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

Output 3 Project CSP00210

Uta Stockmann, Mark Thomas, Kirsten Verburg, Jenet Austin, Mark Glover

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Prepared for Grains Research and Development Corporation
Kaara Klepper, Manager Agronomy, Soils and Farming Systems - North

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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 information in the Western Region. It also includes suggestions for possible future case study areas where different predictive methods could be tested in the Western region.

The GRDC Western Region has 261 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 also associated with dryland cropping, where the use of PAWC data is most relevant.

Over the years many soil and landscape surveys have been carried out within the GRDC Western Region. Apart from the national mapping using the Australian Soil Classification (ASC), which is at a very broad scale within the GRDC Western Region, there is the local Western Australian mapping system, which is consistent across the region and describes the uniqueness of soils across the state through a total of sixty Soil Groups of Western Australia. The distribution of these Soil Groups proportionally in relation to a mapping unit is available online through a GIS-based mapping tool, NRInfo (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). Surveys that underpin these maps were carried out at different scales and at times for different purposes. The soil (profile) data that underpin these surveys, as well as those collected for other purposes are at present only partially available through online GIS-based mapping systems, but can be found in various reports. In addition, there is the MySoil diagnostic tool, available online and through the MyCrop App, which summarizes 15 generic soil types. These can be used as a starting point for yield estimates based on PAWC and for identifying major soil constraints that will likely change PAWC characteristics. Geological surveys and a variety of geophysics data can also be accessed from other online sources.

For the GRDC Western Region there is a great deal of soil information available online through the WA Department of Agriculture and Food's (now known as Department of Primary Industries and Regional Development) online resources. It may therefore likely be overwhelming for growers or advisors to make a decision of which data source to choose and ultimately use. Thus, a good starting point is the Department's main 'Soils' webpage (https://www.agric.wa.gov.au/climate-land-water/soils), which leads the user to more specific and agronomical relevant soil information through various links, such as the 'Soil classification' link (https://www.agric.wa.gov.au/identifying-wa-soils/soil-classification), which provides a general introduction to the different forms of soil information available and again provides further links to relevant resources, such as the National and Western Australian soil classification systems, MySoil and Soilguide. The latter is a handbook developed for growers and advisors to help with understanding and managing WA's agricultural soils. Another, good starting point, especially in relation to finding available resources to help with estimating PAWC, is the Department's website, which summarizes 'Soil water and crop decision support tools' (https://www.agric.wa.gov.au/water-management/soil-water-and-crop-decision-support-tools). It contains information on how to identify the soils in an area of interest and how to estimate PAWC, referring to state wide efforts such as MySoil, and national efforts such as SoilMapp for iPad, the APSoil database, APSIM and Yield Prophet.

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 Western 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 261 records in the Western Region. Data is publically available through the APSoil database: https://www.apsim.info/Products/APSoil.aspx.	2
National mapping	The Australian Soil Classification (ASC) polygon mapping is available for all of the GRDC Western Region at various scales. On-line access to ASC mapping is accessible for all of Australia through the SoilMapp iPad application as well as the Australian Soil Resource Information System http://www.asris.csiro.au/. It provides a composite of best available mapping from approximately 2012.	3.2

Soil profile data	National soil profile descriptions are also available to the public through the Australian Soil Resource Information System http://www.asris.csiro.au/. These records are a collection of soil profiles with accompanying detailed descriptions of site (e.g. landscape, relief), soil morphology, and physicochemical analyses. The types of soil profile data available through ASRIS vary, however. They range from soil profile data sourced from soil surveys and research projects, through to 'idealised' soil profile class descriptions and 'reference' profiles. The latter generally refer to a 'typical or 'best' description of a recognised soil type (P. Wilson, *pers. com.*, Wilson 5.04.18). Soil profile data sourced from surveys and research projects will, and 'idealised' or 'reference' soil profiles may have application to support PAWC work, where soils of interest closely match. There is a current effort to present WA's soil profile data within the "Australian Virtual Soil Archive" (demonstration, www.asris.csiro.au/virtualsoilarchive/). This online web interface which is at present in its development stage brings together Australian soil profile data from various agencies, with the intention to make these available in one location for ease of access for the user. The interface is live, but as it is in its development phase, it should be used with caution.	3.3
CSIRO land resources evaluations	CSIRO land resources 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 in some cases. Mapping and investigation scales vary, from coarse scales (e.g. 1:1,000,000) to finer scales (e.g. 1:25,000). Scale of mapping and level of detail defines the utility of these maps for PAWC work. Potentially useful maps are listed in Table 3.1 contained in this report, and print versions are accessible from CSIRO's library.	3.4
WA soils mapping and land resources evaluation	The soil and land resources evaluation reports worthy of investigation for supporting PAWC work in the Western region are listed in Table 3.2 contained in this report. With a few exceptions, these reports (pdf-format) and if applicable associated map sheets (in un-georeferenced high-resolution pdf-format) are all publically available, and can be downloaded through the WA Department of Primary Industry and Regional Development's research library catalogue (https://researchlibrary.agric.wa.gov.au/). Scale of mapping and level of detail defines the utility of these maps and associated reports for PAWC extrapolation and prediction.	3.5
WA soil landscape mapping	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 directly. 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 (also refer to Section 3.5). The WA Soil-landscape mapping is viewable in WA's natural resource information system, "NRInfo", an online GIS-based mapping application (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). The WA Soil-landscape mapping metadata are also available for download through SLIP, a Shared Landform Information Platform for finding and sharing geospatial data relevant to WA, https://data.wa.gov.au/. Once, downloaded, these can be imported into GIS-based software.	4.1

WA land capabilities and land quality mapping	The WA land capabilities and land quality mapping is based on a methodology outlined in van Gool and Moore (1999) and van Gool et al. (2005) that provides a standard method for attributing and evaluating the best available soil-landscape mapping dataset produced for WA (Purdie, 2006; Purdie et al., 2004). This assessment is available for different agricultural production systems and maps were produced for a range of risks. Maps that may be relevant for informing on PAWC also in relation to identifying subsoil constraints are, e.g.: soil water storage, waterlogging risk, site drainage potential, water repellence risk, subsurface acidification risk, subsurface alkalinity risk, subsurface compaction, and water erosion risk. The WA Land capabilities and land quality mapping is viewable in WA's natural resource information system, "NRInfo", an online GIS-based mapping application (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). The WA Land capabilities and land quality mapping metadata are also available for download through SLIP, a Shared Landform Information Platform for finding and sharing geospatial data relevant to WA, https://data.wa.gov.au/. Once, downloaded, these can be imported into GIS-based software.	4.2
MySoil	MySoil provides soil information for the WA soils of the south-west in relation to agricultural production. MySoil summarises these soils into a total of 15 broad soil types, and was designed by the Department of Agriculture and Food Western Australia (now known as the Department of Primary Industries and Regional Development) as a simple diagnostic tool to identify which soil type an area of interest belongs to and what the key soil issues are most likely to be. MySoil can thus provide a starting point for yield estimates based on PAWC and can also be used as a first evaluation point for identifying potential constraints to crop production. The MySoil product is available through "MyCrop", which is a smartphone app (downloadable for android via the Google play store or the iphone App store) that brings together crop diagnostic tools, https://www.agric.wa.gov.au/mycrop. MySoil can also be accessed through: https://www.agric.wa.gov.au/mysoil.	4.3
Geological mapping	Geological maps can help users to understand soil forming conditions, and some Tertiary and Quaternary era mapping units may be useful for inferring PAWC properties. However, scale may limit how it can support PAWC work (greater than 1:100,000 scale). Information from geological mapping may provide some insights into landscape and soil similarities or dissimilarities (e.g. to compare the site of interest with existing PAWC characterisations). Access to maps varies, refer to Section 5.	5
Digital soil mapping	A suite of digital soil mapping soil attribute products are available as part of the Soil Landscape Grid of Australia (SLGA). These datasets are available here: http://www.clw.csiro.au/aclep/soilandlandscapegrid/index.html For WA, three SLGA soil attribute products are available, the national SLGA, the WA regional SLGA, and a merged national and WA regional product. The national and WA regional approaches developed simultaneously, not with the intention to duplicate the effort, but the assumption behind that certain methods were more appropriate for specific regions of interest in WA than others (Odgers et al., 2015). SLGA data may be used to create maps of new soil properties, or predict PAWC itself. Limitations for the data include the ground resolution, which at 90 m may be too coarse for some landscapes. That said, 30 m digital elevation data is available to the public via the Geosciences Australia portal, Elevation information System ('ELVIS' - http://www.ga.gov.au/elvis/#/), which will have significant impact on the level of local variability (consistent with finer mapping scales) that this data will support.	6

Terrain information	Terrain information can be used as a powerful predictor of soils and soil properties which are often strongly governed by land relief patterns. The principal dataset required for terrain analysis is a digital elevation model, of which the national version is accessible here: http://www.clw.csiro.au/aclep/soilandlandscapegrid/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. For some regions in WA, some high-resolution DEMs at 10 m and 25 m resolution also exist. These elevation data were produced as part of a broad-scale salinity and remnant vegetation assessment conducted within the Landmonitor project (Furby et al., 2010). DEM products are publically available and can be downloaded through: www.landmonitor.wa.gov.au.	7
Gamma radiometrics data	Gamma radiometrics imagery represents the geochemistry of the land surface, which relates strongly to 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
Satellite ASTER geoscience map of Australia	The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite collects land surface reflectance data in wavebands that are suitable for mineral investigation (see above). Full coverage of 14-bands ASTER imagery is available for the whole of WA through CSIRO's data access portal (https://doi.org/10.4225/08/51400D6F7B335), and if calibrated to mineralogy, may have value in estimating PAWC from clay mineralogy (see above), or as a covariate for use in predictive DSM.	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
Regional WA geophysical data	The Government of Western Australia through the Department of Mines, Industry Regulation and Safety website (http://www.dmp.wa.gov.au/Geological-Survey/Regional-geophysical-survey-data-1392.aspx) provides free of charge regional airborne magnetic, radiometric and electromagnetic surveys, ground gravity surveys and deep seismic and magnetotelluric surveys, which were funded by the State or Federal government. Of interest here are the state-wide geophysical compilations that may be available at a finer resolution than products accessible through national sources described above, in particular the radiometric grids of Western Australia available at 80 m resolution, which can be used to inform on soil parent materials, as well as soil texture and clay mineralogy.	8.5

The overview of available data in Sections 2 to 8 of the report indicates that there is a variety of soil and landscape data that could support methodologies to predict PAWC at paddock scale. With a very few exceptions, 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. It also takes some time to navigate through these online tools, which may create a barrier for the user of the systems. Potential case studies in the Western region will need to consider this.

Another challenge is the scale at which the various maps are produced. Some are produced at a scale of 1:50,000, but most are produced at 1:100 000 and 1:250 000 or more. This means some predictions need to be made with sparse data and associated 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 information contained in soil and landscape surveys and associated reports or manuals to build a narrative around soil landscape understanding that can help predict PAWC via extrapolation from known APSoil PAWC characterisations.

The first approach has the advantage that it can provide PAWC predictions at a 90 m resolution using the same approach everywhere. However, the uncertainty in digital soil attributes and models used in the predictions need to be considered and may not be sufficiently accurate everywhere. Another downside of this approach is that the grower/advisor will get a predicted PAWC for a location, but will not have a way to validate this value.

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

Possible future case studies

For the GRDC Northern region a similar data inventory report was prepared that included selection of eight case studies relevant for the next stage in the project, namely to evaluate in detail the different methodologies for predicting PAWC from available information (Verburg et al., 2018). This report includes suggestions for possible future case studies that could be of interest for the Western region. They allow the same approaches to be tested with the regional specific datasets available.

Within the GRDC Western Region there is some variability in the level of available soil and landscape information, although considerably less than in the other regions. This variability may affect the choice of methodology to predict PAWC. The density of data underpinning the digital soil attribute maps, like the national and regional data in the Soil and Landscape Grid of Australia (SLGA), is also uneven. The extent to which this may affect the reliability of PAWC predictions at farm scale has not yet been tested. In addition, the GRDC Western Region includes a range of soil-landscapes, which to some degree vary in complexity and this may also impact on the most suitable predictive approach.

The suggested case studies were chosen to represent different scales and soil-landscape complexity and include:

- **Regional-scale: Narrogin/Katanning/Lake Grace region, Western Australia**. This study area lies between the localities of Narrogin, Katanning and Lake Grace, Western Australia. It could offer a comparison of DSM data, terrain information, and geophysical data at different scales and resolutions (e.g. 90 m versus 30 m/25 m paddock-scale products), to test which resources are necessary to capture and better understand the complexity of this soil-landscape. And how to best use this information to predict PAWC, in a region with low coverage of APSoil sites and large soil-landscape variability.
- **Catchment-scale: Wallatin and O'Brian catchments, Western Australia**. This study area within the central wheatbelt lies between the localities of Kellerberrin and Doodlakine, Western Australia. The catchment has good coverage of APSoil sites, combined with soil-landscape mapping at potentially useful mapping scales, as well as DSM coverage (national and WA regional SLGA), and good coverage of high-resolution geophysical surveys and local soil mapping stemming from previous studies conducted in the catchment. It could therefore offer a comparison between "expert approximation of PAWC" using the soil-landscape polygon narrative approach and DSM approaches (national and WA regional SLGA products).
- **Farm-scale: Buntine region, Western Australia**. The study area is located close to the locality of Buntine, Western Australia. Detailed spatial land resource information and soil data (including a local farmer mud map) are available for the whole farm, including the on-farm location of 5 APSoil sites and 5 close by APSoil sites (refer to Figure 9.5); stemming from previous studies (i.e. GRDC's SIP09 Precision Agriculture Initiative conducted in the early 2000s). It offers an unique opportunity to test a complete suite of soil information to support the prediction of PAWC

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.

Project CSP00210 'Methods to predict plant available water capacity (PAWC)' 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 my 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 included to help identify opportunities for similar work. This report documents the findings of the scoping study for the GRDC Western Region.

1.2 Background

CSIRO, in collaboration with state agencies, catchment organisations, advisors and farmers has characterised more than 1,100 soils around Australia for their PAWC. Most of these PAWC characterisations used a field based method (Burk and Dalgliesh, 2013) to characterise the Drained Upper Limit (DUL; the amount of water a soil can hold against gravity) and the Crop Lower Limit (CLL; the amount of water remaining after a particular crop has extracted all the water available to it) (see Figure 1.1a).

The PAWC characterisations have been collated in a database ("APSoil") that can be accessed on-line (https://www.apsim.info/Portals/0/APSoil/APSRU-Australia-Soils.soils) and viewed spatially via Google Earth or the iPad SoilMapp application. Farmers and advisors use the PAWC information along with an assessment of soil water at sowing to gain an understanding of the amount of soil water that is available to the crop (PAW; Figure 1.1b). They use the information of PAW to forecast yield (through rules of thumb or application of tools like Yield Prophet®) and inform management decisions.

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

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

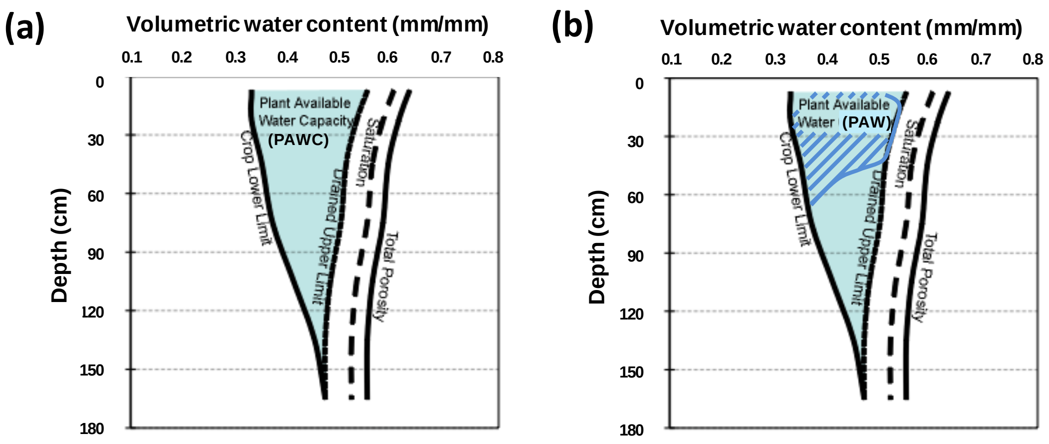


Figure 1.1. (a) The Plant Available Water Capacity (PAWC) is the total amount of water that a soil can store and release to different crops and is defined by its Drained Upper Limit (DUL) and its crop specific Crop Lower Limit (CLL); (b) Plant Available Water (PAW) represents the volume of water stored within the soil available to the plant at a point in time. It is defined by the difference between the current volumetric soil water content and the CLL.

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

The GRDC project CSP00170 informally developed ideas for an approach to use soil-landscape associations (available through state soil surveys in varying formats) to help interpret the PAWC characterisations and extrapolate across the landscape (Verburg et al., 2017; Verburg et al., 2015a; Verburg et al., 2015b). Preliminary concepts presented at workshops were well received and indicated an interest by growers and advisors in the use of on-line soil information resources. More research is needed to determine the predictive power and spatial accuracy. 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 emissions) may provide opportunities to strengthen the predictive capability.

Digital soil attribute mapping, such as the Soil and Landscape Grid of Australia (SLGA; Grundy et al., 2015) or other state-based efforts (e.g. Holmes et al., 2015) provides another approach to prediction of PAWC in space. 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, 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 Western 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 5 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.

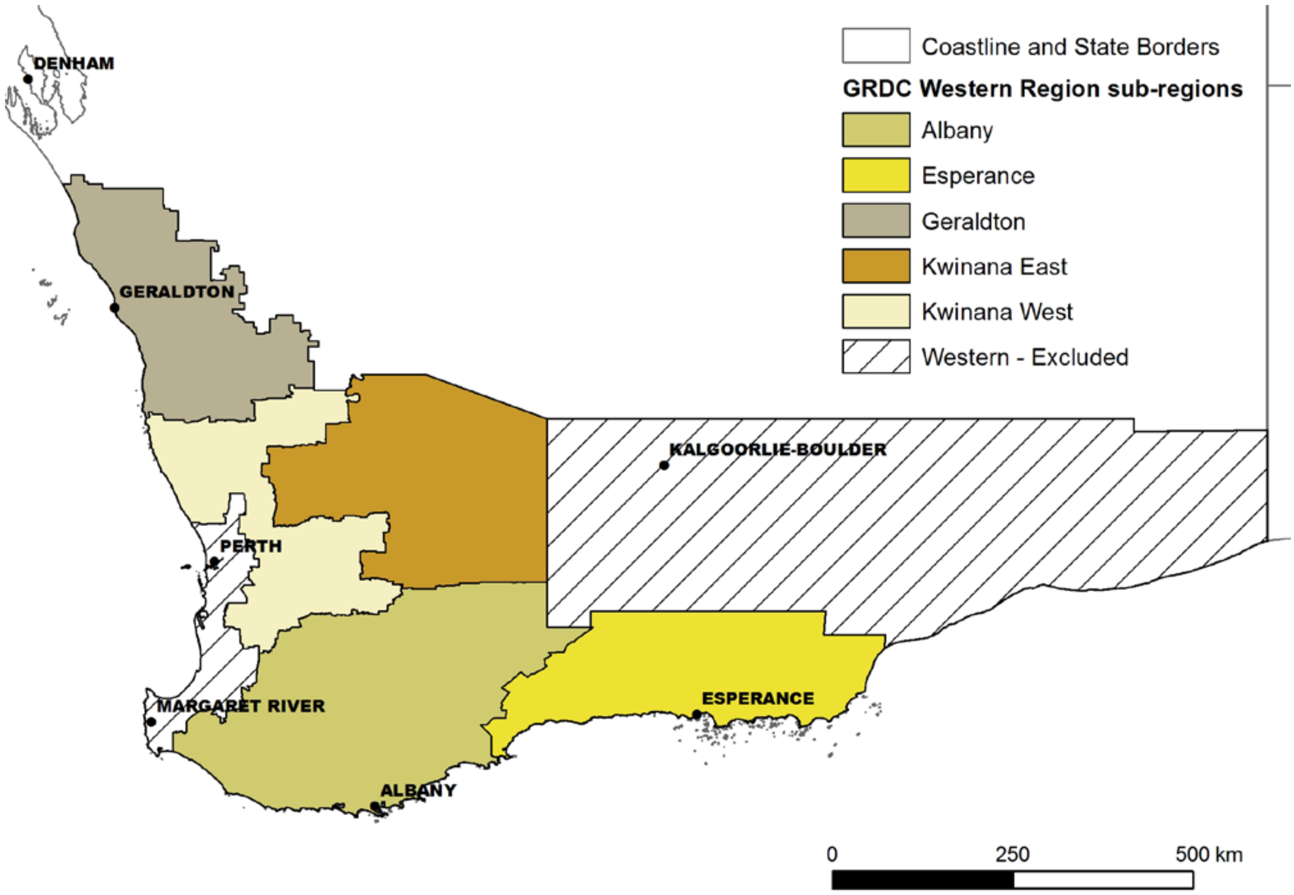


Figure 1.2. GRDC Western Region sub-region boundaries.

Source: Neil Clarke and Associates (2017)

2 PAWC Characterisations

Characterisations of PAWC for more than 1,100 soils across Australia have now been collated in the APSoil database and are freely available to growers, advisors and researchers. Of these, 261 are located in the GRDC Western 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.

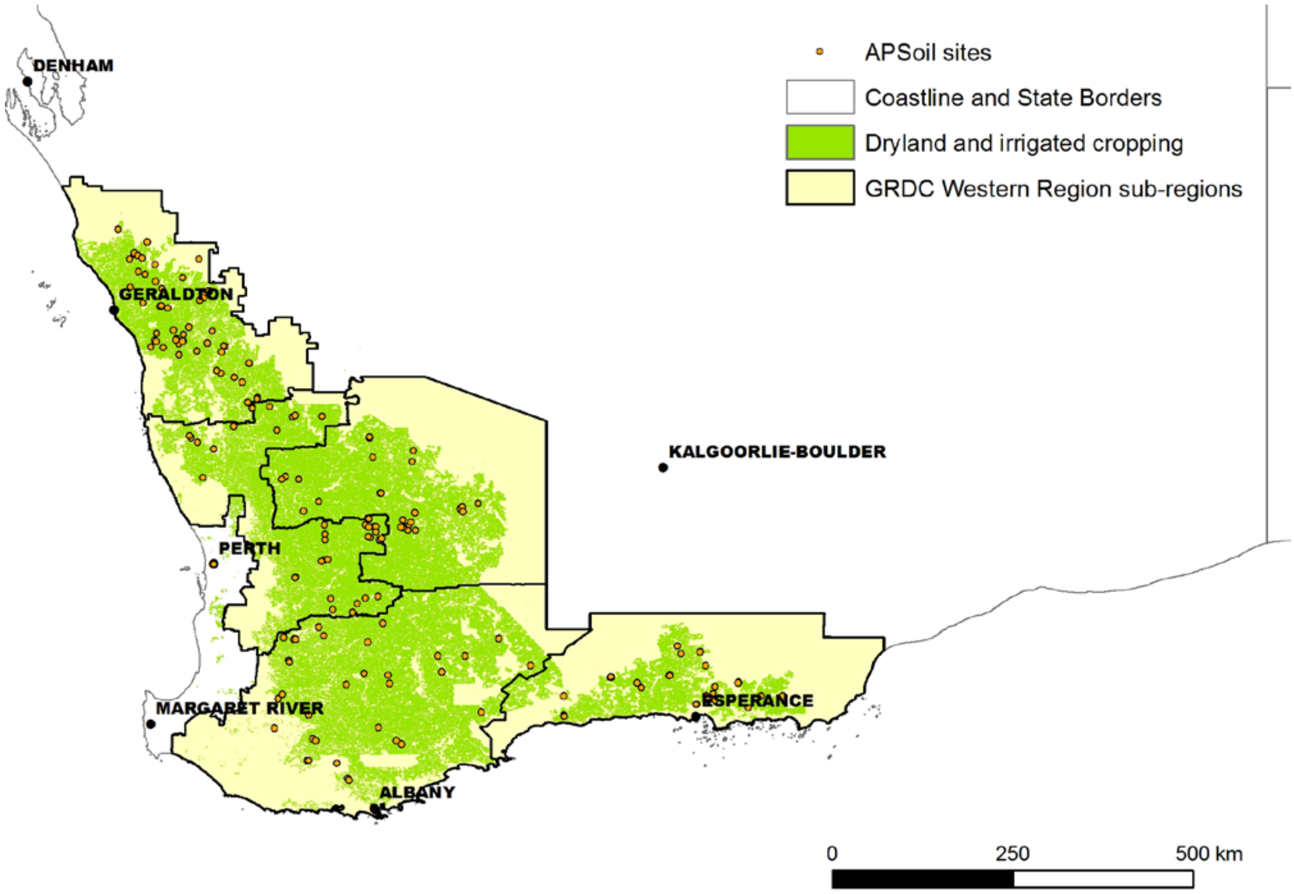


Figure 2.1. Locations of APSoil sites within the GRDC Western Region. Dryland and irrigated cropping extents are from the May 2016 update of the Catchment Scale Land Use of Australia dataset.

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 Western Region sub-regions have multiple APSoil PAWC characterisations. The distribution of PAWC characterisations within the sub-regions relates to the characterisations being associated with grain growing areas within these. Almost all of the characterisations are therefore located in the dryland and irrigated cropping areas of south-western WA (see Figure 2.1).

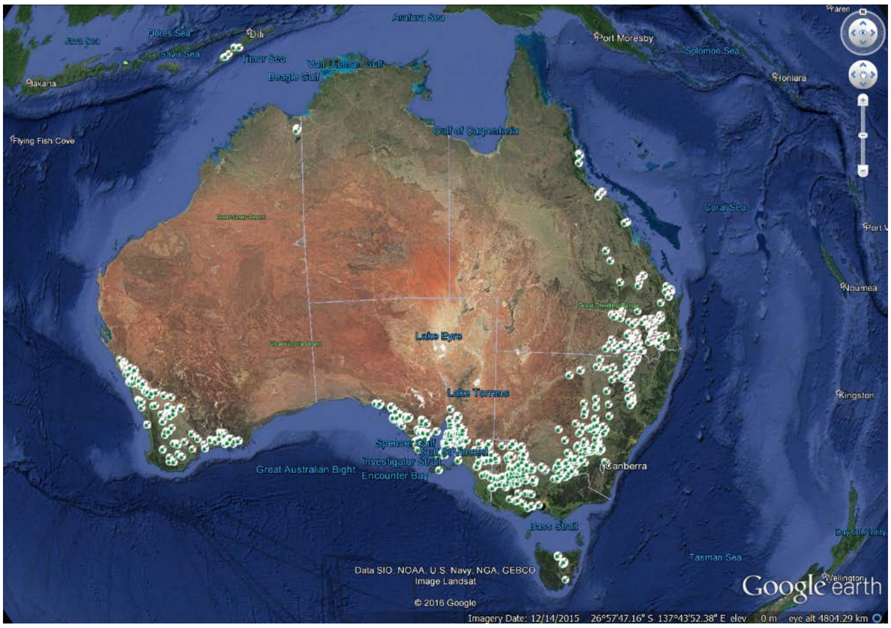
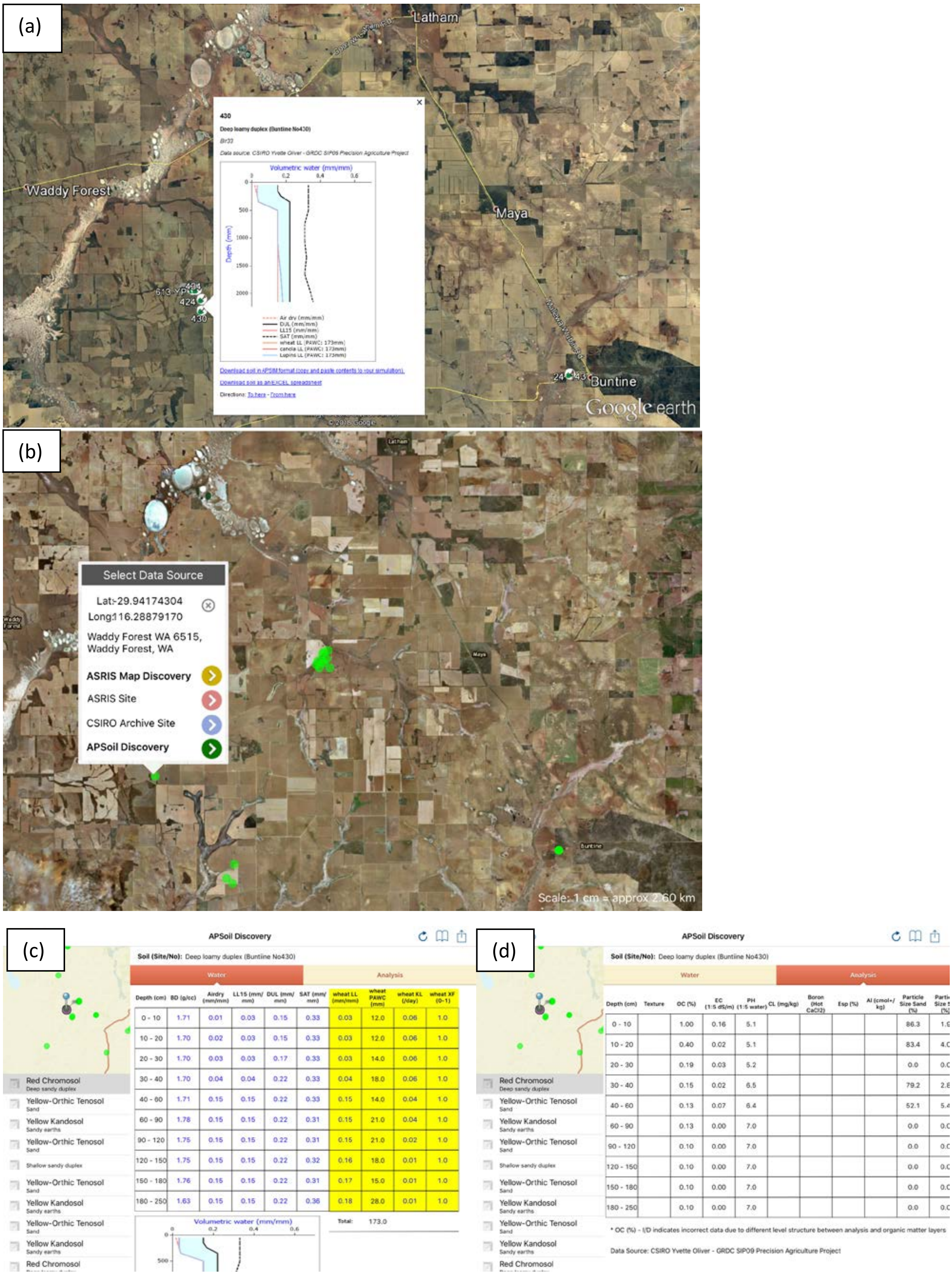


Figure 2.2. Access to geo-referenced soil PAWC characterisations of the APSoil database via Google Earth.



Depth (cm)	BD (g/cc)	Airdry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	wheat LL (mm/mm)	wheat PAWC (mm)	wheat KL (/day)	wheat XF (0-1)
0 - 10	1.71	0.01	0.03	0.15	0.33	0.03	12.0	0.06	1.0
10 - 20	1.70	0.02	0.03	0.15	0.33	0.03	12.0	0.06	1.0
20 - 30	1.70	0.03	0.03	0.17	0.33	0.03	14.0	0.06	1.0
30 - 40	1.70	0.04	0.04	0.22	0.33	0.04	18.0	0.06	1.0
40 - 60	1.71	0.15	0.15	0.22	0.33	0.15	14.0	0.04	1.0
60 - 90	1.78	0.15	0.15	0.22	0.31	0.15	21.0	0.04	1.0
90 - 120	1.75	0.15	0.15	0.22	0.31	0.15	21.0	0.02	1.0
120 - 150	1.75	0.15	0.15	0.22	0.32	0.16	18.0	0.01	1.0
150 - 180	1.76	0.15	0.15	0.22	0.31	0.17	15.0	0.01	1.0
180 - 250	1.63	0.15	0.15	0.22	0.36	0.18	28.0	0.01	1.0

Depth (cm)	Texture	OC (%)	EC (1:5 dS/m)	PH (1:5 water)	CL (mg/kg)	Boron (Hot CaCl2)	Esp (%)	Al (cmol+/kg)	Particle Size Sand (%)
0 - 10		1.00	0.16	5.1					86.3
10 - 20		0.40	0.02	5.1					83.4
20 - 30		0.19	0.03	5.2					0.0
30 - 40		0.15	0.02	6.5					79.2
40 - 60		0.13	0.07	6.4					52.1
60 - 90		0.13	0.00	7.0					0.0
90 - 120		0.10	0.00	7.0					0.0
120 - 150		0.10	0.00	7.0					0.0
150 - 180		0.10	0.00	7.0					0.0
180 - 250		0.10	0.00	7.0					0.0

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.

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 of ASC and WA soil classification system

The Australian Soil Classification (ASC) polygon mapping is available in digital format for all of the Western GRDC sub-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 WA data are from the Department of Agriculture and Food Western Australia (now known as the WA Department of Primary Industries and Regional Development). They are a translation of the local soil classification efforts into ASC soil type classes (2010 status). At a state level, different to NSW and Queensland for example, the ASC soil type mapping is not updated regularly, as WA uses their own local Western Australian soil classification system, the Soil Groups of Western Australia (Schoknecht and Pathan, 2013) (Figure 3.2). This classification is based on Northcote (1992) and better represents the uniqueness of WA soils, which are one of the most ancient and deeply weathered soil landscapes within the Australian context.

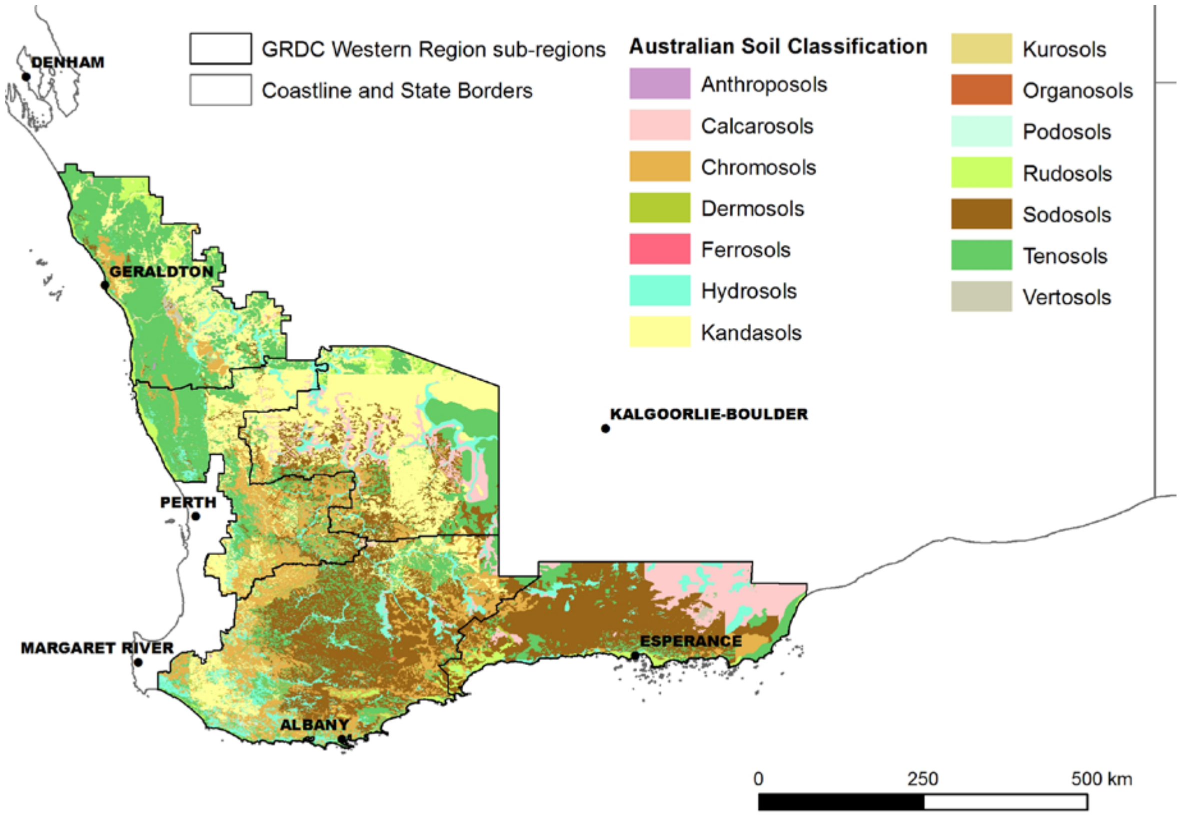


Figure 3.1. Australian Soil Classification (ASC) within the GRDC Western Region.

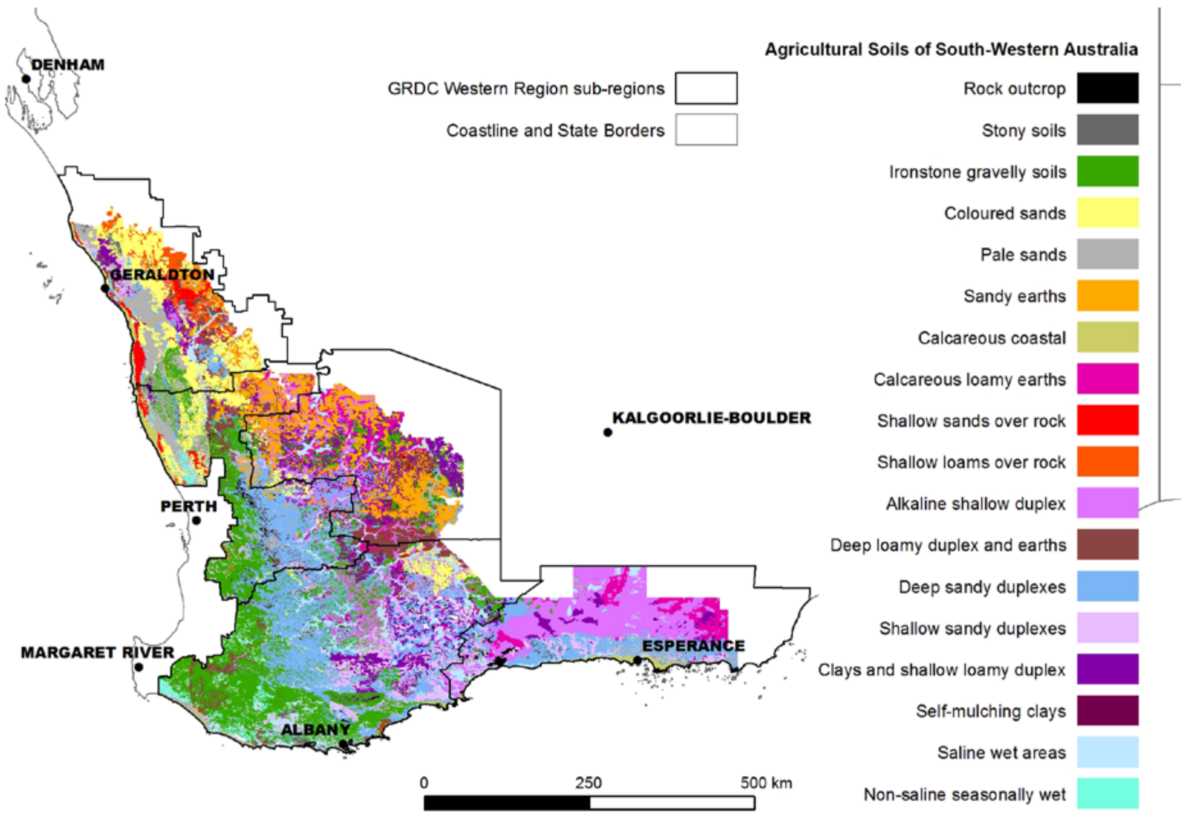


Figure 3.2. Western Australian Soil Classification for South West Western Australia Source (Schoknecht et al., 2013, page 17). The Ag Soils (Agricultural Soils) shown here are a simplification and grouping of the WA Soil Groups (Schoknecht and Pathan, 2013).

Source: Phil Goulding, Department of Primary Industries and Regional Development, WA

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.

Similarly, in the local Western Australian soil classification system, soils are named and described at two levels, Soil Supergroups and Soil Groups. Soil Supergroups are defined based on three main criteria, the texture or permeability of the soil profile, the presence and nature of coarse fragments and the water regime. Soil Groups are then further divided based on soil morphological criteria (e.g. horizon colour and horizon/profile depth, structure, surface texture and profile texture changes, acidity/alkalinity, and susceptibility to waterlogging or salinity). Soil Groups therefore roughly relate to the rank of suborder in the ASC system. A total of sixty Soil Groups are described across the state and maps showing the general distribution of those are available for the state's south-west (Purdie et al., 2004) and the rangelands (Purdie, 2006). As Soil Groups can vary locally, these can have qualifiers assigned to them which further describe these in more detail relevant to the local variation within them (Schoknecht and Pathan, 2013). The GRDC Western regions are part of the south-west, which is characterised in general terms by soils with sandy topsoils ranging from deep sands to sands over clays, and soils dominated by ironstone gravels.

In the national ASC system, 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. In the local WA system, classification typically requires an observation depth down to 0.8 m only. As ASC and the local system draws heavily on soil morphology, it does lend itself to agriculture and understanding PAWC, especially in the ASC system if classification has been accomplished to the family level of classification. 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.

The following paragraph illustrates for the ASC system how the knowledge of soil classification can assist growers and advisors in making a more informed decision on PAWC.

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. This ASC order is, however, limited in the agricultural production areas of south-western Australia and more common in the Ord River Irrigation Scheme and in central NSW and Queensland. 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, also have sizeable PAWCs (>180 mm). Lighter textured Dermosols and Kandosols as well as orders with strong texture contrasts, e.g. Chromosols, Kurosols and Sodosols have on average smaller PAWC, although with a wide range determined by actual texture. Furthermore, the low pH associated diagnostic of Kurosols, and the salinity and structural issues associated with Sodosols may further reduce PAWC due to hostile rooting conditions. Tenosols (ASC concept: undeveloped 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 small PAWC values (e.g. <110 mm). These ASC orders are quite common in the Western GRDC regions, and in dryland agriculture rely heavily on consistent rainfall in the growing season.

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. This is also valid for the local WA soil classification system. Here, the finest level of soil class information are unmapped soil-landform components that are described proportionally within a map unit (e.g. a qualified soil group 'Acid yellow sandy earth with saline subsoil' with landform position 'lower footslope') (Holmes et al., 2015).

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. Similarly, reference soil profiles are also available for the local WA soil classification system.

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 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.

It should be noted here, that for WA, ASCs were assigned as approximate equivalent for the WA Soil Groups present in a map unit. A single Soil Group may then be represented by several different ASCs. This may explain why numerous ASCs show up when SoilMapp is queried for areas in WA.

For information on online access of the local WA soil classification system, the reader is referred to Section 4.

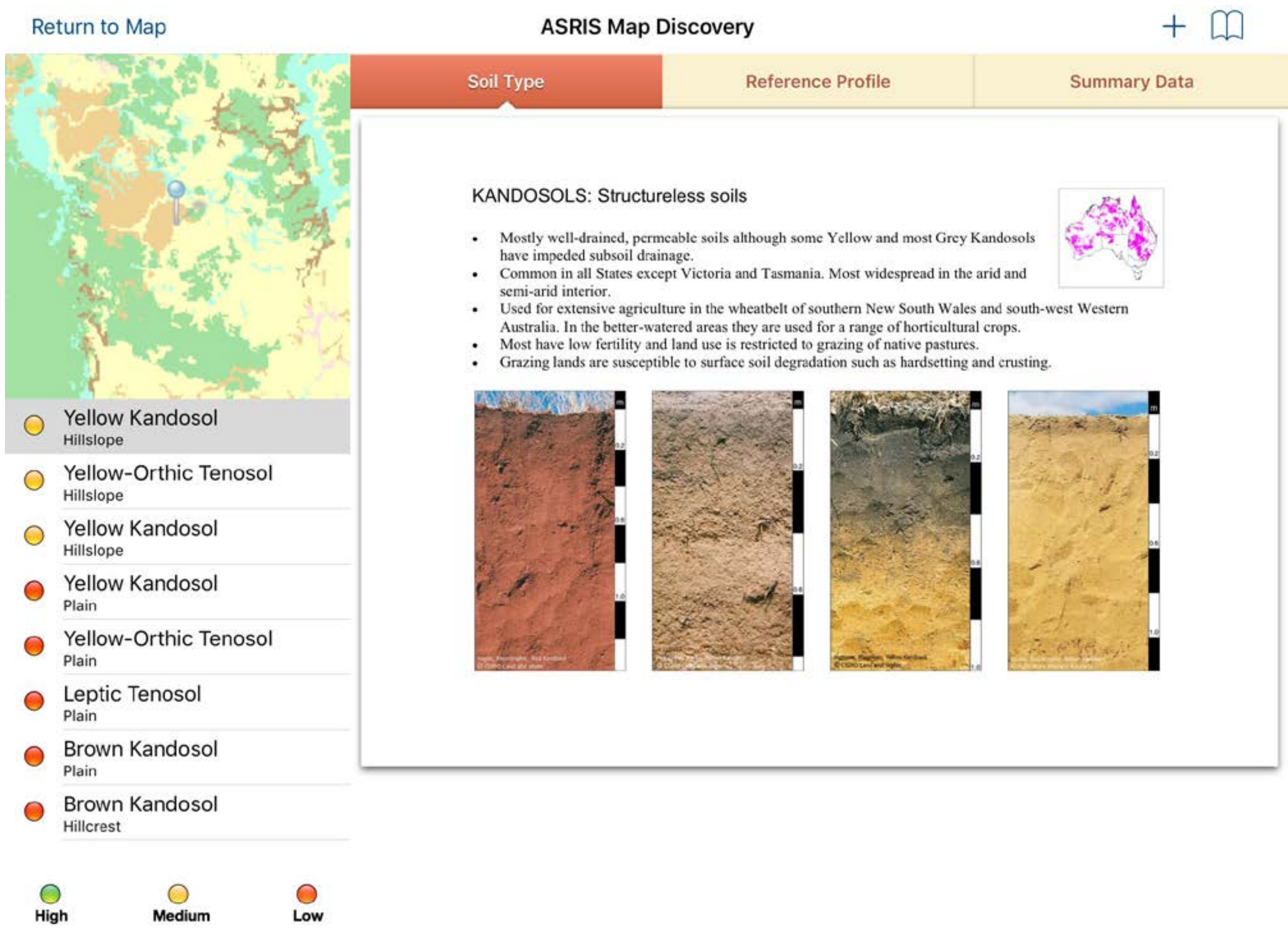


Figure 3.3. SoilMapp Map Discovery tool screen shot for a location near Buntine WA.

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.

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 3.4). 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 3.4, the distribution of reference profile sites in the GRDC Western Region is relatively dense. This dense distribution is highly associated with the strong and systematic land resource evaluation programs in agricultural areas in Western Australia, carried out in the 1970s-2000s.

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).

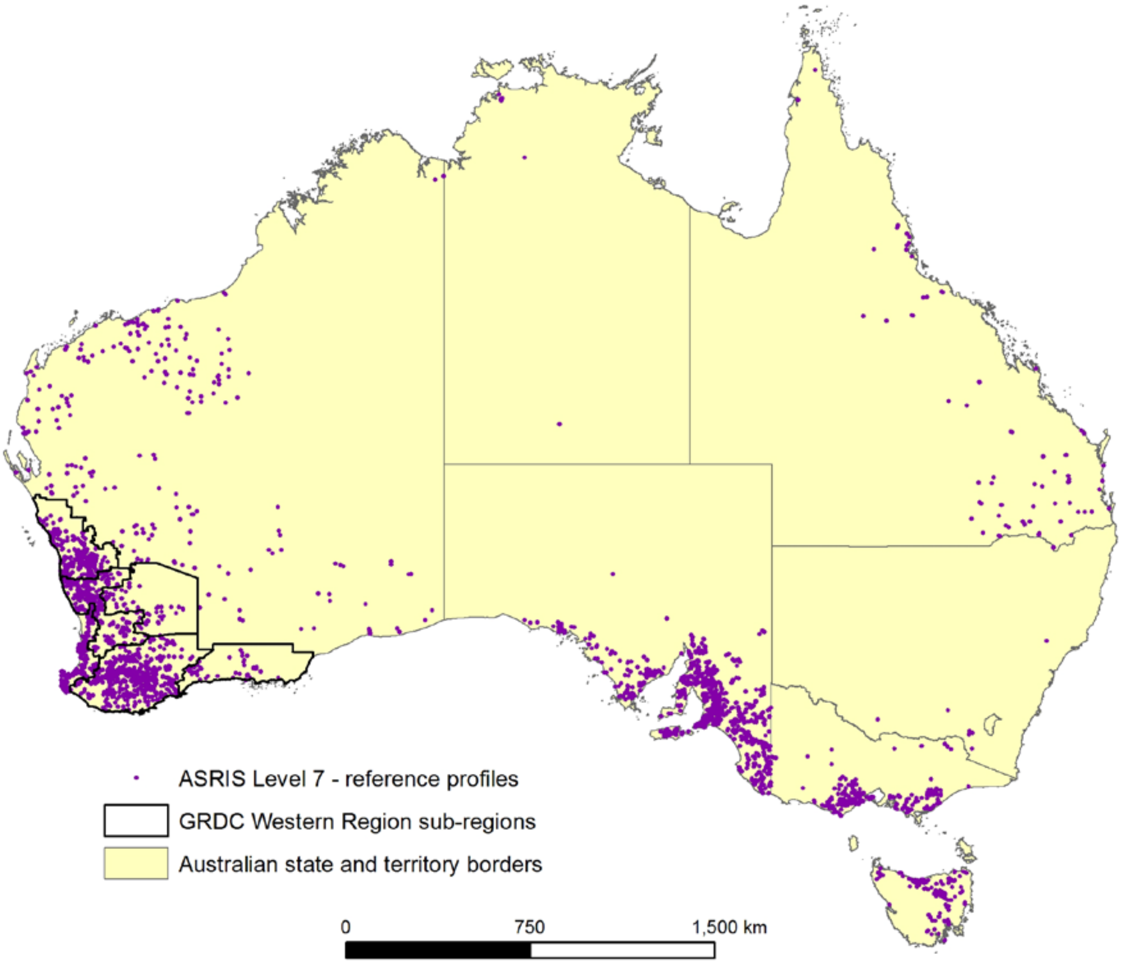


Figure 3.4. CSIRO's Australian Soil Resource Information System soil database interface showing distribution of national soil reference profile sites.

Different to the Northern GRDC region, for example, where soil profile data are accessible through the public domain via online tools provided by the state departments falling within the region (e.g. the "eSpade" tool for NSW, http://environment.nsw.gov.au/eSpade2Webapp), soil profile data download is not embedded in Western Australia's soil and land resource mapping tool "NRinfo" which is explained further in Section 4 (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). Soil site locations are only visible in the tool, and associated map units and Soil Groups are described.

There is a current effort, however, to present WA's soil profile data within the "Australian Virtual Soil Archive" (demonstration, www.asris.csiro.au/virtualsoilarchive/). This online web interface which is at present in its development stage brings together Australian soil profile data from various agencies, with the intention to make these available in one location for ease of access for the user. Data are sourced from the contributing agencies data systems directly, an extraction that is made possible through the application of OGC WFS web services that utilise the ANZSoilML information model. At present, CSIRO Land & Water and the WA Department of Agriculture and Food (now known as the WA Department of Primary Industry and Regional Development) are contributing data services to the "Australian Virtual Soil Archive" demonstration. The interface is live, but as it is in its development phase, it should be used with caution.

Figure 3.5 shows a framegrab of the user interface, which currently allows the user to centre on an area of interest and geographically display the soil profiles that are available there by navigating to the show samples icon. Users then may click on a site icon (with blue indicating profiles from the ASRIS database and green from the WA department database) to reveal a pop-up window which details site and profile descriptions, including laboratory data. Data of interest can be added to a data checkout by navigating to the 'add to cart' icon, and subsequently downloaded in excel spreadsheet format. The interface resembles the Google Earth interface and navigation through the tool is quite intuitive, as most users are now familiar with the Google maps tools through their own personal smart phone, tablet or desktop/laptop devices. A good feature of the tool is also a small inset box, as it provides context of where the zoomed in location is situated within a larger area. The "Australian Virtual Soil Archive" could be a powerful tool for accessing soil profile data once moved to the fully operational stage.

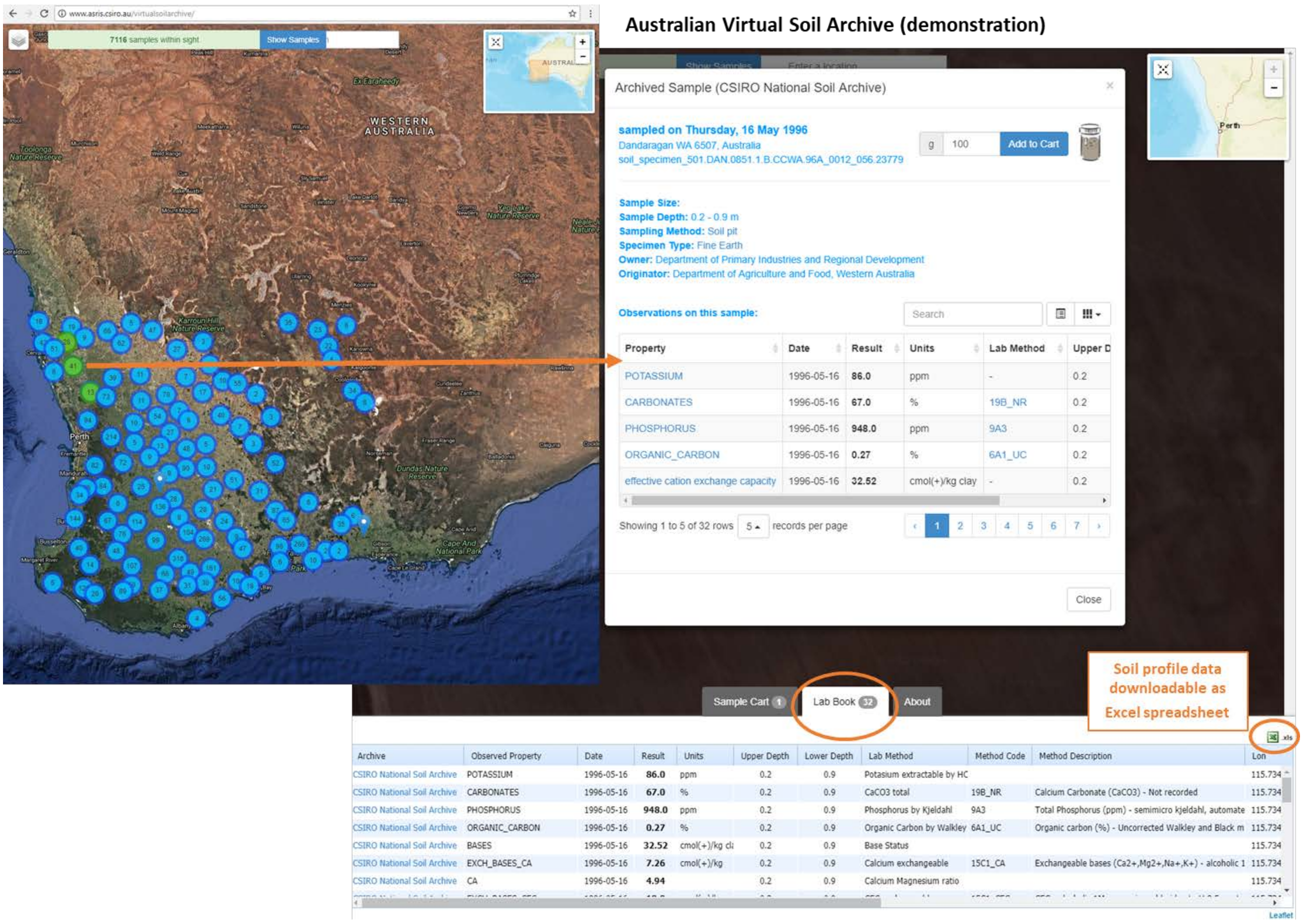


Figure 3.5. Framegrab of the Australian Virtual Soil Archive (demonstration) soil database interface showing distribution of soil sampling sites and preliminary record interface (Blue points: ASRIS database, Green points: WA database).

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 areas 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 sections (Section 3.4 and 3.5) may assist in this respect, or assist in correlations with known PAWC estimations (e.g. APSoil sites).

3.4 CSIRO land resources 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*. Most of CSIRO's land evaluation efforts fall outside the GRDC Western Region, however, a few were conducted, which complement surveys undertaken by the local Western Australian Government (refer to Section 3.5).

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 3.6), and detailed discussions supported by morphological, chemical and physical data. Toposequence model cartoons are used to communicate terrain/soil relationships (e.g. Figure 3.7). 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.

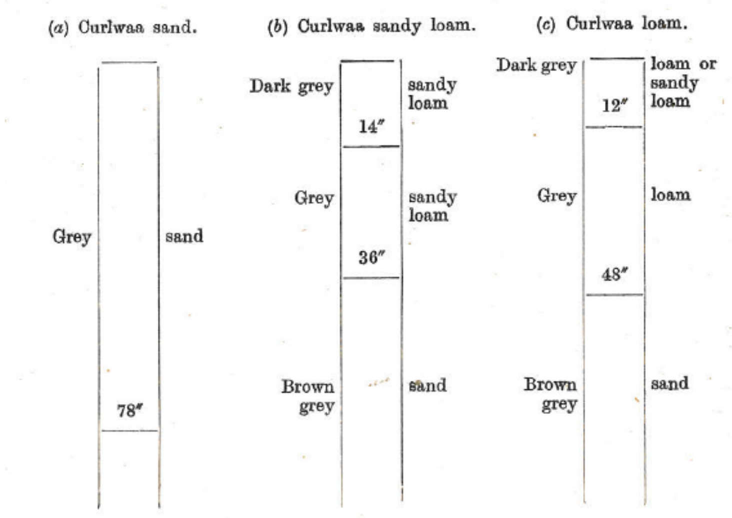


FIG. 1.—CURLWAA SERIES.

Figure 3.6. Soil profile morphologies of three soil associations comprising a soil series (Marshall and Walkley, 1937).

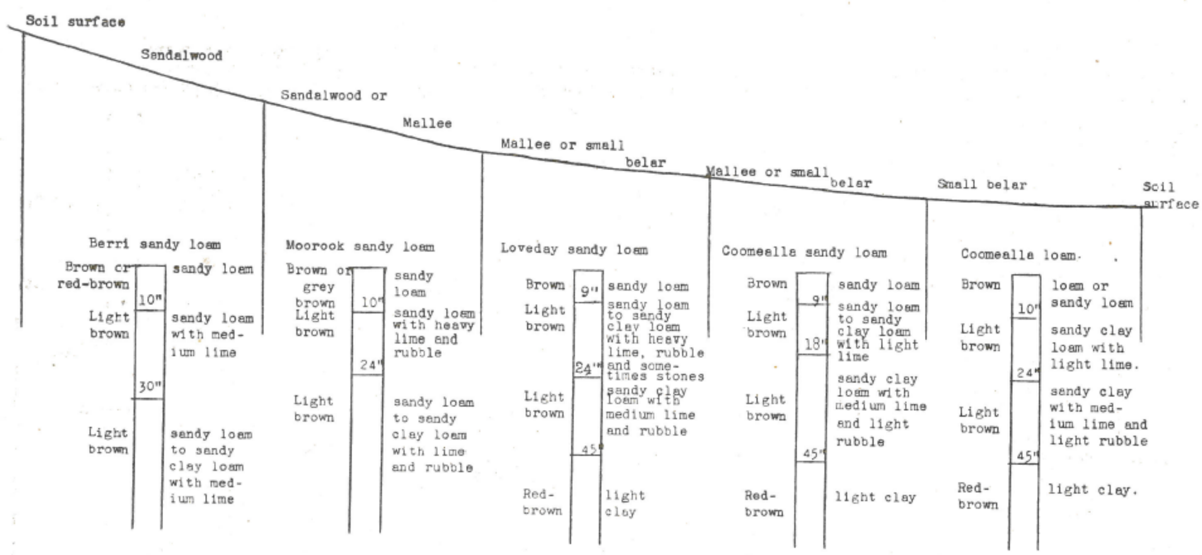


FIG. 10.—Common relationships between the soil type, vegetation and contours of Coomealla soils for the group of types having a brown or grey-brown surface colour.—The Berri sandy loam does not belong properly to this group, and it could be included quite as well with the red-brown soils. Under each type name there is shown a diagrammatic representation of an average soil profile, with horizon depths given in inches.

Figure 3.7. 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 and 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 of 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 of 1:250,000 – 1:1M, and the soil mapping was 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, each containing a discrete set of lower tier soil associations consistent with 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. The few surveys within WA fall outside the GRDC Western Region. The coarse scale of mapping and the high level of soil and landscape aggregation typically contained in the Soil Publications and Soil and Land Use series of reports makes it unlikely that they can be useful in supporting PAWC estimations or guide correlations with APSoil soils. Furthermore, most in these series do not coincide with dryland cropping areas.

The final land evaluation reports in the CSIRO series, *Division of Soil Reports*, typically reverted to smaller area-type land evaluations, e.g. covering areas ~100,000 ha. These addressed the potential to shift existing land uses to more intensive ones, or where current intensive practices could result in local and off-site degradation. 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 'soil phases' or 'variants'. While it is likely that the scale and mapping themes may be sufficient at times to support PAWC work, it is however unlikely that these evaluations cover areas currently under dryland cropping.

The CSIRO driven land evaluation reports worthy of investigation for supporting PAWC work in the Western region are listed in Table 3.1. Readers will note that there is some overlap between CSIR/CSIRO land and soils surveys with state efforts in the literature. This is particularly in terms of custodianship of legacy material (reports and scanned maps) and subsequent value-addition from baseline data. This reflects to a great degree the extent of cross-pollination and collaborations in terms of developing and sharing methodologies, field and laboratory efforts between CSIR/CSIRO and state land evaluation jurisdictions in Australia – especially in the formative era of soil and land survey.

Associated un-georeferenced high-resolution maps in pdf format can be downloaded from the WA Department of Primary Industry and Regional Development's research library catalogue (https://researchlibrary.agric.wa.gov.au/).

Table 3.1. CSIRO soil and land reports with potential to support PAWC work in the GRDC Western Region.

Series	Report Title
CSIR Bulletins	
115	A soil survey of part of the Denmark estate, Western Australia (1938). / by J.S. Hosking, G.H. Burvill and Council for Scientific & Industrial Research
CSIRO Bulletins	
52	The soils of Australia in relation to vegetation and climate (2nd ed. 1952). By J. Prescott
262	Soils of the Margaret river-lower Blackwood river districts, Western Australia (1951). / R. Smith
265	Pedogenesis in the Frankland River Valley, Western Australia (1951). / R. Smith
Soils and land use series	
15	Soils of the Swan Valley vineyard area, Western Australia (1955). / by L.W. Pym
16	The soils and irrigation potential of the Capel-Boyanup area, Western Australia (1956). / by W.M. McArthur and E. Bettenay
20	Soils and land use in the Harvey area, Western Australia (1957). / L.W. Pym and T.J. Poutsma
31	The soils and irrigation potential of the Pinjarra-Waroona area, Western Australia (1959). / W.M. McArthur, E. Bettenay and F.J. Hingston
35	The soil associations of part of the Swan coastal plain, Western Australia (1960). / E. Bettenay, W. M. McArthur and F. J Hingston
41	The soils and land use of the Merredin area, Western Australia (1961). / E. Bettenay and F.J. Hingston
54	Forestry and agriculture in relation to soils in the Pemberton area of Western Australia (1975). / W.M. McArthur and A.J. Clifton
Soil Publications	
16	Development and distribution of soils of the Swan Coastal Plain, Western Australia (1960). / by W.M. McArthur and E. Bettenay
17	The development and distribution of the soils of the York - Quairading Area, Western Australia, in relation to landscape evolution (1961). / by M.J. Mulcahy and F.J. Hingston
20	The chemistry and mineralogy of lateritic soils in the south-west of Western Australia (1962). / by A.G. Turton
27	Australian soils with saline and sodic properties (1972). / by K.H. Northcote and K.M. Skene
Land Research Surveys	
	NA
CSIRO Division of Soils reports	
6/44	The soils of the Margaret River district, Western Australia (1944). / by C.G. Stephens and R. Smith
6/47	Progress report No. 1 – The Kojonup spot survey, Western Australia (1947). / by R. Smith
19/47	Progress report No. 3 – The Rocky Gully spot survey, Western Australia (1947). / by R. Smith
20/47	Progress report No. 2 – The Kybelup spot survey, Western Australia (1947). / by R. Smith
26/47	Progress report No. 4 – The Ucarro spot survey, Western Australia (1947). / by R. Smith
27/47	Progress report No. 5 – The Eulanda spot survey, Western Australia (1947). / by R. Smith, E.W. Boehm
28/47	Progress report No. 6 – The Corrolup spot survey, Western Australia (1947). / by R. Smith

29/47	The Boscabel spot survey, Western Australia (1947). / by R. Smith and E.W. Boehm
12/48	The Tone River spot survey, Western Australia (1948). / by R. Smith
1/52	The soil associations of part of the Swan Coastal Plain, Western Australia (1952). / by R. Smith
2/50	The East Narrikup soil survey, Western Australia (1950). / by R. Smith
5/53	North Stirlings soil and salinity survey, Western Australia (1953). / by T. Poutsma
1/56	The Frankland spot survey, Western Australia (1956). / by L.W. Pym
11/56	Pedology of the soils in the Capel - Boyanup area (1957). / by W. A. E. Bettenay and F. J. Hingston
7/57	Soils of the proposed extension of the Collie irrigation district, Western Australia (1957). / by W.M. McArthur and E. Bettenay
3/58	The soils of the Busselton area, Western Australia W.M McArthur / by E. Bettenay; 1958
4/58	Further investigations of the soils of the Harvey and Waroona Areas, Western Australia (1958). / W.M. McArthur
15/62	Soils of the north Manypeaks area (1962). / by W.A.E. Bettenay and T. Poutsma
10/62	Salinity investigations in the Belka valley, Western Australia (1962). / by E. Bettenay, A.V. Blackmore and F.J. Hingston
2/64	The occurrence of shallow groundwaters in sandy soils north of Meckering, Western Australia (1964). / by E. Bettenay
CSIRO Soils Technical paper	
33	Use of soil and land-system maps to provide soil information in Australia Beckett B.H.T, Bie S.W. 1978
CSIRO Soils Technical report	
1993/ 33	Mineralogy of clay fractions of soils from East Beverley, Western Australia (1993). / by G.G. Riley
N/A	Use of soil and land-system maps to provide soil information in Australia (1978). / by B.H.T. Beckett and S.W. Bie
CSIRO Water Resources Divisional Report	
88/1	Landforms and soils of the south coast and hinterland, Western Australia – Northcliffe, Mount Barker, Deep River Nornalup, Denmark Parry Inlet, Manypeaks (1:100,000) (1988). / by H.M. Churchward, W.M. McArthur, P.L. Sewell and G.A. Bartle
CSIRO Land Resources Management Series	
1	Soil pattern and resources utilization in the Wungong brook catchment, Western Australia (1975). / by H.M. Churchward and F.E. Batini
3	Landforms and soils of the Murray river catchment area of Western Australia (1977). / by W.M. McArthur, H.M. Churchward and P.T. Hick
6	Soils and land use planning in the Mandurah-Bunbury coastal zone, Western Australia (1980). / by W.M. McArthur and G.A. Bartle
Other	
	Atlas of Australian soils: explanatory data for sheet 5. Perth-Albany-Esperance area (1967). / by K.H. Northcote

3.5 WA Soils Mapping and land resources evaluation

The spatial soil information of WA is based on a total of 53 surveys, with the majority collected by the Government of Western Australia. They consist of polygons with similar soil-landscape relationships that were derived between 1932 and 2012 (Holmes et al., 2015). Surveys that were conducted by CSIRO are listed in the previous Section 3.4. Scales at which these soil maps were produced vary across the state and reflect population density and agricultural potential. In general, WA mapping efforts can be classified as follows (after Holmes et al., 2015):

- Highest intensity mapping (1:20,000-1:50,000): south-west agricultural region, developing irrigation areas in the north,
- Moderate intensity mapping (1:250,000-1:500,000): drier areas of cultivation and rangelands,
- Low intensity mapping (1:2,000,000): arid interior.

Most high and moderate intensity surveys were carried out between 1987 and 1999. Soil surveys were conducted in accordance with the standards set in CSIRO's 'Australian Soil and Land Survey – Guidelines for conducting surveys' (Gunn, 1988). Soil classification was based on the local WA system, the Soil Groups of Western Australia (Schoknecht and Pathan, 2013), outlined in Section 3.2. The mapping hierarchy within these surveys typically followed the description of a soil-landscape "system", which delineates repeating patterns of landscapes and associated soils that at most times was further divided into a soil-landscape "sub-system", which equates to the most detailed level of soil landscape polygon mapping in WA. Soil series or qualified Soil Groups combined with landform position were assigned relative to their proportion within a map unit (i.e. these proportionally describe unmapped soil-landform components). At different levels of detail these are distinguished by a repeating pattern of physiogeographic features.

In summary, the WA soil and land resources evaluation followed a hierarchy of 6 map units levels, which was designed to allow for correlation between surveys conducted at different scales (after McArthur et al., 2004):

1. Region: Broad subdivisions of the Australian continent (Division of Soils, CSIRO); e.g. The Western Region (map unit 2).
2. Provinces: Broad overview of the whole state suitable for maps at scale of 1:5,000,000 (Division of Soils, CSIRO); e.g. Avon Province (map unit 25).
3. Zones: Areas defined on geomorphological or geological criteria; suitable for regional perspectives; e.g. Southern Zone of Ancient Drainage (map unit 259).
4. Systems: Areas with recurring patterns of landforms, soils and vegetation; suitable for regional mapping at scales of 1:250,000; e.g. East Katanning System (map unit 259Ek).
5. Subsystems: Areas of characteristic landforms features containing definite suites of soils; suitable for mapping at regional scales of 1:100,000; e.g. East Katanning 1 Subsystem (map unit 259Ek_1).
6. Subsystem phases: Division of subsystems based on land use interpretation requirements; e.g. East Katanning 1 Subsystem sandy phase (map unit 259Ek_1s).

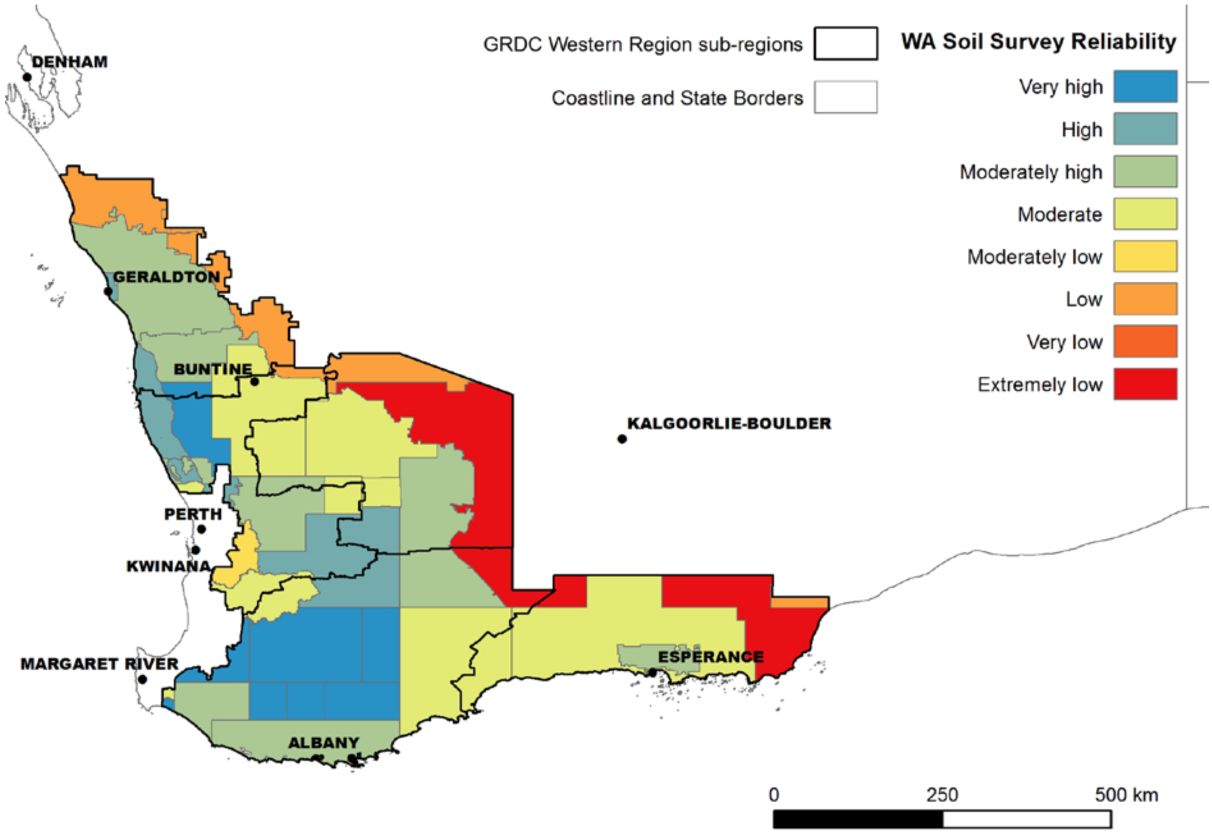


Figure 3.8. WA government and CSIRO Soil and land resources surveys within the GRDC Western Region. Survey reliability is shown based on mapping intensity.

Similar to the previous section, the following paragraphs briefly summarize the main characteristics of the WA Government soil and land resources evaluations, and highlight the utility typically contained in these that may assist with PAWC predictions.

The WA Department of Agriculture and Food (now knows as Department of Primary Industries and Regional Development) *Bulletin* series contains some publications that are aimed at providing readers with the principles underlying the formation of local soil landscapes, and with the information required to identify such landscapes and associated soils. These soil and landscape related Bulletins were written with an emphasis on field application so that users are able to gain a better understanding of the local soils and the capability of their land, salinity and hydrological properties, local farming systems, and landcare and nature conservation. These are available for the WA wheatbelt districts (Geraldton, Three Springs, Moora, Northam, Merredin, Narrogin, Katanning, Lake Grace, Jerramungup, Albany and Esperance), all of which fall within the GRDC Western region. The *Bulletins* are relevant to assist with PAWC predictions, as for each district, several soil reference profiles are described in detail in relation to their soil type, and distinguishing features. In addition, advice is also given on their agricultural use and management, based on soil characteristics including favourable attributes (e.g. good soil water storage) and limitations (e.g. high alkalinity and sodicity in the subsoil), agronomic considerations, soil conservation and water conservation. For each reference soil profile described, its distribution within the districts is also provided. These maps are embedded in the reports.

The *Bulletin* series also contains *Soilguide* (Moore, 2001), a handbook developed by the WA Department of Agriculture and Food (now known as the WA Department of Primary Industries and Regional Development) for farmers and advisors to help in understanding and managing WA's agricultural soils at the paddock scale. It provides links between the soils, their properties, and management options. *Soilguide* also contains stylised diagrams of soil occurrence in relation to their landscape position, explaining stylised regular patterns of soils on divides, sideslopes and valley floors in relation to a WA soil landscape zone (refer to Figure 3.9). In Figure 3.9, one can see that in the "Zone of Ancient drainage" (map unit 258), on the divides soils are predominantly yellow deep sands and sandy gravels, with grey shallow and deep sandy duplex soils on the valley slopes, and calcareous loamy earths and alkaline shallow duplex soils on the valley floors.

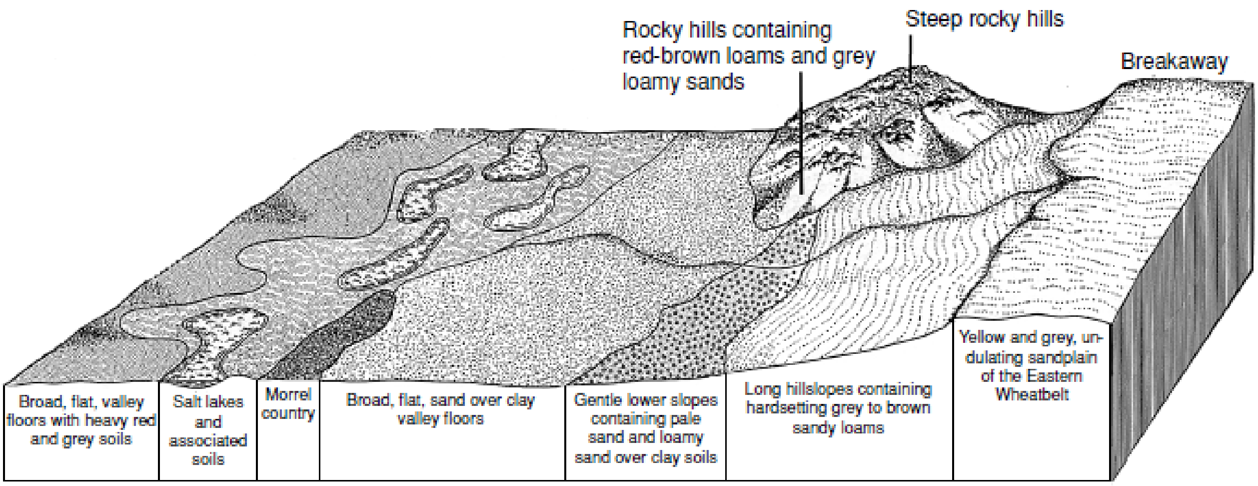


Figure 3.9. Soilguide stylised diagram for the 'Zone of Ancient drainage', showing the soils in relation to their landscape position (Moore, 2001, page 37).

The WA Department of Agriculture and Food (now knows as Department of Primary Industries and Regional Development) *Resource management technical reports series* also contains a variety of publications that can assist with estimating PAWC. A range of reports was written for various areas within the GRDC Western region (e.g. Report 235, Cranbrook-Toolbrunup catchment appraisal report), that focus on the agricultural and natural resources at risk within the catchment studied, and also propose options to manage the potential risks. The *Resource management technical report Soil groups of Western Australia: a simple guide to the main soils of Western Australia* (Schoknecht and Pathan, 2013) is also a helpful guide, as it was designed to be an easy-to-understand tool to recognise the most common soils and their characteristics in WA. The guide details the most common soil groups and for most of those also provides a typical Australian Soil Classification (ASC) equivalent.

All of the GRDC Western region has been surveyed as part of the *Land Resource Series*. This soil-landscape mapping effort was driven by delivering seamless soil information for the agricultural area of south-western Australia. Provided information is aimed to assist planners, researchers and land managers with making sustainable land use decisions, and was conducted at the regional and catchment scale. Associated soil-landscape maps were produced at varying levels of detail, at a scale of 1:50,000 (5 maps), 1:100,000 (9 maps), 1:250,000 (5 maps), and 1:500,000 (1 map). Of these 22 land evaluations, one provides a draft map only, and five are unpublished (i.e. the reports including their maps). Similar to the CSIRO series, *Division of Soil Reports*, some WA Government

Land Resources Series, were conducted on smaller scales (high-intensity mapping), covering areas of ~100,000 ha or less, and produced maps at scales of 1:50,000. Typically all surveys present soil and land resource mapping and land capability assessments for rural residential and associated agricultural activities. The upper mapping tier describes soil-landscape “systems” which were divided further into “sub-systems”, describing their main soils, landforms, geology, land use and native vegetation. Lower tier main soil series are described proportionally within each subsystem. These are typically described in detail, and usually include a representative soil profile with associated soil physical and chemical analyses if undertaken. Associated reports also describe the main properties and land degradation hazards in relation to the soils identified, which can be used as a starting point for evaluating the capability of the soils. It is likely that the scale and mapping themes may be sufficient to support PAWC work.

The WA government *Soil information sheets* series were put together for farmers in the Northern Wheatbelt. These information sheets summarize the characteristic properties of soils occurring in the region in relation to their land use suitability and management. For each soil described, a photo of a representative soil profile is also provided. The *Soil information sheets series* is thus a good starting point informing on PAWC predictions.

In addition, the WA Government provides a range of other resources that may be helpful for PAWC estimation. One of these potentially valuable resources is the book *Reference soils of south-western Australia* (McArthur et al., 2004), an effort initiated by the Australian Society of Soil Science WA Branch in 1991. It documents 160 soil reference sites throughout south-western Australia, and provides a basis for understanding and utilising the soils in the Western GRDC region. The book consistently presents soil morphological and analytical data for the 160 soil reference sites, so that soil attributes for different soil landscapes can be compared and contrasted directly. The location for each soil reference profile is indicated on maps embedded in the report. The location of some reference profiles is also presented in a stylised diagram in relation to geology, landscape history and topography (refer to Figure 3.10, which shows an example for the Wheatbelt).

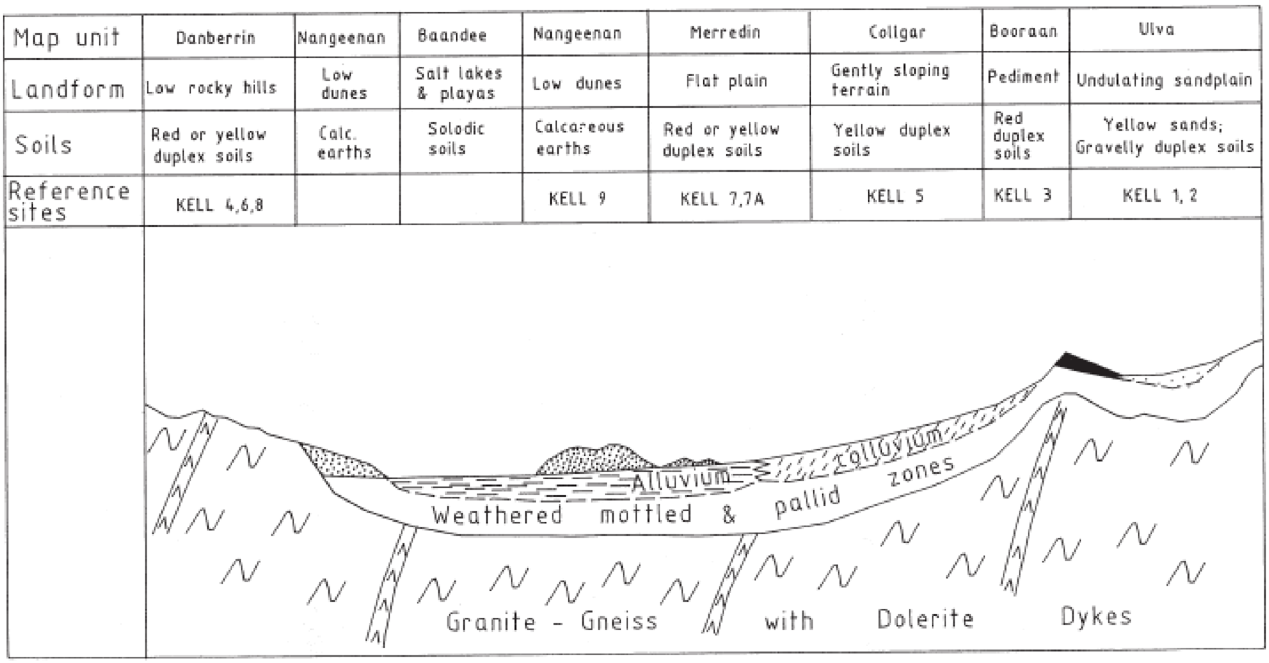


Figure 3.10. Stylised diagram for the Wheatbelt, showing soil reference sites in relation to geology, landscape history and topography (McArthur et al., 2004, page 145).

The soil and land resources evaluation reports worthy of investigation for supporting PAWC work in the Western region are listed in Table 3.2. With a few exceptions, these reports and if applicable associated map sheets (in un-georeferenced high resolution pdf format) are all publically available. They can be downloaded from the WA Department of Primary Industry and Regional Development's research library catalogue (https://researchlibrary.agric.wa.gov.au/). Table 3.2 indicates which reports/maps are unpublished.

Table 3.2. Western Australia Government soil and land reports with potential to support PAWC work in the GRDC Western Region.

Series	Report Title
WA Bulletins	
4178	An Introduction to the Soils of the Lake Grace Advisory District (1990). / by T.C. Stoneman
4180	An introduction to the soils of the Three Springs advisory district (1990). / T.C. Stoneman and National Soil Conservation Program (Australia)
4181	An introduction to the soils of the Geraldton advisory district (1990). / by T.C. Stoneman and National Soil Conservation Program (Australia)
4182	An introduction to the soils of the Moora advisory district (1990). / by T.C. Stoneman and National Soil Conservation Program (Australia)
4201	An introduction to the soils of the Jerramungup advisory district (1990). / by T.C. Stoneman and National Soil Conservation Program (Australia)
4202	An Introduction to the Soils of the Katanning Advisory District (1991). / by T.C. Stoneman
4203	An introduction to the soils of the Albany advisory district (1990). / by T.C. Stoneman and National Soil Conservation Program (Australia)
4221	An Introduction to the Soils of the Narrogin Advisory District (1991). / by T.C. Stoneman
4230	An introduction to the soils of the Esperance advisory district (1990). / by T.C. Stoneman, T.D. Overheu, P.G. Muller and National Soil Conservation Program (Australia)
4343	Soilguide: a handbook for understanding and managing agricultural soils (2001). Bulletin. / by G.A. Moore
4788	Landscapes and soils of the Merredin district (2009) (1:126,720). / by D.N. Sawkins and Department of Agriculture and Food
4803	Landscapes and soils of the Northam district (2010). / by D. Sawkins and Department of Agriculture and Food
4807	Landscapes and soils of the Narrogin district (2010). / by D. Sawkins
4817	Landscapes and Soils of the Katanning District (2010). / by D. Sawkins
4825	Landscapes and Soils of the Lake Grace (2011). / by D. Sawkins
WA Resource Management Technical Reports	
232	Blackwood Catchment: Katanning zone (zone 6): catchment appraisal (2001). / by H. Brockman and Blackwood Rapid Catchment Appraisal Team (WA)
235	Cranbrook-Toolbrunup: catchment appraisal report (2001). / by T.D. Overheu and Western South Coast Catchment Appraisal Team (WA)
236	South Broomehill-Gnowangerup area: catchment appraisal report (2001). / by T.D. Overheu and Western South Coast Catchment Appraisal Team (WA)
241	Phillips Brook catchment appraisal (2001). / by P.D. Galloway
276	Lower Yilgarn catchment appraisal (2003). / by D.G. Cummins

280	Soil-landscape mapping in south-western Australia: An overview of methodology and outputs (2004). Report. / by B.R. Purdie, P.J. Tille and N.R. Schoknecht
284	Agricultural sub-regions of the Avon River basin (2004). / by P.D. Galloway
294	Avon Hotham catchment appraisal (2005). / by S. Sharafi, H. Lauk and P.D. Galloway
298	Land evaluation standards for land resource mapping: assessing land qualities and determining land capability in south-western Australia (2005). Report. / by D. van Gool, P.J. Tille and G.A. Moore
313	Soil-landscapes of Western Australia's rangelands and arid interior (2006). Report. / by B.R. Purdie
330	Land resources in the South-West Agricultural Region: a shire-based summary of land degradation and land capability (2008). / by D. van Gool and W. Runge
380	Soil groups of Western Australia: a simple guide to the main soils of Western Australia (2013). Report. / by N.R. Schoknecht and S. Pathan
WA Land Resources Series	
3	Darling Range rural land capability study (1990) (1:50,000). / by P.D. King and M.R. Wells
4	Geraldton rural-residential land capability study (1990) (1:50,000). / by R.A. Dye, A.M. van Vreeswyk and G.A. Moore
7	Soils of the Mount Beaumont area (1996). / by G.G. Scholz and H. Smolinski
8	Esperance land resource survey (1993) (1:100,000). / by T.D. Overheu, P.G. Muller, S.T. Gee and G.A. Moore
10	Soils and landforms of the Manjimup area, Western Australia (1992) (1:100,000). / by H.M. Churchward
11	Land resources of the Northam region (1994) (1:100,000). / by N.C. Lantzke and I. Fulton
12	Land resources of the Bencubbin area (1995) (1:250,000). / by G.J. Grealish and J. Wagnon
13	Geraldton region land resources survey (1996) (1:250,000). / by L.G. Rogers, L G, and National Landcare Program (Australia)
14	Wellington-Blackwood land resources survey (1996) (1:100,000). / by P.J. Tille, G. Wilson, and National Landcare Program (Australia)
15	Soil assessment of the west Gingin area (1997) (1:50,000). / by H. Smolinski and G.G. Scholz
16	Katanning area land resources survey (2000) (1:150,000). / by H.M. Percy, G.M. Wilson, and T.A. Griffin
17	Lower Gascoyne land resources survey (2003) (1:50,000). / by P.J. Tille, H.J. Smolinski, M.R. Wells, J.A. Bessell-Browne, C.D. Keating, V.P. Oma and A.M. Holm
18	Nyabing-Kukerin area land resources survey (2003) (1:500,000). / by H.M. Percy, D. van Gool, G.A. Moore, N.R. Schoknecht, National Landcare Program (Australia), and Natural Heritage Trust (Australia)
19	Tonebridge-Frankland area land resources survey (2005) (1:100,000). / by A. Stuart-Street, National Landcare Program (Australia), and Natural Heritage Trust (Australia)
20	Corrigin area land resources survey (2004) (1:100,000). / by W.H. Verboom, P.D. Galloway, National Landcare Program (Australia), and Natural Heritage Trust (Australia)
21	Tambellup-Borden land resources survey (2009) (1:100,000). / by A. Stuart-Street and R. Marold
22	DRAFT MAP. Soil-landscape map of the Ravensthorpe-Esperance-Salmon Gums (1998) (1: 250000), 1 and 2 map sheets. / by B.D. Nicholas and S.T. Gee. Unpublished report.
23	Three Springs Land resources survey (1:250,000). Unpublished report and map.
24	Dandaragan Land resources survey (1:100,000). Unpublished report and map.
25	Chittering Land resources survey (1:50,000). Unpublished report and map.
26	North Coastal Plain Land resources survey (1:100,000). Unpublished report and map.

27	Jerramungup Land resources survey (1:250,000). Unpublished report and map.
WA Soil Information Sheets		
16/95	Soil Information Sheets for Ravensthorpe and Part of the Jerramungup agricultural areas (1995). / by T.D. Overheu and Landcare Western Australia
20/96	Soil information sheets for part of the Jerramungup agricultural area (1996). / by T.D. Overheu, Landcare Western Australia and Jerramungup Land Conservation District Committee
21/96	Soil information sheets for the Mount Beaumont, Mallee and Esperance agricultural areas (1996). / by T.D. Overheu, Landcare Western Australia, Esperance Land Conservation District Committee, and Mount Beaumont / Howick Catchment Group (W.A.)
13/97	Soil information sheets for the northern agricultural areas (1997). / by Natural Resources Assessment Group, Agriculture Western Australia, and Landcare Western Australia
Other	
	System 6 Residual (Canning Dam and Wagerup areas) survey (1:250,000). Unpublished
	Darling Scarp and foothills land capability survey (1:50,000). / by P.J. Tille and H. Smolinski. Unpublished.
	Reference soils of south-western Australia (2004). Book. / by W.M. McArthur, Australian Society of Soil Science W.A. Branch and Department of Agriculture and Food
	Report card on sustainable natural resource use in agriculture. Status and trend in the agricultural areas of the south-west of Western Australia (2013). / by N. Schoknecht, D. Bicknell, J. Ruprecht, F. Smith and A. Massenbauer
	Soil Quality. Constraints to Plant Production (2017). Online book (https://itunes.apple.com/us/book/id1317079117) / by D. Murphy, M. Leopold, D. van Gool, F. Hoyle and E. Stockdale

Maps produced as part of the WA Soils mapping and land resources evaluation are viewable in WA's natural resource information system, "NRInfo", an online GIS-based mapping application. The system brings together a variety of natural resource information maps and data from databases maintained by the Department of Primary Industries and Regional Development and other governmental agencies, e.g. Landgate; Department of Planning, Lands and Heritage; Department of Mines and Petroleum; Department of Water and Environmental Regulation; Environmental Protection Authority and Geoscience Australia. NRInfo combines a variety of state and national mapping themes that may be useful to inform on predicting PAWC (also refer to Section 4).

The WA Government Soils mapping and land evaluation metadata are also available for download through SLIP, WA's Shared Landform Information Platform, https://data.wa.gov.au/ which provides a platform for finding and sharing geospatial data relevant to WA. Once, downloaded, these can be imported into GIS-based software.

4 Online access to WA soil-landscape polygon mapping and other soil classification systems

As discussed in the preceding Sections 3.4 and 3.5, Australian soil and land resource mapping has evolved since the 1930's 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 unit ("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 in the mapping polygon.

For WA, different mapping types are available online. The suite of land and soil mapping products include:

- **Soil-landscapes mapping**
- **Land capabilities and land quality mapping**
- **MySoil**

The following describes how to access this suite of products:

The WA Soil-landscape mapping and Land capabilities and land quality mapping is viewable in WA's natural resource information system, "NRInfo", an online GIS-based mapping application (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). The system brings together a variety of natural resource information maps and data from databases maintained by the Department of Primary Industries and Regional Development and other governmental agencies, e.g. Landgate; Department of Planning, Lands and Heritage; Department of Mines and Petroleum; Department of Water and Environmental Regulation; Environmental Protection Authority and Geoscience Australia. NRInfo is a viewing platform that contains a variety of state and national mapping themes that may be useful to inform on predicting PAWC. Spatial information of interest are soil-landscapes, land capability and land qualities, hydrology, digital elevation model and radiometrics. The use of the NRInfo platform is described in Section 4.1.

The WA Soil-landscape mapping and Land capabilities and land quality mapping metadata are also available for download through SLIP, a Shared Landform Information Platform for finding and sharing geospatial data relevant to WA, https://data.wa.gov.au/. Once, downloaded, these can be imported into GIS-based software.

The MySoil product is available through “MyCrop”, which is a smartphone app (downloadable for android via the Google play store or the iphone App store) that brings together crop diagnostic tools, https://www.agric.wa.gov.au/mycrop. MySoil can also be accessed through the following website: https://www.agric.wa.gov.au/mysoil.

4.1 WA Soil-landscapes mapping

The WA Soil-landscape mapping (best available soils) is based on the local classification system, the Soil Groups of Western Australia (Schoknecht and Pathan, 2013), as described in Section 3.3. Maps that show the spatial distribution of these Soil Groups proportionally are available for the south west (agricultural regions) (Purdie et al., 2004), and the rangelands and arid interior (Purdie, 2006). This for the GRDC Western Region seamless best available soil-landscape mapping effort is a compilation of individual surveys that were conducted at different scales, ranging from 1:20,000 to 1:3,000,000, as outlined in Section 3.4 and 3.5 (Figure 4.1). Mapping is based on the nested 6 level hierarchy described in Section 3.5, which was implemented to allow for the incorporation of varying levels of soil landscape information, which resulted from the various scales of mapping of the individual soil and land resources evaluation surveys. Data were digitized and georeferenced, and individual surveys were then edge-matched, to ensure a rationalized joining and overlapping of the different surveys involved to produce the WA map. The attribute accuracy of the dataset corresponds to the scale of survey (refer to the survey reliability map in Section 3.5, Figure 3.7).

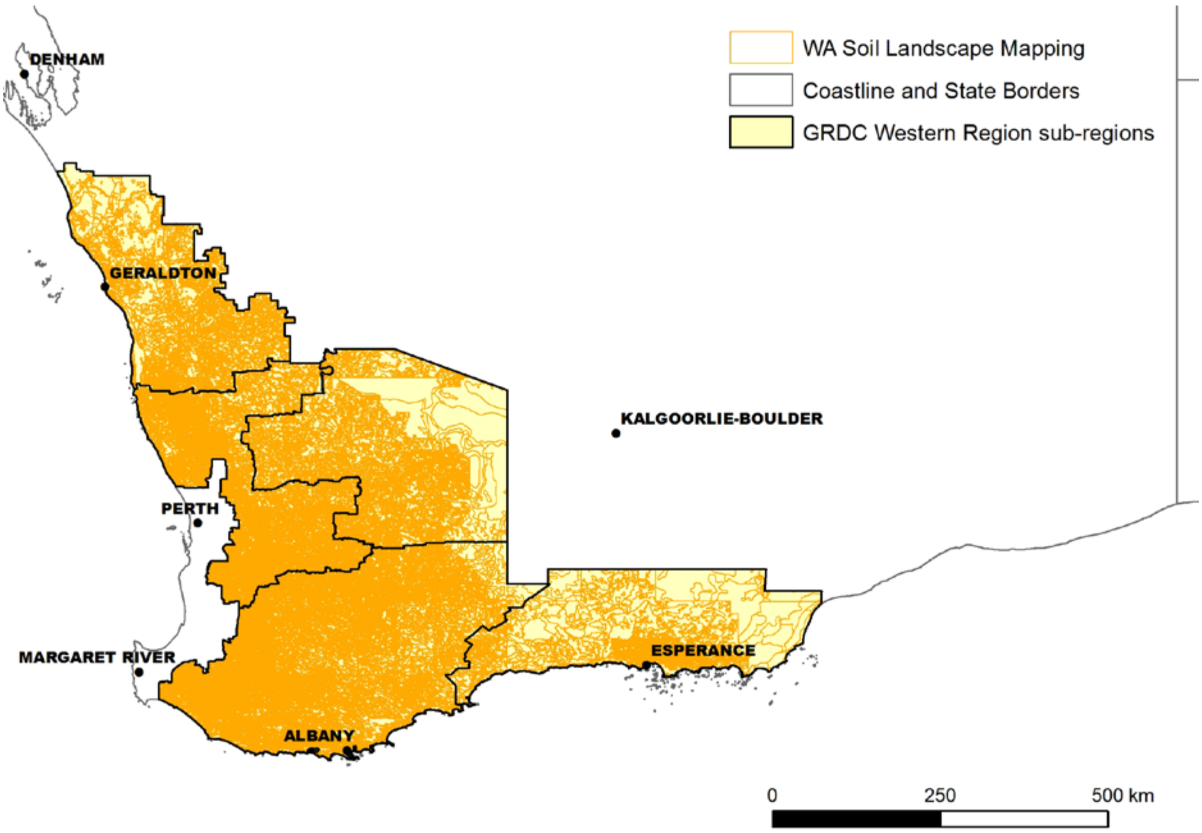


Figure 4.1. WA Soil Landscape Mapping.

As alluded to, at a scale of 1:100 000 or 1:250 000 it is in most landscapes not feasible to map individual soil types. The 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 the WA south-western region generally differs by map sheet (refer to Figure 3.7). 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. 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 growers and advisors. The soil types 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 explicitly, however, they can be used to map PAWC associated with the dominant soils, which will give a regional picture of its spatial patterns. The information can also 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 (also refer to Section 3.5).

As mentioned previously, the WA Soil-landscape mapping is viewable through the online GIS-based mapping tool NRInfo (https://www.agric.wa.gov.au/resource-assessment/nrinfo-western-australia). The advantage of NRInfo is that it strings together a variety of relevant environmental information from various data sources (national and local), and that in general no GIS software knowledge is required for operation. The user can zoom into a location and explore the different information available for the area of interest. Figure 4.2 shows a framegrab displaying the interface of the NRInfo tool. NRInfo contains an Open Street Map and Aerial Photography layer which can at first be used to navigate to an area of interest. In the example, agricultural land close to the locality of Buntine is chosen (Figure 4.2 a). Once navigated to the area of interest, different layers can be activated, and also made transparent through the Translucency tool to still see the location of interest (Figure 4.2a). In Figure 4.2a the Soil-Landscape mapping layer is chosen, and at the current scale, lower mapping tiers, i.e. best available including the location of soil sites can be viewed. The user can then navigate to the info icon and pick a map unit of interest. In Figure 4.3b the pink map unit was chosen, which falls into the "Zone of Ancient Drainage" (map unit 258). Using the info icon and clicking on the map unit of interest opens a Feature Info box, which further explains the map unit at its lower tier (map unit 258_Ud_1). As exemplified in Figure 4.2b, the Feature Info box, also contains a link that opens a Summary Report for this particular map unit, from which a text-document can be downloaded which contains a more detailed description of this mapping unit. The Summary Report also shows the WA Soil Groups falling within this particular soil-landscape unit, including the Soil Group Qualifier and their proportional occurrence within the mapping unit.

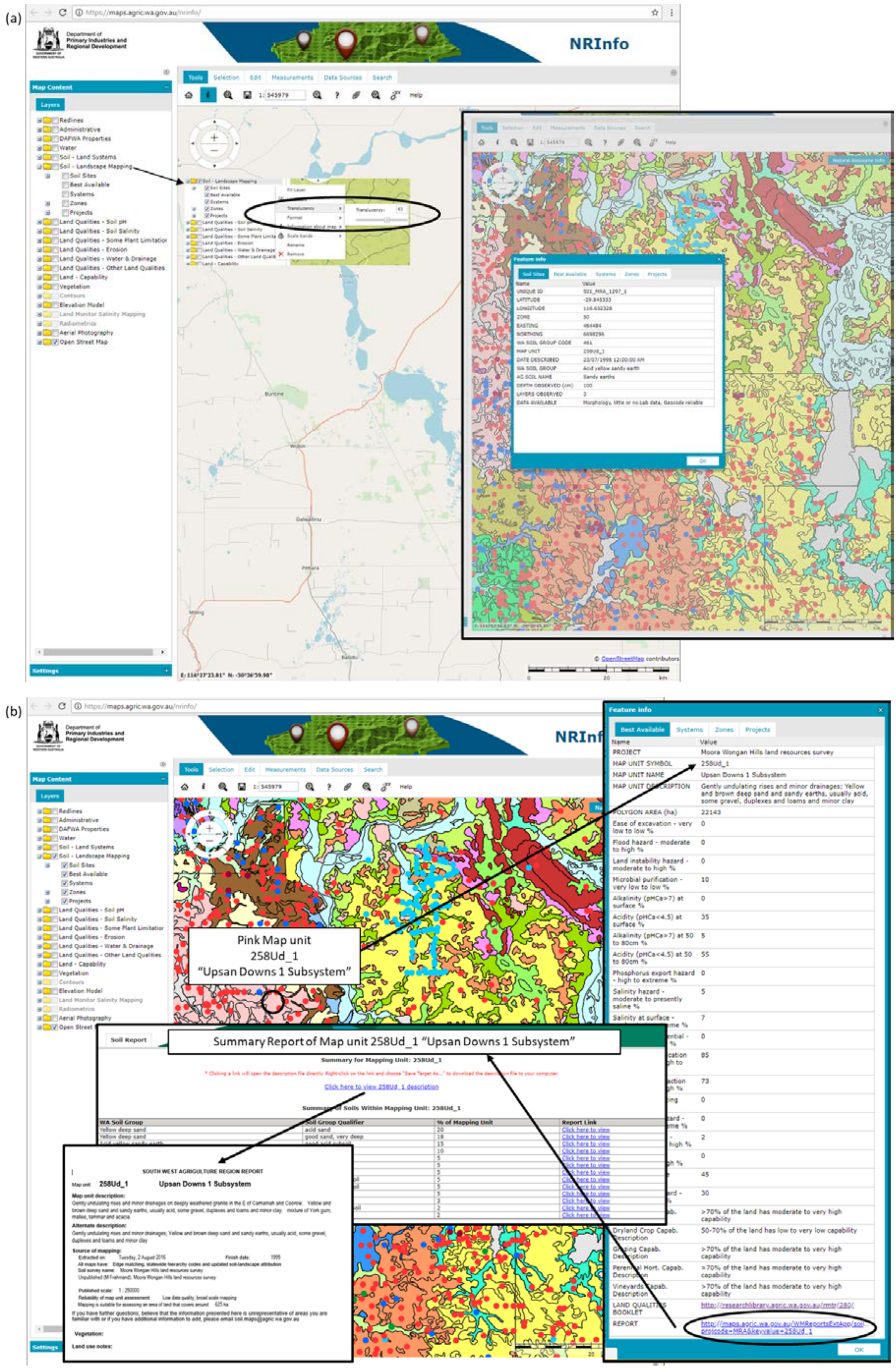


Figure 4.2. Framegrab of the NRInfo online mapping tool, showing an area situated in the 'Zone of Ancient Drainage' (Map Unit 258) close to the locality of Buntine (nearby APSoil Profiles: 24, 143 and 146).

At present, navigating through the NRInfo system is not as intuitive as it could be. For example, it takes some time to load all the layers, especially when the user zooms in and out of a particular location, and the layer Translucency tool is also easily missed at first sight. In addition, the system is designed to render the data scale dependently, which limits locating an area of interest at times. A small location box for context would be beneficial here. When inspecting various soil landscape units that were derived at a smaller mapping scale, it is important to also see their distribution on a broader scale to be able to identify terrain or vegetation patterns in conjunction with the occurrence of these soil-landscape mapping units. At present this is not always possible, because of the scale dependent rendering of data layers. Navigating through the NRInfo system could potentially create a barrier for farmers and advisers.

The following paragraph explains in an exemplary fashion how the soil landscape mapping efforts could be utilised in relation to predicting PAWC. This example is based on findings from a GRDC project conducted in the Northern region (GRDC Project CSP00170). 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 4.3).

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 4.4).

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.

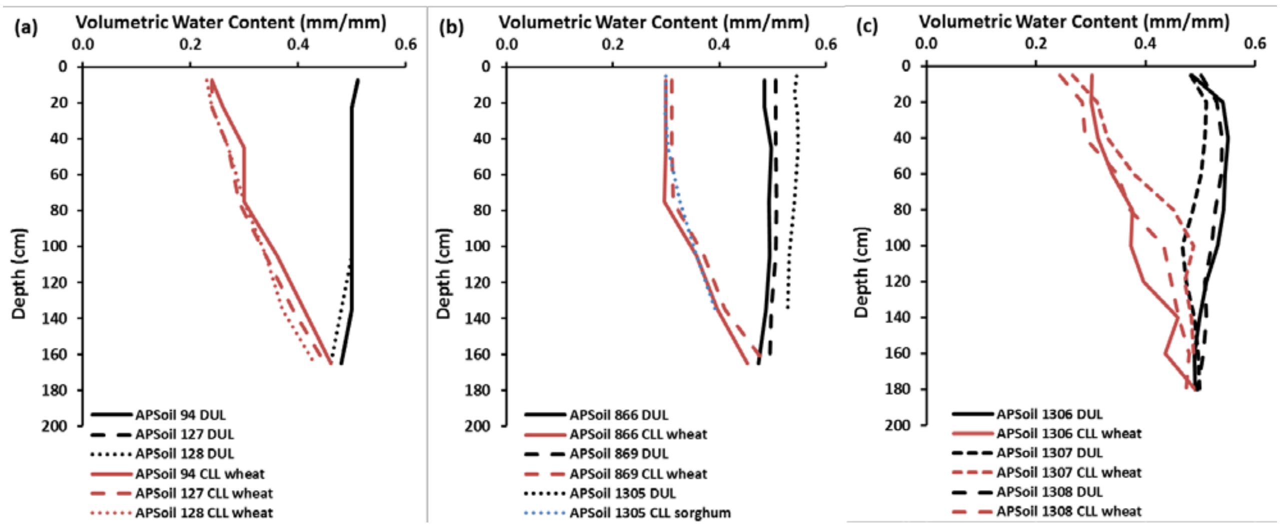
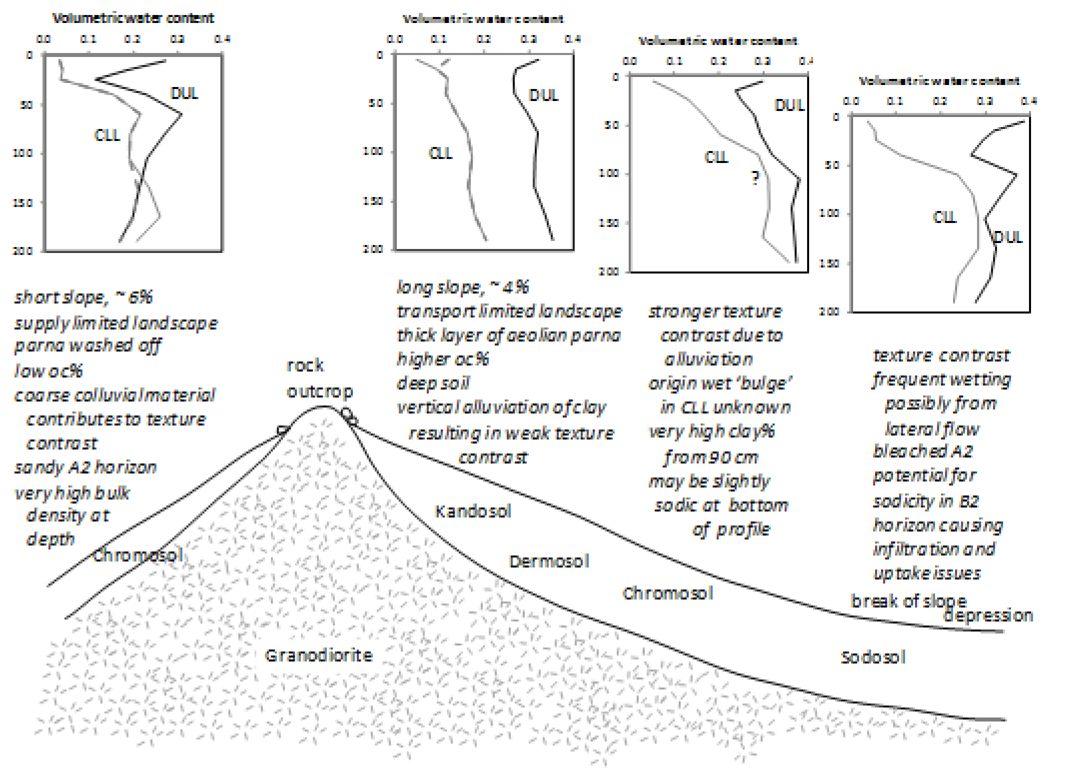


Figure 4.3. APSoil PAWC profiles in select soil-landscape units (SLUs) within the Liverpool Plains; (a) Noojee SLU, (b) Conadilly SLU (southern area between sand hills), and (c) effect of subsoil salinity on variability in PAWC within Yarraman SLU. Based on data presented in Verburg et al. (2017).



Memagong 2:	Memagong1:	Wombat 1:	Wombat 2:
Crop growth is very poor in winter due to sandy low CEC band at 20-30cm, which limits root development. Leaching horizontally through this band also occurs. The use of small multiple nitrogen applications increases yields. Crop finishes well, but with water in subsoil not accessed.	High potential soil, easy to manage, even and consistent plant growth and development, deep root structure, very high yield potential.	Pretty easy to manage. Crop not impeded by any soil constraints.	Running into gully lines. Gets very wet through winter. Crop stops growing due to waterlogging. Bleached layer low in nutrients.

Figure 4.4. 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

4.2 WA Land Capabilities and Land Quality Mapping

The WA land capabilities and land quality mapping is based on a methodology outlined in van Gool and Moore (1999) and van Gool et al. (2005) that provides a standard method for attributing and evaluating the best available soil-landscape mapping dataset produced for WA (Purdie, 2006; Purdie et al., 2004). This assessment is available for different agricultural production systems and maps were produced for a range of risks. Maps that may be relevant for informing on PAWC also in relation to identifying subsoil constraints are, e.g.: soil water storage, waterlogging risk, site drainage potential, water repellence risk, subsurface acidification risk, subsurface alkalinity risk, subsurface compaction, and water erosion risk. Figure 4.4 shows a framegrab of the NRInfo online mapping tool, showing the Land Quality assessment (Subsurface Acidification Susceptibility) for agricultural land close to the locality of Buntine (please refer to the previous section for more information about how to navigate through the NRInfo tool).

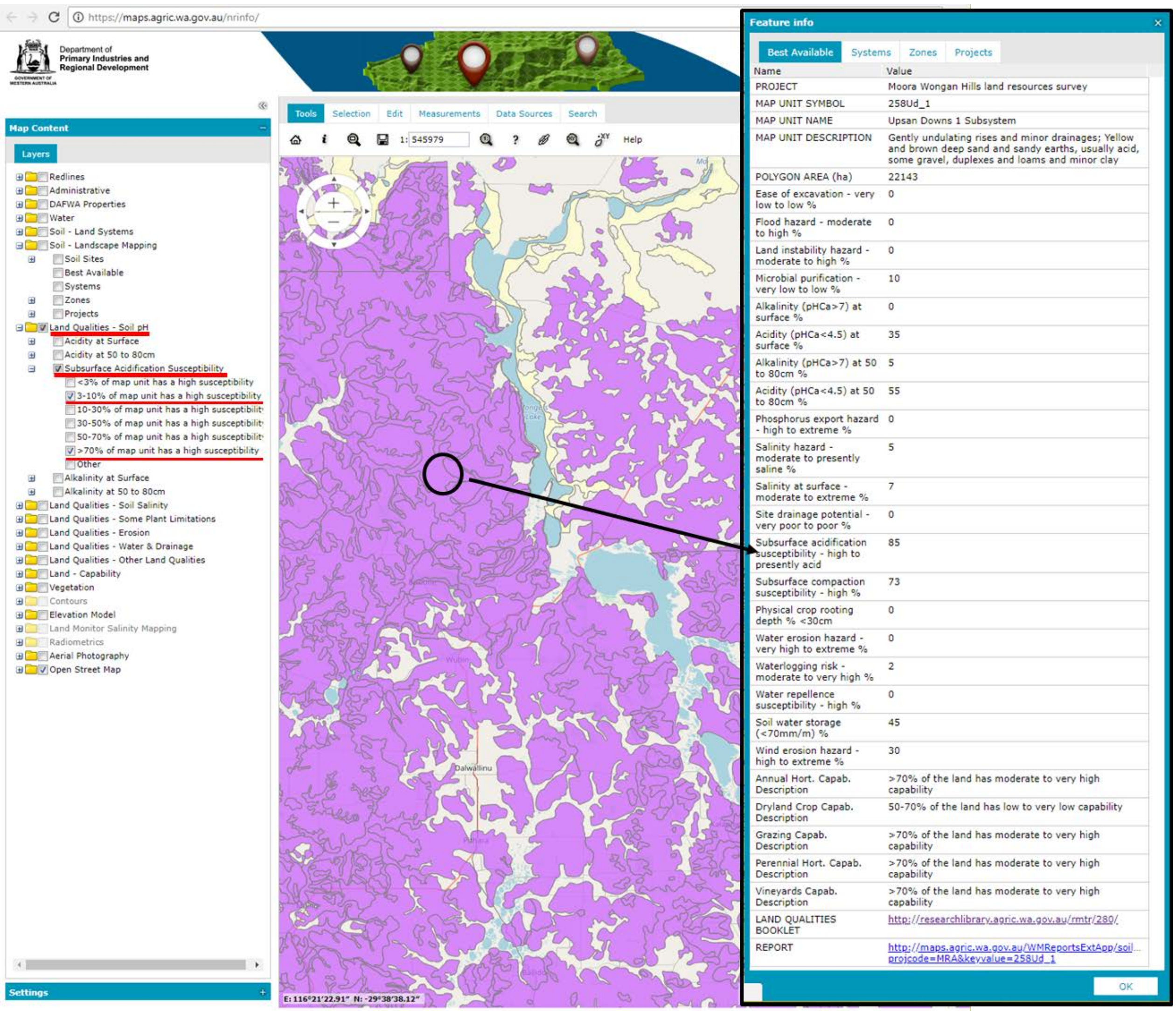


Figure 4.5. Framegrab of the NRInfo online mapping tool, showing the Land Quality assessment for agricultural land close to the locality of Buntine (nearby APSoil Profiles: 24, 143 and 146). Here, the same location as shown in Figure 4.2 is used.

4.3 MySoil

MySoil provides soil information for the WA soils of the south-west in relation to agricultural production. MySoil summarises these soils into a total of 15 broad soil types, and was designed by the Department of Agriculture and Food Western Australia (now known as the Department of Primary Industries and Regional Development) as a simple diagnostic tool to identify which soil type an area of interest belongs to and what the key soil issues are most likely to be.

The use of the MySoil diagnostic tool is explained on the Department's website, through instructions of how to best utilise MySoil in its web-browser interface (https://www.agric.wa.gov.au/mysoil), and through a tutorial video with visual explanations (https://www.agric.wa.gov.au/mysoil-tutorial). The instructions and especially the tutorial video are very useful as they assist with understanding the functionalities of the MySoil diagnostic tool and how to navigate through it, based on its underlying design concept.

Within the MySoil web-interface, the user can select a map-based Agricultural zone that he or she belongs to, e.g. the southern wheatbelt (Figure 4.5a). Clicking on that zone, will navigate the user to another screen that on the left hand side will show the selected soil zone one chooses, with corresponding soil types displayed on the right hand side (Figure 4.5b). The user can then narrow down most likely soil type and its associated constraints by selecting a number of 'features' or clues from a drop down box beneath the selected soil zone (including surface texture, dominant soil colour, or pH properties). If the user is unsure of how to narrow down the selection, there is a 'best' icon tool (green wand) that will assist with the selection, to reduce the number of soil types associated with the selected soil zone. On the right hand side of the tool a list of 'entities' then becomes available that is reduced by the number of 'features' ticked. Each 'entity' has an image that shows a soil profile example and a factsheet with more information about the soil selected (Figure 4.5c). This includes distinguishing features and constraints, as well as a list that points towards further information available.

MySoil can thus provide a starting point for yield estimates based on PAWC and can also be used as a first evaluation point for identifying potential constraints to crop production.

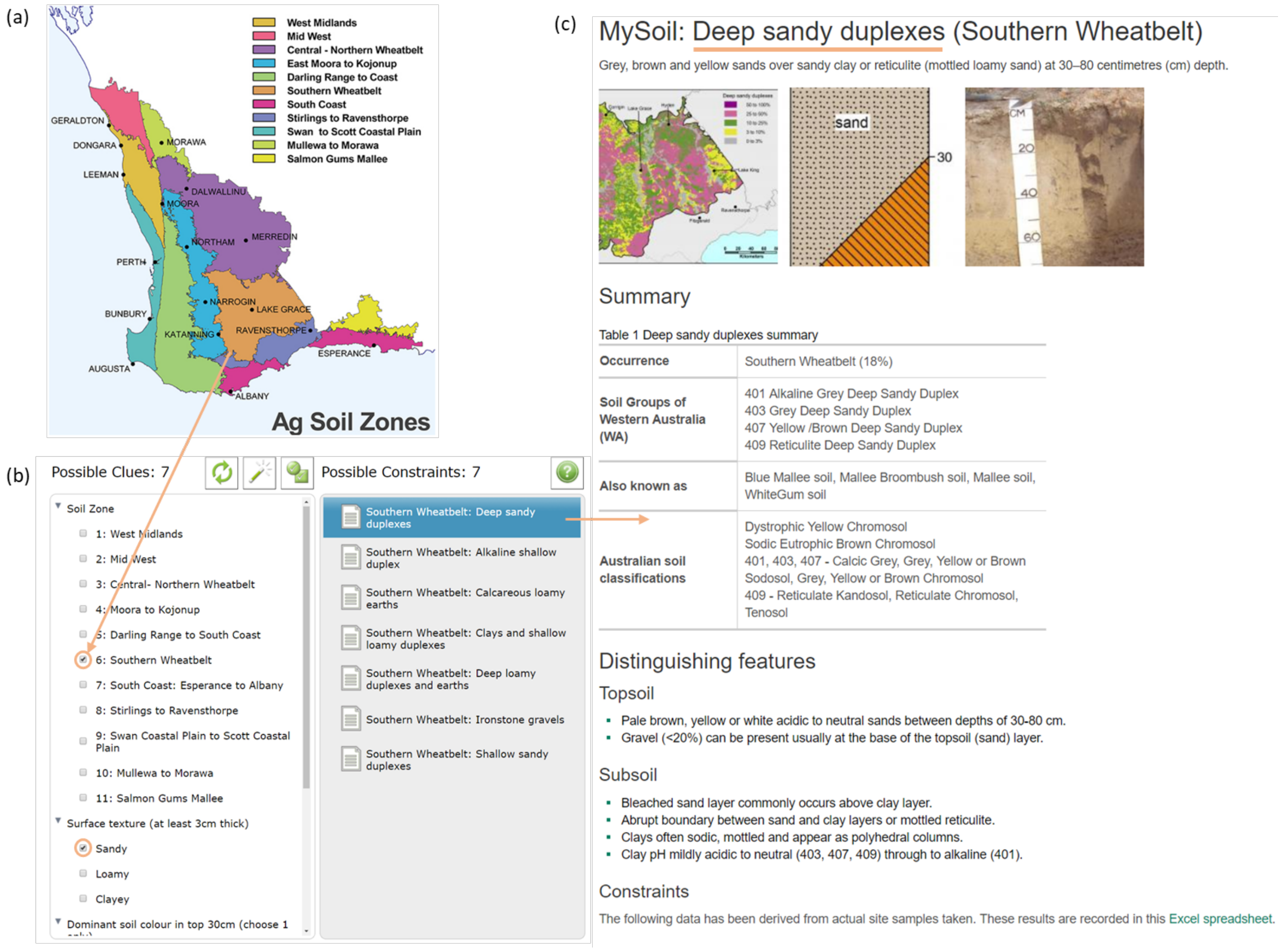


Figure 4.6. Framegrab of the WA MySoil soil diagnostic tool web-browser interface.

5 Geological Mapping

In many situations underlying geology strongly influences soil formation (parent material, see discussion present in Section 3.3 on soil formation) 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. Indeed, these 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 directly mapping PAWC. In addition to soil-landscape mapping it may, however, further provide some insights into soil landscape similarities or dissimilarities.

Access to online geological resources for WA is available via several interfaces:

- The *Geological mapping app* for mobile devices, which brings together state interpreted bedrock geology at a scale of 1:500,000. http://www.dmp.wa.gov.au/Geology-mapping-app-for-mobile-1567.aspx
- The *GeoVIEW.WA* GIS-based interactive mapping tool for desktop application, where the user can view, query and map a range of geology, resources as well as other related datasets. Using this tool, the user can customize a map and scale for an area of interest, which can be printed. Within the online tool, geological information is linked to other mineral and petroleum exploration datasets including mines and mineral deposits, petroleum wells and active leases. http://www.dmp.wa.gov.au/GeoView-WA-Interactive-1467.aspx
- The *DMIRS Data and Software centre* where various meta-datasets from WA's Department of Mines, Industry Regulation and Safety can be downloaded free of charge through https://dasc.dmp.wa.gov.au/dasc/; of relevance may be:
    - Statewide spatial datasets, which include georeferenced *geological series mosaic images* (JPEG2000 format) at scales of 1:100,000 and 1:250,000, covering various regions of WA, including the GRDC Western region. In addition, continuous maps for the whole state of WA are available at 1:1,000,000 (Surface geology of WA, GIS shp-file) and 1:2,500,000 (2015 Geological map of WA, GIS shp-file and Google Earth kmz-file).
    - Georeferenced *geological series maps* at a 1:50,000 (JPEG2000 format); 1:100,000 (JPEG2000 and GIS shp-file format) and 1:250,000 (JPEG2000 format) scale. Maps cover most of the GRDC Western Region of WA.

The download of meta-data sets and their import into a GIS program (open source or commercial, Figure 5.1), or Google Earth (i.e. continuous 1:2,500,000 Geological map of WA, Figure 5.2) allows relative positions of APSoil PAWC sites to be compared.

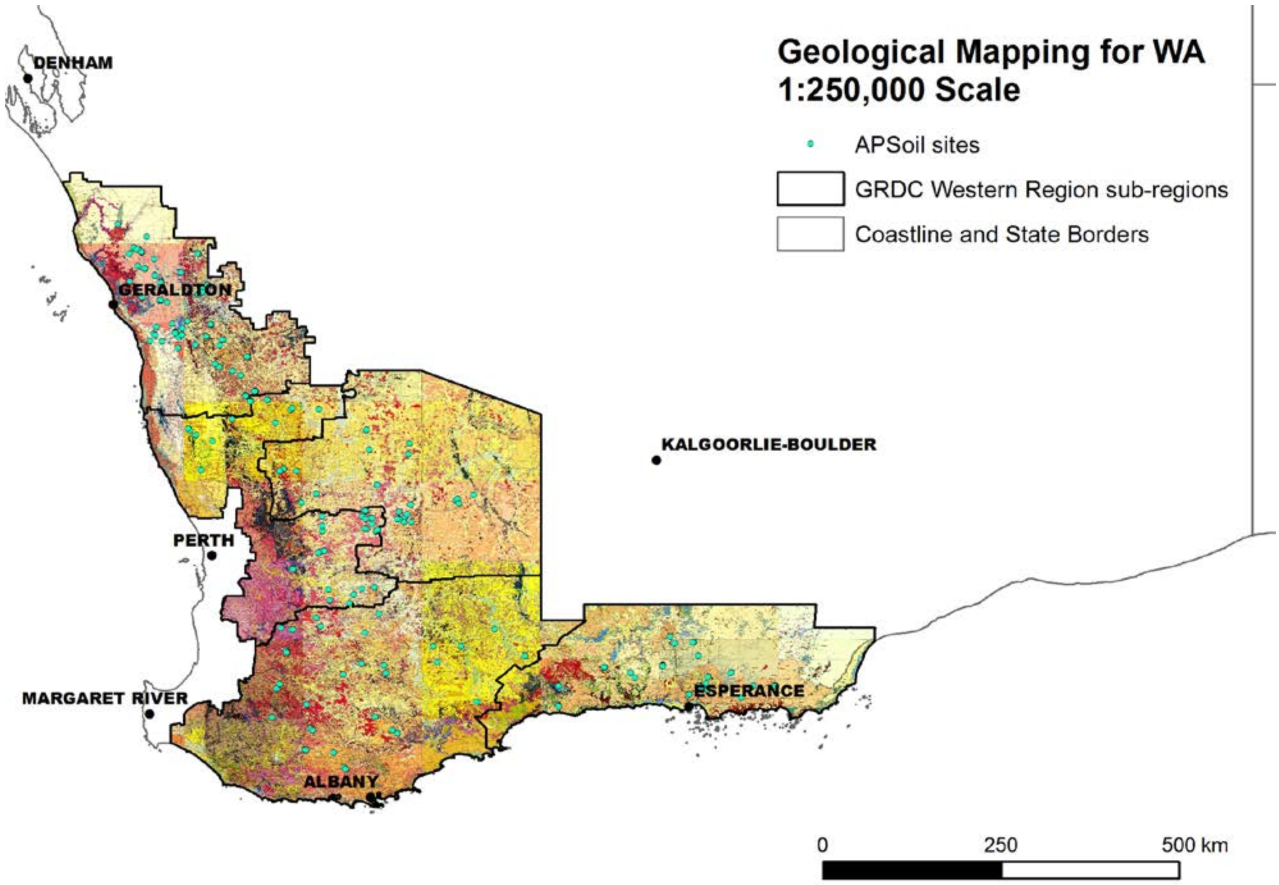


Figure 5.1. Georeferenced geological series map at a scale of 1:250,000 for the GRDC Western Region, and showing APSoil sites relative to geology.

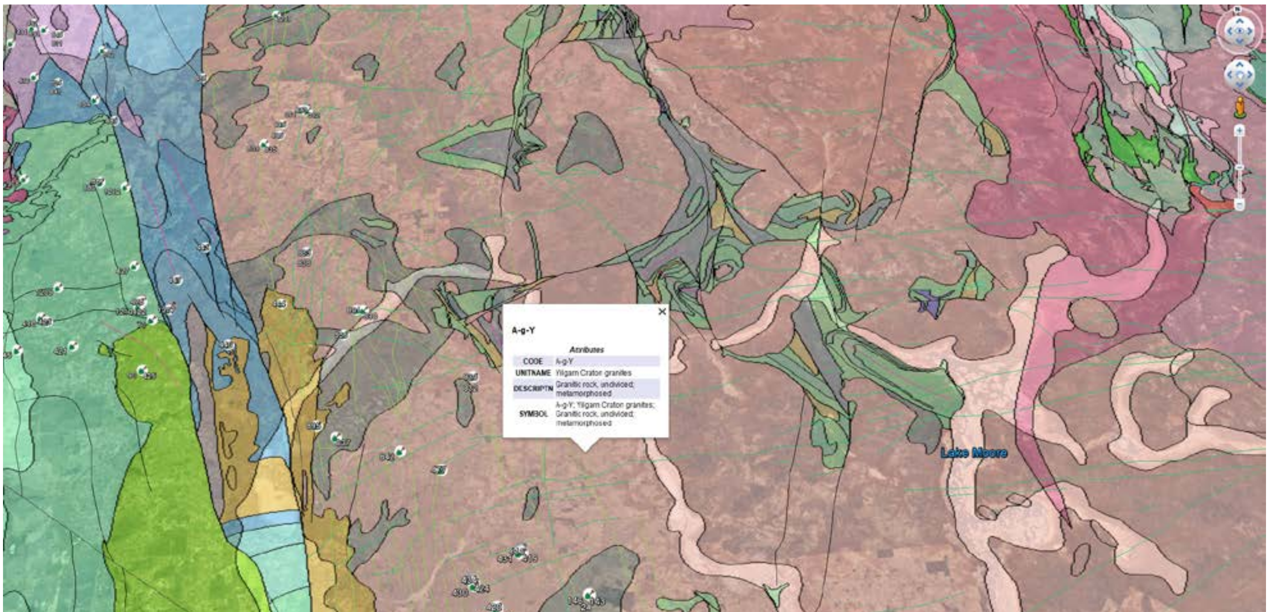


Figure 5.2. Screen grab of 1:2,500 000 Geology map of WA viewed in Google Earth and showing APSoil sites relative to geology for agricultural land close to the locality of Buntine.

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.

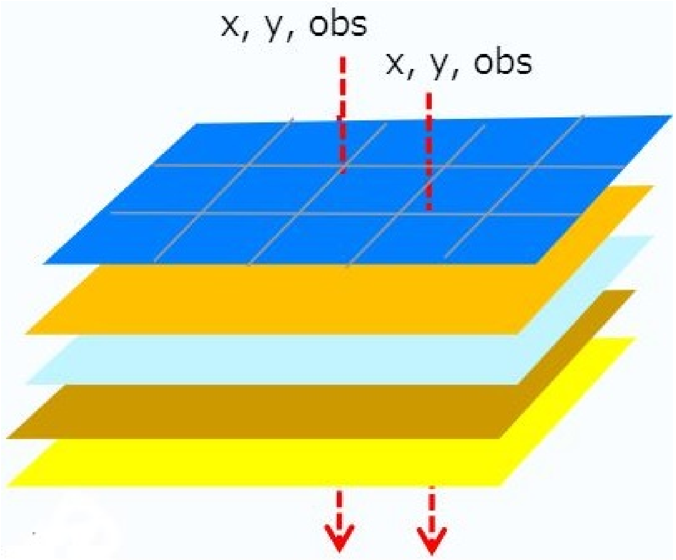


Figure 6.1. DSM models built from the spatial intersection of observations and covariates.

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 WA, three SLGA soil attribute products are available, the national SLGA, the WA regional SLGA, and an integrated version at the national scale of the national SLGA and the WA regional effort which was merged on a pixel-by-pixel basis, where the map with the lowest uncertainty (highest reliability) was used. In the next couple of paragraphs, the national SLGA and WA regional SLGA mapping approach will be briefly explained and illustrated. These two approaches developed simultaneously, not with the intention to duplicate the effort, but the assumption behind that certain methods may be more appropriate for specific regions of interest in WA than others (Odgers et al., 2015). Each of the SLGA soil attributes in the suite of national and WA regional products have been created using DSM approaches fine-tuned to reflect the availability of supporting data and the experience of the mapper.

The national SLGA DSM approach relies on environmental correlation (McKenzie and Ryan, 1999). The soil data (site data and spectroscopic estimates of soil properties) used to generate the national SLGA soil attributes have been gleaned from national and State/Territory soil and landscape databases with locations shown in Figure 6.2, and the covariates were collated into a central database specifically for the SLGA. Many of the landscape covariates used in the national SLGA DSM approach were developed through terrain analysis using the national DEM. These and other terrain analysis attributes are available through SLGA (see Section 7 and Table 7.1). Soil attribute estimates were based on a Cubist-kriging approach (Viscarra Rossel et al., 2015).

The WA regional SLGA soil attributes have been created using a different DSM approach, namely spatial disaggregation of polygon soil maps. In a first DSM step polygon soil legacy maps were spatially disaggregated using the DSMART algorithm (Holmes et al., 2015; refer to Section 6.4) to produce a set of soil-class probability rasters. In a second DSM step, the PROPR algorithm (Odgers et al., 2015) was used to map soil-attributes and their associated uncertainties (90% prediction interval), using reference soil property data and the firstly produced soil-class probability rasters. Estimates were then calculated as the weighted mean of the reference soil-property values, where the weights resembled the probabilities of the relevant soil classes.

The soil attributes available as national and WA regional SLGA rasters at ~90 m (3 arc second) resolution are listed in Table 6.1. Each attribute has been selected because they are functionally important for agricultural and land assessment needs, and supplied at specific depth increments, namely 0 - 0.05, 0.05 - 0.15, 0.15 - 0.30, 0.30 - 0.60, 0.60 - 1.00 and 1.00 - 2.00 m. As such, the specifications (attributes and formats) of SLGA align closely to that of the GlobalSoilMap suite (GlobalSoilMap Science Committee, 2011; Hartemink et al., 2010).

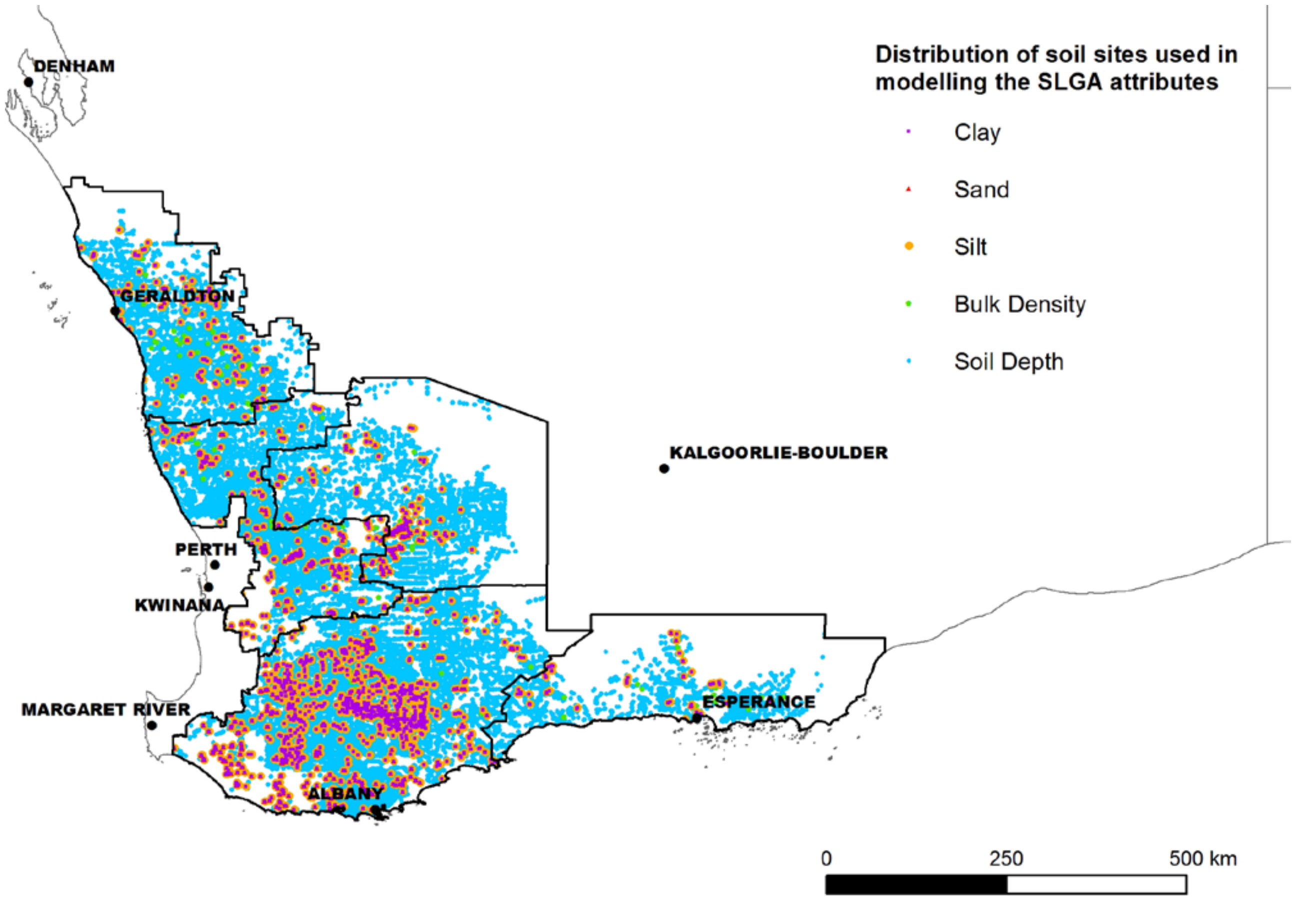


Figure 6.2. Distribution of soil records within the GRDC Western Region which were used in SLGA attribute mapping. Note that many sites contributed information to the modelling of more than one attribute.

Table 6.1. Soil Landscape Grid of Australia soil attributes.

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

Figure 6.3 and 6.4 shows various SLGA national soil maps for an area near Buntine in WA. Both figures are populated using the same value range and colour stretch to allow for direct comparisons. The figures includes clay (Figure 6.3a and Figure 6.4a), sand (Figure 6.3b and Figure 6.4b), silt (Figure 6.3c and Figure 6.4c), available water capacity (Figure 6.3d and Figure 6.4d), and bulk density (Figure 6.3e and Figure 6.4e) for the 5-15 cm depth layer. Depth of soil represents the A & B horizons for the national SLGA (Figure 6.3f), and the depth to the regolith layer for the WA regional SLGA (Figure 6.4f). It becomes clear from Figure 6.3f and 6.4f that the national SLGA product predicts much shallower soils (with a maximum of ~1 m depths) as compared to the WA regional SLGA product (with a maximum of 1.9 m). Both products therefore need to be explored further using expert knowledge. In any case, the impact of local relief on soil properties is apparent.

Each SLGA soil attribute file is supplied with companion reliability maps and a set of mapping reliability statistics (e.g. R^2, RMSE). The reliability maps represent the 90% confidence interval of the prediction (difference between 5th and 95th percentiles). Users of these maps can assess which areas in the maps are weaker or stronger than others, and decide the confidence they can put into using the data in certain areas. It is assumed that the national SLGA soil attribute mapping may be less uncertain in areas with a high density of soil point data, when compared to the WA regional approach derived from spatial disaggregation.

Figure 6.5 and 6.6 show the 90% confidence intervals for the prediction of % clay at 5-15 cm depth for the whole of the GRDC Western Region as well as the area near Buntine WA, for the national and regional soil attribute SLGA, respectively. Comparing the two, it becomes noticeable that the national SLGA approach predicts more clay for the WA region, e.g. refer to the clear difference in the Esperance region. The 90% confidence intervals are quite wide and suggest large uncertainty. The map for the Buntine WA 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. Any future studies 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).

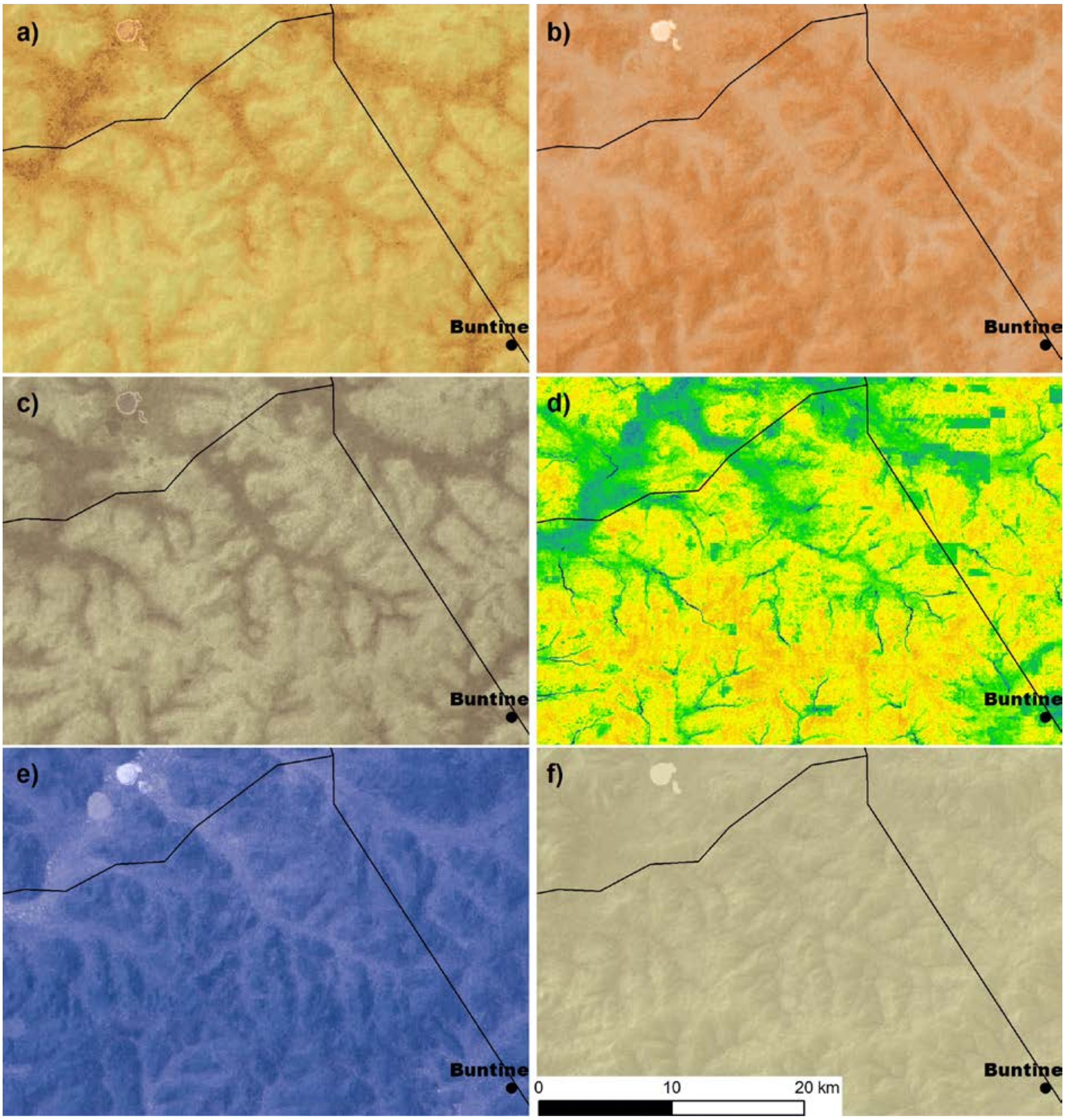


Figure 6.3. Examples of SLGA National Mapping for various soil attributes at 5-15 cm depth near Buntine WA. a) Clay % (min 7 – yellow, max 25 – brown), b) Sand % (min 60 – pale orange, max 90, dark orange), c) Silt % (min 1.5 – pale brown, max 7 – dark brown), d) Available water capacity % (min 5 – orange, max 15 - blue), e) Bulk density gcm-3 (min 1.42 – pale blue, max 1.58 – dark blue), f) Depth of soil m (min 0.6 – pale brown, max 1.9 – dark brown). 1:5 M scale roads (black lines) provides context. The soil attributes in a) to f) are semi-transparent to allow the hillshade underneath to show local relief.

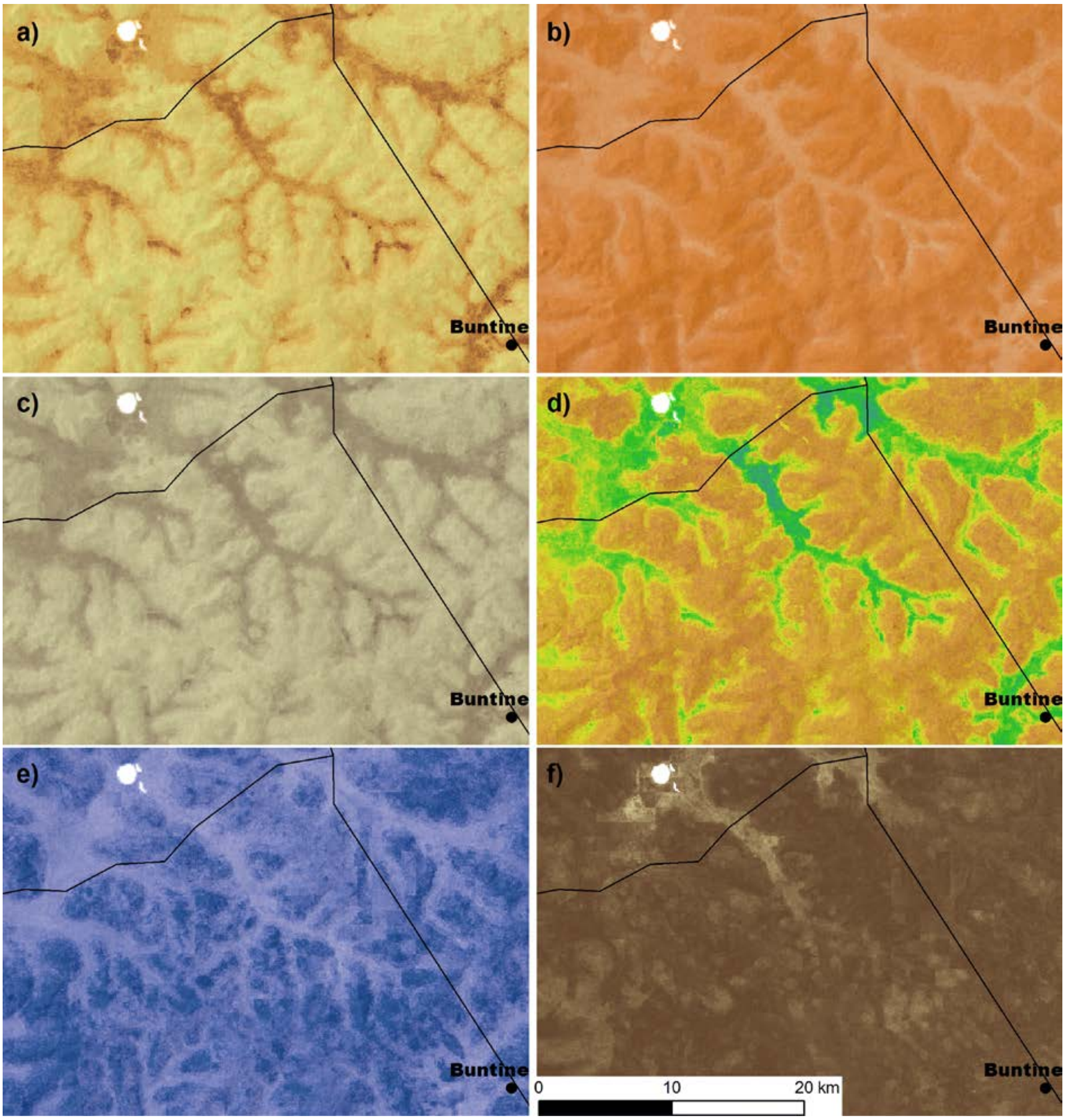


Figure 6.4. Examples of WA Regional SLGA Mapping for various soil attributes at 5-15 cm depth near Buntine WA. a) Clay % (min 7 – yellow, max 25 – brown), b) Sand % (min 60 – pale orange, max 90, dark orange), c) Silt % (min 1.5 – pale brown, max 7 – dark brown), d) Available water capacity % (min 5 – orange, max 15 - blue), e) Bulk density gcm-3 (min 1.42 – pale blue, max 1.58 – dark blue), f) Depth of soil m (min 0.6 – pale brown, max 1.9 – dark brown). 1:5 M scale roads (black lines) provides context. The soil attributes in a) to f) are semi-transparent to allow the hillshade underneath to show local relief.

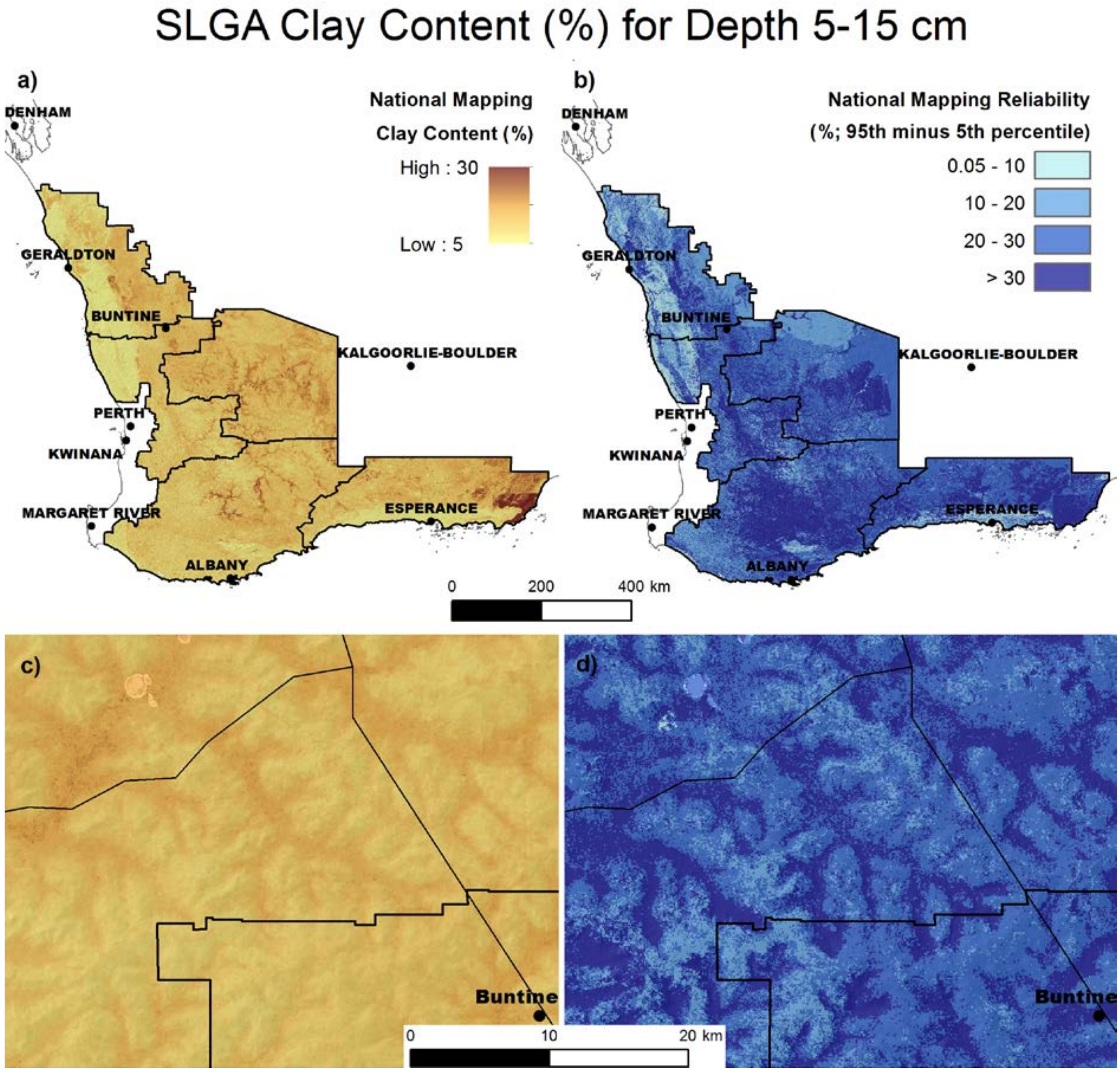


Figure 6.5. Examples of SLGA National Mapping for clay % at 5-15 cm depth for (a) the whole GRDC Western Region and (c) an area near Buntine WA, and (b, d) the associated 90% reliability range. The soil attributes in (a, b, c, d) are semi-transparent to allow the hillshade underneath to show local relief.

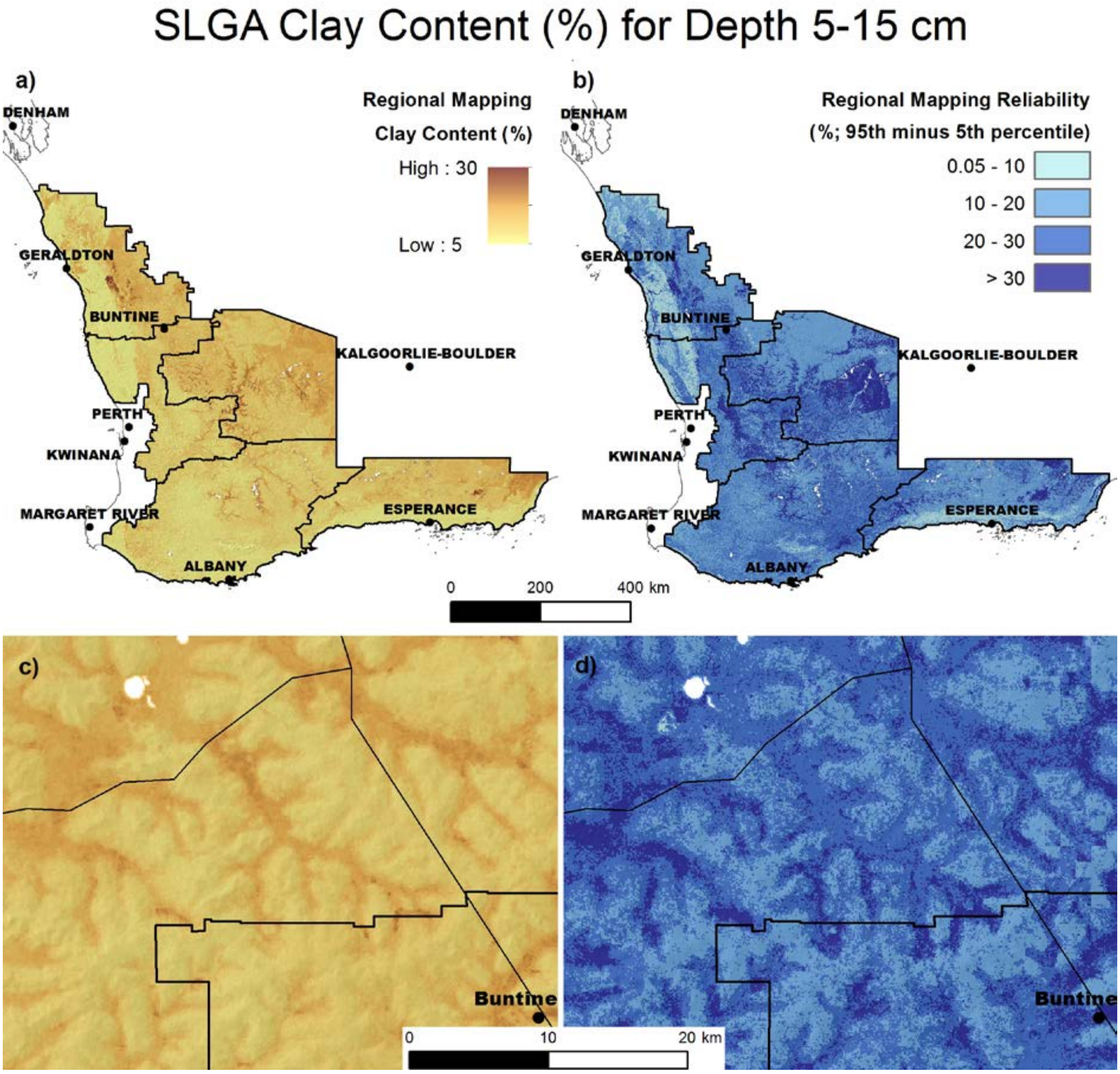


Figure 6.6. Examples of WA Regional SLGA Mapping for clay % at 5-15 cm depth for (a) the whole GRDC Western Region and (c) an area near Buntine WA, and (b, d) the associated 90% reliability range. The soil attributes in (a, b, c, d) are semi-transparent to allow the hillshade underneath to show local relief.

6.3 Prediction of PAWC using SLGA soil 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.

It should also be noted here that in the SLGA, % sand, silt and clay were predicted independently, and therefore may not add up to 100 %. In WA, for example, silt is relatively uncommon, so it may therefore be best to use the clay and sand rasters, and calculate silt as the remainder, and use these maps for PAWC predictions, employing pedotransfer functions (personnel comment Karen Holmes).

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.

6.4 Other local digital soil mapping – DSMART generic soil types map

A new, generic soil type map for WA was produced by Holmes et al. (2015) based on a spatial disaggregation DSM approach, using the DSMART algorithm. The existing mosaic of conventional polygonal soil maps of WA (refer to Section 3.4, Section 3.5 and Section 4) were spatially disaggregated, and in combination with the unmapped soil components were transformed into spatially referenced soil class distributions. From those, rasters of soil class occurrence were subsequently produced at ~90 m (3 arc second) resolution. The accuracy of the rasters was then verified with 43,000 archived soil profiles from the WA Department of Agriculture and Food (now known as the Department of Primary Industries and Regional Development).

The novelty of this product is that through disaggregation unmapped soil information proportionally contained within original map units (expert knowledge of the surveyors), can now be spatially defined. In addition, the new product is also delivered at a scale that is more suitable for on-ground decision making.

This latest generic soil type map of WA based on a DSM approach is currently not part of the SLGA suite of products, but can be obtained in raster format by contacting the corresponding author, Karen Holmes, directly.

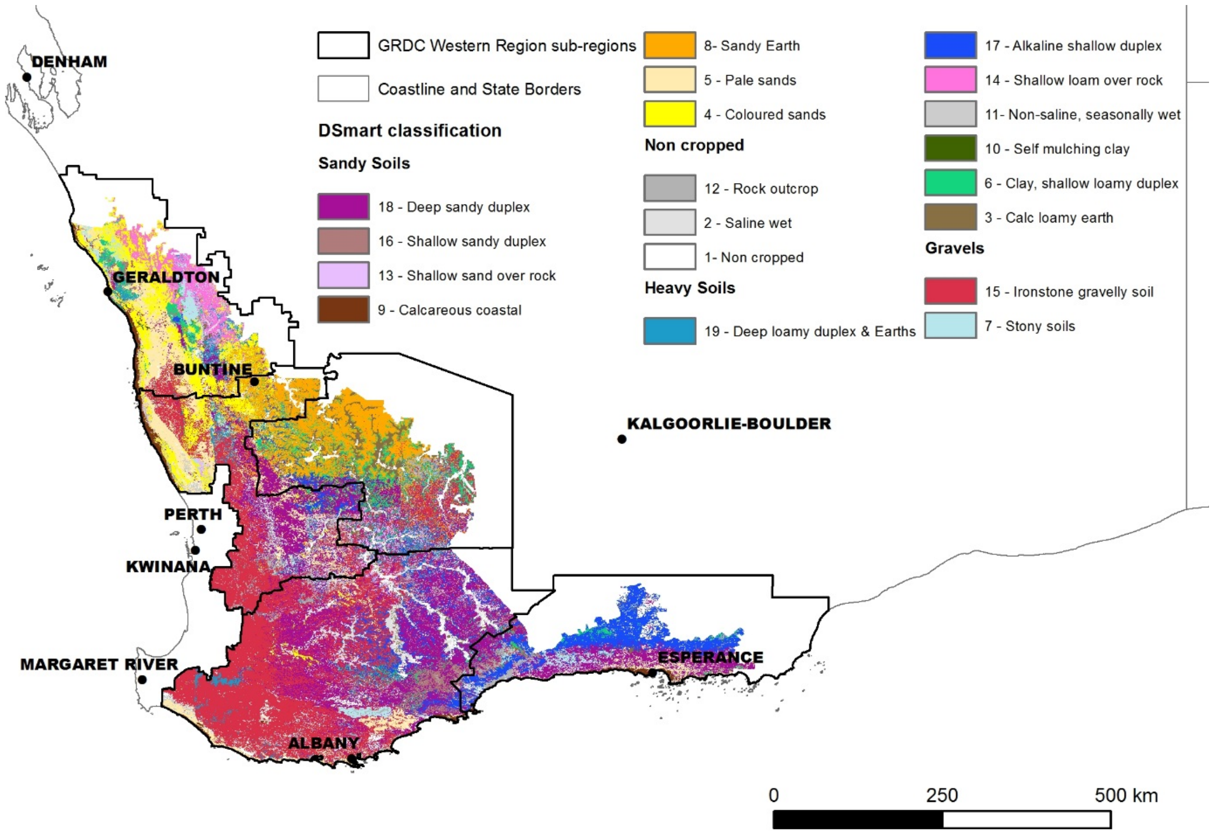


Figure 6.7. DSMART example (Sourced from Holmes et al. (2015)).

7 Terrain information

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

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

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

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

7.1 Terrain analysis

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

Compared to coarser resolution DEMs (e.g. 100 x 100 m), finer resolution ones (10 x 10 m) are capable of representing smaller and finer ground features that would otherwise be 'hidden' in the 100 x 100 m example. DEM grid cells also have a vertical 'resolution', so if fine (e.g. sub-metre) they are also capable of showing finer ground feature details. Terrain analysis on coarser resolution DEMs require less computational power so there is sometimes an operational trade-off between detail of analysis and computational requirements. Australia has in the public domain national DEM datasets at 1 arc second (~30 m) and 3 arc second (~90 m) resolutions (Figure 7.1). These are accessible from Geoscience Australia (http://www.ga.gov.au/data-pubs). For some regions in WA, some high-resolution DEMs at 10 m and 25 m resolution also exist. These elevation data were produced as part of a broad-scale salinity and remnant vegetation assessment conducted within the Landmonitor project (Furby et al., 2010). DEM products are publically available and can be downloaded through: www.landmonitor.wa.gov.au.

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.

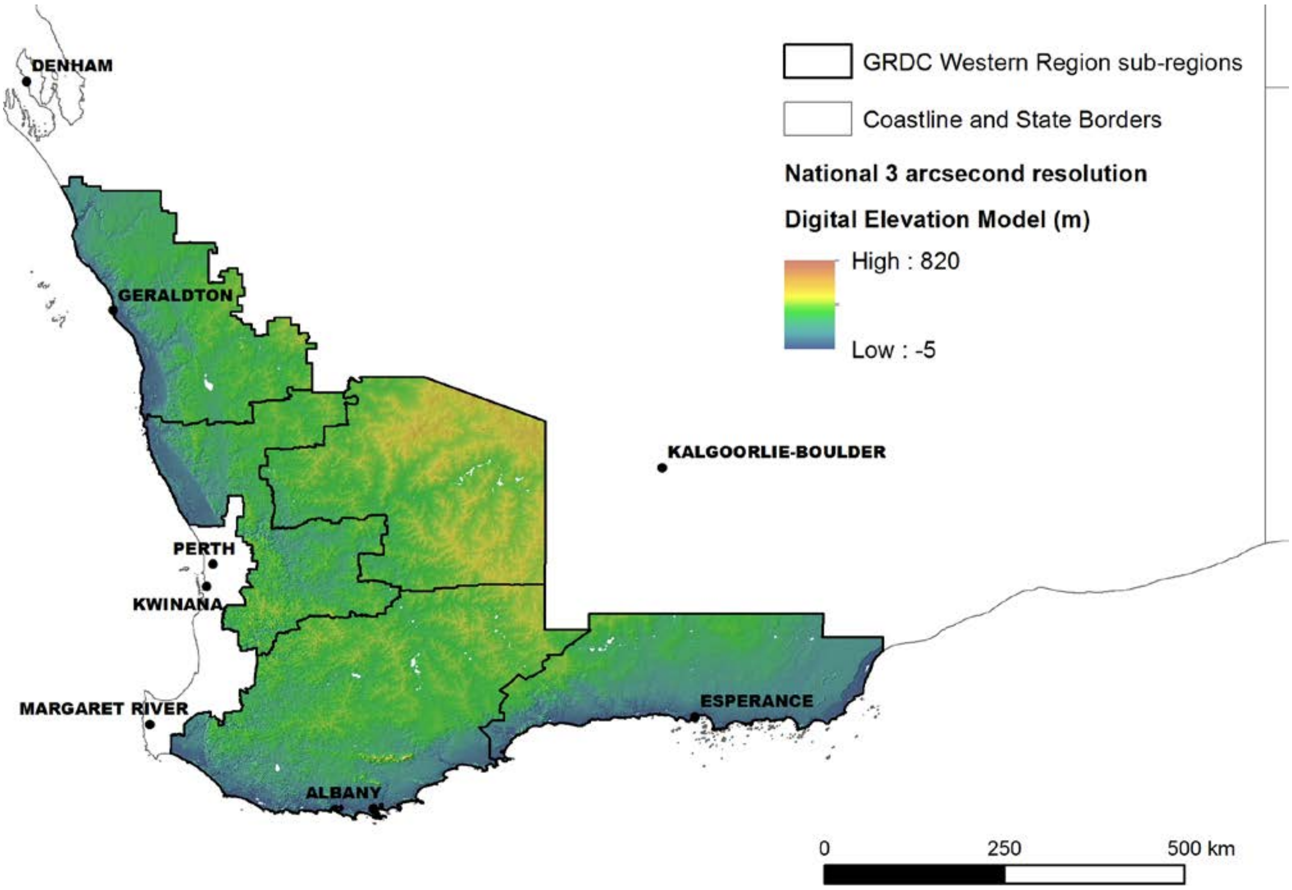


Figure 7.1. National 3 arc second resolution DEM within the GRDC Western Region, with 3 arc second resolution hillshade underneath.

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 and GIS (e.g. ESRI or QGIS, SAGA).

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 Buntine, WA 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 Buntine WA.

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 Buntine WA.

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 Buntine WA.

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 Buntine WA.

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 Buntine WA.

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 Buntine WA.

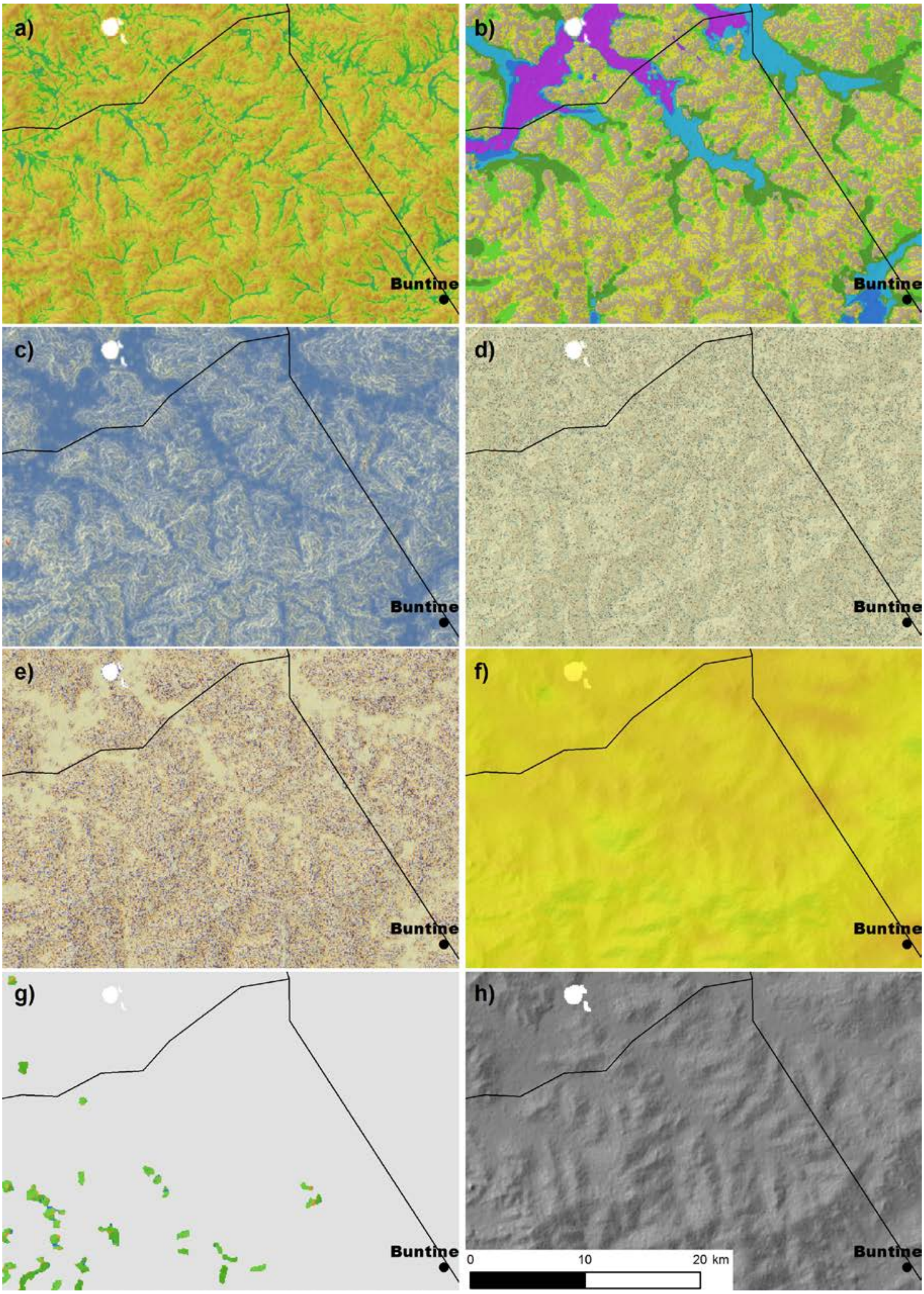


Figure 7.2. Examples of terrain attributes at 3 arc second resolution near Buntine WA. a) Topographic Wetness Index (min 5 – orange, max 19 – blue), b) MrVBF (min 2 – orange, max 9 – purple, grey – 0), c) Percent slope (min 0.1 – blue, max 10 – red), d) Plan curvature (min -0.05 – blue, max 0.05 – brown), e) Profile curvature (min -0.001 –orange, max 0.001 – purple), f) Prescott Index (min 0.2 – orange, max 0.5 – blue), g) Topographic Position Index (lower slope – blue, mid-slope – green, upper slope – orange), h) Hillshade. 1:5 M scale roads (black lines) provides 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 Buntine WA.

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.

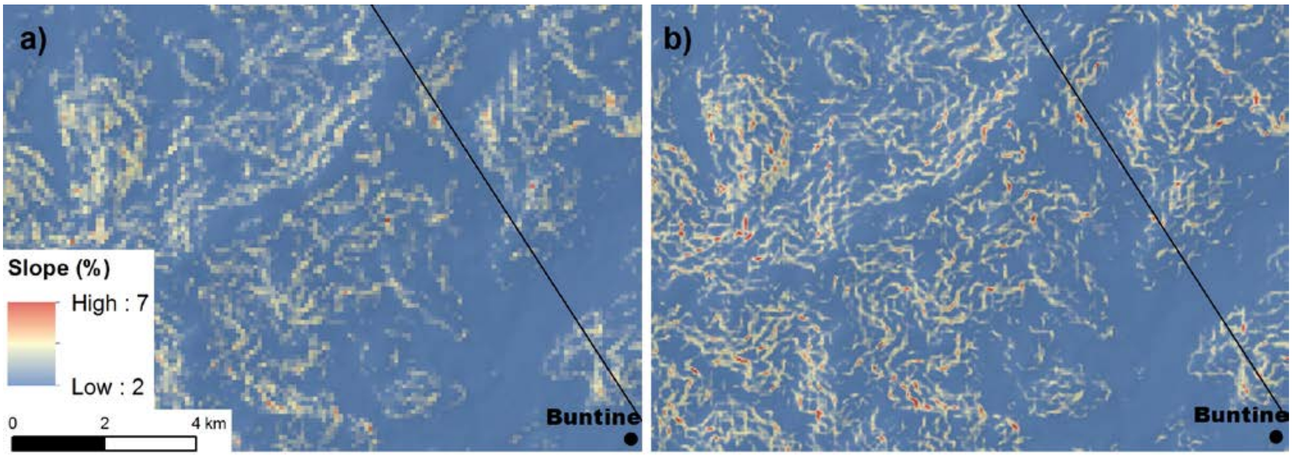


Figure 7.3. Example of the terrain attribute slope (%) at 3 arc second resolution (a) and 1 arc second resolution (b) near Buntine WA. It can be seen readily that the 1 arc second product shows a lot more detail.

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 land 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 Satellite ASTER geoscience map of Australia

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 WA through CSIRO's data access portal (https://doi.org/10.4225/08/51400D6F7B335), 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.

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.

8.5 Regional WA geophysical data

The Government of Western Australia through the Department of Mines, Industry Regulation and Safety website (http://www.dmp.wa.gov.au/Geological-Survey/Regional-geophysical-survey-data-1392.aspx) provides free of charge regional airborne magnetic, radiometric and electromagnetic surveys, ground gravity surveys and deep seismic and magnetotelluric surveys, which were funded by the State or Federal government.

Of interest here are the state-wide geophysical compilations that may be available at a finer resolution than products accessible through national sources described in previous sections, in particular the radiometric grids of Western Australia available at 80 m resolution, which can be used to inform on soil parent materials, as well as soil texture and clay mineralogy.

9 Possible future case studies

For the GRDC Northern region a similar data inventory report was prepared that included eight case studies relevant for the next stage in the project, namely to evaluate in detail the different methodologies for predicting PAWC from available information. It would be of similar value to carry out a few select case studies within the GRDC Western region to evaluate the regional specific information resources. Below, a number of suggestions are briefly outlined, following discussions with Karen Holmes (WA Department of Primary Industries and Regional Development, formerly known as the Department of Agriculture and Food WA) and Yvette Oliver (CSIRO, Floreat, WA). The basis for case study selection is included, however, the exact locations and the relative priority of each area would need to be determined in further consultation with local soil mapping agencies and appropriate grower group representatives. We welcome further discussion in relation to future case studies and site selection.

Within the GRDC Western Region there is some variability in the level of available soil and landscape information, although considerably less than in the other regions. This variability may affect the choice of methodology to predict PAWC. The density of data underpinning the digital soil attribute maps, like the national and regional data in the Soil and Landscape Grid of Australia (SLGA), is also uneven. The extent to which this may affect the reliability of PAWC predictions at farm scale has not yet been tested. In addition, the GRDC Western Region includes a range of soil-landscapes, which to some degree vary in complexity and this may also impact on the most suitable predictive approach.

The following case study areas for which the various information resources available in WA could be evaluated, were therefore chosen to represent different scales and soil-landscape complexity. All fall within the Zone of Ancient Drainage (Figure 9.1 and Figure 9.2; also refer to Figure 3.9, Section 3.5), an extensive undulating plain, which is characterised by a gently undulating plateau, with wide divides, long gentle sideslopes and broad valley floors (2-10 km wide). Soils are formed from laterite, truncated laterite, parna, in-situ weathered rock (granite, greenstone, dolerite), colluvium and alluvium. In general terms, the regular soil pattern is associated with yellow deep sands and sandy gravels on the divides, grey shallow and deep sandy duplex soils on the sideslopes and calcareous loamy earths and alkaline shallow duplex soils in the valley floors. The regional-scale study area also belongs to a different zone, the Zone of Rejuvenated Drainage (Figure 9.1 and Figure 9.2), which comprises of gently inclined rises and low hills formed on dissected laterite with narrow divides; areas of in-situ weathered acid igneous and metamorphic rocks. It is much more disrupted than the Zone of Ancient Drainage, with narrow valley floors where creeks and rivers flow in the winter time. Most soil-landscapes formed on mottled and pallid zones of laterite, or freshly exposed rock, with a high spatial variability of soil properties that may affect agricultural production (e.g. subsoil permeability). This is especially noticeable on sideslope positions where differential erosion and deposition takes place (Moore, 2001).

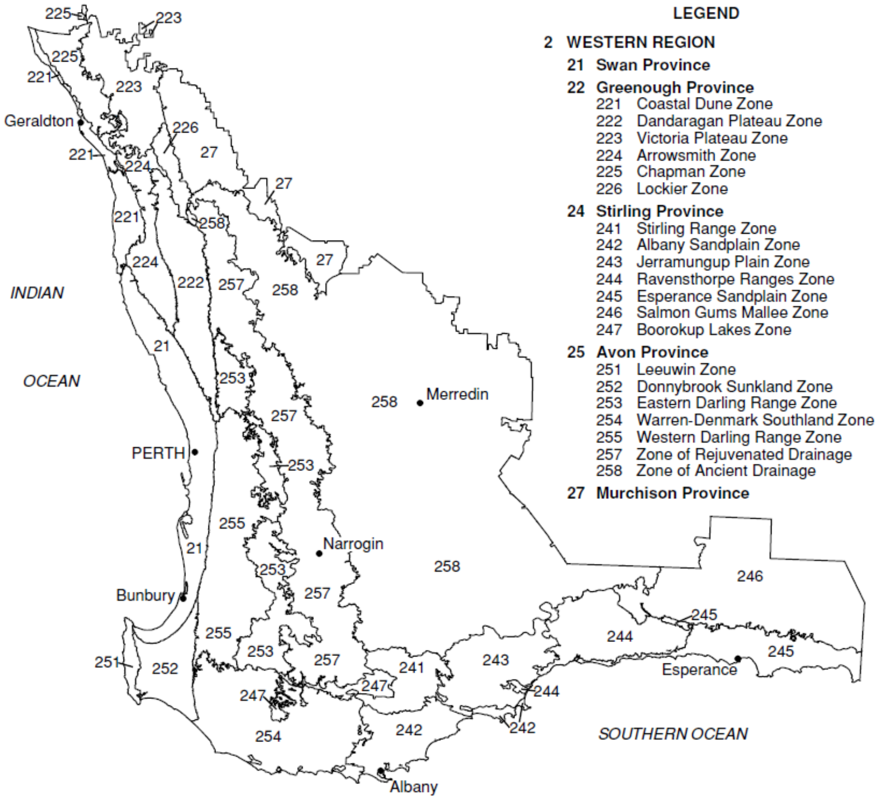


Figure 9.1. Provinces and zones of south-western Australia (Source: Moore, 2001, page 36).

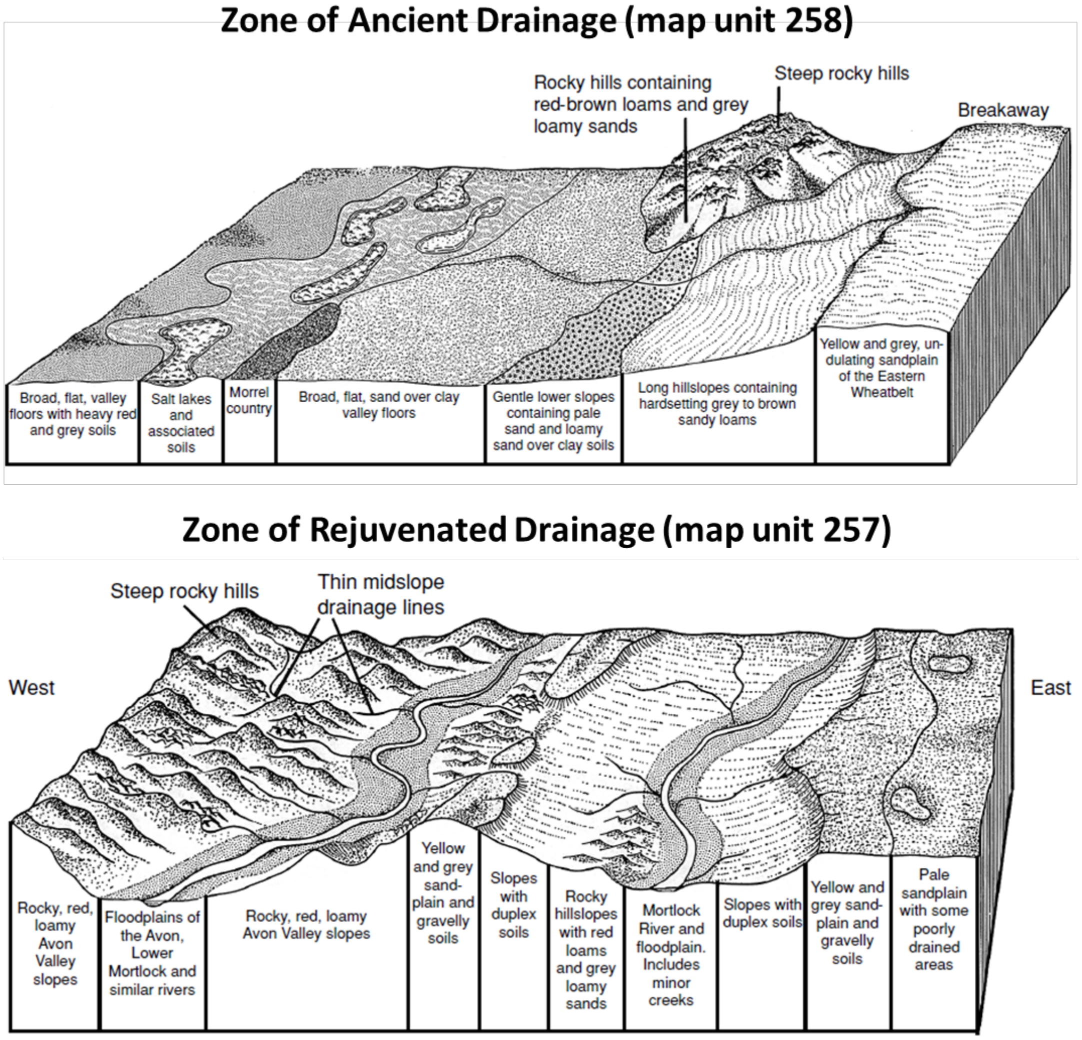


Figure 9.2. Stylised diagram of the Zone of Ancient Drainage and the Zone of Rejuvenated Drainage of south-western Australia (Source: Moore, 2001, page 37).

9.1 Regional-scale: Narrogin/Katanning/Lake Grace region, Western Australia

The proposed regional-scale study area lies between the localities of Narrogin, Katanning and Lake Grace, Western Australia (Figure 9.3). The region stretches over both, the Zone of Rejuvenated and Ancient Drainage described above, and therefore offers the opportunity to test various predictive PAWC approaches in a very complex soil-landscape, with localised outcrop formations, and areas with different stages of weathering, as well as erosion and deposition patterns. As can be seen in Figure 9.3, APSoil profile coverage within the region is generally low, however, soil-landscape data in combination with high-resolution geophysical information is available (e.g. gamma radiometrics at 25 m resolution, also shown in Figure 9.3).

This study area could offer a comparison of DSM data, terrain information, and geophysical data at different scales and resolutions (e.g. 90 m versus 30 m/25 m paddock-scale products), to test which resources are necessary to capture and better understand the complexity of this soil-landscape. And how to best use this information to predict PAWC, in a region with low coverage of APSoil sites and large soil-landscape variability.

In addition, for the sub-set shown in Figure 9.3, Holmes and Griffin (unpublished data) conducted generic soil type mapping using the spatial disaggregation DSM approach (DSMART, refer to Section 6.4) at 25 m resolution (as compared to the state-wide 90 m resolution), which can also be used here for evaluations. Of special interest here would be to evaluate if the paddock-scale disaggregation better captures local soil variability and thus potential subsoil constraints (which lead to localised differences in PAWC).

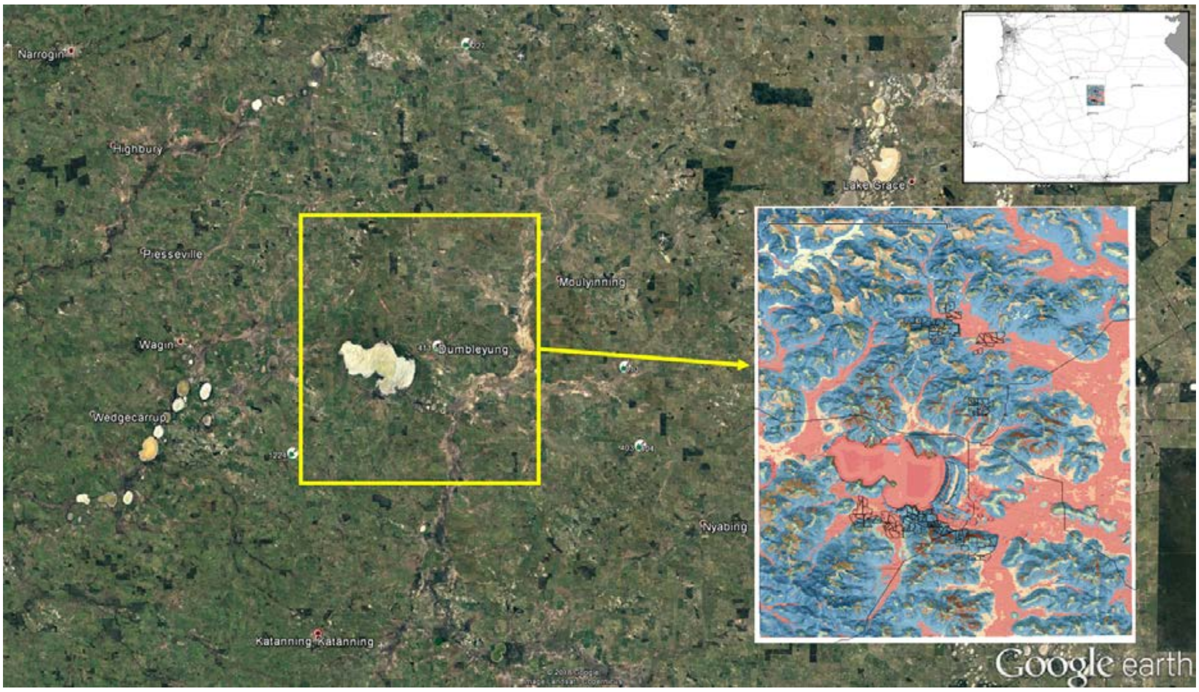


Figure 9.3. Potential Narrogin/Katanning/Lake Grace region study area in Western Australia. The location of APSoil profiles is also shown, including the sub-set where 25m gamma is available for the region (Source: Karen Holmes). Note, only one APSoil profile falls within the subset (record 411, clay loam, Dumbleyung). Source: Framegrab of Google Earth.

9.2 Catchment-scale: Wallatin and O'Brian catchments, Western Australia

The proposed catchment of the central wheatbelt lies between the localities of Kellerberrin and Doodlakine, Western Australia (Figure 9.4). The catchment has good coverage of APSoil sites, combined with soil-landscape mapping at potentially useful mapping scales, as well as DSM coverage (national and WA regional SLGA), and good coverage of high-resolution geophysical surveys and local soil mapping, stemming from previous studies conducted in the catchment. It could therefore offer a comparison between "expert approximation of PAWC" using the soil-landscape polygon narrative approach and DSM approaches (national and WA regional SLGA products).

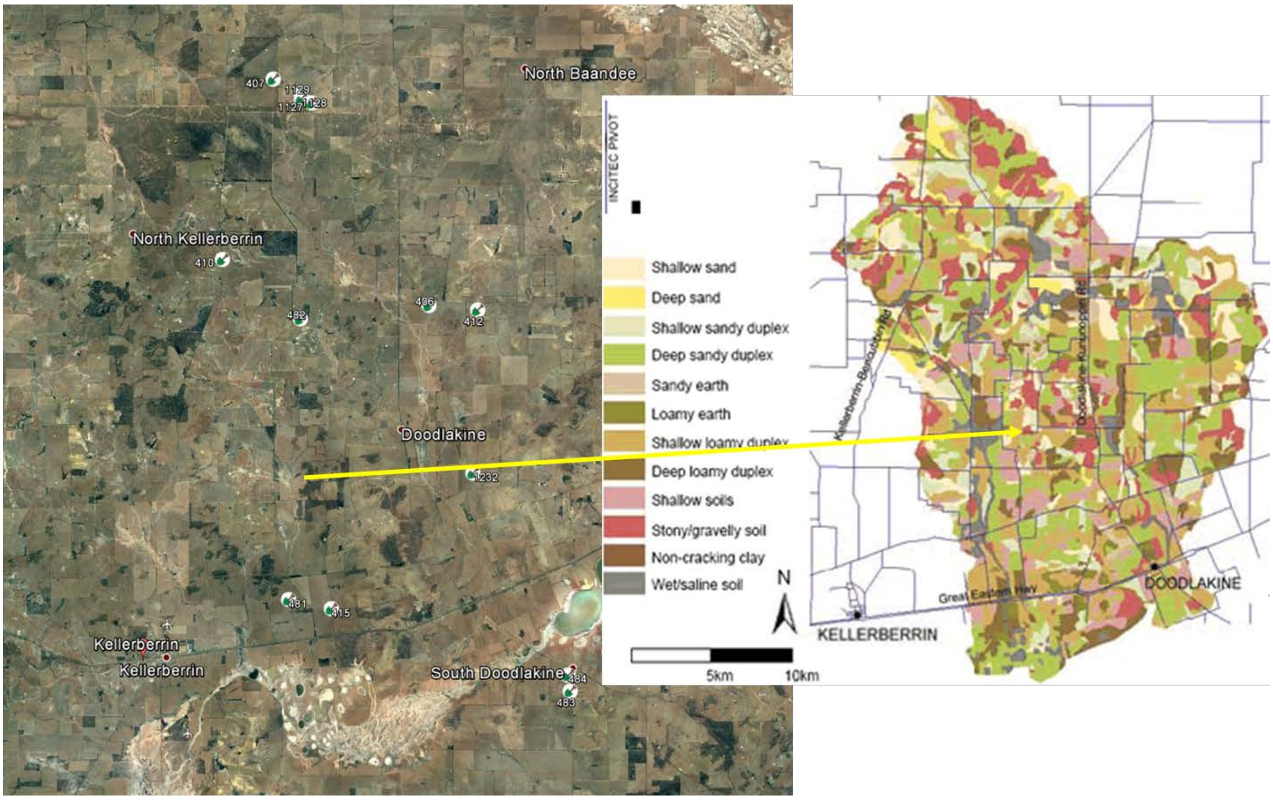


Figure 9.4. Potential Merredin/Walgoolan region study area in Western Australia. The location of APSoil profiles is also shown. Source: Framegrab of Google Earth.

9.3 Farm-scale: Buntine region, Western Australia

The proposed farm-scale study area is located close to the locality of Buntine, Western Australia. Detailed spatial land resource information and soil data (including a local farmer mud map, refer to Figure 9.5) are available for the whole farm, including the on-farm location of 5 APSoil sites and 5 close by APSoil sites (refer to Figure 9.5); stemming from previous studies (i.e. GRDC's SIP09 Precision Agriculture Initiative conducted in the early 2000s). This offers a unique opportunity to test a complete suite of soil information to support the prediction of PAWC.

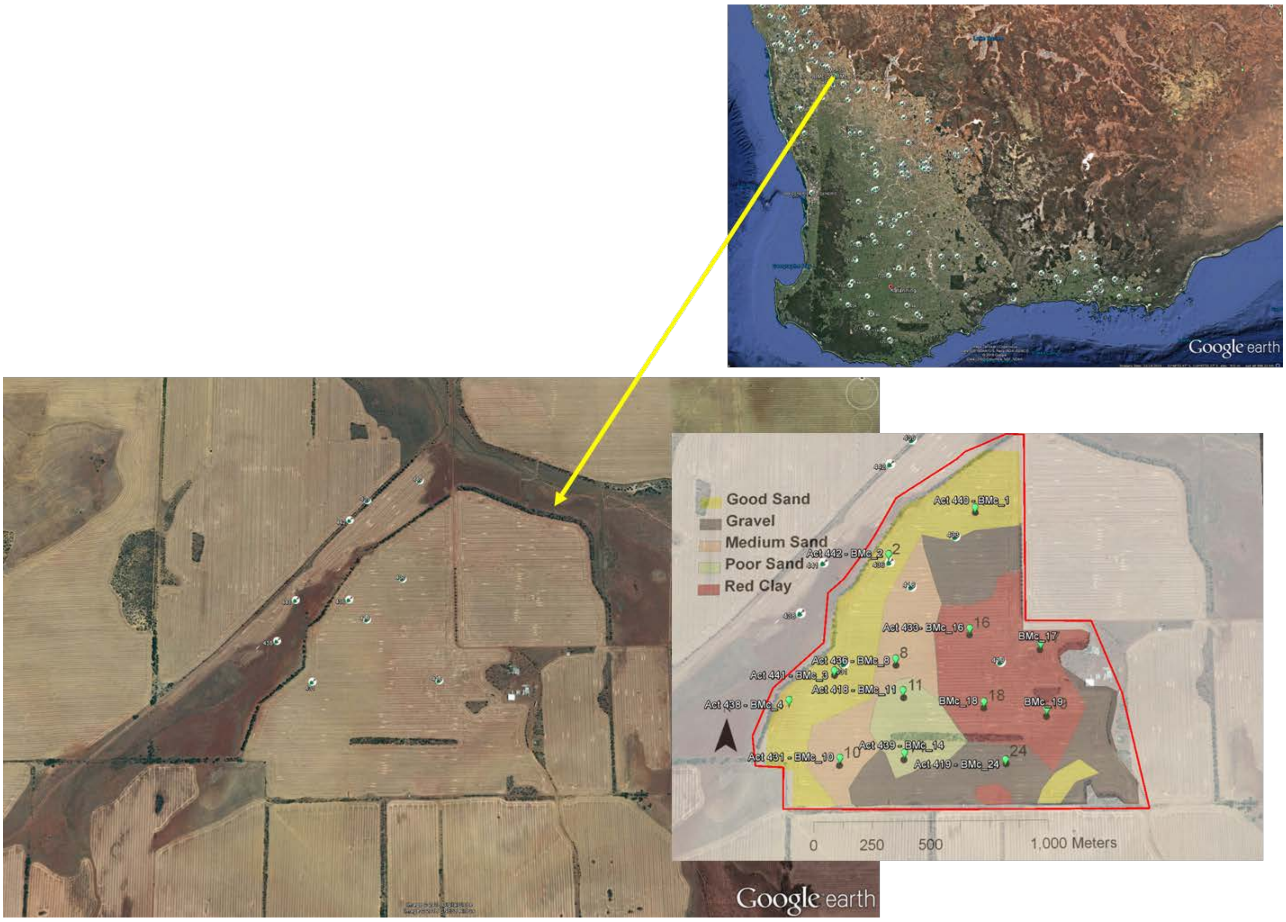


Figure 9.5. Potential farm-scale study area close to the locality of Buntine, Western Australia. The location of APSoil profiles is also shown. Source: Framegrab of Google Earth.

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CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
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CSIRO Agriculture and Food
Dr Kirsten Verburg
t +61 2 6246 5954
e Kirsten.verburg@csiro.au
w www.csiro.au/en/Research/AF

CSIRO Agriculture and Food
Dr Uta Stockmann
t +61 2 6218 3464
e uta.stockmann@csiro.au
w www.csiro.au/en/Research/AF