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Digital Soil Mapping: Application, Opportunity and Challenges

35

Digital Soil Mapping (DSM) has gained increasing traction and application across the globe in assessing and mapping the world's soil resource. There are now numerous scientifically published approaches and case-studies detailing how and why it is being used, its advantages, the diverse techniques, successes and comparisons to traditional/conventional soil mapping and pedology. This is especially true for Australia, where it has increasingly become part of the methodology used by federal, state and territory agencies to map soil and inform various land resource assessment activities, such as agricultural land suitability mapping, assessment of erosion potential and ecological modelling.

WHAT IS DSM?

DSM is a broad term, coined by Alex McBratney[1], for an approach that produces quantitative maps of soil attributes and soil types. It encompasses many scientific disciplines including pedology, predictive modelling, geostatistics, pedometrics, remote-sensing and GIS. DSM utilises the concepts described by Hans Jenny[2] in his work, "Factors of Soil Formation: A System of Quantitative Pedology", to build mathematical relationships between measured soil properties and environmental covariate data to

estimate the spatial distribution of soil properties. These spatial environmental covariate datasets typically include terrain derivatives (generated from digital elevation models), vegetation, geology, land-use, existing soil maps, proximal and remotely-sensed data; anything that might be related to a 'soil-forming-factor'. DSM can also involve disaggregating existing soil association maps. Disaggregation involves estimating the spatial distribution of the individual soil type components from the qualitative data contained in traditional soil association maps. DSM methods can also assist in generating statistically sound and unbiased soil sampling designs. More recently DSM has been utilised as the basis for comprehensive, quantitative Digital Soil Assessment (DSA).

DSM can produce quantitative, 3-D, gridded (pixelated) maps of soil attributes, with prediction uncertainty ranges. Whereas traditional mapping approaches typically produce categorical estimates of attribute values, DSM generated grids can represent the gradational spatial changes in soil attributes, and the uncertainty ranges can provide a confidence measure of the estimated attribute values. DSM has become more viable for use in recent times due to advances in computer-power, readily available GIS software, improvements in GPS accuracy, the broad availability of a range of remote-sensing platforms, and the rapid development in machine-learning technologies.

HISTORY AND DSM DRIVERS IN AUSTRALIA

Predictive spatial modelling techniques were first used in mineral exploration in the 1960s, and later applied to soil mapping in the 1970s and 1980s. These techniques were largely based on spatial interpolation techniques such as 'kriging'. Gradual improvement in mapping accuracy and validation were achieved when spatial correlation with a soil-forming factor was introduced, initially with one predictor variable, then more, until a full environmental correlation approach was being applied, using many explanatory variables.

As an example, in Australia around 1999, Neil McKenzie[3] from CSIRO tested a stratified soil sampling method with environmental correlation of geology, climate and landform to produce digital spatial prediction maps of various soil properties at 25m resolution. This produced promising results, explaining between 42 and 78% of the soil property variance, described as 'unmatched' by traditional mapping validation at the time. Many more DSM theoretical and methodological advances were made during and after this period across the globe. However, DSM, even up to and until about 2012 was still considered as largely an academic exercise; although things were gradually shifting.

Conventional soil survey and mapping had served its purpose well during the 20th century but demands on spatial soil information were shifting to soil-property specific requirements, with greater emphasis on quantitative solutions. The heads of National Soil Survey Organisations in a workshop in Enschede (Netherlands, 1992) identified that the requirements for soil information were shifting in this direction to inform sustainable development and environmental management. Zinck [4] warned that soil survey faced an uncertain future; soil survey agencies should embrace modern technologies to remain relevant and adequately funded. Basher [5] at the 1996 Australian-New Zealand Soil Science Conference in Melbourne postulated whether "pedology is dead and buried"? Basher noted the funding reductions in traditional pedological research and decline in trained soil scientists. Issues of temporal trends in soil properties and their distribution were also gaining momentum. Basher identified the emergence of computer-generated models and the need for traditional soil science to adopt these technological advances.

Through the early 2000s in Australia, a program of 'Enhanced Resource Assessment' (ERA) was being promoted through the Australian Collaborative Land Evaluation Program (ACLEP) and guided by the National Committee on Soil and Terrain (NCST); driven by recognition of a lack of technological uptake in Land Resource Assessment (LRA) in Australia (and elsewhere). One of ACLEP's chief objectives was to foster the effective use and uptake of new technologies, particularly; working in a gridded data environment, incorporating DEMs and derivatives, using digital datasets of soil-forming factors (such as gamma-radiometrics), improved data systems, GIS, GPS, and statistics. This coincided with dramatic development and advances in DSM methods, driven by the CSIRO and the University of Sydney through Alex McBratney.

From the early 2000s, a series of Global DSM and Pedometric Workshops were occurring biennially across the world, at first demonstrating examples of new DSM techniques, disaggregating legacy soil maps, comparisons of output diagnostics to traditionally-derived maps, and the shift in Agency-based soil survey (such as the USDA) to incorporate these new technologies. Later workshops started to address "bridging the gap" between research and operation (Sydney University, 2012). This uptake of applying DSM research to operation, in the form of government agency LRA, gained massive traction and transition from conventional to operational DSM in 2010, when Mike Grundy (CSIRO) secured funding to send several State, Territory and Federal soil scientists to the 3rd Global DSM Workshop in Rome, Italy, endorsed by the NCST, ACLEP, and the University of Sydney. For many of these soil scientists, this was their first exposure to DSM technologies. Many of the attendees realised the potential of DSM approaches to assist in addressing funding issues and the benefits of possible application of technological advances to conventional soil mapping, detailed in the report presented to the NCST "Recommendations for the Advancement of Digital Soil Assessment in Australia" [6]. This led to formation of the (currently active) Digital Soil Assessment Working Group (DSAWG) to advise and guide the NCST on the direction and uptake on DSM in Australia, and training of Agency staff in DSM techniques by The University of Sydney (through ACLEP). From this point, DSM has become an active Agency-based LRA discipline across the country, both as stand-alone and in integrated conventional soil-survey approaches.

SOME BRIEF AUSTRALIAN DSM EXAMPLES

As a result of this shared and collaborative learning over the last ten or so years, DSM has become an accepted part of the soil assessment toolkit. There are now many examples of DSM techniques being used to generate products to address a range of policy and development questions. This list is not exhaustive but indicative of the types of work being undertaken across Australia.

Perhaps the greatest example of collaborative DSM across Australia is the Soil and Landscape Grid of Australia (SLGA), funded by the National Collaborative Research Infrastructure Strategy (NCRIS) through the Terrestrial Ecosystem Research Network (TERN) to provide a new consistent and standardised continental soils information resource. Led by CSIRO (Mike Grundy), with guidance from the University of Sydney (Alex McBratney and Budiman Minasny), this work was a collaboration between Federal, State and Territory Agencies, to produce a suite of 3 arc-second resolution (approximately 90m) soil property maps of predicted values, with upper and lower prediction limits (uncertainties) at six standard depths. These products adhere to the GlobalSoilMap specifications and are Australia's contribution to the GlobalSoilMap effort. Figure 1 shows a website screen-shot of available clay % layers, at 3 arc-second resolution.

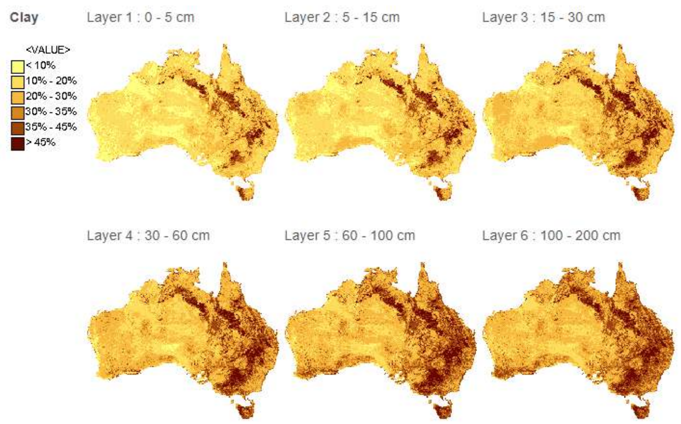


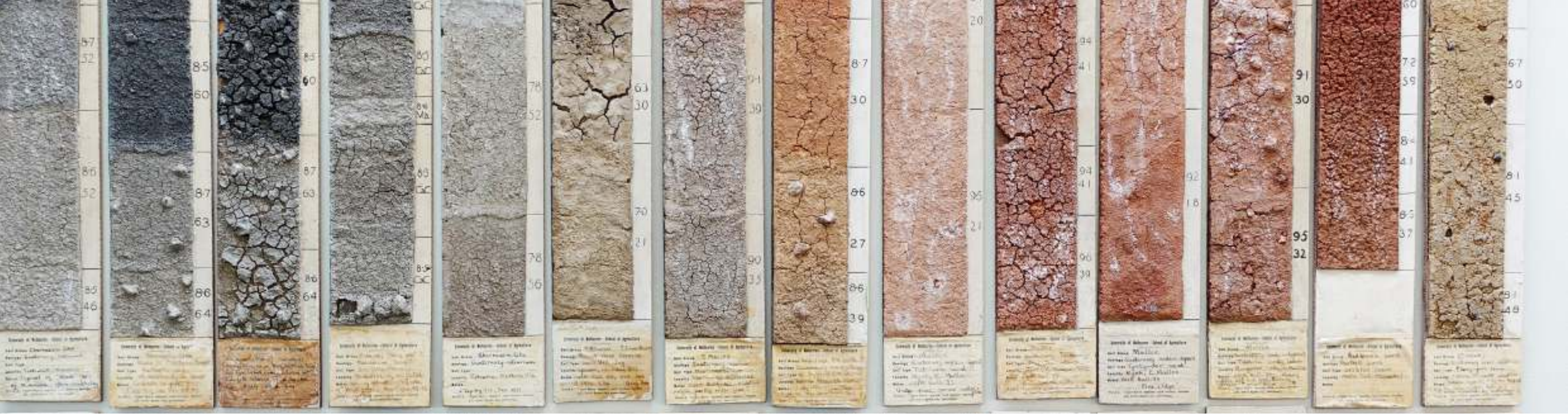
Figure 1 Soil and landscape Grid of Australia - Clay %

The products have been used for national ecosystem modelling, agricultural assessments and environmental reporting by a range of federal, state and local government agencies, as well as academic institutions and private consultants.

Other DSM example summaries from around Australia include;

CSIRO

- Northern Australia Water Resources Audit (NAWRA) digital land suitability assessment, 126 Land Use Types with attached suitability ratings and associated uncertainties
- Flinders and Gilbert Agricultural Resource Assessment
- Digital Australian Soil Classification Map of Australia.



Queensland

- Soil erodibility mapping for the 'Office of the Great Barrier Reef water quality science program' in the Fitzroy and Burdekin.
- Land Suitability Mapping in the Fitzroy and Burdekin catchments.
- Total N & P DSM and soil erodibility mapping using disaggregated soil maps for 'South East Queensland Water (SEQWATER)' in the Upper Brisbane Valley.
- Disaggregation of Legacy Soil Maps for soil constraint mapping in coastal areas
- Mapping land suitability for Biofuel crops throughout Queensland using DSM methods.
- Attribute modelling from legacy soil maps.

Northern Territory

- DSM for Land Suitability in the Roper Catchments, showing promising initial results.

Tasmania

- State-wide Enterprise Suitability Mapping for 36 crops at 30 m resolution using base DSM and digital climate modelling has been completed in 2018, upgrading previous 80m resolution mapping (and the Tasmanian Government's enterprise sustainability toolkit.
- Soil Vulnerability Mapping using DSM at 30 m resolution (soil erodibility, sodicity, salinity and waterlogging).
- Draft Australian Soil Classification Map of Tasmania using DSM at 80 m resolution.
- Draft Sol Security Mapping of Tasmania using DSM.

Victoria

- State-wide DSM as enhancements to the Soil and Landscape Grid of Australia.

South Australia

- DSM disaggregation, quality and purity assessment of polygonal SA soil maps, capturing prior expert knowledge.
- Remote-sensing for determining landscapes for soil health.
- DSM Soil Carbon mapping for the SLGA.

New South Wales

- Suite of new DSM surfaces published for NSW (100m res, SLGA specs) through OEH data portal, with eSPADE integration,
- Spatial predictions of NSW soil attribute changes under climate change.
- Modelling soil C fractions across NSW.
- State of Environment reporting – specifically decadal changes in soil C and pH (2005 – 2015).

Western Australia

- DSM soil attribute modelling, Northern region.
- DSM disaggregation for the SLGA.
- Sand Plain DSM
- DSM gravel extent, abundance and type spatial predictions, and implications to agriculture.
- New DSM work in the Pilbara for Land Suitability Assessment.

GLOBAL DSM EXAMPLES

Australia, through the University of Sydney and CSIRO, is a key player in developing DSM-based research and integration into operation, however, there are also numerous examples of DSM being actively used elsewhere in country-based, continental-based and global soil mapping. This is evident with the formation of a Digital Soil Mapping Working Group under the International Union of Soil Sciences (IUSS), and the GlobalSoilMap project. This project, through an international consortium, is developing accurate and up-to-date soil grids across the globe at 3 arc-second resolution for a suite of standard soil attributes and depths, in response to pressing needs such as global food and water security. Australia is part of the GlobalSoilMap Oceania Node. The previously mentioned SLGA form Australia's contribution to GlobalSoilMap, one of the first and most complete contributions to date. Other global examples include the world-wide 'Soil Grids' developed and hosted by ISRIC (International Soil Reference and Information Centre), as well as numerous country-based mapping efforts from France, the UK, the Netherlands, and the USA for a variety of purposes (too many to document here).

DSM VERSUS CONVENTIONAL MAPPING

A traditional soil surveyor frequently uses an environmental correlation approach to create soil maps, effectively predicting changes in soil types by relating observations made at a site to variations in landform patterns. This is done using expert landscape interpretations in the field, and by using a variety of existing underlying data sources that might help explain changes in soil formation, such as geology and vegetation maps, and aerial photo interpretation (API) to determine landscape patterns. Increasingly, remotely-sensed data such as elevation models are being used in conventional soil mapping to remove some of the inherent subjectivity. It is evident that much of the DSM undertaken is essentially using the same approach, interpolating changes in soil attributes (or types) between existing calibration sites using underlying explanatory data but quantifying the subjectivity through processes such as data-mining and machine-learning.

However, despite the published research and real-world examples demonstrating the success and benefits of DSM, even enhancements to traditional soil mapping, it is still met with resistance by some traditional soil scientists. Ahrens et al. [7] compared the introduction of API into conventional soil survey as a technological advancement in soil science, that was also met with resistance by soil scientists at the time, much the same way that DSM is still criticised in some facets of soil science. They acknowledged the potential of DSM, but a reluctance to adopt it stating "DSM has the potential to deliver the needed information and in fact may provide better and more accurate information. However, the technology of DSM must overcome the scepticism associated with any new technology in the traditional world of soil survey where new technologies have been few and far between" [7]. DSM is not seen as replacing conventional (and legacy) soil mapping, but as providing the capacity to enhance it.

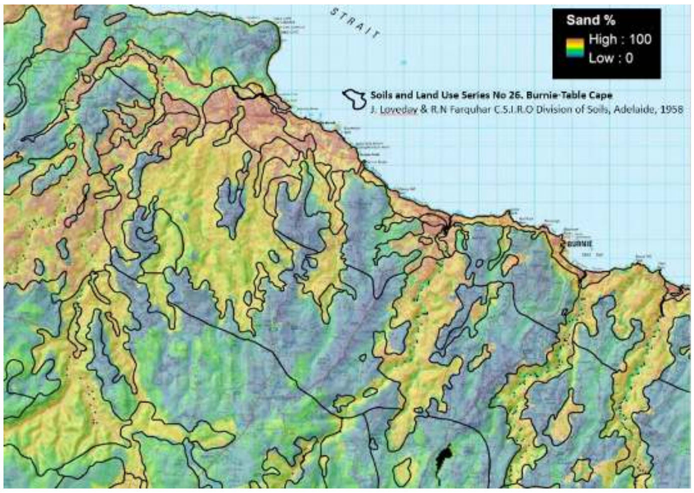


Figure 2 DSM Sand% near Burnie, Tasmania.

Using a Tasmanian example, it can be seen from Figure 1 that DSM for surface sand % at 80 m resolution spatially agrees with the legacy soil mapping (black polygon lines) undertaken by Loveday and Farquhar (CSIRO) in 1958 [8] at a scale of 1: 63,360, where minor soils were described as being 'in association' with the major soil types, but could not be physically mapped out. It does, however, show that we now have the capacity to identify the minor soil components and variations within soil types that was not previously possible at the scale or resources available to the surveyors at the time, e.g. available aerial imagery, allotted time, personnel and funding. It also highlights that Loveday and Farquar did a great job working with what they had!

FUTURE CHALLENGES OF DSM

As mentioned, there are numerous examples of DSM now being used around the world. As with any scientific discipline, there are always challenges to overcome that will improve the development and application of DSM further into the future. These include;

- Obtaining good quality observed soil attribute data. Just as in traditional approaches, access to relevant observed soils data is key to producing useful products. The continued funding of ongoing field and laboratory data collection is a challenge for the entire soils community.
- Validation of those mapped areas that have been extrapolated from sparse input data
- Obtaining good quality, fine resolution spatial explanatory data – DEMs, radiometrics, multi and hyper-spectral remotely sensed data
- Ensuring DSM practitioners have good pedological training and landscape understanding. Being able to provide enough

resources (personnel) to ensure realistic products are being produced and evaluated by soil experts

- Capturing soil expert-knowledge and geomorphic processes into the DSM modelling
- Continued demonstration of the efficacy and utility of DSM and integrated approaches for addressing policy and development questions
- Adequate processing power, data storage and delivery systems – some DSM datasets are becoming huge depending on area size and resolution
- Testing Global vs Local variations, and capturing this within the modelling process chosen
- Removing artefacts due to modelling method and underlying spatial variables – i.e. making realistic maps
- Making more easily understood and better use of DSM uncertainties in final products, as a measure of confidence
- Ensuring that statistical DSM sampling designs have the flexibility to allow soil scientists to develop morphological understanding of the inherent soil forming processes in the field, which is important in validating final products (not just statistical validation, but validation in terms of 'real-world' soil patterns).

WHERE TO NEXT – THE FUTURE OF DSM

To date, DSM has produced fine resolution LRA and associated products, typically focussing on continuous soil attributes rather than soil types. DSM has also incorporated uncertainties (as a measure of confidence and probability) into map products and produced raster-based outputs that can represent the gradual changes of soil properties within landscapes (as opposed to crisp polygon boundaries), i.e. "prettier" maps. Some recent DSM projects have also been reasonably high-profile, enabling and reinvigorating funding and collection of new soil site information that had been gradually declining over past decades. DSM continues to evolve, with present development heading into some exciting directions;

- Dynamic modelling, producing new products 'on-the-fly' as new calibration and landscape data is collected
- Better resolution and diagnostics through improved explanatory data (such as Sentinel Satellite data), proximal soil sensing, digital soil morphometrics and modelling processes
- Incorporating DSM into biophysical modelling to make it 'spatial', such as APSIM.
- Spatial and Temporal Assessment of Soil Security

CONCLUSIONS

Both traditional soil mapping and DSM systematically use an environmental-correlation approach. The former is more subjective, but uses soil expert knowledge, the latter more quantitative and repeatable. If the DSM practitioner is a soil science expert, (or works closely with soil experts), the advantages of both disciplines can be realised. The challenge and future of DSM is in building close working relationships between expert pedologists and DSM practitioners. DSM is here to stay in agency-based land resource assessment. The future is in making a concerted effort to understand the technology, collaborating in DSM-based projects, and embracing it as a powerful tool to enlist for producing the highest-quality soil maps possible; maps that are 'fit for purpose', which help secure and promote appropriate and better use of our soil resources; a goal that traditional pedologists and pedometricians are both striving to achieve. It is also up to the pedometricians to ensure that soil scientist's knowledge and skill is effectively utilised and captured into components and final evaluation of DSM outputs

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