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Digital Soil Mapping in ACLEP 2012 and beyond

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CSIRO, Australian Collaborative Land Evaluation Program

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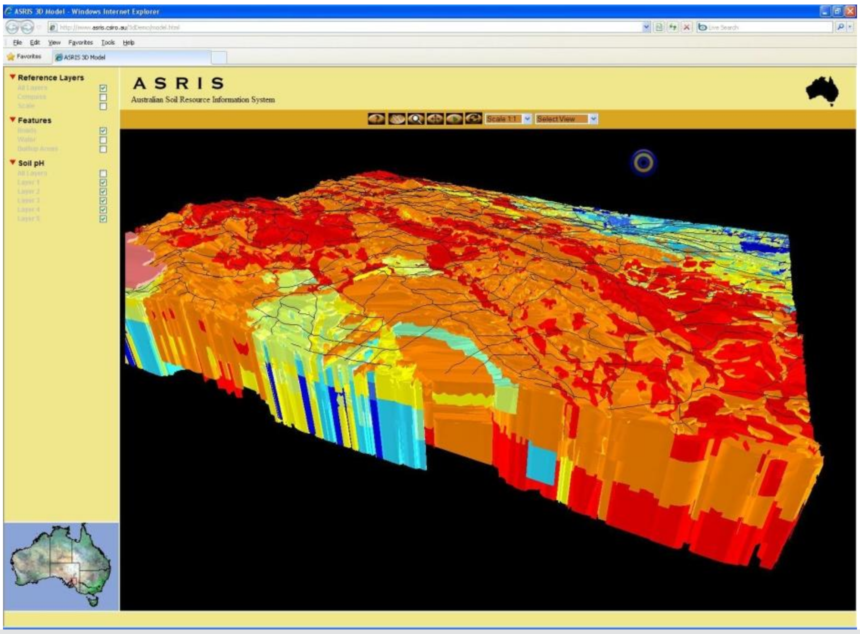

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1. EXECUTIVE SUMMARY

Digital soil mapping (DSM) refers to the computer-aided analyses and prediction of soil properties (e.g. pH, clay content) and/or soil classes. DSM uses measured soil data with remote and proximal sensing, elevation and terrain parameters and a range of (geo)statistical modelling to predict the characteristics of soil across landscapes. Products derived from DSM processes incorporate quantitative estimates of uncertainty, which conventional soil mapping does not.

Many contemporary natural resource management issues (e.g. climate change, food security, water management, biodiversity conservation) have a related soil information component. However, existing soil information across Australia is often at inappropriate scales, lacks content or quantification, or is altogether absent. Available soil data and information is generally old, and has been derived from surveys, often utilising inconsistent approaches and methods. These data do not adequately represent soil variability at an appropriate resolution in space or time, as most of the data have been compiled using conventional mapping methods that produce polygonal (area-class) maps. There is an increasing demand, particularly from environmental modellers, for soil data that describe the continuously variable nature of soil properties.

The development of new technologies and methodologies for measuring and predicting soil attributes has facilitated recent advances in DSM, which addresses a globally recognised need for current, accurate, spatially referenced soil information. This need has been expressed by the modelling community, natural resource managers and policy and decision makers. There is an immediate need to operationlise DSM within a reinvigorated soil data and information program across Australia and to support modelling approaches that take advantage of new quantitative soil data.

ACLEP delivers the soil information infrastructure for Australia and builds on the national capacity in land resource assessment to provide support for emerging priorities. Therefore, ACLEP plays a key national role in the development of DSM. ACLEP will facilitate:

- coordination, collaboration and training on DSM;
- the development of standards and guidelines; and
- coordination of data collection and development of national data infrastructures through linkages to activities such as the TERN Soil and Landscape Grid Facility and the National Plan for Environmental Information.

ACLEP provides a forum for interaction between DSM researchers, practitioners (including the States and Territories, CSIRO and academia) as well as stakeholders such as CSIRO, the Commonwealth and States and Territories through the National Committee on Soil and Terrain.

1.1 Recommendations

Recommendations for progressing DSM presented in this report are twofold, including strengthening of current activities through ACLEP, and supporting new opportunities which would require significant investment through a reinvigorated and coordinated national soil program.

In the short term, ACLEP should:

- Continue to provide a national soil information infrastructure that supports the collation, and delivery of the best available digital soil and other landscape related data sets for Australia
- Complete collaborative DSM projects in Tasmania and the Northern Territory. Publish project reports and present results through national DSM workshops
- Support opportunities for development of new projects – e.g. in Qld, NSW, Vic-SA to further advance DSM operations across the country by creating collective national capacity, capabilities and skills
- Facilitate focussed training in DSM and support inter-jurisdictional working visits, following recommendations from the NCST DSM Advisory Group
- Promote DSM operations and opportunities at scientific meetings, e.g. ASSSI Soil Science Conference Hobart, and develop a set of brochures for wider communication of DSM approaches and benefits
- Develop a program of regular national DSM technical workshops. Opportunities should allow the sharing of lessons and experiences among DSM practitioners by using state-based projects as foci at these events.

A reinvigorated national soil program could progress the operational implementation of DSM and stimulate further scientific evolution by:

- Strategically reviewing the soil data and information needs of the nation, including data gaps
- Supporting a coordinated program of data collection, collation and DSM activity at appropriate resolutions identified by regional and national needs
- Engaging with the National Plan for Environmental Information (NPEI) to ensure that DSM data and products are aligned with emerging priorities and are recognised as a fundamental contribution to Australia's environmental information infrastructure
- Fully supporting the ongoing delivery of a national soil information infrastructure which facilitates the collation, management, discovery, access and use of nationally consistent soil data and information products for all users
- Developing new nationally consistent environmental covariates, e.g. surface mineralogy, soil water coverages and regolith characterisations
- Accelerating "fundamental research" to advance new, cost-effective methods, e.g. spectrographic methods, proximal sensing, sample design, soil modelling/predictive

methods, including for soil carbon, and responding to emerging scientific issues identified through State-based operational projects

- Growing the national soil archive and associated spectral library as key components of a national soil information infrastructure supporting operational DSM; and
- Providing an online repository of DSM tools, references and datasets and operational handbooks to guide the application of DSM methods.

2. SOILS IN SPACE AND TIME

Soils are an essential component of the environment upon which life on Earth depends. Soils are probably the most complex biological material known to man, being an intimate mix of mineral, liquid, gaseous and biological material. Processes of soil formation and change respond to different factors, operating at a range of spatial and temporal scales. The resultant characteristics and function of the soil material at any one location have intrinsic links to the function of the environment and the provision of a wide range of ecosystem services.

Data, information and a deep understanding of soils characteristics, processes, condition and function is therefore essential to support informed, evidence based policy and decision making at site-specific, local, regional, national and global scales.

Soil scientists engage in the development and application of knowledge about soils and the processes which effect their characteristics and functions. This is done through mapping, modelling and monitoring our soil resource base. To date, considerable scientific research has been directed towards understanding processes of soil formation and degradation. Significant investment has been made in measuring soil properties at know locations and in developing standards and systems for their description and classification. Mapping of our soils has occurred at various scales across the continent, largely in response to development pressure or to assist with remediation of land degradation related issues (such as salinisation or erosion).

As computational capacity has expanded, so too has the ability of soil scientists, and those of other disciplines, to integrate and model a range of data sets relevant to environmental processes. This is not a replacement for traditional science and still requires an intimate knowledge of the environmental systems and processes which computational models aim to replicate. Pure data driven approaches to modelling may produce output with significant limitations and fundamental flaws. Model-data assimilation allows the explicit information about environmental characteristics obtained through detailed field analysis and laboratory experimentation to be incorporated in computer based models to provide outputs more aligned with recognisable and accepted real-world conditions.

3. TRADITIONAL APPROACHES AND DIGITAL SOIL MAPPING

Soil mapping provides a basis for spatially and temporally defining the characteristics and attribute values of soil and land resources. Expressions of real-world conditions, through soil maps, soil type descriptions and gridded surfaces of continuous variation of attributes of interest, provide valuable mechanism for conveying data and information to a wide variety of users. Soil maps and their associated data and reports are a fundamental knowledge base utilised by a wide range of users, either directly (such as for agricultural or infrastructure development planning) or indirectly as part of complex investigations (such as components of climate change and mitigation, water quantity and quality modelling or assessment of habitat condition for biodiversity impacts and conservation).

Soil mapping has traditionally involved the development of a deep understanding of soil forming processes which is applied to predict the location of classes of soil and the likely range of variation in particular attributes. Many approaches have used descriptive (e.g. colour and texture) and diagnostic (such as pH or cation exchange capacity) characteristics to classify soil so that these ‘artificial’ divisions can be utilised to convey spatial and temporal variance in soil properties. In this way opportunities and limitations for land and soil development and use can be considered and management decisions can be based on evidence and an understanding of likely impacts and consequences.

Aerial photography, and to a limited extent satellite imagery, has provided a spatial context for the mapping of soil and landscape features since the 1950’s. Trained soil surveyors have been able to differentiate soil types, classes and complexes at a range of mapping scales based on the recurring patterns identifiable on these base products. Descriptions of the mapping units and associated soil types have been developed from field and laboratory analyses and collated within published reports and map legends. From the early 1990’s both the spatial and attribute data have been incorporated into computerised data bases and geographic information systems which has greatly increased the utility and accessibility of soil data and information.

Many environmental communities have progressed with the collection and collation of digital data sets over the past 20 years. There is now a significant national resource of environmental data covering climate, terrain, geology and geophysics, vegetation and water – all of which can be integrated and analysed to deliver new data and information products. In the soil community there is a realisation that many of these spatially extensive environmental data layers represent various components of soil forming factors and processes which influence the characteristics or condition of our soil and land resources.

DSM is a computerised mapping and modelling toolset which utilises location explicit soil data (so-called “predictors” - including soil site and profile descriptions, analytical lab results and interpreted soil maps) that is expensive to collect and therefore sparsely available, to predict soil properties (so-called “target variables”) at unvisited locations using relationships with other environmentally correlated data that is available from other sources and is spatially extensive. DSM methods derive relationships - or “models” - between the predictors and the environmental covariate data to predict the target variables across the area to be mapped.

DSM is therefore an analogue of traditional soil survey and mapping frameworks. Both techniques apply soil-landscape process models that explain soil distribution in the landscape. The models are developed from relationships identified between the soil patterns and co-varying sources of environmental and landscape patterns (e.g. aerial photography, geology maps) or other data. Overwhelmingly, the models are based on covariance of field-based soil observations and landform, parent material and vegetation. Much is made in traditional soil survey of the relationship between soils and landform [catena concept (Milne, 1936)]. Jenny’s (Jenny, 1941) soil forming factors increase the complexity of modelling by including the influences on soil formation of landscape history (time), biotic activity, climate and parent material. As a traditional soil survey progresses, models are translated to *qualitative rules* before the commencement of mapping. In traditional survey, relatively few sites are visited (sampled) within the study area landscape, and predictions (i.e. the mapped output) are made based on the rules that relate the soil properties at the sampled sites to the covariates (e.g. as expressed on aerial photographs or geology maps). Typically, the models and rules are held tacitly in the minds of the soil surveyor, and are rarely expressed in detail other than as soil mapping legends (Hudson, 1992).

Many approaches underlying DSM strongly echo the traditional survey - particularly in incorporating relationships between soil patterns and covariates in digital format. However, in DSM, the relationships are statistically-based and are translated into *quantitative rules*. The philosophical similarities between the traditional and DSM approaches means that little conceptual shift is needed to transfer between the two mapping approaches, and, as such, they are highly complementary. DSM strongly preserves and builds on the legacy of past investment in terms of time, effort, data acquisition and knowledge-development of traditional survey. Indeed most DSM practitioners have a background in traditional soil survey, and understand that soil-landscape process knowledge developed through traditional soil survey is indispensible in guiding options used in DSM.
One of the key features of DSM is the output of continuous soil property data (e.g. as raster or grid formats). This contrasts sharply with traditional mapping, which supplies so-called *crisp*, categorical maps of soil taxa, i.e. soil classification. Whilst categorical maps are suitable tools for communicating soil concepts and aggregated soil properties, they have limited capacity to spatially represent the many soil attributes that vary continuously within the soil mapping unit, and are therefore not suited to addressing site-specific issues. The inability to express spatial variability through categorical mapping means the utility of traditional soil mapping has limited application in spatially-explicit environmental modelling (e.g. soil carbon sequestration or assessing soil degradation due to acidification).

At the core of DSM are *soil and environmental* datasets. These are used to construct, apply and test soil process models. Linked to these are applied research domains including - *geographic information systems (GIS)*, which provides the spatio-temporal analytical and production environment; *statistics,* which forms the basis of soil estimation models and their evaluation; and *soil science,* providing underpinning knowledge, experience and context to the approaches taken.

DSM currently, however, is mostly within the research arena. For example, there is a strong emphasis on testing and integrating new components, or adapting to new opportunities as DSM components evolve. Most – if not all – DSM reporting describes the development and testing of new and improved methods. New statistical approaches and new soil and covariate measurement methods are currently undergoing rapid development. Furthermore, research is needed to satisfy the developing needs of multiple types of users who have a call on soil data and information. This is particularly evident as the demand grows from environmental modellers for soil data that is fit-for-purpose in terms of location coverage, scale, thematic content and currency. How these various and sometimes conflicting demands are met remains a strong research challenge. That said, the general consensus is that DSM is now heading towards an era of increased operational application.

DSM is not a replacement for traditional soil mapping. In much the same way as traditional soil survey and mapping, DSM relies on inputs of detailed field and laboratory based soil data, a deep understanding of soil formation and impact processes, and the availability of spatially explicit and relevant environmental covariate data.

3.1 Digital soil mapping systems

DSM involves the application of predictor datasets (i.e. soil observations and sample data) to create models used to predict target variables (i.e. the features or variables of interest, maps). Predictors can be thought as the "inputs" and target variables, the "outputs". There are three main approaches used in DSM (Hengl and MacMillan, 2009), i.e.:

- statistically-based;
- deterministic, process-based; or
- expert knowledge-based – or heuristic.

Choice of approach is determined by a number of factors including: the quality of expert knowledge; the complexity of the soil-landscape; the available datasets (predictor, environmental covariate), and; practitioner skill and competency. For example, use of knowledge-based and deterministic systems pre-supposes a prior understanding of the soil-landscape rules/equations that correctly represent the pedogenesis of the study area. In turn this knowledge allows selection of a strongest possible set of environmental covariates. Conversely, statistically-based systems are suited to soil-landscapes where the rules are poorly known beforehand, and a system is needed to "discover" them. However, while these systems seemingly require lower human input than the knowledge- and process-based systems, expert input remains important for selecting the best possible environmental covariates, and pre-supposes, at minimum, a rudimentary soil-landscape understanding of the area to be mapped. If done well, the results are strong statistical models and quality maps, and efficient computation. This illustrates the fact that DSM approaches are rarely exclusive, and in reality most (the best?) include elements of one or more of the mapping approaches.

3.1.1 Statistically-based systems

At the heart of statistically-based systems is the creation of quantitative models generated from a model fitting process. The models "explain" the relationship between predictor and target variables, and are typically applied to environmental covariates to achieve the spatial predictions. These models are called statistical models, and there are four main types (Hengl and MacMillan, 2009):

Classification-based models

These models are used when the output is to be discrete target variables (e.g. soil classifications) where the output is boundaries or classification rules. They employ either Boolean methods of classification for crisp class boundaries, or Fuzzy methods for continuous class boundaries.

Tree-based models

Tree-based models are fitted by successively splitting a database of continuous and/or discrete environmental covariates into increasingly homogenous groupings. The result of model fitting is a decision tree that can be employed to predict individual soil property values or class types over an area of interest.

Regression models

Regression models fall into two categories: generalised linear models (GLMs) and general additive models (GAMs). GLMs assume a linear relationship between predictor and target variables, with regression coefficients as output. GAMs are suitable for non-linear relationships between predictor and target variables, and operate by one-step data fitting or using iterative data fitting, e.g. employing neural networks.

Hybrid geostatistical models

These models employ a combination of methods described above, and also modifications to kriging. These modified types split into cokriging and regression kriging, which both simultaneously apply predictor-target variable correlations to environmental covariates as well as spatial autocorrelations models. As such, these involve creation of regression coefficients and variogram parameters.

3.1.2 Process-based systems

This approach includes a suite of techniques that already have strongly established relationships between predictors and environmental covariates to arrive at the target variables. As such, the greatest challenge of using these systems is in calibrating the predictor/target variable response, which becomes an extremely complicated task when the inputs are large in number and/or sensitive. The models used are often also known a “pedotransfer functions”.

These mapping systems are suitable for process-based, mechanistic, and spatiotemporal modelling. An example would be a model that predicts changes in soil-regolith depth over time in which the key factors of soil-landscape weathering and removal are reasonably well known and can be parameterised (e.g. soil porosity, rock density, rates of chemical weathering and mass movement, etc.). At its most rudimentary, such a model only requires elevation as an input as all other factors remain constant.

As discussed, these models are suitable for spatiotemporal modelling with mapping outputs provided at defined time increments (e.g. days to millennia). Coupled with 3D visualisation, such approaches provide powerful educational tools to show change over time. The power of these systems can be further increased with addition of user-interaction through interactive manipulation of input factors, e.g. land use changes, and the visualisation of outcomes to the soil resource.

3.1.3 Expert knowledge-based systems

These systems rely on human understanding of relationships between the predictors (e.g. location-specific soil data and observations) and the target variables. In terms of DSM, these systems have the strongest analogues to traditional survey. As discussed in previous sections, both methods involve time in the field and soil sample data to infer soil-landscape models, generally based on relationships with covariates such as aerial photography and remote sensing. In traditional soil mapping the surveyor translates the tacitly-held models to lines on maps (e.g. soil classes), whereas in DSM the models are translated to a digital framework of environmental covariates thresholds typically in the form of decision trees, and the outputs are typically soil class maps. Refinement of the mapping quality can be achieved iteratively by modifying the framework thresholds.

Other expert knowledge-based systems employ supervised computer-generated classification, suitable when the coverage of predictors across the mapping area is dense, or unsupervised classification when predictor coverage is limited but the operator has an adequate knowledge of the number of soils types and their distribution. These computer-based methods employ statistical models (e.g. maximum likelihood algorithm) to either define environmental covariate thresholds (supervised classification) based on predictor statistics or allow human interaction to manipulate covariate thresholds to fit predictor statistics (unsupervised classification).

Fuzzy logical approaches are also expert knowledge-based classification systems, which are suited to generating continuous mapping output suited to categorical and continuous data output. Fuzzy logic output is given a fuzzy likelihood of class inclusion as well as a value, which is attractive because conceptually this follows soil property transitions in landscapes, and because of this, mapping uncertainty.

3.2 Statistically-based survey design

Irrespective of the mapping style, a critical component of soil mapping is a suitable survey design so that the collection of samples and observations provides appropriate coverage of the area to be mapped. In traditional survey, such methods have included random and regular-based sampling design. Implicit in each is the expectation that the sampling population is unbiased, and in the case of random design, the hope is that the surveyor is given good access to the whole mapping area. More advanced methods like stratified-random designs ensure a non-biased sample population within key study area strata (e.g. geological units or landscape facets).

As discussed, DSM involves spatial estimation of soil properties by correlating patterns with environmental covariates via statistically-based soil models developed from soil property measurements. For this reason, significant effort has been directed in recent times towards providing suitable DSM sampling designs that provide statistically suitable sample populations. To be effective, the soil sampling design must cover the range of soil properties in the area to be mapped. Conditioned Latin Hypercube sampling (cLHS) achieves this by performing maximally stratified random sampling in the presence of covariates. A predefined number of samples (N) is equal the number of strata. cLHS samples the multivariate so-called *feature space* of the covariates, and translates the N feature space coordinates into geographic coordinates, i.e. the N sampling sites. The technique is discussed fully in Minasny and McBratney (2006). A number of projects have attempted to apply cLHS design in operational surveys, and have encountered various degrees of success due to the lack of human interaction with the design and the operational hardship of locating alternative sites when sites cannot be navigated to due to accessibility constraints. Modifications to cLHS and alternatives are under development to achieve statistically-based sampling that is operationally achievable.

4. THE DSM VALUE PROPOSITION

Digital soil mapping is a new technologically-based approach and tool set which greatly improves our ability to provide soil data and information for an ever increasing set of users and applications. With an increasing availability of digital environmental data sets which have a direct relationship to soil related processes, there is emerging capacity to deliver soil data at spatial and temporal scales previously unattainable. In particular the availability of fine resolution, detailed and nationally consistent digital elevation data (through the NASA Shuttle Radar Digital Elevation Mission) and associated terrain derivative data layers has vastly improved the predictive capacity of DSM for soil and landscape attributes. Similarly the national availability of geophysics data (particularly gamma radiometrics) has improved the predictability of soil mineral, weathering and nutrient related characteristics. Advances in ground based proximal sensing (such as electromagnetics, ground penetrating radar and near- and mid-infra red spectrometry) are further progressing the availability of digital data sets able to be incorporated into DSM estimation procedures.

Other benefits to applying DSM approaches include the capture of explicit landscape process models and assumptions, previously held within the minds of experienced soil surveyors. They can also be used to make quantitative predictions of soil attributes, thereby removing some of the qualitative and implicit assumptions of more traditional approaches. Computerised approaches are repeatable and can be updated and re-run as new process understanding or improved input data sets become available. In addition the underpinning input data sets can be interrogated and the uncertainty of soil attribute estimates more readily calculated and presented for use. The ability to quantitatively express the mapping quality and level of confidence is important, particularly in complex ecosystem modelling. Here modellers require objective and defensible statements on the reliability of inputs to infer the quality of outputs - particularly in a number of currently increasingly charged spheres such as climate and carbon research.

DSM builds on the currently available historically collected soil data (“legacy datasets”) and knowledge assets implicit in existing map and report products. It can make considerable improvements to our available soil data and information in both spatial and temporal dimensions. Recent research from the Netherlands shows an estimated cost ratio of 4:1 when comparing mapping by traditional methods to DSM (Kempen, SSSAJ in press). This research compared the creation of two soil maps of comparable specifications in terms of mapping theme and scale. Although not necessarily applicable to all areas, it is likely that the magnitude of the ratio would be repeated.

5. NEED FOR DIGITAL SOIL MAPPING

Site specific and map based soil data have been important sources of information for many users over the past decades and will continue to be required to covey specific or broadly based spatial soil information for the foreseeable future. They provide an important communication tool and are generally understood by the majority of users.

Computerised environmental models can now incorporate large data sets and handle detailed spatially and temporally explicit inputs. In recent time models for salinity risk and hazard assessment, agricultural suitability, carbon accounting, climate change modelling, water harvesting and biodiversity modelling have sought improved soil attribute inputs. Traditional soil map (polygon) based products can be manipulated to provide some inputs, but the lack of variability of attributes within mapping units do not represent known variability well. DSM derived soil attribute products, with their predicted variability based on the associated environmental covariate layers (along with estimates of uncertainty of soil attribute values) provide a much richer source of data for use in modelling.

Soils are being increasingly recognised as a major conditioning factor to the provision of a wide range of ecosystems services such as biodiversity habitat, food and water security, and climate adaption and regulation. These are now seen as issues of paramount global importance. An immediate and key "client" of soil data and information is therefore the environmental modelling community, tackling these issues at local, on-ground and continental to global scales. Modellers require inputs that are: up-to-date; feature appropriate functional properties; are systematic and regionally consistent, and; spatially accurate and supplied at a resolution consistent with the other modelling inputs and output requirements. Furthermore, estimations of error and explicit communication of the methods used are needed to ensure that modelled outputs successfully endure the rigours of critical scrutiny and remain defendable. Other earth sciences communities such as geology, ecology and climate are already successfully addressing modelling needs while soil science lags behind. DSM is in a strong position to satisfy environmental modelling needs.

6. CURRENT APPROACHES AND ACTIVITIES

Digital soil mapping is not new. Early attempts to progress DSM were embedded in the Enhanced Resource Assessment Program supported by ACLEP and facilitated by the Queensland government in the late 1990's. Research into DSM techniques and approaches has been progressive, particularly within Australia. Improved availability of computational resources and spatial data sets over the last 5-10 years has encouraged operational agencies to utilise DSM approaches within projects. Particular progress has been made within Queensland and Western Australia where a number of DSM derived project products are available.

Following broad Australian representation at the 4th Global Digital Soil Mapping Workshop and a resultant enthusiasm for progressing DSM nationally, ACLEP invested in building skills and capacity through workshops and training (particularly with the support of Sydney University). A number of DSM pilot projects were also discussed, with initial activity in Tasmania and the Northern Territory (see 6.1.2). These projects have highlighted some of the operational difficulties with establishing new approaches, particularly where the skills and capacity base is relatively low. Even so, collation of environmental covariate layers, skills development with DSM software and investigation into the development of field based sampling strategies have been useful.

Initial DSM project work in Tasmania was supported with significant state government investment through the Wealth from Water Program, allowing considerable advances in the application of DSM techniques in that project. Dedication of staff resources to the project facilitated skills development and the application of a number of DSM techniques including hypercube sampling strategies, use of infra-red spectrometry, proximal sensing including - ground based gamma radiometrics and model estimation of a range of soil parameters for agricultural suitability assessment.

CSIRO continues to research and develop new approaches and information resources for DSM. In particular the application of near and mid-infra red spectroscopy is proving useful for the estimation of a range of soil properties. A number of national mapping products have been developed as a result of research projects, including soil colour, mineralogy and mapping of broad soil types associated with principal component analysis of the spectra themselves. These products show broad correlation to known spatial patterns of soil attributes at the national level, but as yet lack validation and general acceptance at regional and local scales. Further refinement and inclusion of additional soil and covariate data will undoubtedly improve these national products in the future.

The Terrestrial Ecosystems Research Network (TERN) Soil and Landscape Grid of Australia Facility (the TERN Soil Facility) has digital soil mapping at the heart of its approaches to producing a fine resolution grid of soil attributes across the nation. DSM will be applied in two ways, firstly through utilising environmental covariate layers to disaggregate existing broad scale soil maps, and secondly by using available soil data and environmental covariate data to estimate values of specific functional soil attributes. This project activity will greatly improve the DSM skills and knowledge base of practitioners and develop methods and approaches which will be applicable to other DSM based project activity within Australia and internationally. ACLEP has a significant role in collaboration with the TERN Soil Facility in terms of national soil and terrain data collation, in the future delivery of TERN derived national soil data sets, and in sharing and promoting DSM lessons and approaches.

DSM related activity in Australia, including ongoing research and development through CSIRO and the University of Sydney; the application of methods and data development through jurisdictional, ALCEP and TERN Soil projects; the development of DSM derived data discovery and delivery infrastructures through the TERN Soil Facility portal and ASRIS, are all contributing to Australia's involvement in global DSM related initiatives such as the GlobalSoilMap.net project and the International Union of Soil Science Working Group on Soil Information Standards. These activities are aimed at the production and delivery of globally consistent and relevant soil data and information to inform significant international priorities such as managing climate change and the global food security. Ongoing and increased investment in DSM is essential for Australia to continue its leadership roles in this area and to ensure development and delivery of the best possible soil data and information for the nation.

6.1 Building coordination, partnerships and skills

The National Committee on Soil and Terrain Advisory Group on DSM ('the advisory group') currently consists of 13 members drawn from operational and research backgrounds and constitutes an important "community of practice" and focal point for DSM. The key functions of the advisory group are to ensure that, on a strategic level, (i) DSM is viable for infilling major data gaps in Australia, and (ii) to ensure that the NCST is kept abreast of developments in DSM technology and the capability to address the national data issues.

The advisory group concerns itself with the development and maintenance of DSM capacity in Australia with the objective being that the appropriate use of DSM becomes a nationally viable option. This is achieved through a number of activities identified by advisory group consensus, and committed to a workplan. The current workplan (2011-12) contains the following activities:

- Assist through various tasks and promote the 5th Global DSM Workshop, April 2012;
- Promote DSM techniques and methodologies in broader Australia;
- Develop an online collaboration platform to disseminate public domain DSM software and datasets;
- Formulate technical training courses in DSM and related areas;
- Develop operational guidelines and manuals for DSM
- Advocate and convene DSM sessions as part of the Australian Soil Science Society Inc. national conference, Hobart, December 2012; and
- Formulate and undertake state-based collaborative DSM projects.

The advisory group convenes in person when possible, e.g. coinciding with DSM meetings, workshops and courses, or by teleconference. The advisory group has direct input into the NCST via the DSM representative. Progress against the workplan is reviewed, new plans discussed and the workplan amended accordingly.

The development and then maintenance of an operational DSM capability in the states and territories is critical if Australia is to take full advantage of the opportunities that DSM offers.

At present there exists a wide range of competencies within these jurisdictions, which range from almost no DSM skills to an advanced operational capability. Reflecting this need to uplift and sustain Australian-wide DSM capability, ACLEP has a two-pronged strategy guided by specific capacity development needs identified by the advisory group. This strategy includes:

- provision of training through formal courses and workshops; and
- implement state-based collaborative projects for the development of DSM skills for participants and demonstration of DSM capability amongst peers.

6.1.1 Training

A DSM course was presented by the University of Sydney during February 2011 in response to the need identified by the advisory group to uplift the general level of DSM competency across all states and territories. This course, entitled "Getting Operational - An introductory course of practical exercises for Digital Soil Mapping", was structured to develop a basic level of skills in operational DSM platforms/software, drawing on datasets compiled during real mapping projects. The training included the integrated use of freely available SAGA GIS, R, Tinn-R, Jump, VESPER, FuzMe, and Cubist software. The course was conducted over two days and consisted of lectures and guided, hands-on sessions. ACLEP funded the costs of running the workshop, and a contributed to travel and accommodation costs incurred by approximately 20 attendees.

The course made significant impact amongst participants in the key areas of (i) raising awareness of suitable platforms and software, (ii) general approaches (e.g. data analysis, manipulation and modelling) to solve operational mapping challenges, as well as (iii) providing a mentored hands-on opportunity to apply these in an operational sense. The course notes are presented in Appendix 1. Future course requirements will be discussed by the NCST DSM advisory group, and may include training in geostatistics, soil sampling approaches, geomorphology, use of covariate data layers and data modelling approaches and software (e.g. regression kriging, decision trees, etc.).

6.1.2 ACLEP DSM collaborative projects

Two collaborative DSM projects have been supported by ACLEP over the 2010-12 financial years as a means of progressing national capacity development. The support given includes funds to facilitate DSM-specific tasks, mentorship and ultimately elevation of capacity in the participating state. Contracts are drawn up between ACLEP (though CSIRO) and the partner agency and payments are made on delivery of project milestones.

A project with the Tasmanian Department of Primary Industries, Parks, Water & Environment is now completed. A second project with the NT Department of Natural Resources, Environment the Arts and Sport is in the early stages. Both projects differ significantly, reflecting their diverse environmental, scale, data access and economic and capacity settings of different jurisdictions. This diversity makes these projects suitable for demonstration purposes and their outcomes to date are summarised below.

Tasmanian project

The ACLEP project collaboration fell within the larger Tasmanian "Wealth from Water Pilot Program". The objective of the Program is to identify suitable areas for high-value irrigated crops using a land suitability classification covering an area of 340,000 ha in the north and midland region of the state. Prior to full scale roll out, however, a sub-regional pilot project was conducted over 20,000 ha of the Meander East and West areas to refine irrigation suitability mapping protocols. The specific objectives of the pilot project were to:

- generate specific soil and climate maps for use in an irrigation suitability mapping framework, and
- develop an irrigation suitability mapping framework for a range of crops at a nominal scale of 1:50,000 equating to a 30 m grid size.

The irrigation suitability mapping framework relies on a number of DSM coverages as inputs. The following DSM sub-tasks were completed before it was possible to implement the irrigation suitability framework:

- compilation and collation of suitable environmental covariates;
- field survey design;
- spectrographic soil property predictions;
- generation of soil models and spatial soil property predictions; and
- validation of soil coverages

CSIRO scientists undertook the following DSM sub-tasks with funding support from ACLEP:

1. **In-filling gamma-radiometric coverage of the Meander West section.** Gamma-radiometrics is a valuable environmental covariate in DSM soil property prediction. However, there existed only partial coverage (15%) of the Meander West section, which is a low relief alluvial area featuring a seemingly intractable soil association. For this reason coverage by gamma-spectrometry was deemed all-the-more important and so methodology was developed to create "synthetic" coverage of the area. A transect-based survey was undertaken of the section using CSIRO's eRover multi-sensor surveying vehicle. The 600 m transects were based on random bearings at 15° increments emanating from a regular array of grid points (Figure 1). Radiometric coverages for Potassium %, and total count, Uranium and Thorium ppm were statistically modelled and predicted in the presence of the pre-existing covariates (e.g. terrain, geology, soil mapping, satellite imagery and land use and cover mapping) to yield an acceptable accuracy ($R^2 = 0.60$). A paper reporting this component has been submitted to a scientific journal and will be made available following publication.

2. **Spectral scanning using near- and mid-infrared (NIR/MIR).** The pilot project soil survey design yielded approximately 1,400 samples required for development of robust soil predictive models, so a comprehensive suite of physicochemical analyses via traditional methods was impractical due to budgetary constraints. Instead, low cost and rapid soil property predictions using NIR/MIR spectroscopy was chosen to predict a number of properties, including pH, EC, CEC, N, P, K and particle size. The spectrographic protocol applied a set of 280 soil samples (i.e. 20% of total) analysed using traditional methods to develop spectral calibrations to fit the local conditions. The quality of predictions ranged from good to poor, with particle size performing the best. The quality of the predictions is set to increase once a more comprehensive library of local spectra has been developed. This is now underway since the Tasmanian government purchased their own MIR spectrometer, which they operate under methods recommended by CSIRO.

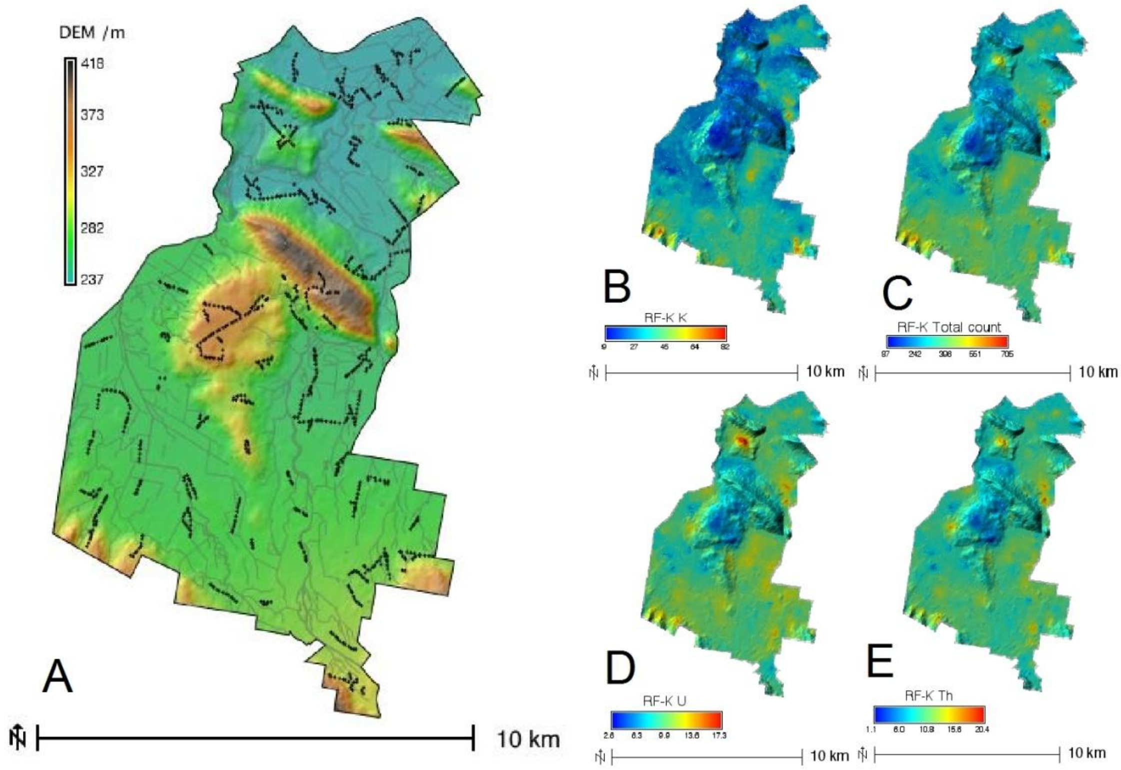

Figure 1 Meander West gamma-radiometric survey. (A) survey transects and gamma-spectral maps: (B) K%; (C) total count; (D) Uranium ppm; and (E) Thorium ppm.

ACLEP's contribution is discussed more fully in the report "*ACLEP-Tasmanian Digital Soil Mapping Project – (a component of the Wealth from Water Land Suitability Project)"* (Kidd et al., 2011), which is presented in Appendix 2. The key findings from the report emphasising the ACLEP contribution are as follows:

- It would not have been possible to adequately map some of the complex soil associations in the Meander West section had the "synthetic" gamma-radiometric coverage not been created. The project has successfully demonstrated the use of the eRover for DSM proximal sensing at a regional scale.

- Budgetary constraints meant that soil property analysis by spectrographic methods was the only viable option using the tailored analytical protocols developed during the ACLEP collaboration. These predictions were generally good to poor, and the quality is likely to improve during the course of the larger Program as the local spectral library grows. These calibrations will be added to the National Spectral Library.

- Spatial predictions through digital soil mapping, such as clay%, with an R-squared 0.73 and 0.57 for training and validation respectively, show that the available spatial covariates (including the newly acquired radiometric surfaces) are good predictors of certain soil properties to certain depths.

- The pilot project has achieved a high level of interest within Tasmania, and has been extended to another 50,000 ha within the Central Midlands and remaining Meander Irrigation Districts during 2012, for twenty enterprises. Subject to review and available funding, the project has the potential to map the remaining 300,000 ha of Tasmania's newly commissioned and proposed irrigation schemes, trialling new covariates and prediction techniques.

Northern Territory project

The NT project features a collaboration between CSIRO and the Department of Natural Resources, Environment the Arts and Sport. It will demonstrate a DSM methodology to map soil properties at a scale approximating 1:50,000 (i.e. 30 m grid size) in areas with, at best, 1:250,000 scale land system mapping. As with most of remote Australia, such areas are sparsely served in terms of soil observations, yet routinely covered by national datasets useable as environmental covariates, e.g. gamma radiometrics, 30 m SRTM DEM and remote sensing. The project's key challenge therefore, is to develop a methodology to create a suitable database of soil observations to model predictive soil maps using the routinely available national coverages. Part of this involves the use of a statistically representative distribution of soil sampling sites for creation of statistically robust models.

The study area comprises the Brunchilly Station (~431,000 ha) northeast of Tennant Creek. The Station occupies a transitional zone bordering the Barkly Tableland, and features a variety of soils including Vertosols, Rudosols and Dermosols. For operational expediency, the project work program will be conducted along with the Territory's on-going incremental soil survey and Statewide Land Cover and Trees Study (SLATS) ecological survey. Brunchilly's "Stud Paddock" (~6,500 ha) was selected as a focus area because the NT government wish to leverage the ACLEP support with a project underway in the paddock with the University of Queensland.

The following soil properties are to be predicted at approximately 1:50,000 scale:
- Carbon %;
- Clay %;
- pH; and
- bulk density.

The project will be conducted over the following five phases:
1. Data collation and soil sampling design;
2. Reconnaissance, including survey design evaluation;
3. Operational soil survey;
4. Soil analyses, featuring spectrographic predictions; and
5. Mapping soil properties.

At present, existing soil and covariate data collation is complete and a soil sampling design has been created and tested during a reconnaissance survey. The following sections outline progress and recommendations for project completion.

Data collation and sampling design
A selection of routinely available national coverages was accessed from both CSIRO and NT Government databases. So that the processing was optimised for the computation of the statistically-based survey design, the principal components of each were computed. The environmental covariates and the principal components used are listed below:
- SRTM DEM;
- 7-band Landsat Thematic Mapper remote sensing, PCAs 1-3;
- gamma-ray mapping; PCAs 1-3; and
- modelled spectra, PCAs 1-3.

The reconnaissance survey tested the viability of using the conditioned Latin hypercube sampling (cLHS) technique as a sampling design system in the remote conditions of the study area. The design comprised 40 sites with 10 sites inside the Stud Paddock and 30 outside (Figure 2 Brunchilly Station, showing wider Brunchilly candidate survey sites (circles) and Stud Paddock candidate sites (squares).

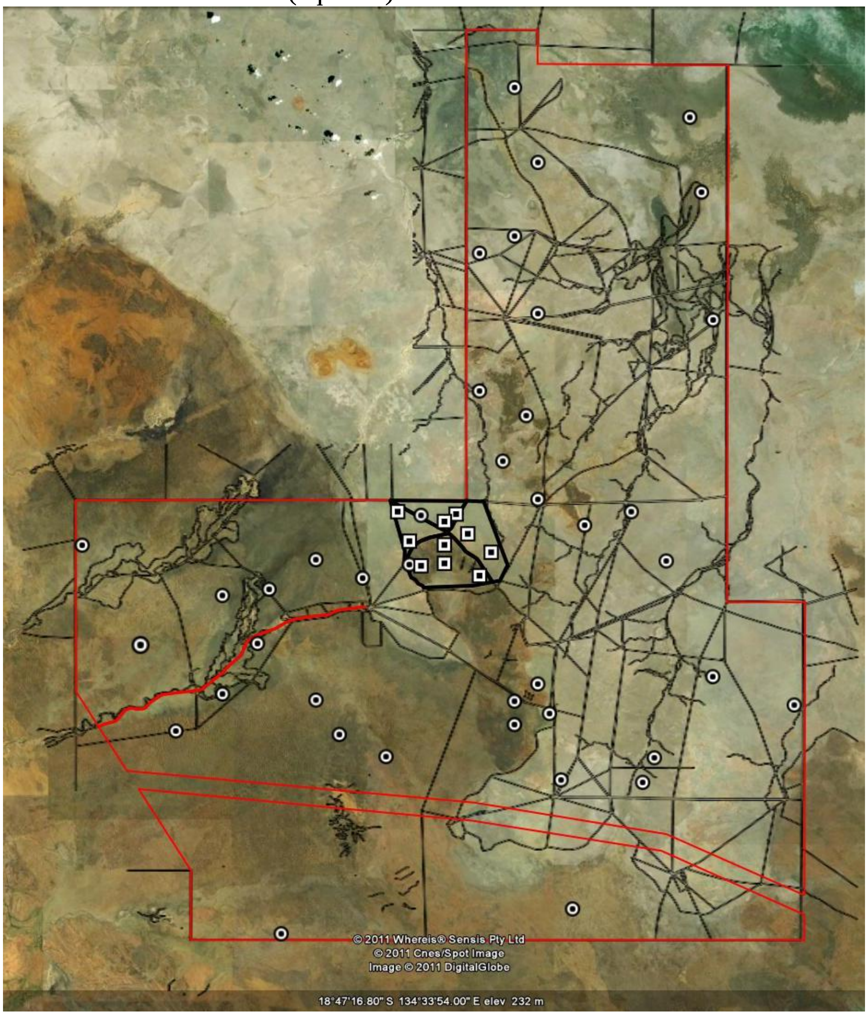

Figure 2 Brunchilly Station, showing wider Brunchilly candidate survey sites (circles) and Stud Paddock candidate sites (squares).

The sampling design also incorporated nested sampling along 100 m transects intersecting the cLHS sites. The logic of this approach was that the cLHS sites would account for the long range soil variability of the study area (i.e. the 30 sites: "seed sites", SS), whereas the nested sites would account for mid- and short-range variations. Sampling over the various ranges ensures that the soil predictive models would take into account the spatial structure of soil variability, and hence the development of more statistically robust estimates. In the field, at the seed site (SS1) the 100 m transect was aligned along a random bearing. Sampling sites were selected at random distances within pre-defined incremental distance ranges as follows (see Figure 3 Brunchilly sampling design, incorporating cLHS and nested sampling along a 100 m transect.

- S2: >0 - <10 m of SS1
- S3: >10 - <50 m of SS1
- S4: >50 - <100 m of SS1

The SS- can be "swapped" for another site (most likely S3) if the transect cannot extend far enough along the bearing, e.g. if the way is impenetrable. The weight of the mechanical corer meant it was necessary to get the vehicle to every sampling site, adding to difficulty of access.

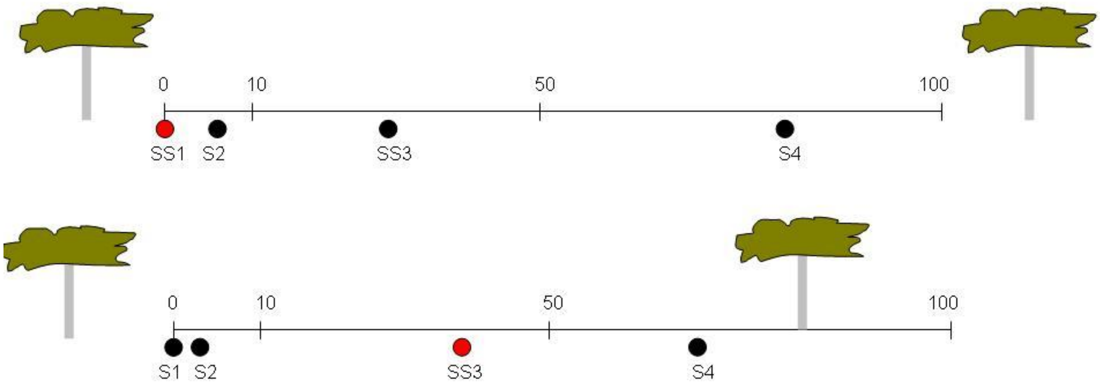

Figure 3 Brunchilly sampling design, incorporating cLHS and nested sampling along a 100 m transect.

Reconnaissance survey
Effort was put into devising a rapid system to retrieve samples for efficient sampling during the operational survey. An electric hammer-mounted push core system powered by petrol generator was evaluated during the reconnaissance (Figure 4 The electric hammer-mounted push corer evaluated during the reconnaissance.
. A number of 1 m corers of different diameters were tested: 28 mm; 32 mm, and; 48 mm. Cores were retrieved using a star-picket lifter, and the extruded core split into the following depth increments for subsequent laboratory analyses: 0 - 5; 5 - 10, 10 - 20, 20 – 30 and 90-100 mm.

Figure 4 The electric hammer-mounted push corer evaluated during the reconnaissance.

A 2-day reconnaissance survey was completed during August 2011. The outcomes (described below) form the basis of the proposed operational survey scheduled during the next NT field season (April 2013 - or soon afterwards). Ongoing commitment to this project will however be dependent on arrival of suitable field conditions, NT Government survey priorities and availability of skilled survey staff.

The key results and recommendations from the reconnaissance survey area summarised as follows:

- Four sampling transects were completed. The sites represented typical soils expected in the Brunchilly area, including: one Vertosol (“black soil”); two red Dermosols (“red soils”), and; one Rudosol (“dune soil”).
- The survey was slow-going due to challenging field conditions, particularly on the red Dermosols. Here it was necessary for slow, careful driving due to hard-to-penetrate thicket and the constant risk of tyre puncture. Careful consideration should be given to the use of solid tyres in these areas, albeit with the operational time-penalty of slow travel between transects, or otherwise the need for regular type changes.
- The 32 and 48 mm cores were the most effective for soil retrieval. The small volume retrieved by both, however, meant that it was necessary to take three cores to achieve sufficient sample for further analysis.
- Retrieval from the Vertosol was difficult due to hardness, so careful consideration is needed regarding timing the operational sampling of these soils (i.e. when soils are moist), otherwise a more powerful system for core retrieval and extrusion is required. Retrieval of the Dermosol and Rudosol samples were considerably easier, and it is estimated that once a routine is established a site can be completed within 30 minutes. This equates to 2 – 3 transects per day on Dermosols, 3 - 4 transects on Vertosols, and 2 – 4 on Rudosols.
- Notwithstanding the compelling statistically-based argument of using the cLHS design methodology in DSM, it has a tendency of making surveys difficult to implement in challenging environments, which has major operational implications. The issue lies with the inability for the surveyor to interact with the design and make changes on-the-run. This is an issue where survey points are impractical due to access or safety. The lack of surveyor-interactivity means that alternative sampling sites cannot be located in the field without prior knowledge of the implications to the statistical profile of the modified set of sample points. It will be important in the design of the operational survey to allow surveyor interaction.

6.2 Promoting DSM guidelines and standards

The need to develop a national consistency in DSM methodology has been identified as necessary by the NCST DSM Advisory Group. Accordingly, ACLEP has started to evaluate the need for a handbook outlining Australian DSM standards and methods. This would be a compendium to the present CSIRO series of Australian soil and land survey handbooks comprising the “Blue Book” (soil and land survey), the “Green Book” (soil chemical methods), the “Brown Book” (soil physical methods), the “Yellow Book” (soil and land description), and the “Red Book” (Australian Soil Classification). The edited DSM handbook – possibly the “Orange Book” – would contain content by Australian and international experts outlining the current state of DSM approaches, technologies and standards. The purpose of the publication would be to enable DSM practitioners - a community ranging from students to experts – providing a checklist of the current suite of techniques and data available, rationale for selection of the techniques, and output standards. The book would neither serve as a prescriptive menu of project steps, nor provide an overview of broad philosophical and technical approaches. Rather, it would span these to provide an operational reference outlining current options (and their rationale) that users will draw from in designing their project-specific methodological framework. A broad draft outline of content is presented in Table 1.

Table 1. Outline of Australian DSM standards and methods document (the "Orange Book"), a compendium to the series of Australian soil and landscape handbooks.

Section	Content and themes
Introduction	• DSM in the Australian context, issues and challenges • Statement of mapping purpose • Scale and thematic considerations • The DSM workflow

Data sources	• Legacy data
	  o Data custodians, formats
	• Collecting new data
	  o Sampling design
	  o What to sample, and depths
	  o Measuring soil properties using spectral methods
	  o Measuring soil landscape patterns using proximal sensors
	  o Data fusion

Environmental covariates	• Soil formation, the scorpan approach (McBratney et al., 2003)
	  o S, soil
	  o C, climate
	  o O, organisms
	  o R, relief
	  o P, parent material
	  o A, age
	  o N, location
	• Sources
	• Formats

Data preparation and exploration	• Formats, projections and conversions • Data exploration, query and evaluation

Soil models and spatial prediction	• Continuous soil properties
	  o Geostatistical
	  o Regression
	  o Data mining
	  o Hybrid approaches
	• Soil classes
	  o Generalised linear mixed modelling
	  o Logistic regressions
	  o Data mining (although this is a very general term)
	  o Expert systems
	  o Disaggregation, etc.

Understanding uncertainty and error	• Model uncertainty • Predictive uncertainty
Software	• Data management and evaluation • Modelling and predictive
Output and presentation	• Cartographic principles • Media
Developing and maintaining skills	• Links to online resources • Key publications • Registry of peers

Given that the rapid pace of change in DSM technology (hardware, software and knowhow) is likely to continue for the foreseeable future, a key issue for the Orange Book will be maintaining currency. An option is to publish versions online as an eBook with periodic updates as these occur. In the long-term new editions of the book will be published to reflect significant changes in approaches. Other publication media for sharing content in a user-friendly was may include YouTube-type presentations and PowerPoint presentations, which will be best suited to training content. The key benefit of using online media to serve the publication includes significantly lower publication costs so that the book could possibly be supplied free of charge or by low cost subscription. However, this option would make it necessary to fund the project on an on-going basis so that regular online versions capture changes in the “DSM state of play”, which are likely to continue rapidly - at least in the short-term. This would involve maintaining an expert committee to manage invited or volunteered content for inclusion in version releases.

7. MOVING FORWARD WITH DSM IN AUSTRALIA

There is a growing interest in the adoption of DSM methods within operational soil survey agencies throughout Australia. Unfortunately progress is hampered by a low skills and capacity base amongst most agencies. Added to this is a current lack of investment in primary soil data capture and collation, which is essential both as inputs to the modelling and mapping of soil characteristics and for validation of output products. A lack of temporally sensitive soil attribute data, such as is required for assessing current soil condition (for e.g. soil carbon stocks or soil acidification rates) and for monitoring and forecasting change due to land management and climate impacts, also needs to be addressed.

There is a need and opportunity for renewed investment in soil survey throughout Australia to support evidence based policy and land management decisions for a sustainable future. DSM provides a new technologically advanced and efficient methodology for developing the best estimates of soil characteristics across the nation. DSM is a valuable tool set which needs to be incorporated within a broader program of soil data development and delivery, including improved knowledge and understanding of key soil formation and impact processes, development of soil and environmental covariate input data sets, research and development of new and improved DSM techniques and tools, a reinvigorated soil survey program collecting primary field and laboratory data from key landscapes, and a national soil information infrastructure supporting management, discovery, access and use of the best available nationally consistent and comprehensive spatial and temporal soil data and information for all users.

7.1 Recommendations to support Australian DSM progress

Recommendations for progressing DSM presented in this report are twofold, including strengthening of current activities through ACLEP, and supporting new opportunities which would require significant investment through a reinvigorated and coordinated national soil program.

In the short term, ACLEP should:

- Continue to provide a national soil information infrastructure that supports the collation, and delivery of the best available digital soil and other landscape related data sets for Australia
- Complete collaborative DSM projects in Tasmania and the Northern Territory. Publish project reports and present results through national DSM workshops
- Support opportunities for development of new projects – e.g. in Qld, NSW, Vic-SA to further advance DSM operations across the country by creating collective national capacity, capabilities and skills
- Facilitate focussed training in DSM and support inter-jurisdictional working visits, following recommendations from the NCST DSM Advisory Group

- Promote DSM operations and opportunities at scientific meetings, e.g. ASSSI Soil Science Conference Hobart, and develop a set of brochures for wider communication of DSM approaches and benefits
- Develop a program of regular national DSM technical workshops. Opportunities should allow the sharing of lessons and experiences among DSM practitioners by using state-based projects as foci at these events.

A reinvigorated national soil program could progress the operational implementation of DSM and stimulate further scientific evolution by:

- Strategically reviewing the soil data and information needs of the nation, including data gaps
- Supporting a coordinated program of data collection, collation and DSM activity at appropriate resolutions identified by regional and national needs
- Engaging with the National Plan for Environmental Information (NPEI) to ensure that DSM data and products are aligned with emerging priorities and are recognised as a fundamental contribution to Australia’s environmental information infrastructure
- Fully supporting the ongoing delivery of a national soil information infrastructure which facilitates the collation, management, discovery, access and use of nationally consistent soil data and information products for all users
- Developing new nationally consistent environmental covariates, e.g. surface mineralogy, soil water coverages and regolith characterisations
- Accelerating “fundamental research” to advance new, cost-effective methods, e.g. spectrographic methods, proximal sensing, sample design, soil modelling/predictive methods, including for soil carbon, and responding to emerging scientific issues identified through State-based operational projects
- Growing the national soil archive and associated spectral library as key components of a national soil information infrastructure supporting operational DSM; and
- Providing an online repository of DSM tools, references and datasets and operational handbooks to guide the application of DSM methods.

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Appendix 1: Sydney University DSM training course notes

Digital Soil Mapping

Getting Operational

An introductory course of practical exercises for Digital Soil Mapping

February 2011

Note: submitted as separate document due to file size and formatting.

Appendix 2: ACLEP - Tasmania DSM project report

ACLEP-Tasmanian Digital Soil Mapping Project – (a component of the Wealth from Water Land Suitability Project). Darren Kidd and Raphael Viscarra Rossel 2012. Department of Primary Industries, Parks, Water & Environment, Hobart, Australia.

Note: submitted as separate document due to file size and formatting.

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