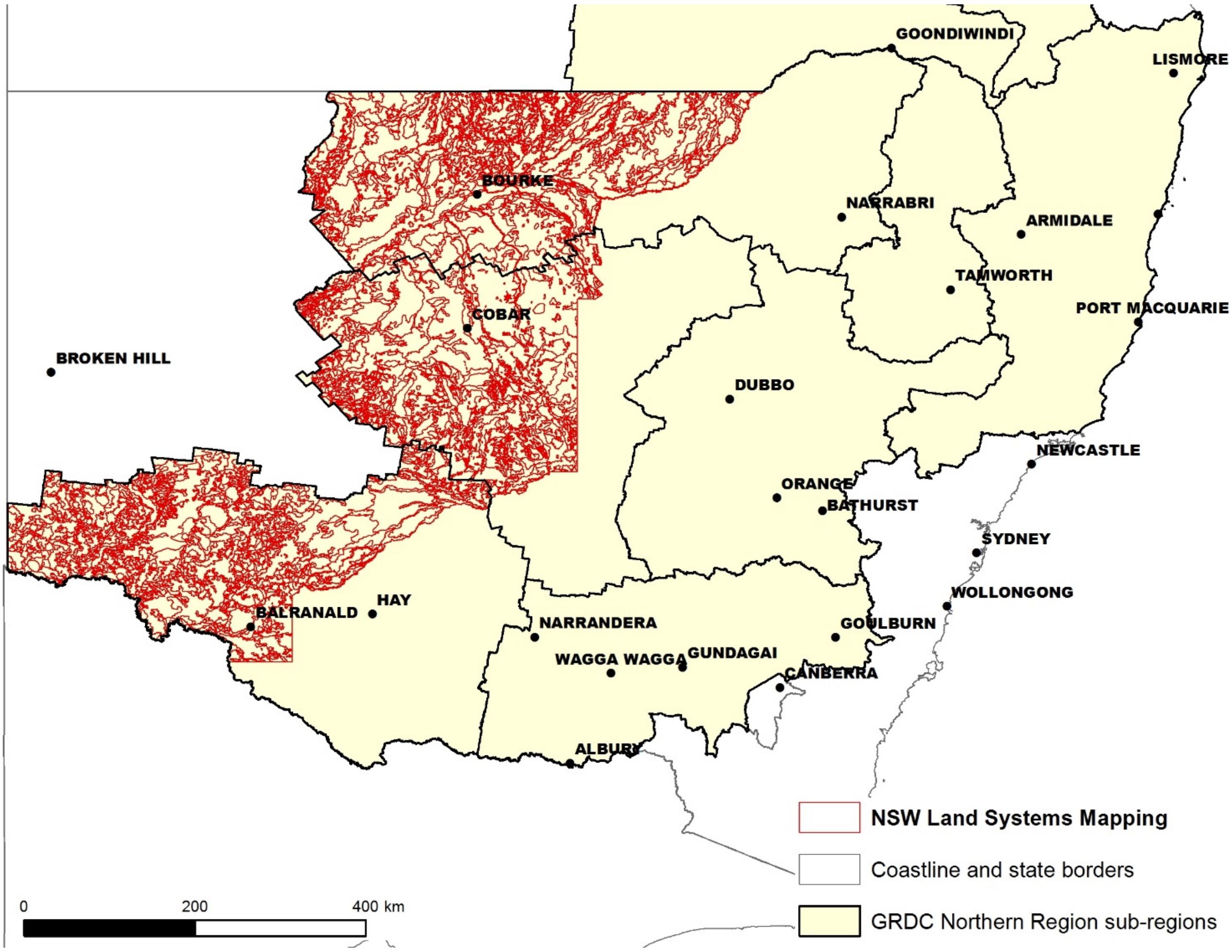

Figure 4.6. NSW Land Systems Mapping within the GRDC Northern Region.

4.2 Qld soil and land mapping

For Queensland, similar information is available through the Queensland Globe (https://qldglobe.information.qld.gov.au/). The suite of land and soil mapping products for Qld include:

- Land Resource Area Mapping
- Land Systems Mapping
- Various soils Mapping (see Section 3.4)

4.2.1 Qld Land Resource Area Mapping

Land Resource Area mapping in Queensland is similar to the NSW Soil Landscape Mapping and the NSW Soil and Land Resource Mapping. It is accessible via Queensland Globe, and the distribution of mapping is presented in Figure 4.9. Further information is available here: https://data.qld.gov.au/dataset/land-resource-areas-series.

Queensland's Land Resource Area (LRA) program started in 1979. Focussing on farming districts, the objectives of the program included to define major agricultural soils and give soil conservation guidance for the major soils. Land resource areas are units of land based on geological and landform characteristics with a recurring pattern of soils and vegetation. The scale of mapping ranges from 1:100,000 to 1:500,000, and so LRA mapping may vary significantly in terms of mapping concepts behind these, and the level of spatial information regarding the distribution of soils that may be gleaned from them; usage of mapping should therefore assessed on a case-by-case basis. This is illustrated by comparing Figure 4.7, which shows a proportion of the Central Highlands (CHL) LRA mapping 1:500,000 scale with Figure 4.8 that shows a portion of the Sandstone Waloons (AGW) mapped at a scale of 1:100,000 scale. Each cover the same area on the ground (90,000 ha), and despite the Central Highlands representing a lower rainfall and more extensive landscape compared to the Sandstone Waloons mapping, the level of information presented in each is considerably different, which will be reflected in the soil mapping and descriptions.

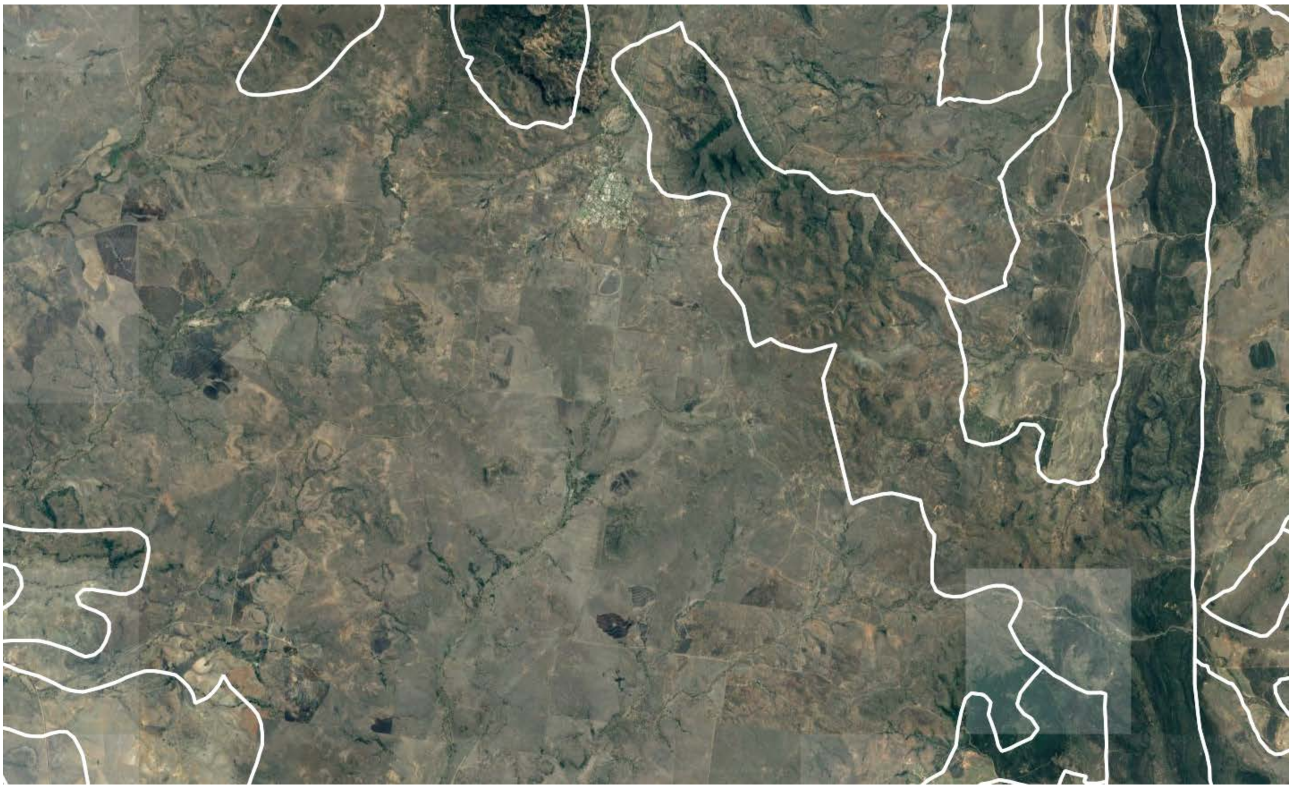

Figure 4.7. 90,000 ha extract of Central Highlands (CHL) Land Resource Area mapping mapped at 1:500,000 scale.

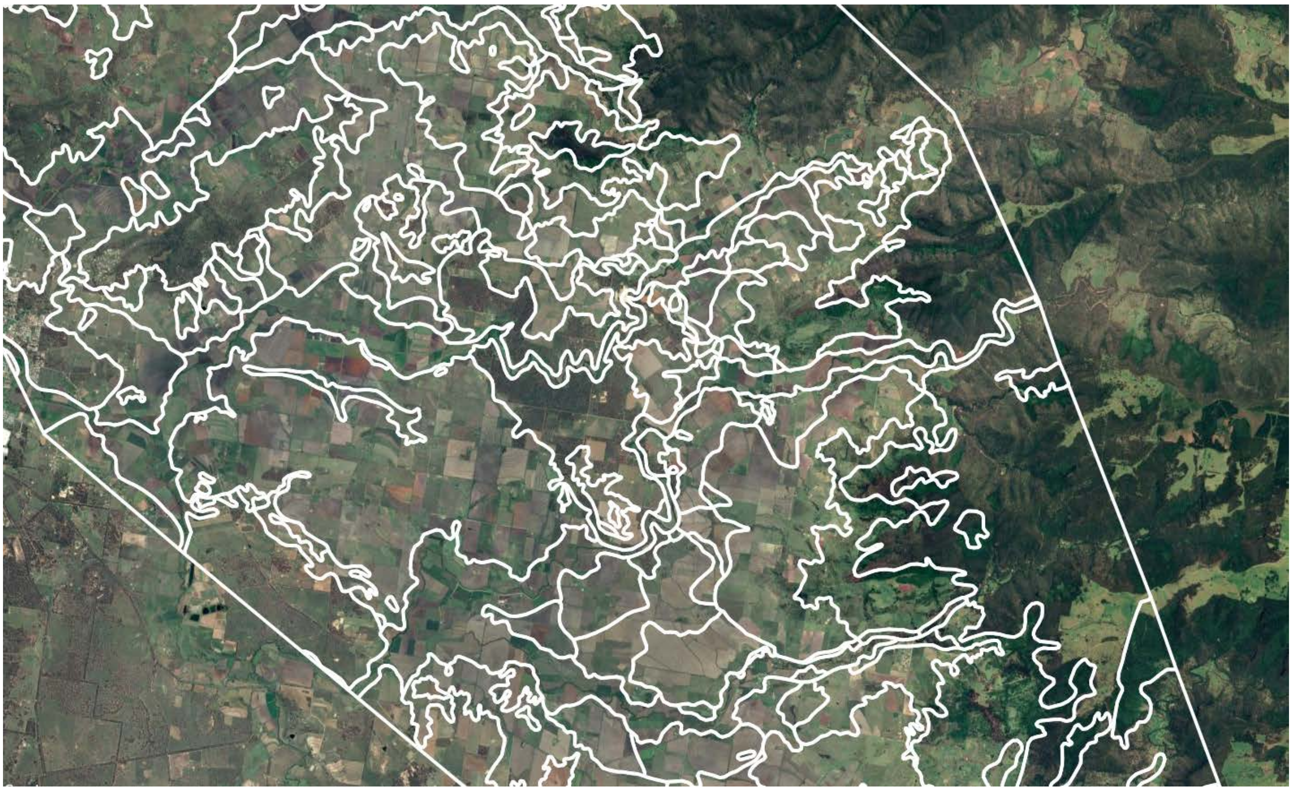

Figure 4.8. 90,000 ha extract of Sandstone Waloons (AGW) Land Resource Area mapping at 1:500,000 scale.

As in NSW, the information about the different soil types within the LRAs is contained in the description of the LRAs. The information is hence not suitable for mapping of PAWC, but can inform predictions or extrapolations from APSoil PAWC sites.

The LRA mapping shown in Figure 4.9 is divided into 12 survey areas and maps. As in NSW the mapping approaches and level of detail differs by map. The Central Darling Downs LRA mapping and manual (Harris et al., 1999) is the most detailed. It is also underpinned by a local soils classification. Figure 4.10 shows an example presented at the 2016 GRDC Research Update in Goondindi (Verburg et al., 2016b) that illustrates the possible use of this LRA map to estimate PAWC for a location of interest. Drawing on the LRA unit descriptions in the accompanying manual (Figure 4.10a) and considering the mapping within Google Earth (Figure 4.10b), allows one to identify the LRA unit – in this case "LRA 1a: Broad level recent alluvial plains of mixed basaltic and sandstone alluvium." The descriptions and diagrams (Figure 4.10c) of this LRA in the manual are then used to identify the local soil type, which can then be matched the relevant APSoil profiles for that soil type, where Figure 4.10d and e are examples of contrasting soil types with different size PAWC.

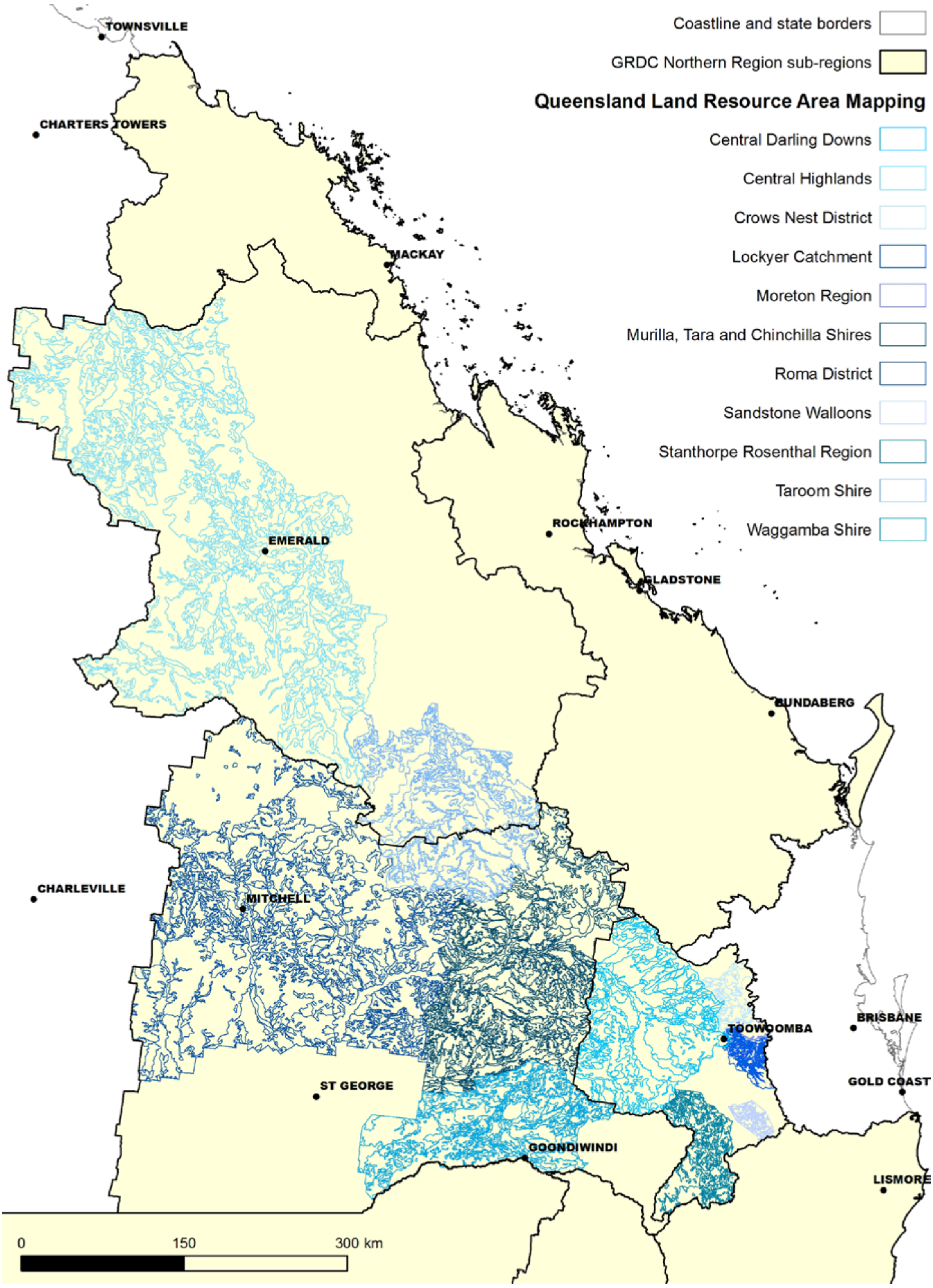

Figure 4.9. Queensland Land Resource Area mapping within the GRDC Northern Region.

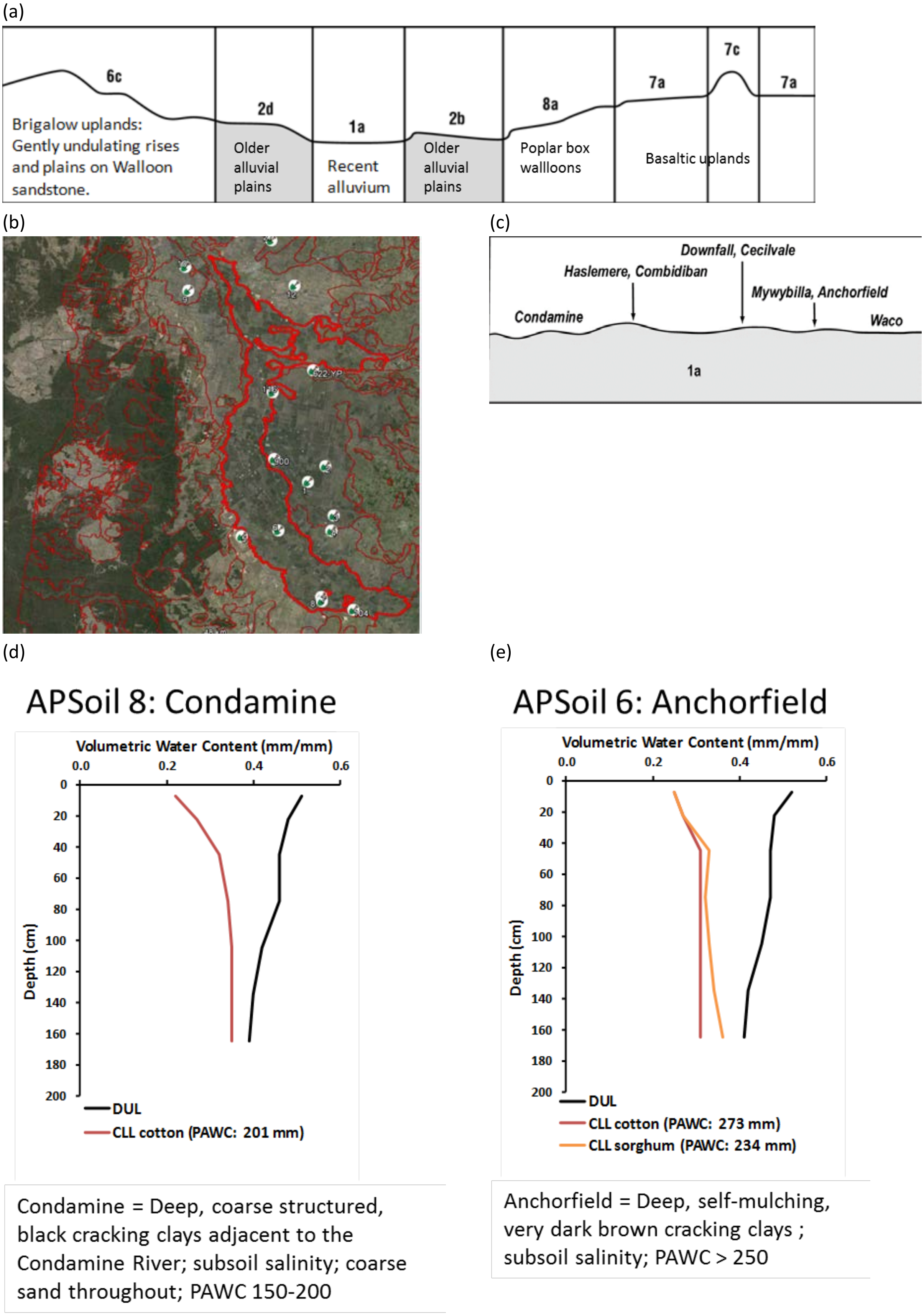

Figure 4.10. Example illustrating possible use to draw on LRA unit descriptions (a) and mapping (b) to identify the local soil type at a location of interest using descriptions of the local soils provided in the accompanying manual and (c) and matching these with APSoil profiles (d,e) for that soil type.

4.2.2 Qld Land Systems Mapping

The Queensland Globe online data access points also supplies Land Systems mapping presented in Figure 4.13 (https://data.qld.gov.au/dataset/land-systems-series). Land System mapping units comprise a recurring pattern of geology, topography, soils and vegetation. Mapping scales vary between 1:70,000 scale (e.g. Three Mon Creek (3MC) and 1:500,000 (e.g. Isaac-Comet (ZDK3), although most are mapped at 1:250,000 scale, and many were generated during the 1950s and 1960s. Indeed, a number of the Land Systems maps in Queensland and presented in the online Queensland Globe tool were generated by CSIRO (see Section 3.1). It is likely that many of the mapping scale and soil mapping limitations highlighted in the Land Resource Area discussion of the previous section will be repeated for the PAWC work, namely many of the mapping scales and soil information that the reports contain will be too coarse for PAWC estimations and correlations. Examples are shown in Figure 4.11, which shows Land Systems mapping for Three Moon Creek area mapped at 1:70,000 scale, compared to the 1:500,000 scale Land Systems mapping of Isaac-Comet area shown in Figure 4.12. The Three Moon Creek area presents a significantly higher level of mapping detail compared to the Isaac-Comet area mapping, hence likely to be of greater utility in PAWC estimation and correlation work.

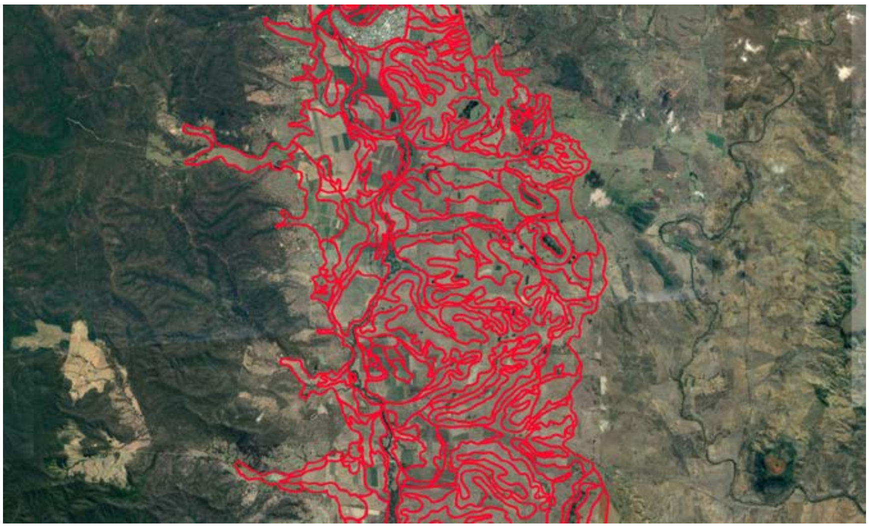

Figure 4.11. 90,000 ha extract of Three Moon Creek Land Systems mapping mapped at 1:70,000 scale.

Figure 4.12. 90,000 ha extract of Isaac-Comet Land Systems mapping mapped at 1:500,000 scale.

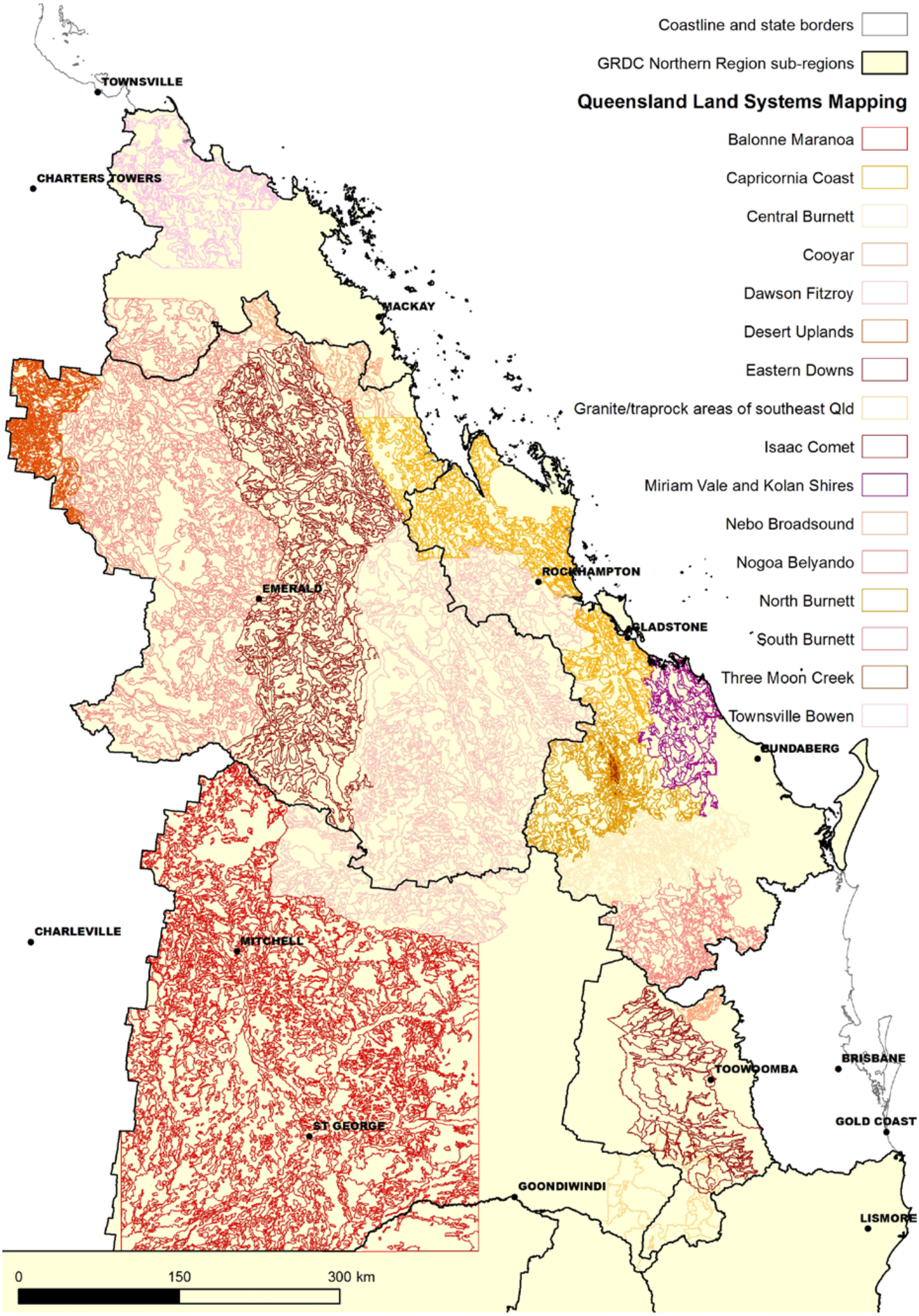

Figure 4.13. Queensland Land Systems mapping within the GRDC Northern Region.

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.

Access to online geological resources for NSW are available via https://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/geological-maps and for Queensland via https://data.qld.gov.au/dataset/queensland-geology-series.

The NSW maps are available at 1:250,000 and 1:100,000 scales:

- https://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/geological-maps/1-250-000
- https://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/geological-maps/1-100-000

The 1:250,000 maps cover all of NSW, whereas the 1:100,000 maps are more sporadic, but with a cluster of them in Central NSW. Comprehensive explanatory notes for many of these maps are available as reports that can be downloaded: https://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/books-and-brochures/explanatory-notes

The maps can be downloaded in a variety of formats, including georeferenced Google Earth overlays (KML file), which allows relative positions of APSoil PAWC sites to be compared (see e.g. Figure 5.1).

A continuous map of geology across NSW is available in the iPad NSWGeology application (https://itunes.apple.com/au/app/nsw-geology-maps/id986240992?mt=8). Internet versions of this map and a more detailed one are also available on-line: https://www.geoscience.nsw.gov.au/phonemaps/internetmaps

Individual maps sheets of state-wide geology maps and geophysics images (1:25,000 to 1:250,000) can also be viewed on iPad or Android using Gaileo or Locus Map mapping tools (see https://www.geoscience.nsw.gov.au/phonemaps/apple and https://www.geoscience.nsw.gov.au/phonemaps/android for instructions.

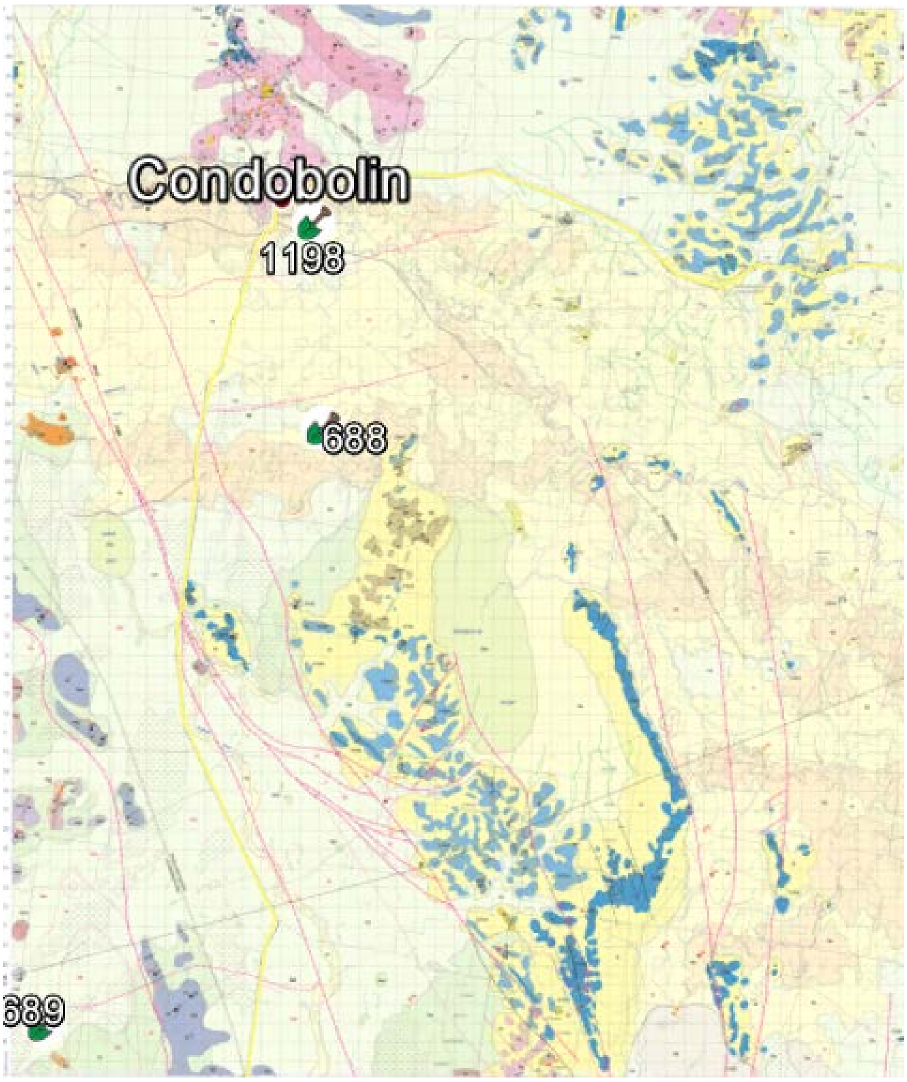

Figure 5.1. Screen grab of 1:100 000 Condobolin geology map viewed in Google Earth and showing APSoil sites relative to geology.

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.

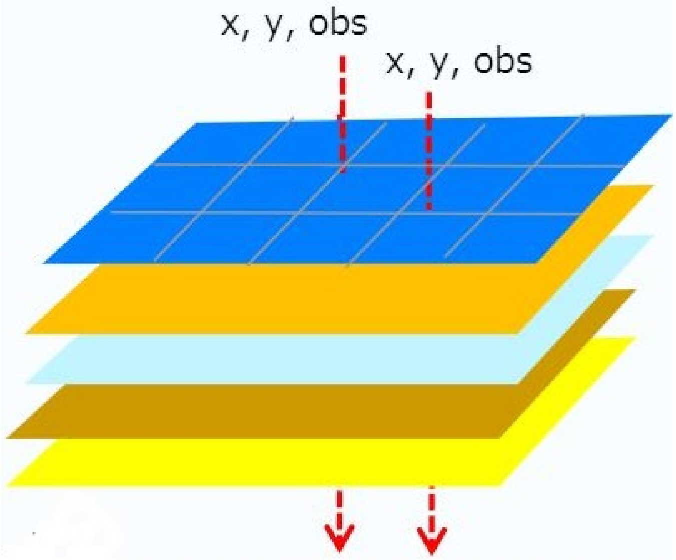

Figure 6.1. DSM models built from the spatial intersection of observations and covariates.

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 Landscape Grid of Australia

The Soil Landscape Grid of Australia (SLGA) represents the culmination of a national effort to create a suite of DSM soil attribute rasters (Grundy et al., 2015; Rossel et al., 2015). For NSW and Queensland a national SLGA soil attributes product is available. Each of the soil attributes in the suite 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 attribute estimates were based on a Cubist-kriging approach (Viscarra Rossel et al., 2015).

The soil attributes available as SLGA rasters at ~90 m (3 arc second) resolution are listed in Table 6.2. 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 the GlobalSoilMap suite (GlobalSoilMap Science Committee, 2011; Hartemink et al., 2010).

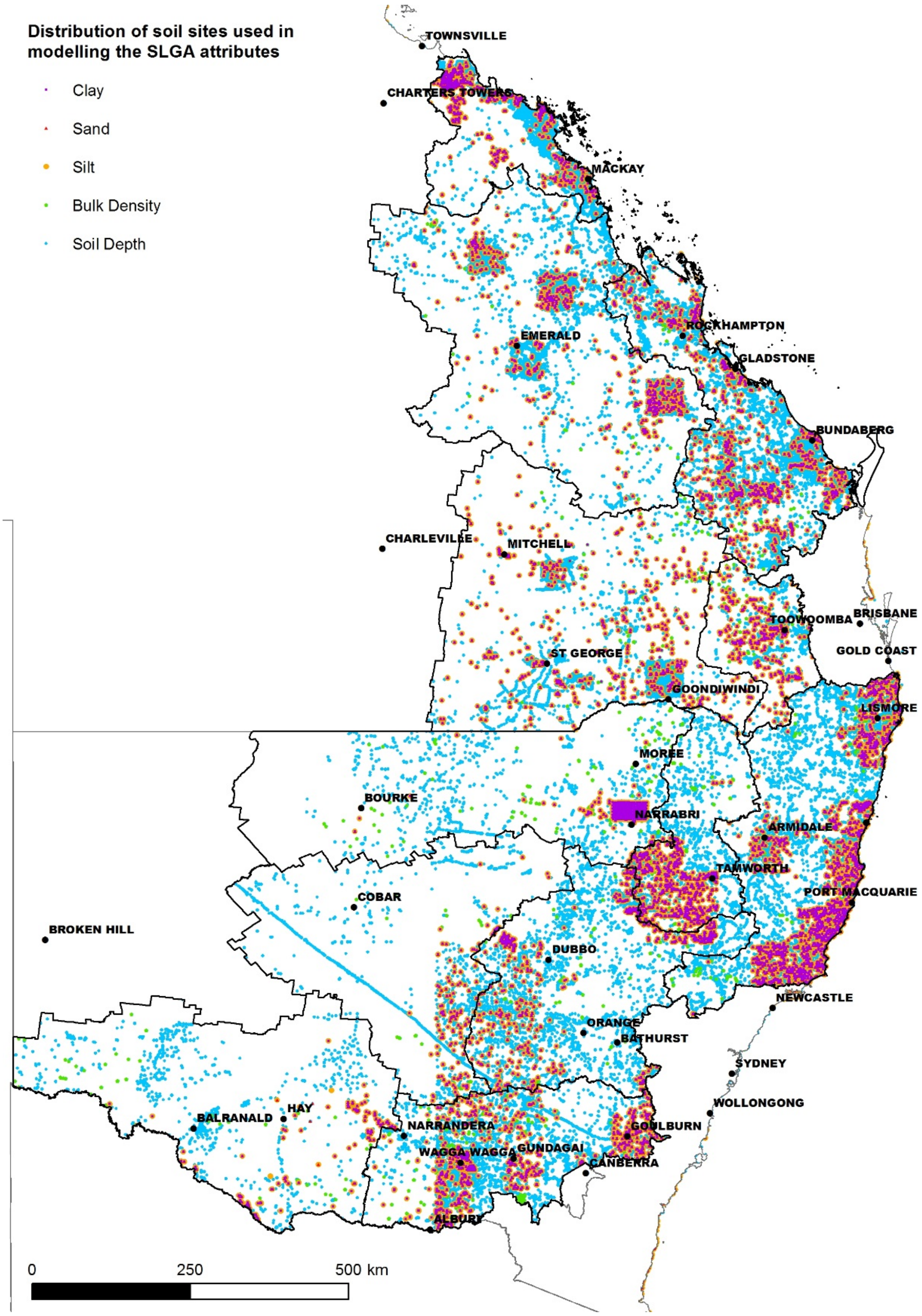

Figure 6.2. Distribution of soil records within the GRDC Northern Region which were used in SLGA attribute mapping. Note that many sites contributed information to the modelling of more than one attribute.

Table 6.1. Soil Landscape Grid of Australia 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/cm³)	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)

Figure 6.3 shows various SLGA national soil maps for an area near Tamworth in NSW. The figure includes clay (Figure 6.3a), sand (Figure 6.3b), silt (Figure 6.3c), available water capacity (Figure 6.3d), and bulk density (Figure 6.3e) for the 5-15 cm depth layer. Depth of soil (Figure 6.3f) represents the A & B horizons. 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.

Figure 6.4 shows the 90% confidence intervals for the prediction of % clay at 5-15 cm depth for the whole of the GRDC Northern Region as well as the area near Tamworth NSW. The 90% confidence intervals are quite wide and suggest large uncertainty. The map for the Tamworth NSW area shows, however, that changes within the landscape are captured well. It should also be noted that for a normal distribution the 5th and 95th percentiles would represent two standard deviations. Experimental agronomic results are often presented as ± one standard deviation. The project case studies for Output 4 will need to explore the best ways to represent the appropriate uncertainty.

SLGA datasets are available for download 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).

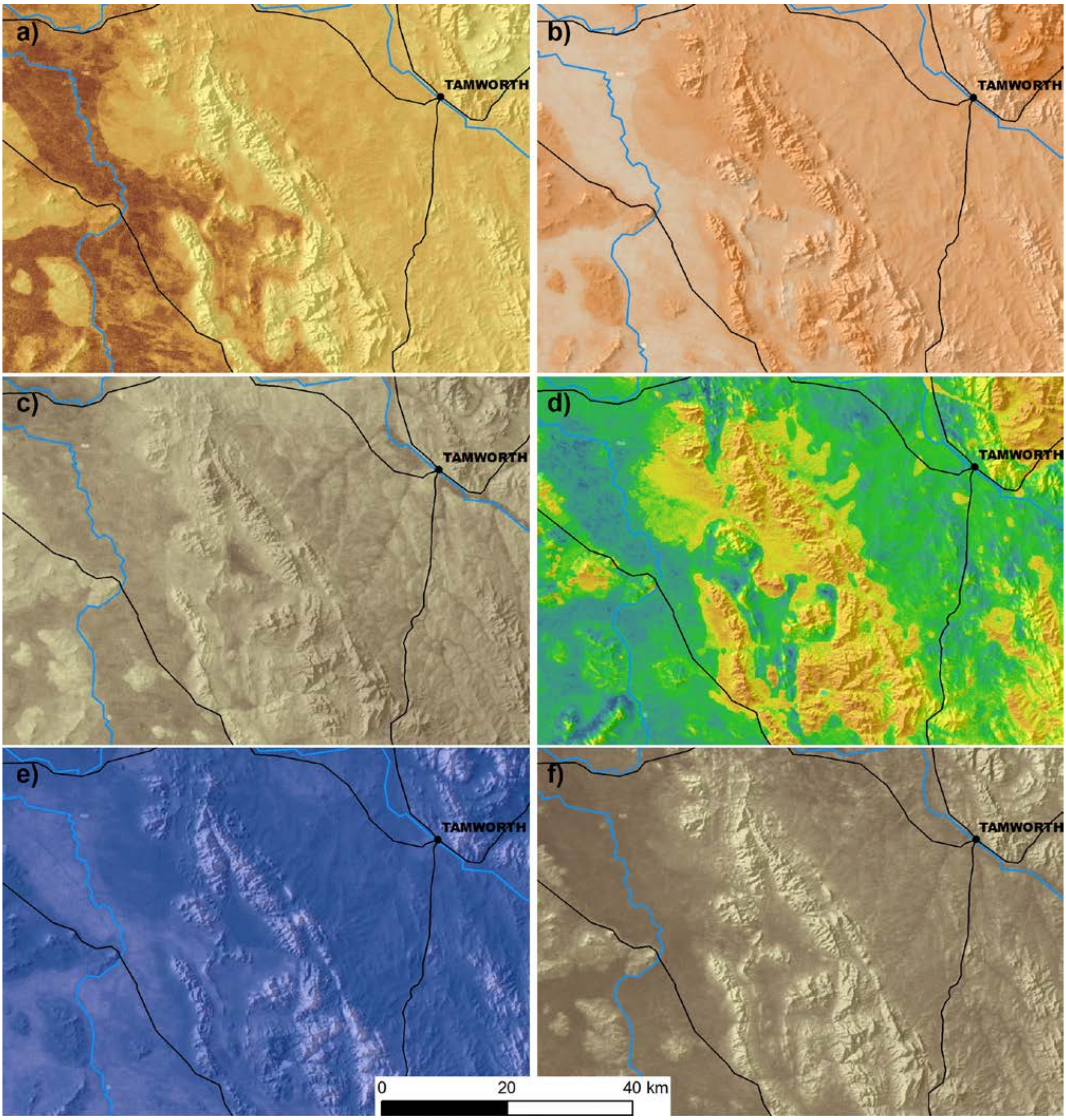

Figure 6.3. Examples of SLGA soil attributes at 5-15 cm depth near Tamworth NSW. a) Clay % (min 12 – yellow, max 60 – brown), b) Sand % (min 18 – pale orange, max 75, dark orange), c) Silt % (min 9 – pale brown, max 32 – dark brown), d) Available water capacity % (min 10 – brown, max 21 - blue), e) Bulk density gcm^{-3} (min 1.02 – pale blue, max 1.5 – dark blue), f) Depth of soil m (min 0.5 – pale brown, max 1.27 – dark brown). 1:10 M scale roads (black lines) and 1:5 M scale watercourses (blue lines) provide context. The soil attributes in a) to f) are semi-transparent to allow the hillshade underneath to show local relief.

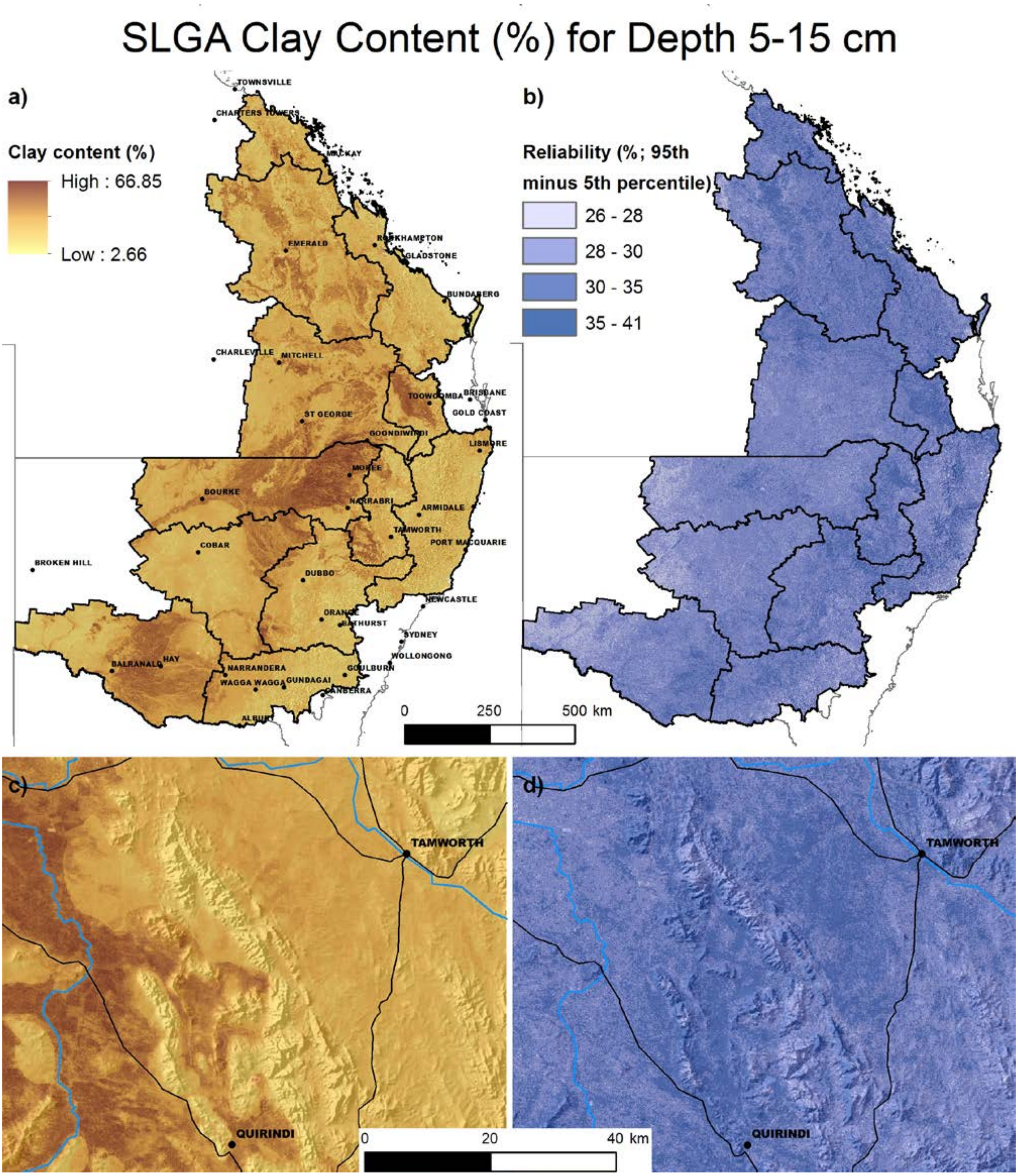

Figure 6.4. Examples of SLGA clay % at 5-15 cm depth for (a) the whole GRDC Northern Region and (c) area near Tamworth NSW, and (b,d) associated 90% reliability range. The soil attributes in (c, d) are semi-transparent to allow the hillshade underneath to show local relief.

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 describes local (i.e. other than national) DSM projects. The ones highlighted are selected because data is in the public domain (i.e. created by state agencies or universities) and have large and consistent enough coverage to be relevant to PAWC projects covering a large enough spread of dryland cropping areas in the GRDC Northern Region.

Digital soil mapping of key soil properties over NSW

The NSW Office of Environment and Heritage (OEH) generated digital soil maps of NSW mainly based on multiple linear regression models (OEH, 2017). These are an alternative to the national SLGA product, and were derived using state-wide (NSW) data. The NSW DSM product is available for the topsoil (0-30 cm) and subsoil (30-100 cm) at a resolution of 100 m. The NSW OEH DSM product contains modelled soil properties (i.e. Electrical conductivity and Exchangeable Sodium Percentage) that can help to inform on the occurrence of subsoil constraints. However, different to the national SLGA DSM efforts, companion reliability maps of the modelled soil properties were not produced, which limits the user in assessing this product. This needs to be investigated further.

The digital soil mapping of key soil properties over NSW is accessible and downloadable through NSW's "eSpade" interface (http://www.environment.nsw.gov.au/eSpade2Webapp), under "Custom layers" and "Modelled soil properties" (as shown in Figure 6.5).

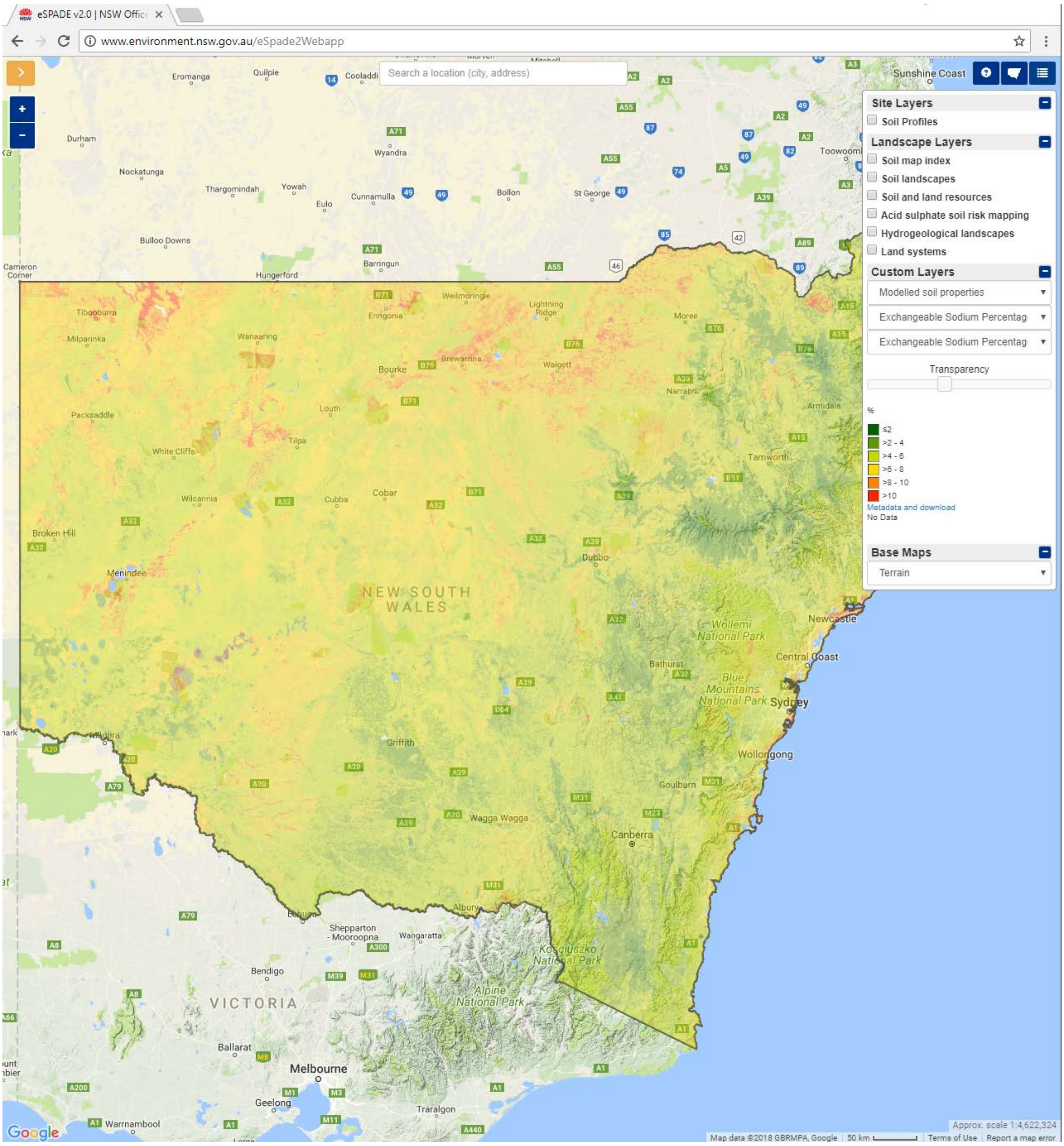

Figure 6.5. Screenshot of NSW's "eSpade" interface, showing the NSW OEH "Modelled soil property" Exchangeable Sodium Percentage for the 30-100 cm prediction.

TerraGIS

TerraGIS is a web-based GIS application bringing together a range of digital biophysical data that were generated during projects funded by the Cotton Research and Development Corporation "Understanding the salinity threat in the irrigated cotton growing areas of Australia". It provides mapping for a set of small areas across central and northern NSW (Figure 6.6), and can be accessed through: http://www.terragis.bees.unsw.edu.au/TerraGIS/TerraGIS.html.

Figure 6.6. Screenshot of areas with DSM coverage from *terra*GIS (clay 0-5 cm prediction shown).

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 patrial/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 then on selected important digital terrain attributes from terrain analysis that are useful in inferring or predicting soil properties.

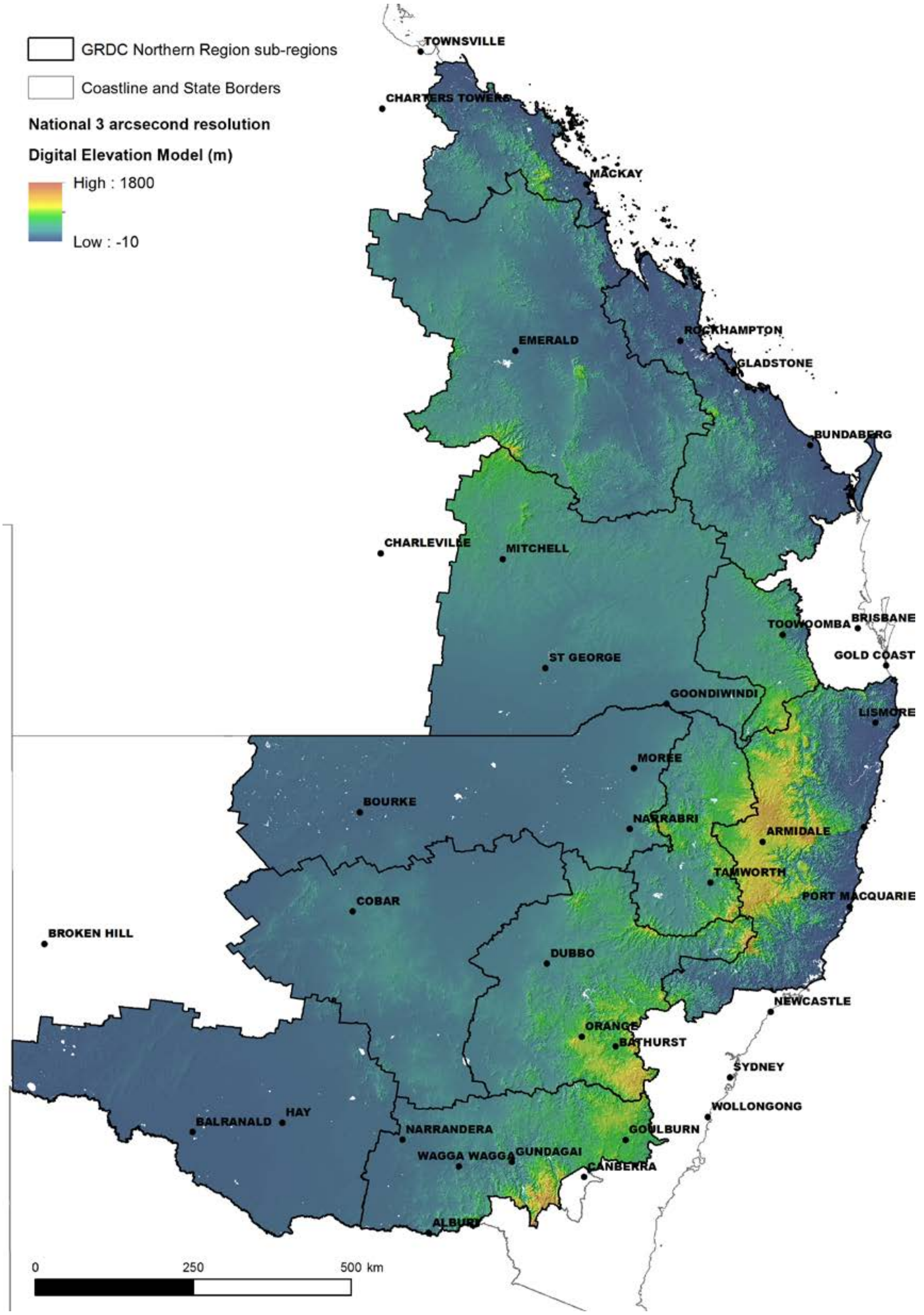

Figure 7.1. National 3 arc second resolution DEM within the GRDC Northern Region, with 3 arc second resolution hillshade underneath.

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 terrain analysis options to support digital soil mapping (see Grunwald, 2006; Hengl and MacMillan, 2009; Wilson and Gallant, 2000), the selection presented below have proven consistently useful in many Australian land and soil evaluations. These options are either widely accessible from public databases (e.g. see Table 7-1 showing the suite of terrain analysis available nationally associated with the SLGA) or are readily computed through various computing options, including the open source R statistical platform (R Core Team, 2014) and GIS (e.g. ESRI or QGIS).

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.

The terrain analysis options most relevant to PAWC prediction include:

- 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

Below we discuss these attributes in more detail, along with an illustration of each of them in an area near Tamworth NSW in Figure 7.2.

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 Tamworth NSW.

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 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 Tamworth NSW.

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 Tamworth NSW.

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 7.2c and Figure 7.2d respectively show examples of plan and profile curvature at 3 arc second resolution for an area near Tamworth NSW.

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 Tamworth NSW.

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 Tamworth NSW.

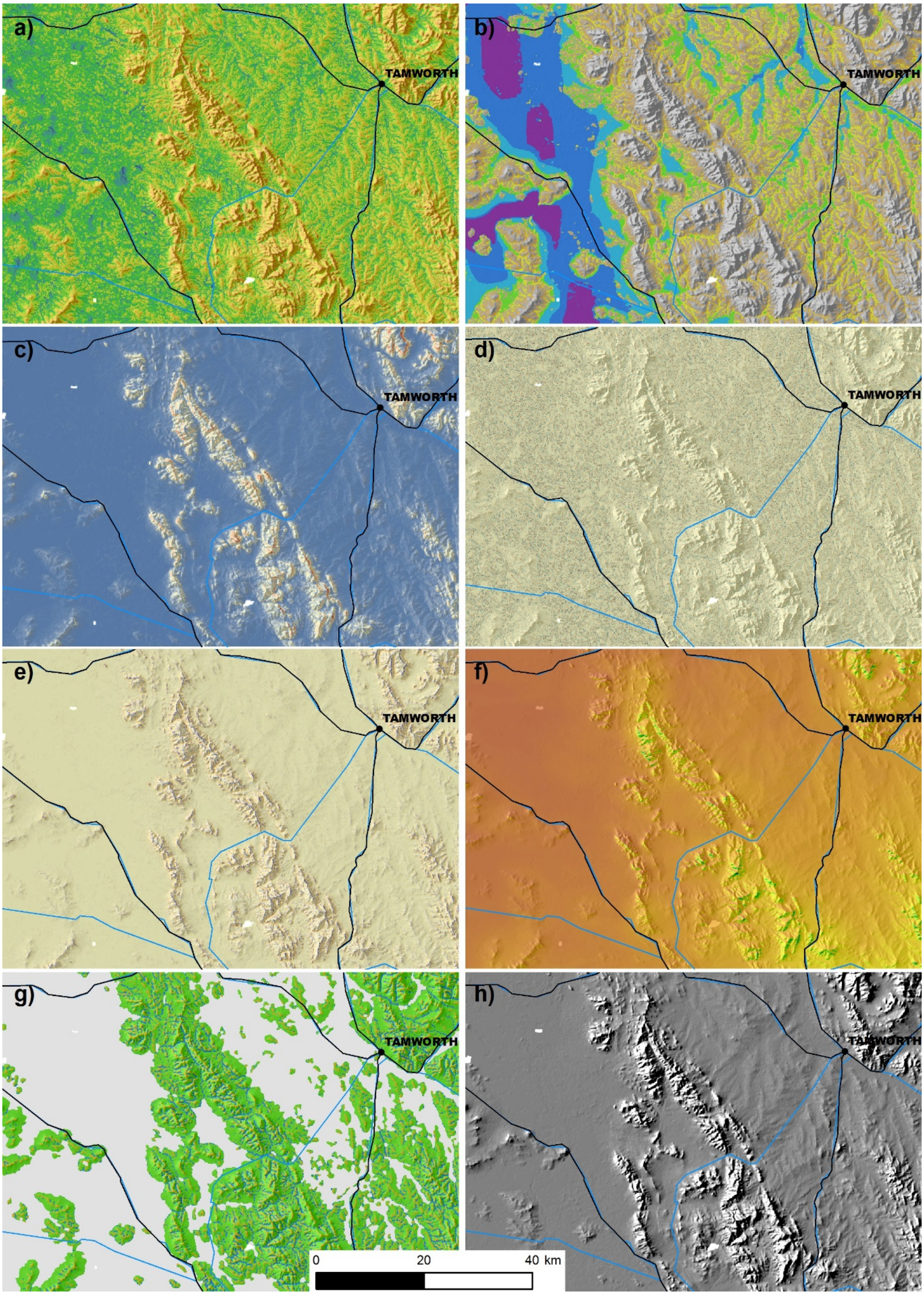

Figure 7.2. Examples of terrain attributes at 3 arc second resolution near Tamworth NSW. a) Topographic Wetness Index (min 3 – orange, max 16 – blue), b) MrVBF (min 0 – orange, max 7 – purple), c) Percent slope (min 0.1 – blue, max 110 – red), d) Plan curvature (min -1 – blue, max 1 – brown), e) Profile curvature (min -0.1 –orange, max 0.1 – purple), f) Prescott Index (min 0.5 – orange, max 3 – blue), g) Topographic Position Index (lower slope – blue, mid-slope – green, upper slope – orange), h) Hillshade. 1:10 M scale roads (black lines) and 1:5 M scale watercourses (blue lines) provide context. The terrain attributes in a) to g) are semi-transparent to allow the hillshade underneath to show local relief.

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 Tamworth NSW.

7.4 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.

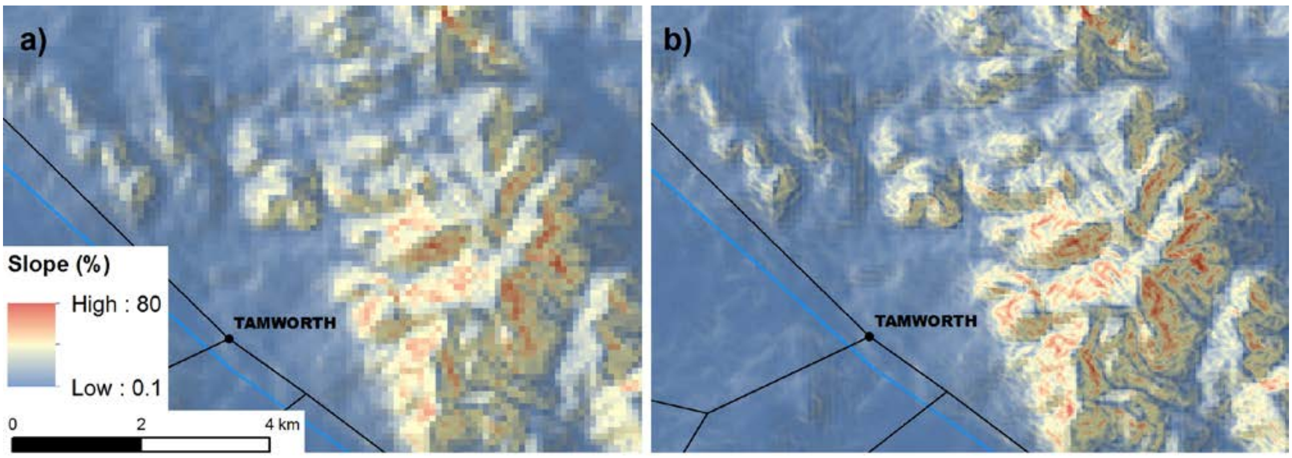

Figure 7.3. Examples of terrain attribute slope (%) at 3 arc second resolution (a) and 1 arc second resolution (b) near Tamworth NSW. It can be seen readily that the 1 arc second product shows a lot more detail.

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 3D mineral mapping of Queensland

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite collects information on the land surface in 14 visual-near infrared, short wave-infra red, and thermal infrared wavebands at a 30 m (1 arc second) and 90 m (3 arc second) ground resolution. The ground reflectance of the various wavebands has been synthetically removed so that the signal is a response to various surface soil components, especially mineralogy and carbon content. Full coverage of 14-bands ASTER imagery is available for the whole of Queensland through CSIRO's data access portal (http://doi.org/10.4225/08/59068b8b07cf6), and if calibrated to mineralogy, may have value in estimating PAWC from clay mineralogy (see Section Mineralogy), or as a covariate for use in predictive DSM. Other products are part of the data suite at the data access portal (http://doi.org/10.4225/08/59068b8b07cf6) including 5 m ground resolution HyMap airborne remote sensing, again potentially suitable for surface mineral mapping and field and core samples, although the HyMap imagery is not available for dryland cropping areas of Queensland, and the core and field samples are sporadically distributed.

8.4 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 Case studies GRDC Northern Region

The data inventory presented in this report prepares for the next stage in the project, namely to evaluate in detail the different methodologies for predicting PAWC from the available information in eight case study areas within the GRDC Northern Region. The proposed case study areas reflect areas with different types of landscapes and different levels or type of soil and landscape information available. The eight proposed case study areas and the rationale for their selection is outlined below.

9.1 Young and Harden granodiorite hill country, NSW

- Area of Wallandbeen, Young, Greenethorpe, Boorowa
- South East NSW GRDC subregion
- Erosional landscape
- Soil landscape mapping available (1:250,000 Cootamundra and Goulburn maps)
- SLGA DSM available
- NSW OEH DSM of key soil properties over NSW available
- Focus on hill slope type and position and implications this has for soil texture, chemistry and PAWC
- Building on preliminary work (Verburg et al. 2015a,b) to explore extrapolation of soil landscape narrative within the region and compare with DSM based approaches mapping of PAWC
- Contacts for local collaboration and industry connections already established

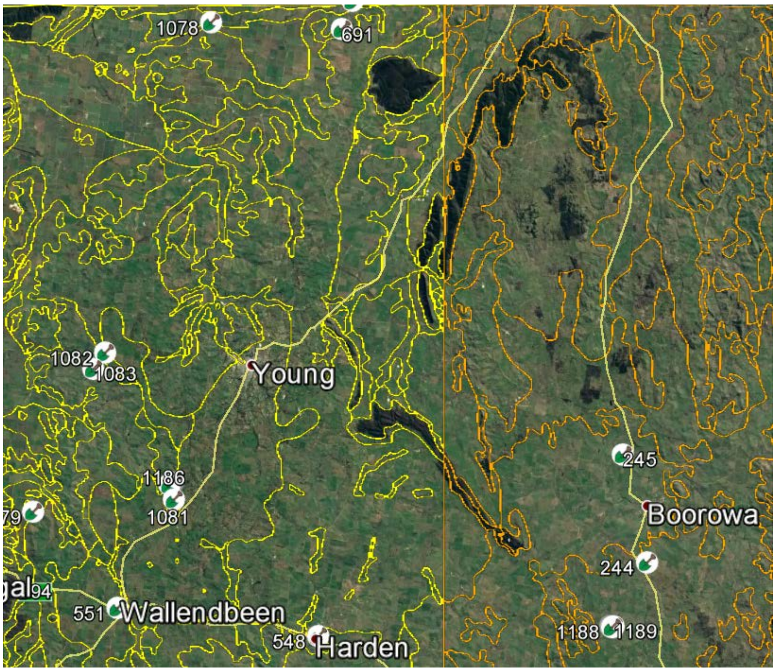

Figure 9.1. Young and Harden granodiorite hill country, NSW, case study area; with state SLU mapping overlaid.

9.2 Central West NSW

- Area north west, west and south west of Condobolin
- Central West NSW GRDC subregion
- Older plains, mix of residual and colluvial landscapes and some Aeolian influences
- No soil landscape mapping available, only Cargellico 1:250,000 geological mapping
- SLGA DSM available
- NSW OEH DSM of key soil properties over NSW available
- Test use of geological mapping and supporting geophysics data versus SLGA
- Contacts for local collaboration and industry connections already established
- Case study for an area with minimal soil landscape information

Figure 9.2. Central West NSW case study area.

9.3 Macquarie-Bogan flood plains, NSW

- Area Nyngan, Trangie, Coonamble
- Parts of North West NSW, Central West NSW and Central East NSW GRDC subregions
- Riverine landscape, with differences in texture of parent materials and subsoil salinity due to changing deposition conditions over geological times
- Hydrogeological landscape map and unpublished soil and landscape map
- SLGA DSM available
- NSW OEH DSM of key soil properties over NSW available
- Small area near Trangie covered by terraGIS
- Focus on distinguishing riverine landscape positions and associated soil texture differences as well as identification subsoil constraints.
- Texture differences lend themselves for evaluation of benefits from DSM direct mapping of PAWC versus a narrative based on soil-landscape understanding. Also explore whether hydrogeological landscape information can add information on subsoil constraints.
- Use of supporting geophysics data
- Contacts for local collaboration and industry connections already established
- Possible future extension opportunity to link PAWC information to the other soil properties and management recommendations contained in the Glovebox guide to Soil of the Macquarie-Bogan Flood Plain.

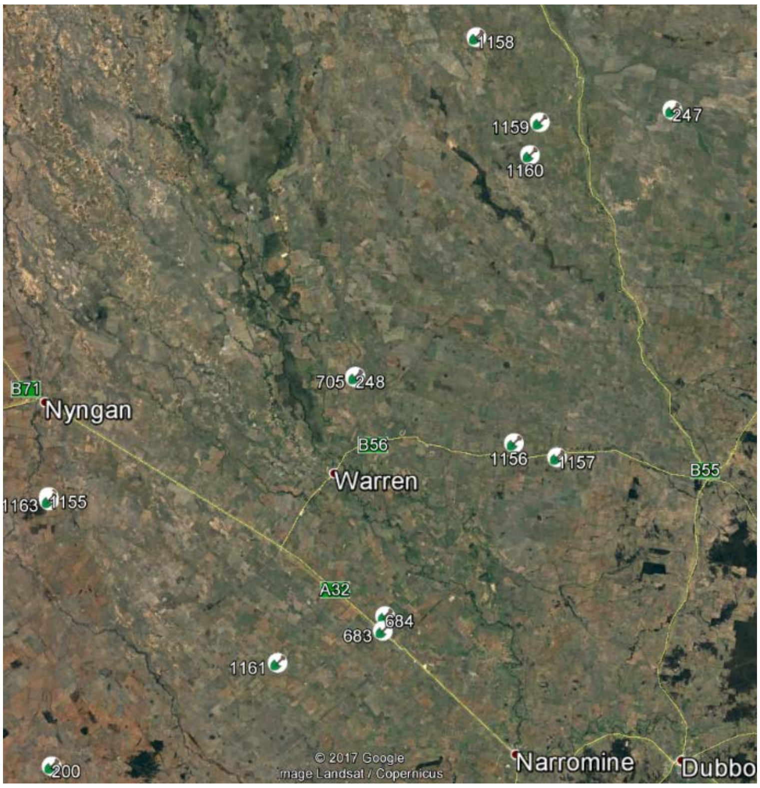

Figure 9.3. Macquarie-Bogan flood plains, NSW, case study area.

9.4 Liverpool Plains, NSW

- Area bounded by the Liverpool Plains soil and land resources map
- North East NSW GRDC sub-region
- NSW Soil and Land Resources and NSW Soil Landscape mapping (1:100,000)
- Intensive local sampling underpins SLGA attribute predictions
- NSW OEH DSM of key soil properties over NSW available
- Small area near Gunnedah covered by terraGIS
- Preliminary study (Verburg et al. 2017) highlighted that within soil-landscape unit needed to be explored further
- Focus on differences among Vertosols due to parent material/mineralogy, conditions during soil formation and subsoil salinity
- Contact with local pedologist who has in-depth understanding of the landscape and some in-house experience in the area
- Contacts for local collaboration and industry connections already established
- Case study allows comparison of predicting and mapping PAWC based on both local and national DSM approaches and predicting PAWC on the basis of a narrative of soil landscape understanding. It also allows investigation of added benefits from terrain analysis and local EM measurement efforts

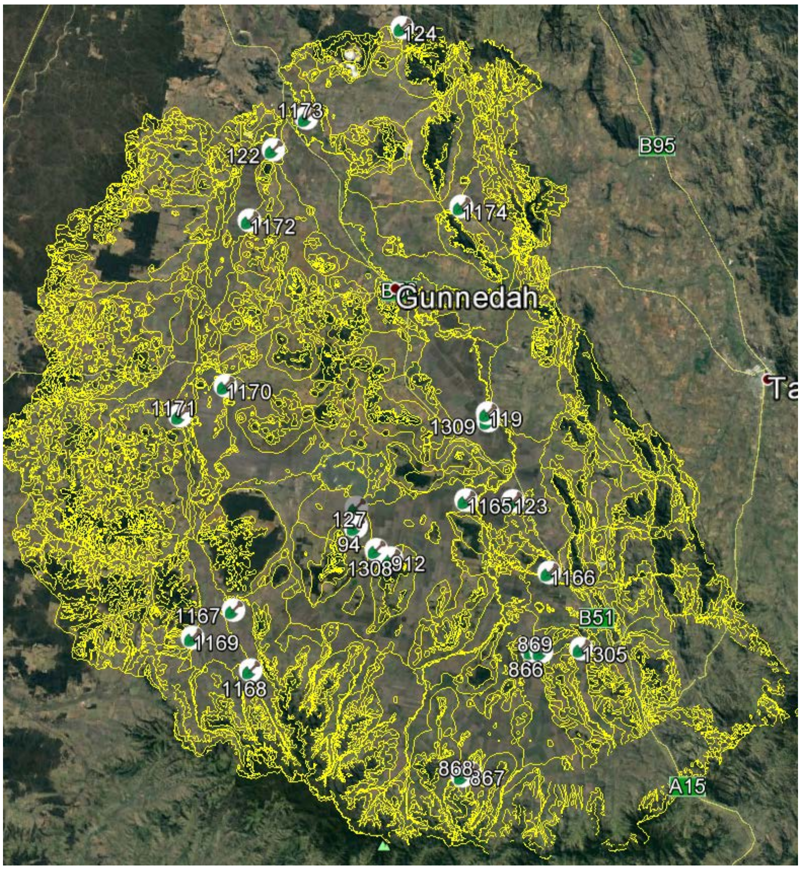

Figure 9.4. Liverpool Plains, NSW, case study area; with state SLU mapping overlaid.

9.5 Northern half of the Moree plains, NSW

- Area between Moree and the NSW - Qld border, bounded by the soil and land resources map
- North West NSW GRDC subregion
- NSW Soil and Land Resources map (new)
- SLGA DSM available
- NSW OEH DSM of key soil properties over NSW available
- Small areas near Ashley NSW covered by terraGIS
- Landscape of alluvial plains and fans as well as erosional and residual landscape of sandstone hills
- Focus on soil type (Black and Grey Vertosols and ‘Red soils’) vs landscape position and parent material
- Case study with less intensive soil-landscape information
- Texture differences lend themselves for evaluation of benefits from DSM direct mapping of PAWC versus a narrative based on soil-landscape understanding

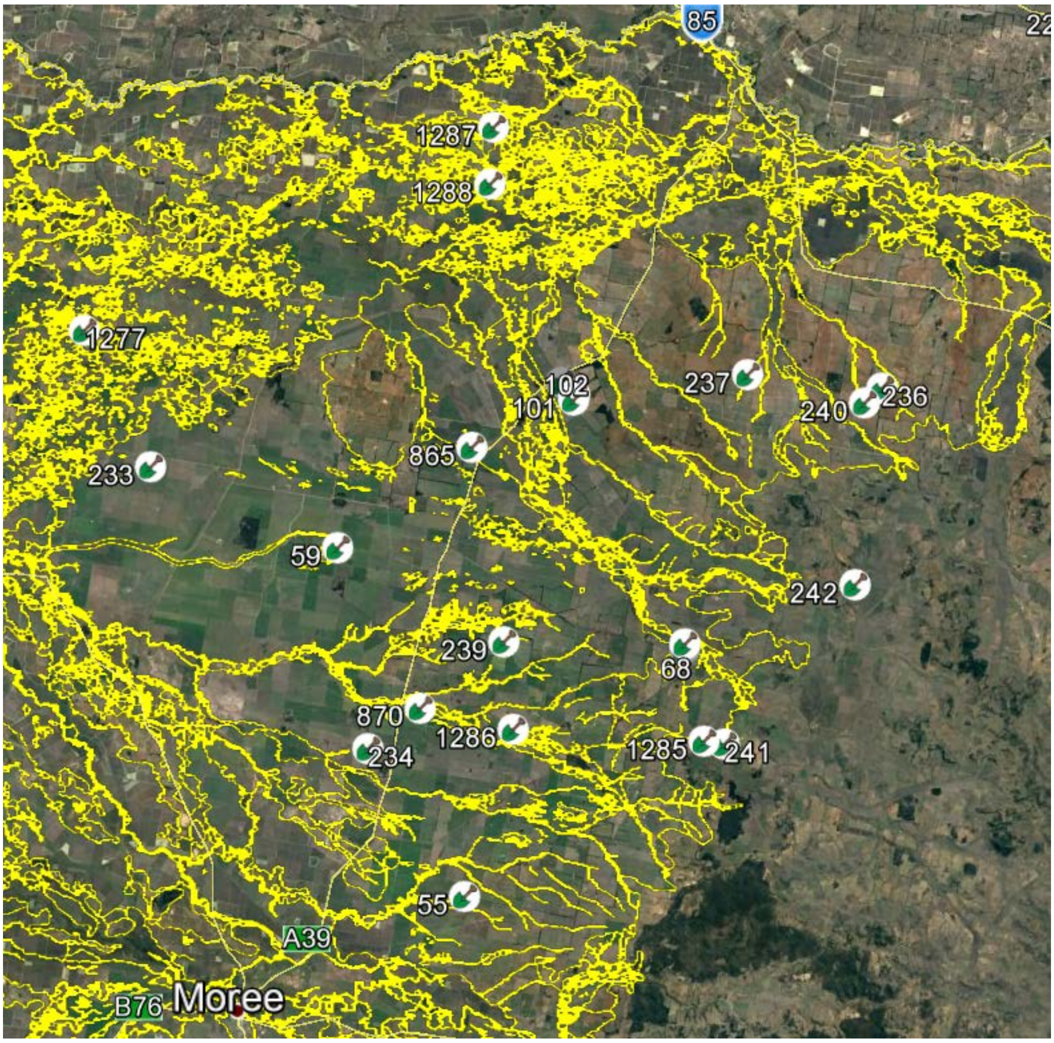

Figure 9.5. Northern half of the Moree Plains, NSW, case study area; with state SLU mapping overlaid.

9.6 Central Darling Downs, Queensland

- Area bounded by Central Darling Downs LRA mapping
- South East Queensland GRDC subregion
- Detailed LRA mapping underpinned by local soil surveys and a consistent local soil classification
- Opportunity to test if APSoil profiles can be linked to advice in LRA manual or whether direct mapping of PAWC using DSM is better
- Alluvial and colluvial landscapes with different sediment origins

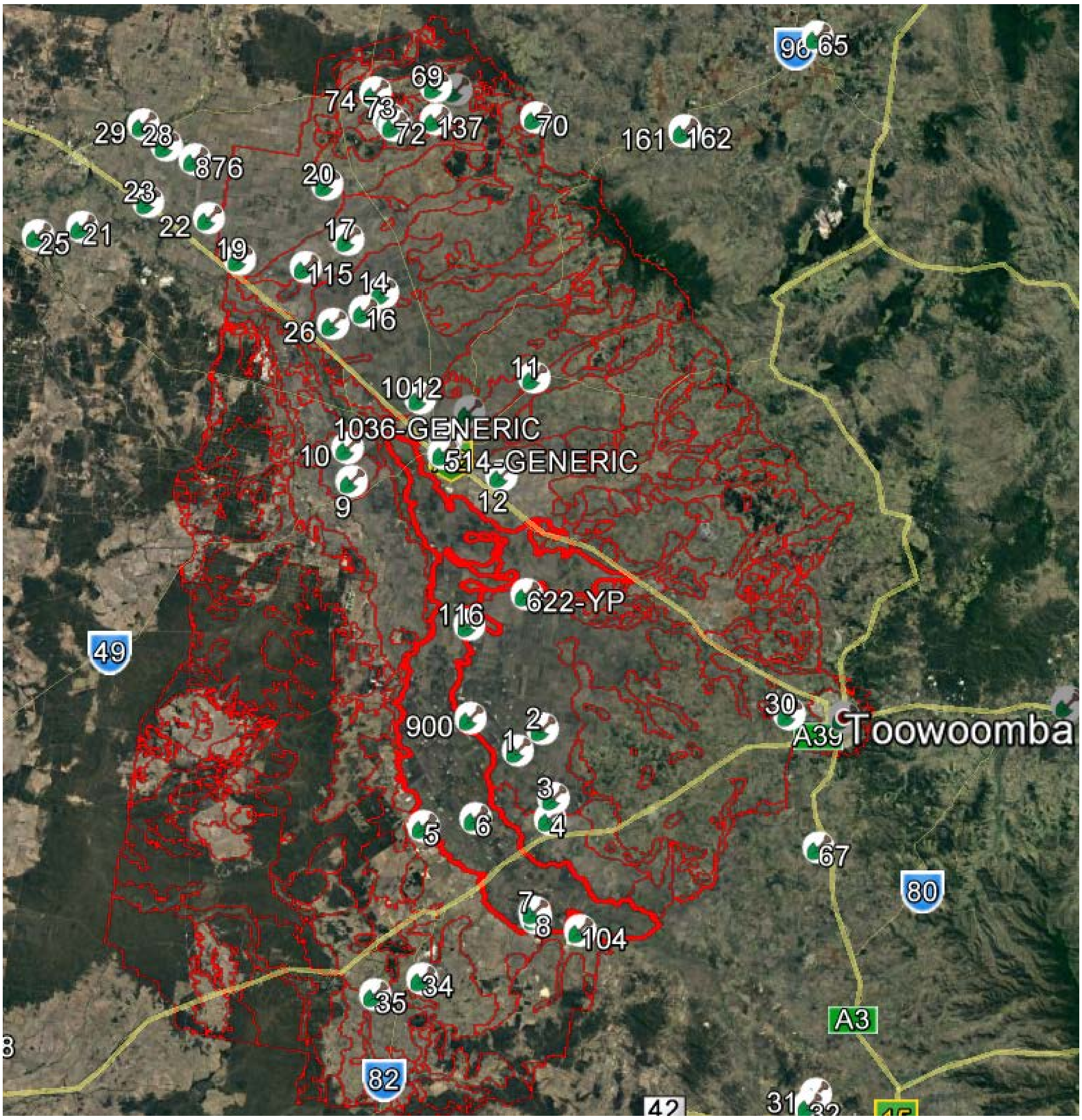

Figure 9.6. Central Darling Downs, Queensland, case study area; with state SLU mapping overlaid.

9.7 South West Queensland

- Area bounded by LRA mapping of Murilla-Tara-Chincilla LRA
- South West Queensland GRDC subregion
- Ancient alluvial plains, with a wider variety of Vertosols than on the Condomine Plains of the Central Darling Downs and also some duplex soils.
- LRA mapping available, but not as detailed as that of the Central Darling Downs

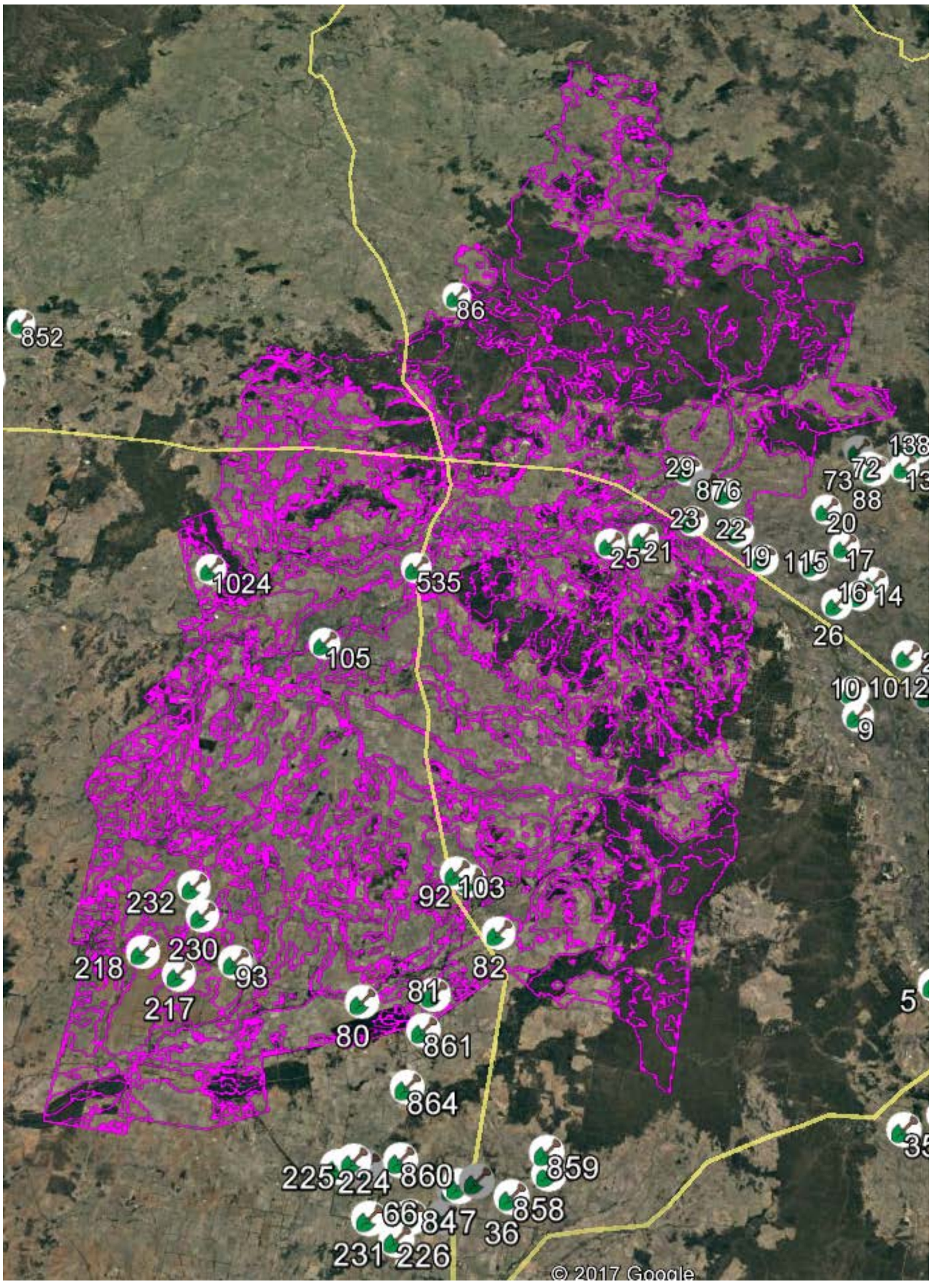

Figure 9.7. South West Queensland, case study area; with state SLU mapping overlaid.

9.8 Central Highlands, Queensland

- Area bounded by Central Highlands LRA mapping, possibly extending to out to Biloela Qld
- Central Queensland GRDC subregion
- Landscape of alluvial plains and undulating plains and rises, including basalt and tertiary soils
- LRA mapping available, but more at level of land systems information, as well as some local 1:100,000 soil surveys (south west of Moranbah, Qld and north-west of Bioela)
- SLGA DSM available
- Soil depth and subsoil constraints (salinity) influence on PAWC and will be the key challenge

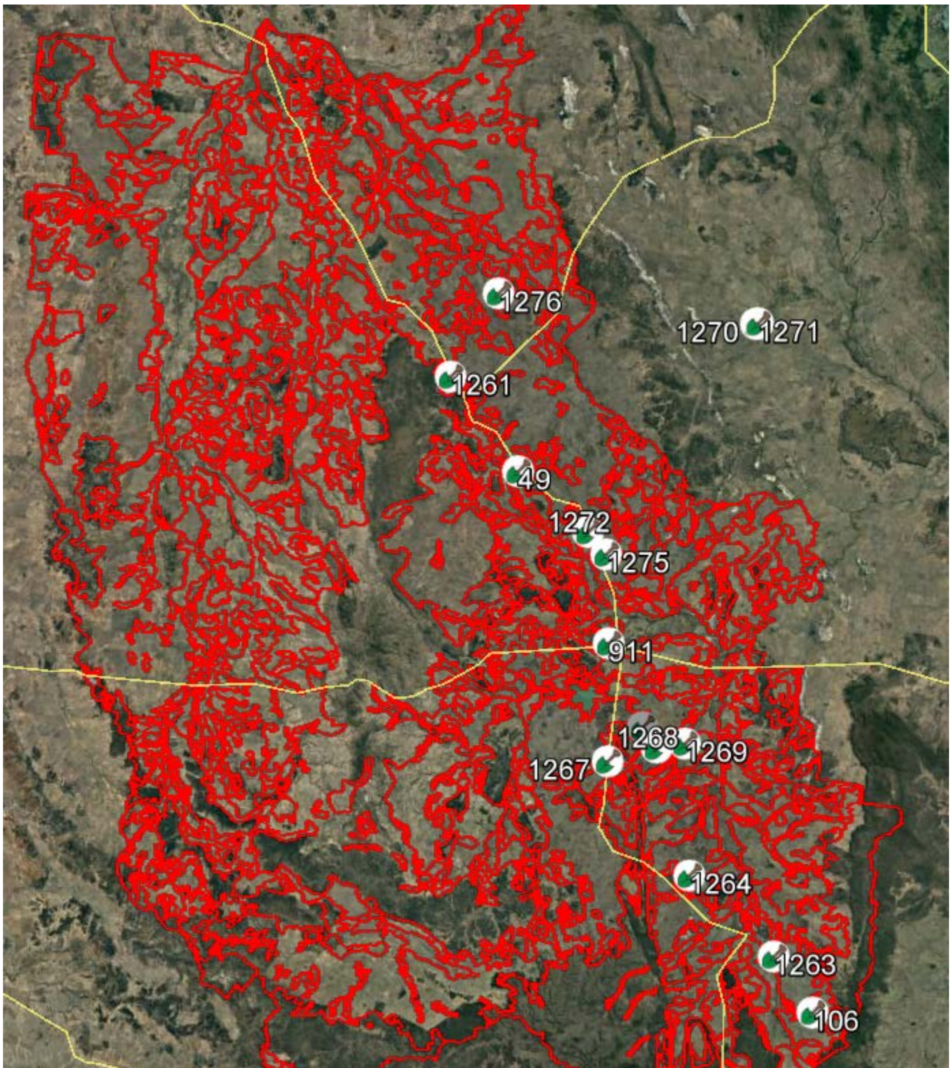

Figure 9.8. Central highlands, Queensland, case study area; with state SLU mapping overlaid.

References

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrological Sciences Bulletin 24(1), 43-69.

Bigham, J.M., Ciolkosz, E.J., 1993. Soil Color: Proceedings of a symposium sponsored by Division S-5 and S-9 of the Soil Science Society of america in San Antonio, Texas, 21-26 Oct. 1990. Soil Science Society of America, Madison, Wisconsin, USA.

Bui, E., 2007. A review of digital soil mapping in Australia. In: P. Lagacherie, A.B. McBratney, M. Voltz (Eds.), Digital Soil Mapping: An Introductory Perspective. Developments in Soil Science, pp. 25-37.

Burk, L., Dalgliesh, N.P., 2013. Estimating plant available water capacity, CSIRO, Canberra.

Christian, C.S., Stewart, G.A., 1953. General Report on Survey of Katherine-Darwin Region, 1946, CSIRO, Melbourne.

Christian, C.S., Stewart, G.A., Perry, R.A., 1960. Land research in Northern Australia. Australian Geographer 7(6), 217-231.

Doolittle, J.A., Brevik, E.C., 2014. The use of electromagnetic induction techniques in soils studies. Geoderma 223–225(0), 33-45.

Edye, J.A., Murphy, C.L., Chapman, G.A., Milford, H.B., McGaw, A.J.E., Macleod, A.P., Simons, N.A., 2001. What's in a landscape? describing natural resources with soil landscapes, Geospatial Information and Agriculture Symposium, Sydney.

Goldrick, G., Chapman, G., McGaw, A., Simons, N., Milford, H., Murphy, C., Edye, J., Macleod, A., 2001. New technology and soil landscape mapping in NSW, Proceedings of the Geospatial Information and Agriculture Symposium, Sydney.

Gallant, J., Dowling, T., Read, A., Wilson, N., Tickle, P., Inskeep, C., 2011. 1-Second SRTM derived digital elevation models user guide, Geoscience Australia, Canberra, Australia.

Gallant, J.C., Austin, J.M., 2015. Derivation of terrain covariates for digital soil mapping in Australia. Soil Research 53(8), 895-906.

Gallant, J.C., Dowling, T.I., 2003. A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resources Research 39(12), 1347.

GlobalSoilMap Science Committee, 2011. Specifications Version 1 GlobalSoilMap.net products http://www.globalsoilmap.net/system/files/GlobalSoilMap_net_specifications_v2_0_edited_draft_Sept_2011_RAM_V12.pdf, pp. 50.

Goldrick, G., Chapman, G., McGaw, A., Simons, N., Milford, H., Murphy, C., Edye, J., Macleod, A., 2001. New technology and soil landscape mapping in NSW, Proceedings of the Geospatial Information and Agriculture Symposium, Sydney.

Grundy, M.J., Rossel, R.A.V., Searle, R.D., Wilson, P.L., Chen, C., Gregory, L.J., 2015. Soil and Landscape Grid of Australia. Soil Research 53(8), 835-844.

Grunwald, S., 2006. Environmental soil-landscape modeling: geographic information technologies and pedometrics. Books in soils, plants, and the environment. CRC/Taylor & Francis, Boca Raton.

Harris, P.S., Biggs, A.J.W., Stone, B.J., 1999. Central Darling Downs Land Management Manual, Brisbane.

Hartemink, A.E., Hempel, J., Lagacherie, P., McBratney, A., McKenzie, N., MacMillan, R.A., Minasny, B., Montanarella, L., de Mendonça Santos, M.L., Sanchez, P., Walsh, M., Zhang, G.-L., 2010. GlobalSoilMap.net – A New Digital Soil Map of the World. In: J.L. Boettinger, D.W. Howell, A.C. Moore, A.E. Hartemink, S. Kienast-Brown (Eds.), Digital Soil Mapping: Bridging Research, Environmental Application, and Operation. Springer Netherlands, Dordrecht, pp. 423-428.

Hedley, C.B., Yule, I.J., Eastwood, C.R., Sheperd, T.G., Arnold, G., 2004. Rapid identification of soil textural and management zones using electromagnetic induction sensing of soils. Australian Journal of Soil Research 42, 389-400.

Hengl, T., 2006. Finding the right pixel size. Computers & Geosciences 32(9), 1283-1298.

Hengl, T., MacMillan, R.A., 2009. Geomorphetry - A Key to Landscape Mapping and Modelling. In: T. Hengl, H.I. Reuter (Eds.), Geomorphetry: Concepts, Software, Applications. Developments in Soil Science. Amsterdam, Elsevier, pp. 433-460.

Hengl, T., Reuter, H.I., 2009. Geomorphometry: concepts, software, applications. Elsevier, Amsterdam.

Huang, J., Buchanan, S.M., Bishop, T.F.A., Triantafilis, J., 2017. terraGIS – a web GIS for delivery of digital soil maps in cotton-growing areas of Australia. Soil Use and Management, n/a-n/a.

Hudson, B.D., 1992. The Soil Survey as Paradigm-based Science. Soil Sci. Soc. Am. J. 56(3), 836-841.

Hulme, P., 2003. Glovebox guide to the soils of the Macquarie and Bogan Floodplain, Sustainable Soil Management, National Heritage Trust and Macquarie 2100.

Isbell, R.F., CSIRO, 2016. The Australian Soil Classification. Australian Soil and Land Survey Handbook Series (Vol 4). 2nd ed. CSIRO Publishing, Melbourne.

Isbell, R.F., National Committee on Soil and Terrain, 2016. The Australian Soil Classification. Australian Soil and Land Survey Handbook Series (Vol 4). 2nd ed. CSIRO Publishing, Melbourne.

James, I.T., Waine, T.W., Bradley, R.I., Taylor, J.C., Godwin, R.J., 2003. Determination of Soil Type Boundaries using Electromagnetic Induction Scanning Techniques. Biosystems Engineering 86(4), 421-430.

Jenny, H., 1941. Factors of soil formation, a system of quantitative pedology. McGraw-Hill, New York.

Kidd, D., Webb, M., Grose, C., Moreton, R., Malone, B., McBratney, A., Minasny, B., Viscarra-Rossel, R., Sparrow, L., Smith, R., 2012. Digital soil assessment: guiding irrigation expansion in Tasmania, Australia, Digital soil assessment and beyond. CRC Press, Boca Raton, Fl, pp. 3-9.

Kidd, D.B., Malone, B.P., McBratney, A.B., Minasny, B., Webb, M.A., 2014. Digital mapping of a soil drainage index for irrigated enterprise suitability in Tasmania, Australia. Soil Research 52(2), 107-119.

Littleboy, M., 2002. Integrating biophysical modelling and soil physical properties for quantitative land evaluation. In: N.J. McKenzie, K. Coughlan, H.P. Cresswell (Eds.), Soil physical measurement and interpretation for land evaluation. Australian soil and land survey handbook series; Vol. 5. CSIRO Publishing, Collingwood, Australia, pp. 324-331.

Marshall, T.J., Walkley, A., 1937. A Soil Survey of the Coomealla, Wentworth (Curlwaa), and Pomona Irrigation Settlements, NSW, Council for Scientific and Industrial Research, Melbourne.

McBratney, A.B., Santos, M.L.M., Minasny, B., 2003. On digital soil mapping. Geoderma 117(1-2), 3-52.

McKenzie, N.J., Grundy, M.J., Webster, R., Ringrose-Voase, A.J., 2008. Guidelines for surveying soil and land resources. Australian soil and land survey handbook series ; v. 2. 2nd ed. CSIRO Publishing, Collingwood, Vic.

McKenzie, N.J., Ryan, P.J., 1999. Spatial prediction of soil properties using environmental correlation. Geoderma 89(1-2), 67-94.
McKenzie, R.C., George, R.J., Woods, S.A., Cannon, M.E., Bennett, D.L., 1997. Use of electromagnetic-induction meter (EM38) as a tool for managing salinisation. Hydrogeology Journal 5(1), 37-50.
McNeill, J.D., 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6, Geonics Ltd., Ontario, Canada.
Minasny, B., McBratney, A.B., Bristow, K.L., 1999. Comparison of different approaches to the development of pedotransfer functions for water-retention curves. Geoderma 93(3), 225-253.
Minty, B.R.S., 1997. Fundamentals of airborne gamma-ray spectrometry. AGSO Journal of Australian Geology & Geophysics 17(2), 39 - 50.
Murphy, C.L., Macleod, A.P., Chapmen, G.A., Milford, H.B., McGaw, A.J.E., Edye, J.A., Simmons, N.A., 2001. NSW state soil landscape mapping program and derivative products, Geospatial Information and Agriculture Symposium, Sydney.
National Committee on Soil and Terrain, 2009. Australian soil and land survey field handbook. Australian soil and land survey handbook series ; no. 1. 3rd ed. CSIRO Publishing, Collingwood, Vic.
Northcote, K.H., 1992. A factual key for the recognition of Australian soils. Rellim Technical Publications Pty. Ltd., Coffs Harbour, NSW.
Northcote, K.H., Beckmann, G.G., Bettenay, E., Churchward, H.M., Van Dijk, D.C., Dimmock, G.M., Hubble, G.D., Isbell, R.F., McArthur, W.M., Murtha, G.G., Nicolls, K.D., Paton, T.R., Thompson, C.H., Webb, A.A., Wright, M.J., 1960-1968. Atlas of Australian Soils, Sheets 1 to 10. With explanatory data, CSIRO, Melbourne.
OEH, 2017. Digital soil mapping of key soil properties over NSW. Technical Report, NSW Office of Environment and Heritage, Sydney.
Prescott, J.A., 1950. A climatic index for the leaching factor in soil formation. Journal of Soil Science 1(1), 9-19.
R Core Team, 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Rayment, G.E., Lyons, D.J., 2011. Soil chemical methods: Australasia. Australian Soil and Land Survey Handbook Series, 3. CSIRO Publishing, Melbourne.
Rossel, R.A.V., Chen, C., Grundy, M.J., Searle, R., Clifford, D., Campbell, P.H., 2015. The Australian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project. Soil Research 53(8), 845-864.
Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulchay, M.J., Hallsworth, E.G., 1968. A Handbook of Australian Soils. Rellim, Adelaide.
Thomas, M., Clifford, D., Bartley, R., Philip, S., Brough, D., Gregory, L., Willis, R., Glover, M., 2015. Putting regional digital soil mapping into practice in Tropical Northern Australia. Geoderma 241–242, 145-157.
Thomas, M., Fitzpatrick, R.W., Heinson, G.S., 2009a. Distribution and causes of intricate saline-sodic soil patterns in an upland South Australian hillslope. Australian Journal of Soil Research 47(3), 328-339.
Thomas, M., Fitzpatrick, R.W., Heinson, G.S., 2009b. An expert system to predict intricate saline-sodic subsoil patterns in upland South Australia. Australian Journal of Soil Research 47(6), 602-612.
Verburg, K., Cocks, B., Manning, B., Truman, G., Schwenke, G.D., 2017. APSoil plant available water capacity (PAWC) characterisation of select Liverpool Plain soils and their landscape context, CSIRO, Canberra.

Verburg, K., Cocks, B., Webster, A.J.F., Whish, J., 2016a. Methods and tools to characterise soils for plant available water capacity, Goondiwindi NSW.
Verburg, K., Cocks, B., Webster, T., Whish, J., 2016b. Methods and tools to characterise soils for plant available water capacity, Coonabarabran NSW.
Verburg, K., Glover, M., McKenzie, N., Jackman, A., van Rees, H., Dalgliesh, N.P., 2015a. Soil-landscape effects on plant available water capacity (PAWC). In: T. Acuña, C. Moeller, D. Parsons, M. Harrison (Eds.), 17th Australian Agronomy Conference, Hobart, pp. 506-509.
Verburg, K., Glover, M., Minehan, C., van Rees, H., Jackman, A., McClelland, T., Dalgliesh, N.P., Hunt, J., Cocks, B., Henry, S., Oliver, Y., Thomas, M., Mowat, D., Caldwell, L., Hall, A., 2015b. Soil characteristics and Yield Prophet® for better decisions, GRDC Research Update Wagga Wagga.
Viscarra Rossel, R.A., 2011. Fine-resolution multiscale mapping of clay minerals in Australian soils measured with near infrared spectra. Journal of Geophysical Research: Earth Surface 116(F4).
Viscarra Rossel, R.A., Chen, C., Grundy, M.J., Searle, R., Clifford, D., Campbell, P.H., 2015. The Australian three-dimensional soil grid: Australia’s contribution to the GlobalSoilMap project. Soil Research 53(8), 845-864.
Weiss, A.D., 2017. Topographic Position and Landforms Analysis, Seattle.
Wilford, J., 2012. A weathering intensity index for the Australian continent using airborne gamma-ray spectrometry and digital terrain analysis. Geoderma 183, 124-142.
Wilford, J., Thomas, M., 2012. Modelling soil-regolith thickness in complex weathered landscapes of the central Mt Lofty Ranges, South Australia. In: B. Minasny, B.P. Malone, A.B. McBratney (Eds.), Digital Soil Assessments and Beyond. Taylor & Francis Group, London, UK, pp. 69-76.
Wilford, J.R., Searle, R., Thomas, M., Pagendam, D., Grundy, M.J., 2016. A regolith depth map of the Australian continent. Geoderma 266, 1-13.
Williams, B.G., Baker, G.C., 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Australian Journal of Soil Research 20, 107-118.
Wilson, J.P., Gallant, J.C., 2000. Digital terrain analysis. In: J.P. Wilson, J.C. Gallant (Eds.), Terrain analysis: principles and applications. John Wiley & Sons Inc., New York, pp. 1-27.

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