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Operationalising digital soil mapping – Lessons from Australia

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ABSTRACT

Australia has advanced the science and application of Digital Soil Mapping (DSM). Over the past decade, DSM in Australia has evolved from being purely research focused to become 'operational', where it is embedded into many soil-agency land resource assessment programs around the country. This has resulted from a series of 'drivers', such as an increased need for better quality and more complete soil information, and 'enablers', such as existing soil information systems, covariate development, serendipitous project funding, collaborations, and Australian DSM 'champions'. However, these accomplishments were not met without some barriers along the way, such as a need to demonstrate and prove the science to the soil science community, and rapidly enable the various soil agencies' capacity to implement DSM. The long history of soil mapping in Australia has influenced the evolution and culmination of the operational DSM procedures, products and infrastructure in widespread use today, which is highlighted by several recent and significant Australian operational DSM case-studies at various extents. A set of operational DSM 'workflows' and 'lessons learnt' have also emerged from Australian DSM applications, which may provide some useful information and templates for other countries hoping to fast-track their own operational DSM capacity. However, some persistent themes were identified, such as applicable scale, and communicating uncertainty and map quality to end-users, which will need further development to progress operational DSM.

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Contents

1. Introduction

Digital soil mapping (DSM) has gained increasing traction and application in assessing and mapping the world's soil resource. There are now many published scientific approaches and case-studies detailing how and why it is being used, the techniques applied, their advantages and disadvantages in operationalisation, successes, and comparisons to traditional/conventional soil mapping and pedology. Over the past decade, DSM has moved from academic-based research into operational mapping of soil physical, chemical, biological properties and soil types at various spatial resolutions and extents. The realisation of DSM as a practical, cost-effective operational approach has been a result of the confluence of ideas and technologies over time, combining aspects of pedology with mathematical approaches and honing these through experimentation and projects. In Australia, DSM is now an accepted and practiced methodology used by federal, state and territory agencies to map soil and inform various land resource assessment activities. These activities include agricultural land suitability mapping, assessment of erosion, potential and ecological modelling at scales from individual fields and farms through to districts, catchments, states and the entire continent. There is now an active DSM community-based in Australia (https://aussoilsdsm.esoil.io/) applying operational DSM for various uses, benefiting from long-term collaboration between state and federal agencies and universities in knowledge and resource-sharing.

DSM operationalisation in Australia has been driven by a lack of adequate land resource assessment mapping to meet 'end-users' increasing and diverse soil information needs. A set of key drivers, enablers, and barriers have shaped the pathway to operationalisation in Australia. These include;

Drivers

- Sparse and incomplete soil data across vast extents of the continent.
- A general decline in government investment in strategic soil mapping activities.
- Continually increasing demand for high-quality soils information driven by biophysical modelling technology.

Enablers

- Development and implementation of standardised soil data collection and distribution formats.
- The advent of many new remotely sensed data streams creating easily accessible sets of spatially extensive environmental covariates, particularly those relevant to soil forming processes (e.g. gamma radiometrics and digital elevation model (DEM) derivatives).
- Increasing availability of relevant open source analytical software and increases in computing power.
- Ad hoc but timely funding opportunities providing ability for training and national capability development.
- Collaboration and cooperation between DSM practitioners in sharing of experiences and software coding amongst the community.
- Numerous 'champions' and organisations willing to support and promote the development and application of DSM.

Barriers

- A need to overcome resistance to and demonstrate the science behind DSM to the traditional pedological community.
- A need to develop and maintain capacity amongst government agency soil scientists.

The intentions of this paper are to provide a summary of the evolution to operational DSM in Australia and the key factors that led to the successful implementation for the nation. We present a historical account of what led to the implementation of DSM in Australia including the principal drivers and enablers. Operational DSM case studies are also presented to illustrate lessons learned in their development. Finally, we will touch on the impact of DSM mobilisation in Australia (see Grundy et al., 2020, this issue for further details) and the future prognosis for continued operationalisation to meet growing demands (see Searle et al., 2020, for further details).

1.1. DSM overview and definitions

DSM is a broad term, coined by Alex McBratney et al. (2003), for approaches that produce quantitative maps of soil properties and soil types. As a pedometric approach, it encompasses many scientific disciplines including pedology, predictive modelling, geostatistics, remote-sensing and Geographic Information systems (GIS). DSM utilises the concepts described by Hans Jenny (1941) in his work, "Factors of Soil Formation: A System of Quantitative Pedology" to build mathematical relationships between measured or described soil properties and environmental covariate data to predict the spatial distribution of soil properties or types. These spatial environmental covariate datasets typically include terrain derivatives (generated from a DEM), vegetation, geology, land-use, climate, existing soil maps, proximal and remotely-sensed data and anything that might be related to a 'soil-forming-factor'. DSM can also involve disaggregating conventional (legacy) soil maps through estimating the spatial distribution of the individual soil type components from the qualitative data contained in traditional soil maps, (e.g. DSMART, Odgers et al., 2014). DSM methods can also assist in generating statistically sound and unbiased soil sampling designs. More recently, DSM has been applied as the basis for comprehensive, quantitative digital soil assessment (DSA), i.e. application and interpretation of DSM (Carré et al., 2007).

DSM can produce quantitative, 2.5-D and 3-D, gridded maps of soil attributes, with a prediction uncertainty interval. Whereas traditional mapping approaches typically produce categorical estimates of soil property values, DSM generated grids can represent the gradational spatial changes in soil attributes, and uncertainty ranges can provide a confidence measure of the estimated attribute values. DSM has become more viable 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 with extensive time-series datasets; evolving time series analysis techniques; and the rapid development in machine-learning technologies (Minasny and McBratney, 2015).

1.2. 'Operational' DSM

Functional, practical, ready, usable, viable, working; these are some of the adjectives that describe the term 'operational', which is usually applied in relation to an activity, or in the context of something that is working. In soil science, specifically DSM, it has become a popular term pertaining to the 'real world' application of DSM to practical situations, something that is tangible, with products provided to a community who have the potential to use and apply these outputs. Operational DSM can also mean user-demanded and repeatable, creating spatial layers that can be applied using an analytical framework (e.g. land suitability), where decisions can be made, and a change on the land can occur; i.e. DSA. It can also mean operational in terms of large area application, and repeatable systems that can be applied to new areas. Finally, when the technology is adopted and used by organisations that oversee the collection and provision of soil policy and land resource mapping, (usually state and federal Government within Australia), the science is considered to have become 'operational'.

1.3. History, DSM drivers and enablers in Australia

1.3.1. History of land and soil survey in Australia

Australia is a vast and sparsely populated landmass, and as a nation, collecting enough data to understand and document the distribution of its soil resource has always been a challenge. Traditional soil mapping has served historical land development needs well. With hindsight, however, it was unrealistic to believe that enough resources would ever be available to fully map the country in its entirety at a scale fine enough to be useful in development and conservation decisions. Over the years, soil mapping practitioners have developed qualitative approaches to address these limitations, such as land system and soil association mapping.

Land inventories and soil surveys have occurred in Australia for over 170 years, with technical reports first published in 1845 describing New South Wales and Van Diemen's Land (Tasmanian) soils (Strzelecki, 1845). Primarily identifying suitable agricultural land for vegetation clearing and expansion, the first regional surveys were undertaken by Jensen (1914) in New South Wales. The Australian Constitution left land management to be administered individually by the states. Over time, this led to the development of state-specific soil survey practices across the country, resulting in disparate data sets and mapping by different state government agencies with different priorities. Around the end of the second world war in 1943, general and special-purpose surveys were undertaken for farm planning and layout of research stations, land suitability for various irrigated crops, and small-scale ecosystem surveys with a conservation emphasis, e.g. reducing erosion and edaphic needs. Wartime developments such as aerial photography were being used in land survey by CSIRO Division of Soils, including land systems surveys to enable rapid mapping of vast areas, used extensively in northern Australia. The CSIRO delivered much of Australia's soil survey between 1940 and 1967, comprising 1:63,360 scale soil mapping, reports, site descriptions, and analytical samples (Lee, 1998).

However, the merits of soil mapping and its usefulness to meet general purpose requirements of land managers were being questioned as early as the 1950s by Butler (1958) and Leeper (1956). Their major concerns were that the prioritization of soil classification and genetic origins had negated the mapping of properties and soil attributes that were relevant to contemporary land management. While general purpose maps had proved an effective approach for introducing soil information to users 'quickly and efficiently', there was a greater demand for detailed information that addressed specific land use recommendations. Following reviews led by Becket and Brie (1978), Hallsworth (1978), and Olson (1973), changes in soil mapping practices included the delivery of specific purpose soil maps with requirements for soil and land properties used in classification systems, e.g. land capability assessment.

The advent of numerical taxonomy and quantitative ecology (led by CSIRO) in the 1960s were used in the application of multivariate analysis to understand the spatial variation of soils in the field (Lee, 1998). Philip Beckett and Richard Webster (as visiting scientists from the United Kingdom) were to play key roles in further exploring the concept of spatial variability during stays in Australia in the 1970s, publishing works on soil variance at scales from within paddock (Ginninderra: Webster and Butler, 1976) to reconnaissance levels (Beckett and Bie, 1976). New survey techniques, including the use of geostatistics in the 1980s and 1990s to model spatial variability and map soils, was driven by the widespread adoption of computer technology and GIS, DEM and terrain analysis, and remote sensing (Bui et al., 2006). Pedometric developments in Australia at that time were focused on so-called environmental correlation methodologies, including works by Gessler et al. (1995), McKenzie and Austin (1993), McKenzie and Ryan (1999), and Odeh et al. (1994). Alex McBratney brought ideas formed in his doctoral studies (McBratney 1984) and further developed concepts on spatial variability (with Richard Webster) and the application of geostatistics for mapping of soil properties (e.g. Mcbratney and Webster, 1986). This period represents the beginnings of pedometrics and DSM in Australia.

DSM was the logical next step in the pursuit of more detailed soils understanding in the most efficient manner. Conventional soil survey and mapping continued into the 21st century, but user demands for soil information were shifting to more spatially explicit representations (including grid/raster data for modelling) and more functional 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 (1995) warned that soil survey faced an uncertain future; soil survey agencies should embrace modern technologies to remain relevant and adequately funded. Basher (1997) 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.

1.3.2. National soil mapping efforts

For over 80 years, national collaborative efforts in soil mapping focused on soil classification and distinguishing soils of like character (zones) (Prescott, 1931; Stephens, 1953; Stace et al., 1968), while Northcote (1960–1968) was responsible for leading a national mapping exercise (The Atlas of Australian Soils: 1:2,000,000) to provide a consistent national description of Australia's soils. Subsequent to this national mapping exercise, no nationally coordinated or consistent soil infrastructure was further developed to progress the on-going collection of detailed soil information across the entire nation. In the late 1980s, lobbying from the Australian Conservation Foundation and the National Farmers Federation proposed a "Decade of Landcare" in which community action would raise awareness and catalyse investment to repair and nurture the land (Curtis and De Lacy, 1998). This led to a large national funding program focussed on improving land management (Salt, 2016). This precipitated a new and concerted effort to harmonise approaches in soil survey and data collection in Australia, leading to the formation of the Australian Collaborative Land Evaluation Program (ACLEP), led by CSIRO in partnership with the states and territories. Agreed standards and guidelines were developed for soil survey (McKenzie et al., 2008a, 2008b), soil description (NCST, 2009), soil classification (Isbell, 2002), soil analytical methods (Rayment and Lyons, 2011) and soil physical measurements (McKenzie et al., 2002). Through the early 2000s, a program of 'Enhanced Resource Assessment' (ERA) (Grundy, 2001) was developed and promoted through ACLEP and guided by the National Committee on Soil and Terrain (NCST) (https://www.soilscienceaustralia.org.au/about/ncst/); driven by recognition of a lack of technological uptake in Land Resource Assessment 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 spatial GIS environmental covariates representative of soil-forming factors, improved data systems, GPS, and statistics. This coincided with dramatic development and advances in DSM methods, driven by the University of Sydney and CSIRO. While this increasing collaboration across Australian soil agencies and the University of Sydney was driving the development of operational DSM, the funding opportunities, harmonised datasets and infrastructure created through ACLEP were also enabling operational DSM.

The evolution of operational DSM and DSA in Australia has progressed to its current position through a series of 'drivers' (e.g. increasing demand for gridded, quantitative soil products, and demand for broader area soils information, and finally, lack of funding of conventional soil survey leading to the need for alternative methodologies), and 'enablers' (the technological developments, tools, and infrastructure development that supported large-area DSM to progress). Australia has a strong history developing DSM methods, often with a focus on how these may be applied in the operational context.

1.3.3. Pioneering DSM 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, Odeh et al. (1995) combined geostatistics and multivariate linear regression modelling for the prediction of soil properties in the Mt. Lofty ranges in South Australia using landform attributes, in what they called 'regression kriging'. In 1999, McKenzie and Ryan 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 25 m resolution. This pioneering DSM example produced promising results, explaining between 42 and 78% of the soil property variance, described as 'unmatched' by traditional mapping validation at the time. McBratney et al. (2000) outlined "modern regression techniques" such as neural networks and regression trees and the use of ancillary variables (covariates). They identified this "hybrid *clorpt* with geostatistics" technique as a powerful method for spatial prediction. Later, Henderson et al. (2005) successfully demonstrated the Australia-wide prediction of soil properties using Cubist (Quinlan

2015), a regression tree approach which is now termed 'machine learning'. Many more DSM theoretical and methodological advances were made during and after this period across the globe. However, DSM, even up to around 2012 was still considered as largely an academic/experimental exercise, although things were gradually shifting towards enabling operational DSM.

1.4. DSM drivers in Australia

1.4.1. Increasing demand for gridded, quantitative soil products

Conventionally, many land custodians and managers use soil data and information in their decisions on agricultural production, conservation and infrastructure development. The demand for spatial soil information continues to grow with the demands for land to deliver many competing ecosystem services. A shift from soil class assignment using qualitative techniques to mapping of soil properties that support the implementation of simulation models has ensued in response to this need for quantification and uncertainty estimation. The nexus of increasing technological developments leading to higher precision decisions on soil and land-use, combined with a suite of new spatial decision support tools and models, has fostered the demand for high-resolution spatial soil information at national to regional scales. Climate and carbon models (Amundson et al., 2015), as an example, operate at national through to global scales, requiring quantitative soil mapping to embed into scale-specific mechanistic modelling algorithms. Higher-resolution and quality-controlled soil information are needed by biophysical modellers to refine, develop and run simulation and process models to address questions on production constraints and environmental impacts (e.g. rainfall, physical or chemical soil limitations or variety suitability). The use of DSM has tended to focus on the needs of traditional users, such as farmers, agricultural consultants, natural resource management groups, and government decision-makers. But there is a considerably broader user market that is unaware of, or not exposed to this information yet (Wilson and Thomas, 2012), which presents future opportunities for DSM practitioners, and motivation for this community to be agile in response to delivering custom digital soils information that squarely meet the specifications of the end-users.

1.4.2. Demand for broader area soils information

Legacy soil maps have typically been created for specific purposes at a point in time, which has led to mapping that is inconsistent across scales for much of Australia. There have been concerted efforts to produce contiguous and correlated soil mapping for some regions (e.g. agricultural zones of South Australia and Western Australia). There was also a large effort to create nationally consistent legacy mapping under the Australian Soil and Land Resource Information System (ASRIS) (McKenzie et al., 2008a, 2008b) (McKenzie and Jacquier, 2004), but, due in part to extensive qualitative inputs, it lacked the consistency and spatial resolution for reliable national soil reporting or incorporation into modern soil or environmental models.

The National Soil Research, Development and Extension Strategy (https://www.agriculture.gov.au/ag-farm-food/natural-resources/soils/national_soil_rd_and_e_strategy) identified that improvements to soil information, including maps of functional soil properties at appropriate resolutions, were required. These maps would underpin assessments of monitoring change across Australia's 'soilscapes', linking of land use and management with changes and the ability to forecast condition. Furthermore, broader coverage ensures that all Australian biomes are mapped with soil attributes in a contiguous and correlated manner (Grundy et al., 2015). Demand for broad area and detailed soil mapping at regional, state/territory or national scales is implicit in the higher resolution demands of models and decision support tools (e.g. climate change forecasts, land capability assessment, agricultural management).

1.4.3. Lack of funding of soil survey leading to the need for alternative methodologies

Historically, well-funded and supported programs in land resource assessment and soil mapping have occurred in Australia. This translated into a vast array of soil maps being produced, but the momentum stalled as these maps were now either considered too expensive to produce, or of lower benefit than other institutional priorities. Economic liberalisation policies and short-term funding programmes (Lobry de Bruyn and Andrews, 2016) has resulted in a decline in new soil survey and the decay of existing pedological expertise within these institutions (Robinson et al., 2019). Fig. 1 from Biggs et al. (2018) shows the number of profile data sets collected every year since 1956. The intensity of data collection mirrors the levels of strategic investment in soil mapping.

Consequently, and due to the increasing demand for quantitative higher-resolution soil products, DSM provides an expedient and valuable approach that exploits the wealth of available and accessible spatial environmental data correlated with soil properties to use in spatial prediction models. New technologies combined with improved efficiencies in computing are vital benefits of DSM that were identified as aspirational goals by Gibbons (1961) and Butler (1963).

1.5. DSM enablers in Australia

1.5.1. Covariates development

An expedient component of the progression of operational DSM in Australia has been the development and availability of useful DSM covariates, i.e. '*scorpan*' soil-forming factors (McBratney et al., 2003). Australian science and resource management agencies had adopted enhanced remote sensing approaches to managing a large and sparsely populated country. Particularly, mineral exploration required both innovation in geophysical methods by mining companies, state and national geological agencies and innovation in coordination, e.g. the National Geoscience Mapping accord (Commonwealth of Australia, 1989). Terrain models were originally generated through digitization of large topographic data sets using software such as ANUDEM (Hutchinson, 1988), then soft photogrammetry (AUSLIG, (Tickle et al., 2015)), and later from space and airborne remote-sensing produced DEM, such as the SRTM-DEM (Gallant et al., 2011), enabling the development of useful terrain derivatives. Climate grids used for meteorological applications and crop modelling were also becoming increasingly available and reliable (Queensland Government, 2019a). Vegetation and multi-spectral remote sensing developments from the visible spectrum through to microwave (radar) were also becoming available, much of this initially developed for the surveillance of land clearing. Geoscience Australia was also collecting airborne gamma-ray spectrometry, initially used to detect surface anomalies indicating uranium and other ore bodies, but also for identifying geological units and assisting geological mapping, and later in soil geomorphology (Cook et al., 1996). Acquisition and compilation of national geoscientific data through activities of Geoscience Australia as part of the National Geoscience Mapping Accord provided several key thematic layers that were critical for later regional and national scale DSM. These included the Radiometric Map of Australia (Minty et al., 2009) which combined all the individual radiometric surveys into one national coverage showing the spatial distribution of potassium, thorium and uranium radioactive isotopes. Total gamma count was also derived, as well as the 1:1million surface geology map of the Australian continent (Raymond, 2012). More recently, Roberts et al. (2019) compiled Landsat images from the past 30 years to create bare-earth images of Australia.

1.5.2. Soil information systems

Australia benefited from the early development and adoption of soil data systems, initially WARIS (Rosenthal et al., 1986) and then ASRIS/SITES (Peluso and McDonald, 1995). This enabled data transfer standards between disparate state systems, eventually superseded by open data standards (e.g. OzSoilML (Simons et al., 2012), and

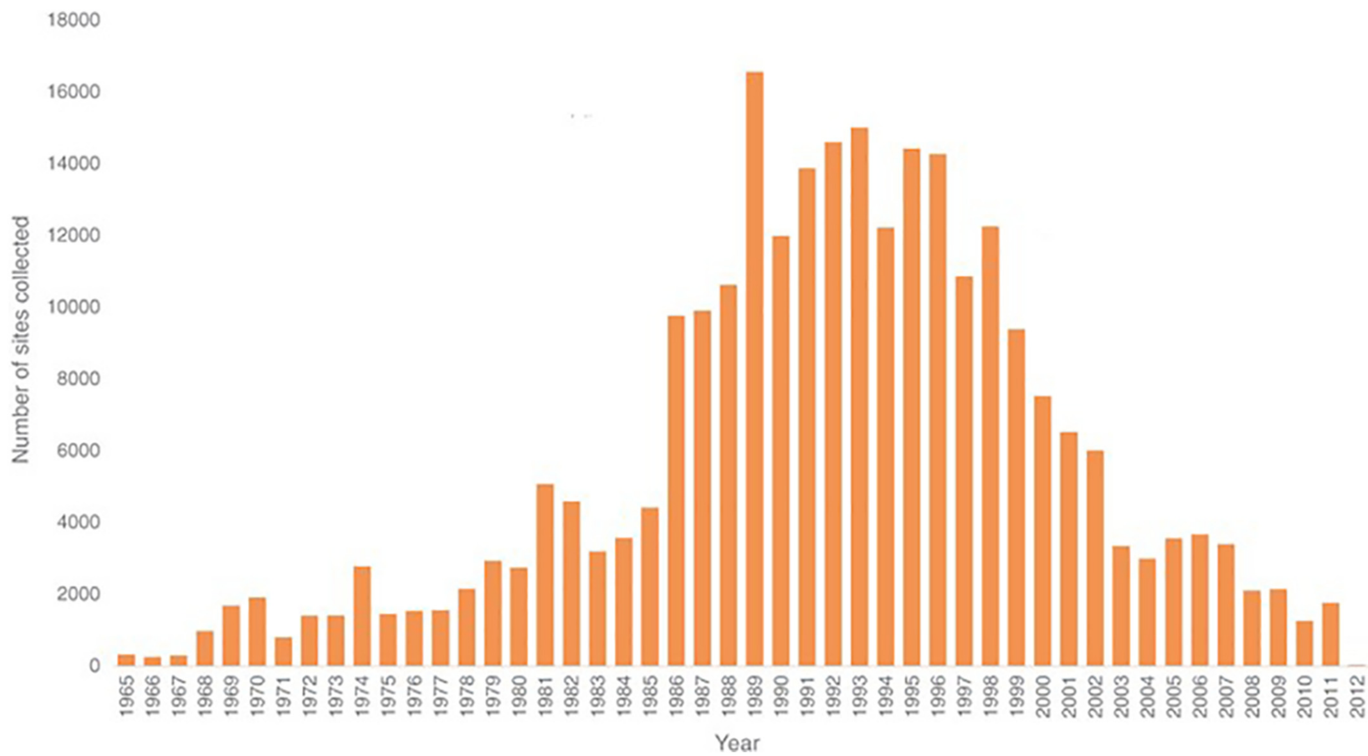

Fig. 1. Number of soil profile descriptions collected in Australia per year.

ANZSOILML (Simons et al., 2013)). These systems ensured that Australian soil site data was in a consistent and queryable format, enabling DSM calibration site data harmonisation from state and national sources. Without these systems, there would have been a significant delay in DSM development around Australia.

1.5.3. Funding background

Although significant, consistent, long-term strategic funding for soil mapping has all but disappeared in recent decades, there is still a strong demand from a broad stakeholder group for soils information to inform regional developments and environmental policy. Major projects such as Great Barrier Reef water quality modelling, land suitability assessments in northern Australia and the development of precision agriculture, along with other purpose specific projects (see Operational DSM Case Studies) have allowed the Australian soil science community to retain and develop a reasonable technical capacity. By working as a community and pooling resources, DSM practitioners have been able to leverage these smaller scale funding resources to continue to operationalise DSM in Australia. Consequently, DSM has become part of land resource assessment decision-support and associated policy, with datasets having direct legal and environmental consequences.

1.6. Operational DSM progression in Australia through linked drivers and enablers

At the confluence of emerging spatial data streams and technologies to produce DSM products at large extents, there was an equal need to have human capacity and expertise across Australia to deliver soil mapping outputs that leveraged these technologies. From the early 2000s, a series of Global DSM and Pedometrics Workshops, organised within the Commission and Working Group systems of the International Union of Soil Sciences (IUSS), were occurring biennially across the world. At first these meetings provided a forum to showcase new DSM techniques, methods for disaggregating legacy soil maps, and illustrating comparisons of output diagnostics to traditionally-derived maps, and the shift in Agency-based soil survey to incorporate these new technologies. Later workshops started to address "bridging the gap" between research and operation (Boettinger et al., 2010) and moving into and beyond DSA, (Minasny et al., 2012). This uptake of applying DSM research to operational situations, in the form of government agency land resource assessment (LRA), gained massive traction and transition from conventional soil mapping 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, it 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 the 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", (Robinson et al., 2010). This led to the formation of the Digital Soil Assessment Working Group (DSAWG) to advise and guide the NCST on the direction and uptake of DSM methodologies in Australia. An initial recommendation of this group was for the provision of training for practicing soil scientists in DSM techniques to be run by the university of Sydney. 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.

The first national DSM training workshop was held in 2011 where more than 20 soil survey practitioners from soil mapping agencies across Australia converged upon Sydney University for a 3-day workshop covering the practical components of DSM. This included soil data analysis, harmonisation of soil profile data with mass preserving splines, working with such data in a GIS through to processing and harmonising environmental covariates, and ultimately fitting soil spatial prediction functions and spatially applying these to generate maps. A follow-up workshop was held in 2013 (again at the University of Sydney) that built upon lessons learned from the first workshop. This workshop included around 20 attendees, many from the 2011 workshop, and focused on delivering the DSM practical teachings exclusively with 'R' computing software (Malone et al., 2017). The workshops formalised a method for operationalisation, with training designed by the University of Sydney in collaboration with CSIRO. These have been held approximately every two years, frequently at the University of Sydney, but also in other locations such as Darwin in 2016 (with again around 20 attendees). A range of skills were taught at these courses accompanied by detailed notes and supporting data. Practical examples were worked through, usually using data from the participant's local area. These training courses resulted in the publication "Using R for Digital Soil Mapping" (Malone et al., 2017). In total, around 30 attendees participated in one or all of the 3 workshops. Of these, around 12 of the participants were directly involved in the Australian operational DSM case-studies summarised in Section 2 of this paper and the supplementary DSM inventory.

An important enabler in the success of operational DSM in Australia has been the development of a strong community of practice fostered by the DSAWG. Through joint participation in training activities, conferences, workshops, and collaborative projects, a community of core practitioners has emerged. The strong collaborative nature of this group has facilitated skills development, helped in overcoming technical problems, the progression of improved techniques, and promoted interest, shared resources, and enthusiasm amongst the DSM practitioners. At a broader level, the community of practice has contributed to greater recognition of DSM by all State and Territory agencies.

Another major driver and enabler of operational DSM in Australia have been the existence of DSM "champions", particularly Mike Grundy from CSIRO and Alex McBratney from the University of Sydney. These two have directly lobbied for and promoted DSM to Australian Governments, led training programs, obtained essential funding, and promoted the merits of DSM to the broader scientific community. Without this leadership, DSM would not have progressed as far as it has in Australia. The Federal Government funding secured has supported the training programs and sponsorship at international conferences and workshops and provided the national digital infrastructure to support the final DSM products. Neil McKenzie from CSIRO was another instrumental figure in Australian DSM. Apart from his scientific role in early DSM case studies, he was the founder and initial leader of ACLEP, establishment of the Oceania node and a driver in the inception of the GlobalSoilMap (GSM) initiative.

2. Australian operational DSM case studies

Some of the major examples of operational DSM/DSA across a range of scales within Australia are summarised in the following section, as well as a supplementary inventory of other operational DSM activities undertaken or in progress. From these, an operational framework for different aspects of DSM has evolved, providing valuable insights that other parts of the world could possibly use to fast-track their own operational DSM and DSA development.

2.1. Continental extent DSM

2.1.1. Case study 1 – the soil and landscape grid of Australia

Perhaps the clearest example of collaborative DSM across Australia is the Soil and Landscape Grid of Australia (SLGA) (Grundy et al., 2015), funded by the National Collaborative Research Infrastructure Strategy (NCRIS) through the Terrestrial Ecosystem Research Network (TERN). SLGA provided a new consistent and standardised continental soils information resource. Fig. 2 shows a website screenshot of available clay % layers, at 3 arc-second resolution.

2.1.1.1. What was produced?. A suite of standard, comprehensive, nationwide soil attribute surfaces at 90 m pixel resolution, for six standard depths with upper and lower prediction limits at the 90% confidence interval. The soil grids are provided online for display and download and comply to the specifications laid out for the GSM project (Arrouays et al., 2014b).

2.1.1.2. The problem. Information on the soil, its characteristics, and functions has been essential since the advent of agriculture and has been systematised since the beginnings of scientific agriculture (Grundy et al., 2015). This need has grown along with the need and capacity to understand and model the Earth's climate, ecosystems, and food production systems (Sachs et al., 2010).

In Australia, the state and territory government agencies are primarily responsible for the collection and management of soils data. For the last 70 years these agencies have been collecting soil site data to meet their policy needs. Soil site data and polygon map data are managed in data systems tailored to the requirements of the individual agencies. The systems were typically purpose-built and supported the operating requirements of each state agency under state policy, legislation, and regulation. Thus, across Australia, there was fragmentation and inconsistency. Given this, it has proved difficult over the years to produce nationally consistent and comprehensive soils information that is readily accessible and useful at multiple scales.

2.1.1.3. The solution. The Soil and Landscape Grid of Australia was the first nationally consistent soil information resource covering all the continent to be developed. Led by CSIRO with substantial input from the University of Sydney, this work was a collaboration between Federal, State, and Territory Agencies, to produce a suite of gridded soil property maps of estimated values, with upper and lower prediction limits (uncertainties) at six standard depths. These products adhered to the GSM specifications and were Australia's contribution to the GSM effort (http://www.clw.csiro.au/aclep/soilandlandscapegrid/). The SLGA used all existing soil sites (the National Soil Site Collation (NSSC); Searle, 2015), soil mapping polygon data and both existing and newly developed covariates to generate modelled surfaces of soil attributes using machine learning approaches (Viscarra Rossel et al., 2015). The process depended heavily on the expert knowledge of collaboration partners to supply relevant data sets as well as interpreting and validating modelled outputs.

2.1.1.4. Lessons learnt. The SLGA was only made possible through effective collaborations between all the involved organisations. Local knowledge and data were crucial to the development of useful national scale soil information products. The community of practice established during the development of the SLGA has brought many benefits, which resulted in optimal outcomes through information and knowledge sharing.

The effort in creating the National Soil Site Collation was a significant undertaking; an effective solution will only be in place when there is a clear update cycle. This is now in the process as part of the Terrestrial Ecosystem Research Network (TERN) SLGA updates and will be underpinned by a collated soil site data resource, using more dynamic and repeatable data federation approaches. Free and easy access has been essential to the overall success of the SLGA. The general public, along with scientists and other technical experts, can obtain the soil attribute data where and when they need it with little effort. In the first version of the SLGA, too few resources went into making the process readily repeatable, and thus readily updateable, as new data becomes available. With new resources becoming available to generate updated versions of the SLGA, a key focus going forward is to make the process as repeatable as possible into the future to allow for a dynamic evolution of soil attribute products based on more and better data inputs.

2.1.1.5. Dissemination. The SLGA has a dedicated website (https://www.clw.csiro.au/aclep/soilandlandscapegrid/) describing details of the products available and methods by which they can be accessed. The modelled products were made publicly available in a range of easily accessible formats via either file downloads, OGC compliant web services or tailor-made web service data delivery endpoints.

Entire raster datasets can be downloaded as geotiff format files directly from an FTP site (ftp://qld.auscover.org.au/tern-soils/Products/

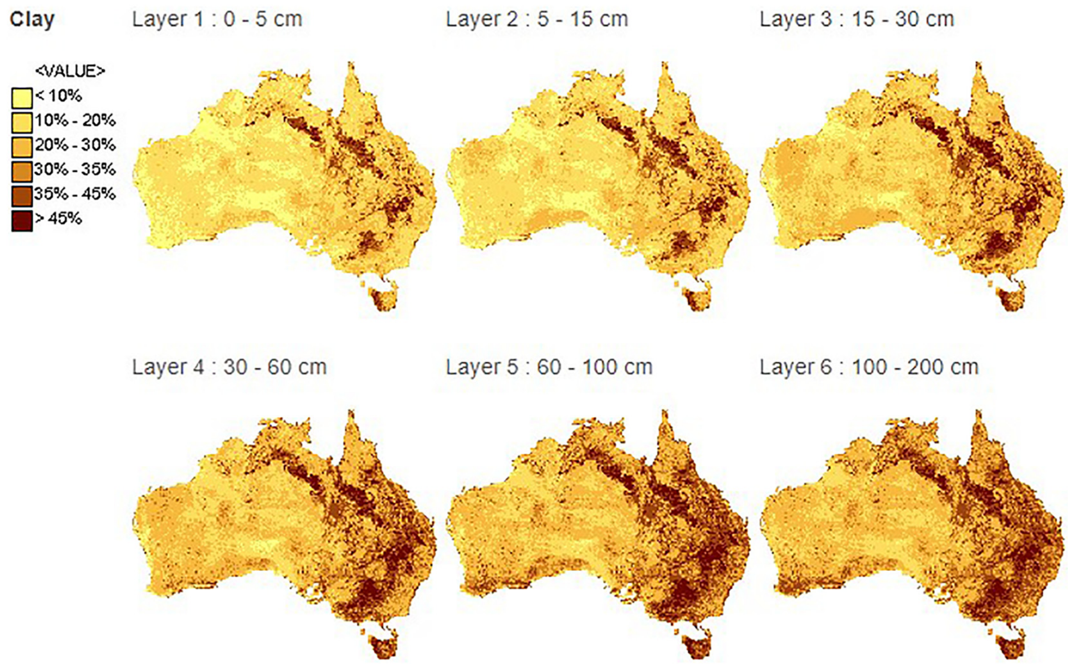

Fig. 2. Soil and landscape Grid of Australia – Clay %.

National_digital_soil_property_maps/) or via the CSIRO Data Access Portal (https://data.csiro.au/dap/search?q=TERN+Soil). Web Coverage Services (WCS) allow for the publication of "coverages" of digital geospatial information representing space-varying phenomena via web service endpoints. Using WCS, raster data can be subsetted for a defined region and downloaded directly to a user's device. All of the SLGA products can be downloaded via OGC services. As well as accessing data in geospatial raster formats, data can also be accessed on a per-pixel basis from a range of bespoke web API endpoints (https://www.asris.csiro.au/ASRISApi). These endpoints allow users to access data at a specific location as raw SLGA pixel values or in formats specific to the requirements of some commonly used biophysical modelling platforms. Through these mechanisms, soil data from the SLGA is being integrated into decision support tools to assist land management decisions (Freebairn et al., 2018).

2.1.1.6. Persistent impact. Where previously in Australia there might not have been adequate soil information available at many locations, we now have a modelled estimate of key soil properties available across the country at 90 m pixel resolution. Furthermore, these predicted data have an associated estimate of uncertainty to communicate the reliability of these products for particular use cases. The SLGA is being used by a broad range of users from policy makers, scientists, educational institutions, app developers, agriculture industry consultants and advisors and the general public to assist decision making. The ubiquitous nature of the SLGA has made it a valuable resource from the moment it was made publicly available. In the first 4.5 years since publication, over 170 Terabytes of data products have been downloaded, with levels of access being relatively constant over that period (Fig. 3, SLGA Downloads), see Grundy et al. (2020), this issue.

The facility is 'open access', therefore users don't require a login, and cannot be accurately traced. However, access to generic Apache web logs provide a summary of user groups, which was only available for around of one-third of the actual web-traffic. User stats include universities at approximately 52% of traffic, government (30%), industry (8%), schools (5%), and research organisations (5%), which is described further in Grundy et al. (2020), this issue. Analysis of the regular download 'peaks' in Fig. 3 is largely attributed to universities using the SLGA data in course work assignments, where multiple students download large volumes of data in the same weeks.

2.1.1.7. Resources. The SLGA was a two-year project. Staff directly funded by the project, full-time equivalent (FTE), 36 h working week (per year);

- 1.2 x FTE DSM modeller (DSM development)
- 0.4 x FTE Project management
- 0.6 x FTE data management – covariate development, data acquisition, data harmonisation
- 0.4 x FTE product delivery

In kind contribution from collaborating partners;

- 0.1 x FTE for seven agencies

There was also financial support to enable collaborators to undertake specific tasks such as data entry, data cleansing, support for workshop attendance, and travel costs for meetings and conferences.

2.2. Sub-continental extent

2.2.1. Case study 2 – Northern Australia land and water resource assessments

A ready-developed national DSM capability has allowed CSIRO and partners to deliver land and soil assessments for implementation of new agriculture development policy objectives in the Tropical North of Australia. To date, two Assessments have been completed by CSIRO covering catchments selected by the National Government: The Flinders and Gilbert Agricultural Resource Assessment (FGARA) and the Northern Australian Water Resource Assessment (NAWRA), while a third, the Roper Water Resources Assessment (RoWRA) is underway.

2.2.1.1. What was produced?. FGARA and NAWRA have generated a suite of online digital mapping products and reports delivered to the National Government and general public. The mapping products include a suite of 30 m grid size land and soil attribute maps in various formats including binary (e.g. salinity, surface rockiness), categorical (e.g.

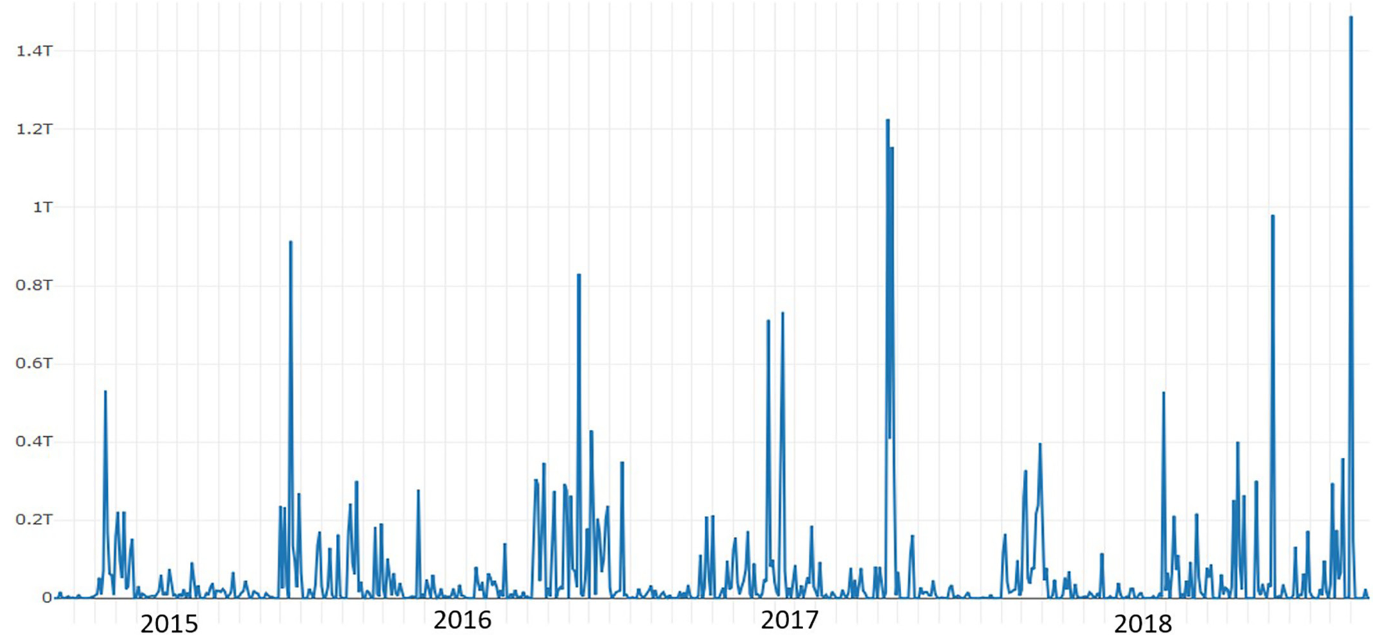

Fig. 3. SLGA Downloads. Daily Web Coverage Service downloads from the SLGA from late 2014 to mid-2018.

permeability), and continuous (e.g. pH, texture), with predictions at predefined depths. This suite was specifically selected to drive land suitability modelling and mapping for a set of crops under various irrigation management options. Finally, soils were also mapped according to "Soil Generic Group "classes devised to assist non-technical end-user communication using a simple mapping legend based on prominent morphological attributes of soil types while allowing inference of soil capability. All attribute maps were delivered with companion quantified uncertainty maps, enabling users to evaluate the quality and reliability of maps.

2.2.1.2. The problem. Under evolving policy settings imposed by National and State Governments, an analytical framework was required to enable investment and development in northern Australia by reducing investment risk. This involved identification of areas most suitable to transition from extensive livestock systems to more intensive forms of agricultural land uses, typically around irrigation but also including aquaculture in NAWRA. Identification of suitable areas for development was required in the broader context of geographic, infrastructure, and hydrological limitations. As such, the DSM and land suitability analysis were conducted as part of a wider multi-disciplinary project framework that considered, in addition to agricultural land suitability, issues around water and ecological sustainability, as well as Indigenous needs and aspirations. With land use and capability at the centre of almost all these issues, a rigorous and unbiased methodology was paramount to achieve acceptance of all stakeholders.

In addition to these technical and data demands, DSM needed to, in tight sequence, feed quality digital mapping into other Assessment activities to ensure final overall Assessment deliverables within demanding client-driven timeframes of less than 3 years. In effect, the DSM component needed to deliver early to high data quality specifications, while also having to cater to major logistical impositions around ill-defined field seasons, large and remote survey areas, and availability of trained staff and equipment.

2.2.1.3. The solution. DSM was deemed the only viable option for delivery of digital soil and land information products given the key project constraints highlighted above, particularly those around tight timeframes to delivery. However, CSIRO no-longer has the capability it once had to conduct multiple, prolonged and sometimes simultaneous surveys in remote areas and so it was necessary to partner with the various state and territory jurisdictions to share resources for the field components (e.g. skilled field staff, equipment, on-ground contacts) and the laboratory (soil analyses, land suitability expertise). The methodologies followed for FGARA are described in Thomas et al. (2015) and Harms et al. (2015), and for NAWRA in Thomas et al., 2018a, 2018b. The technical highlights employed to make DSM operational in the circumstances include:

- A survey design was used based on conditioned Latin hypercube sampling (Minasny and McBratney, 2006), and adapted to be pragmatic by sampling only within 150 m of known tracks and roads, with contingency sites in analogous covariate space where the target sites are inaccessible (Clifford et al., 2014);
- Augmenting new survey data with legacy land and soil survey data within thresholds of date, positional accuracy, and analytical qualities
- Selective use of mid-infrared spectroscopy for rapid and low-cost soil analyses

What started under FGARA as a limited R-Shiny online platform used within the project team to explore mapping outputs evolved under NAWRA to be a highly developed on-line platform enabling all data users (government, potential land investors, the general public) to interactively explore, interrogate and download maps. NAWRA's iteration of the platform gave data users the ability to explore the multifactorial problem that goes into investment decisions for development. Fig. 4 shows an example product of modelled land suitability for Darwin catchments, for wet-season cucurbit under trickle irrigation and dry-season Asian vegetables under trickle irrigation.

2.2.1.4. Lessons learnt. The overriding lesson learned from the FGARA and NAWRA experiences is that DSM can deliver large-area land and soil mapping for remote areas under challenging operational circumstances to satisfy national land development objectives. However, underpinning this national capability are numerous factors that have been put in place across Australia through forethought and investment decisions, without which these achievements would not have been possible. These include the investment in environmental covariates. It is important to note that

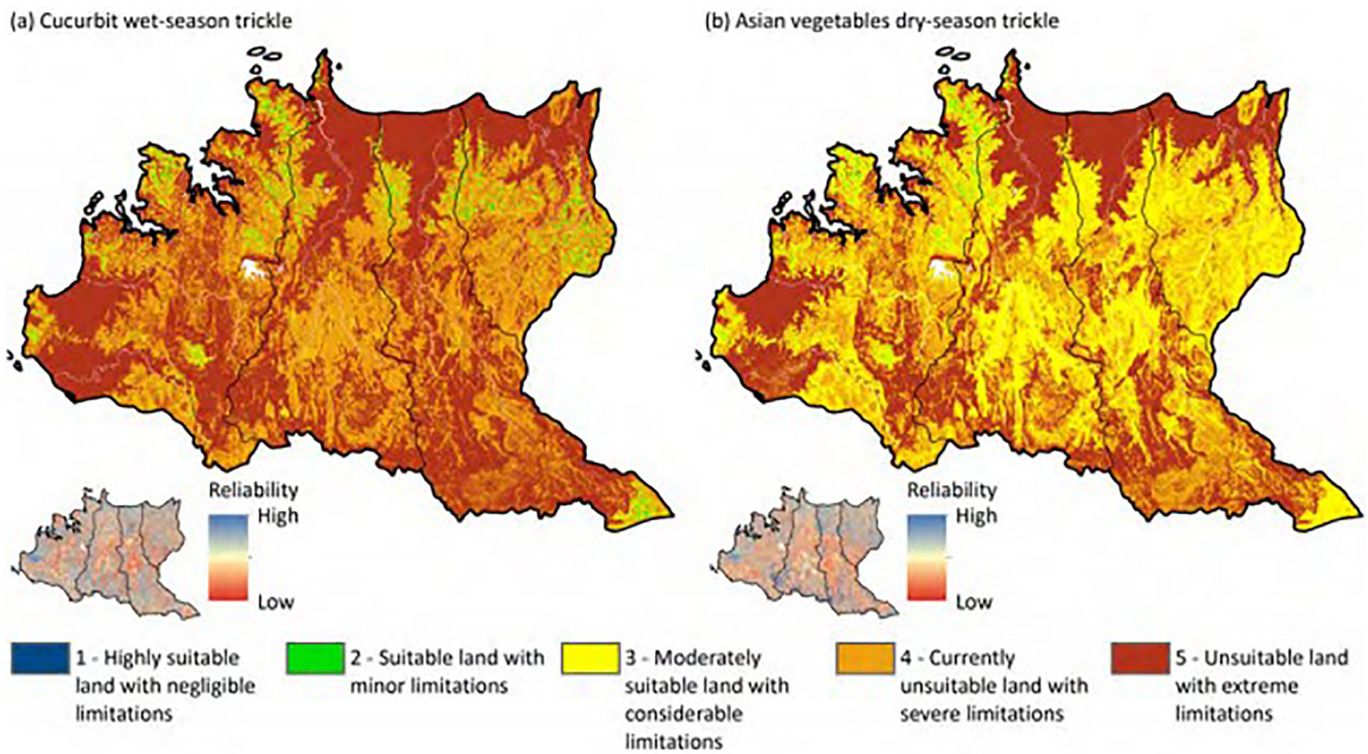

Fig. 4. Modelled land suitability for Darwin catchments; (a) wet-season cucurbit under trickle irrigation and (b) dry-season Asian vegetables under trickle irrigation.

the number of covariates available is not a good indicator of this, rather the more desirable measure is the number of soil-forming factors are accounted for in the suite of available covariates. Australia has accomplished a lot in this regard. Particularly around publicly available gamma radiometrics data and terrain analyses from the national 30 m digital elevation model. Australia's DEM data (both 30 m and 90 m SRTM products), for example, have been subjected to rigorous post-processing to remove artefacts, remove vegetation influences and correction of hydrological inconsistences that are created in the raw data collection and initial processing (Gallant et al., 2012). Furthermore, the investment in a national DSM capability through ACLEP, supported through fundamental research by the University of Sydney and CSIRO, has led to the adoption of DSM technologies and a strong community of practice and resources that can be accessed, often at short notice, as described. Finally, the past investments leading to strong Australian field and analytical standards has ensured that staff of various jurisdictions can combine quickly and successfully in the field, while also helping to make legacy data more accessible and usable.

2.2.1.5. Resources. The Australian Government funded NAWRA, it covered an area of 197,000 km2 and was completed in 2.5 years. The DSM component of the larger multidisciplinary project combined numerous staff from CSIRO, the governments of Queensland, Northern Territory, and Western Australia, as well as consultants. Staff were employed in the following key areas with effort levels averaged per year through the life of the project:

- 0.25 FTE DSM modelling
- 0.5 FTE project management
- 0.5 FTE data management
- 0.7 FTE field survey
- 0.4 FTE delivery and reporting

Dovetailing with the DSM activities and outputs was a digital land suitability modelling component engaging almost all staff involved in the DSM component. The land suitability drew on additional resources consisting of:

- 0.4 FTE land suitability framework development and checking
- 0.25 FTE land suitability modelling and delivery

2.3. Regional extent (state level) DSM

2.3.1. Case study 3 – disaggregation of legacy soil mapping, Queensland

A disaggregation approach was used on legacy soil mapping to improve resolution of products for identification of constraints to sugarcane cropping.

2.3.1.1. What was produced?. The project produced: Soil profile class (SPC) prediction maps with improved resolution from existing low to medium-intensity surveys conducted in key cropping areas in the Great Barrier Reef catchment; a framework for identifying soil constraints to sugarcane cropping (O'Brien and Thomas, 2018); information on soil constraints based on the disaggregated soil maps and available reference site data; environmental characteristics information specifically for the Burnett-Mary basin (Queensland Government, 2019b); and finally, a pilot assessment and method for assessing Production Unit Yield Potential for sugarcane as a vital component of a Farm Nutrient Management Plan (Moody, 2016).

2.3.1.2. The problem. The Office of the Great Barrier Reef (OGBR) and the sugarcane industry desired higher-detail information on the location of subsoil constraints to agriculture in order to tailor application of soil amendments, particularly 'mill mud', which is in relatively short supply. Existing soil mapping in the areas of concern was largely at 1:100,000 or 1:50,000 scale and end users were finding the linework too general to use on individual farms or blocks. It was also apparent that end users often did not appreciate the multiple soil classes present on most of the polygons, focusing exclusively on the dominant soil. Anecdata suggested that end user ability to identify SPCs accurately in the field was also quite mixed.

2.3.1.3. The solution. The available mapping was considered suitable as an input for the DSMART algorithm (Odgers et al., 2014), with the potential to predict soil classes at a 1 arcsecond (~30 m) pixel resolution. DSMART is a DSM method that attempts to spatially disaggregate composite soil mapping units. The soil data available would then be classified against a constraints model, and the DSMART predictions used to spatialise the constraints. A workshop was held with industry and government participants to choose a set of constraints that were a) understandable and relevant to sugarcane agronomists and b) generally had enough available data to parameterise. Median or modal soil attributes were determined for each SPC from information held within the Queensland Soil and Land Information database (SALI). Site data was unified to set depth ranges using the mass-preserving spline (Bishop et al., 1999; Malone et al., 2009) and the GSM depth specifications. Median values were calculated by SPC and depth slice. Categorical data were processed into GSM depths without back-converting to continuous data using an algorithmic process, and modal category values were calculated. Attribute values for the top four GSM slices (0-60 cm) were classified against constraint thresholds, and the final rating determined based on how many soils layers 'failed' (Table 1).

A modified version of the DSMART algorithm that enabled area-proportional sampling was run across 6 subregions and outputs were considered acceptable enough to use as indicative pilot constraints mapping in five. The rejected region was the lower Burdekin River coastal plain, where it is suggested that substantial land surface modification has erased key terrain features from the available covariates. End users expressed a preference for a vector-based final product for compatibility with their existing spatial workflows. As such, in each subregion, the most-probable soils prediction surface was slightly despeckled to force a minimum legible area of 4000 m^2 (scale) and then vectorised. Constraint ratings for the most probable predicted SPC were attached to the polygons as attribute columns.

2.3.1.4. Dissemination. The final product supplied was a 'data package' download for each subregion, containing a GeoPackage (Open Geospatial Consortium, 2017) polygon dataset, metadata, and the SPC calculated attributes in a set of CSV files. The constraints framework was published as a technical report on the Queensland Publications Portal (O'Brien and Thomas, 2018), and a technical report on the disaggregation is in preparation.

2.3.1.5. Lessons learnt. Feedback from end-users was minimal to the time of writing, and conversations amongst soil survey colleagues focussed on validation of the resulting products, clear metadata and fitness for stated purposes. Various flaws discovered in the existing legacy data during its preparation for DSMART uses prompted a critical reassessment of the quality of some traditional soil maps. Data cleaning, data import, and soil database improvement tasks also had their priority lifted. The work has also prompted a data availability audit, which will attempt to summarise in detail the quality and quantity of available soils data in Queensland on a per-catchment basis. The value of clear 'for-purpose' statements in soil spatial metadata has also been recognised, and efforts are underway to formulate standard language to accompany future soils data products (conventionally produced or otherwise).

2.3.1.6. Resources. The project covered 66,096 km^2 over a 1.5-year period. Around 50% of the resources were used for DSM, 25% for DSA, 20% for product development and 5% for project management.

Staff included (per year)

- 1.2 x FTE DSM Practitioner/Soil Scientists
- 1.0 x FTE data validation and review

Legacy mapping

- 19 legacy soil maps, which were disaggregated into 1610 SPCs.

2.3.2. Case study 4 – Tasmanian enterprise suitability DSA

One of the first jurisdictions in Australia to test and develop a program of operational DSM and DSA was Tasmania, an island state of approximately 68,000 km^2. The Tasmanian Department of Primary Industries Parks Water and Environment (DPIPWE) developed a DSA of 30 m resolution Enterprise Suitability Assessment maps for 36 crops across the State (Kidd et al., 2015b), as part of the 'Water for Profit' Program (DPIPWE, 2015b; UTAS, 2015).

2.3.2.1. What was produced?. A set of 30 m resolution soil grids for multiple soil attributes at standard depths were produced for the entire state. In addition, a set of 30 m resolution climate grids for multiple attributes were also produced and combined with the soil grids to generate Enterprise Suitability maps for 36 crops, made available on online mapping portal 'LISTmap', https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=406683

2.3.2.2. The problem. Professor Jonathan West was commissioned by the Tasmanian Government in 2009 to research and develop an 'innovation strategy' (West, 2009) to promote economic growth in Tasmania. In assessing Tasmania's agricultural potential, West noted empirical evidence showed that areas of low production could be transformed into high value agriculture but is limited by adequate water. An example of an earlier irrigation scheme in the Coal River Valley region of the state showed that a combination of ideal soil and climate, coupled with a source of reliable irrigation water, had the potential to stimulate economic change, leading to intensification and diversification of regional agriculture. West's innovation strategy research and recommendations were the main impetus for the Tasmanian Government's recognition of the need for developing enhanced soil and climate data using innovative approaches, the commissioning of new irrigation schemes across the state, and a program of land suitability mapping to better target and stimulate appropriate agricultural enterprises within these new schemes. Nineteen new irrigation schemes have been commissioned and developed across the state since 2009, with a new need identified to undertake land suitability mapping in these areas to stimulate water-allocation uptake, agricultural intensification and diversification, and a shift towards higher-value agriculture (Tasmanian Irrigation, 2015). However, existing agricultural soils mapping was incomplete, and at a scale that wouldn't provide enough detail for a land suitability assessment. In addition, the resources available to the Tasmanian State Government at the time would either only allow small areas to be mapped using a conventional approach, or larger areas at a broader scale; a need was identified for methods that would provide objective mapping of soil properties directly, at a resolution that would inform the land suitability questions at the landscape (or sub-catchment scale), and within available budgets.

2.3.2.3. The solution. After undertaking research to identify alternative soil mapping methods, in conjunction with the national direction in DSM promoted by ACLEP, CSIRO and the University of Sydney, an operational pilot project 'Wealth from Water' was developed as an Australian Research Linkage Project (LP110200731) in partnership with the University of Sydney, Faculty of Agriculture and Environment. The project tested various aspects of DSM, including different sampling design and modelling approaches, testing different soil attribute and climate modelling approaches through a temperature sensor network (Webb et al., 2015), MIR analysis of soil properties, and combining these using Enterprise Suitability rulesets developed by the Tasmanian Institute of Agriculture (TIA) into a suite of 30 m resolution Enterprise Suitability maps (ESM). The project was eventually rolled out state-wide through new soil sampling and temperature loggers and integrated with legacy soil site data to produce state-wide ESM at initially 80 m resolution, then 30 m resolution in 2018. Modelling approaches

Table 1
Four of the 20 constraint definitions used to evaluate SPC attributes, demonstrating how constraints can be defined on a per-layer or whole-profile basis.

Constraint	Severity			
	None	Mild	Moderate	Severe
Acidity pH (1:5, water)	pH > 5.2 in top four layers	pH < 5.2 in top two layers only	pH < 5.2 in layers 3 and/or 4	pH < 5.2 in majority of top four layers
High salinity EC_{SE} dS/m	EC_{SE} < 2 in top four layers	EC_{SE} between 2 and 4 in top four layers	EC_{SE} > 4 in any of layers 2–4	EC_{SE} > 4 in majority of top four layers
Insufficient Drainage Class	Drainage rating ≥ 4	Drainage rating 3	Drainage rating 2	Drainage rating 1
Low Plant Available Water Capacity (PAWC; Dryland)	PAWC to effective rooting depth (ERD) ≥ 95 mm	PAWC to ERD 80–95 mm	PAWC to ERD 65–80 mm	PAWC to ERD < 65 mm

used a combination of regression and decision trees (Quinlan, 2005; Quinlan, 2014), and random forests (Liaw and Wiener, 2002), and a cross-validation approach to reduce modelling bias and produce uncertainties (Figs. 5 and 6).

2.3.2.4. Communication/distribution of DSA. The LISTmap resource provides a regional decision-support tool for farmers, consultants and investors to interactively query any part of the viewed map to determine suitability class, and soil, climate and terrain parameters of interest, as well as identification of vulnerable soils (erosion by wind and water, sodicity, salinity, and waterlogging hazards), and appropriate management guidelines (see Fig. 7). The system also identifies what soil or climate parameters might be individually economically feasible to manage to raise suitability and was linked to enterprise market information and business planning tools (DPIPWE, 2015a).

2.3.2.5. Lessons learnt. From the development of operational DSA in Tasmania, there have been several lessons learnt, in terms of fast-tracking agency DSM skillsets, adaptations, and sometimes compromises to sampling, DSM development, and application of datasets and delivery platforms. These include;

2.3.2.5.1. Resistance to change. When first proposing DSM as a potential alternative to conventional soil mapping for the suitability work, there was much internal and external reticence from the Tasmanian soil science community in the described approaches, similarly described in other operational DSM examples from around the world (Arrouays et al., 2020a, 2020b). An important mechanism in addressing these concerns was the sharing of information around the new methodologies through presentations and journal publication of results. It was also advantageous to complete a preliminary pilot-study area to demonstrate the feasibility of the DSM approach, following suggestions from

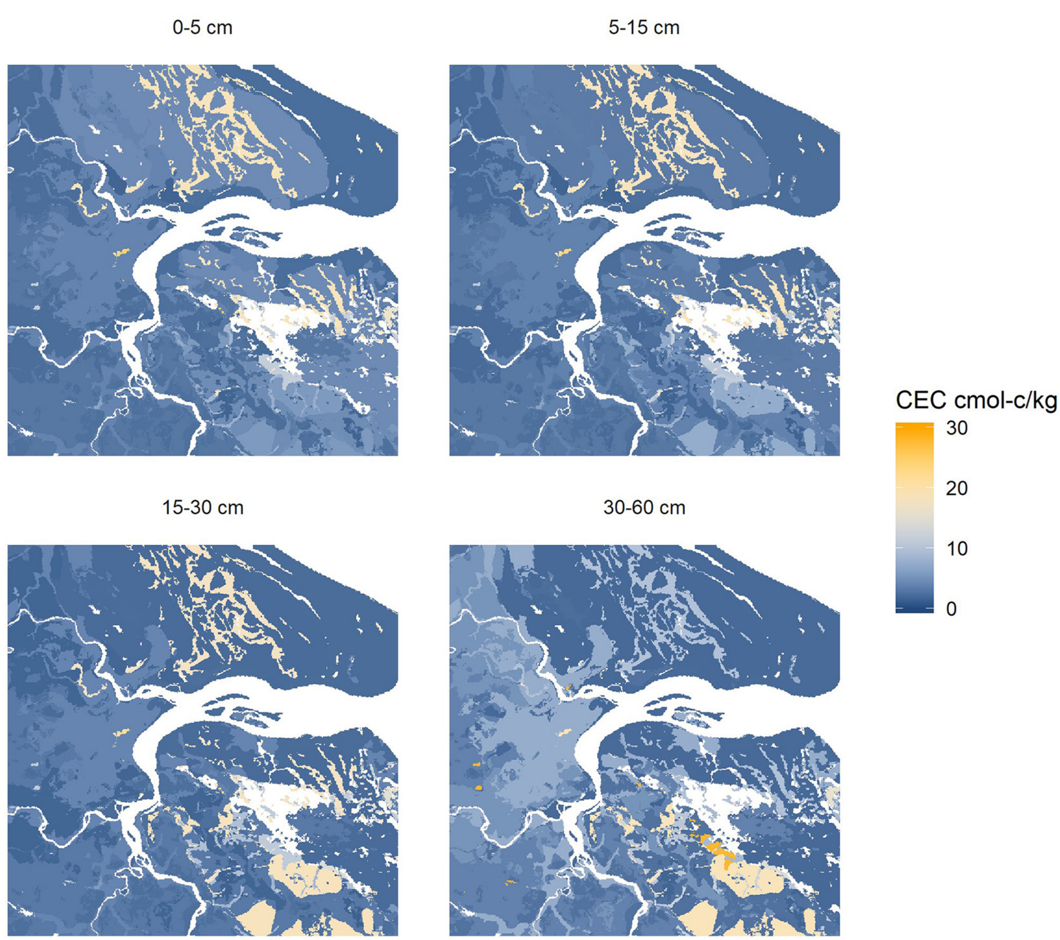

Fig. 5. Raster surfaces showing most-probable Cation Exchange Capacity (CEC) for four GSM.net depth slices, Burrum Heads area, near Fraser Island in South East Queensland. The predicted CEC for each pixel is calculated as a weighted median of the CEC for any predicted soil profile class with a probability of >0.1.

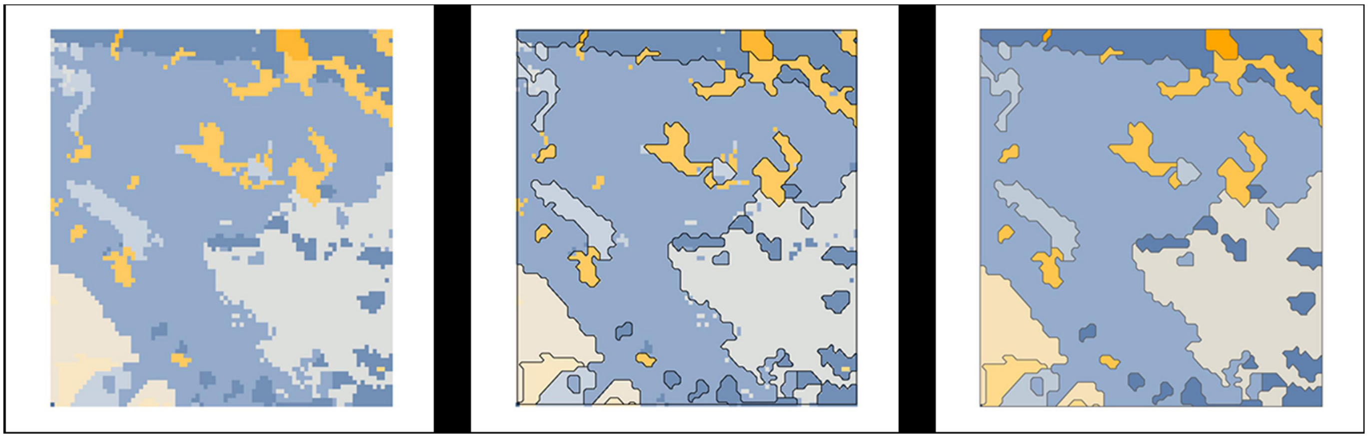

Fig. 6. Demonstration of raster vs polygonised DSMART most probable soils prediction surface. Left: Original raster surface with ~30 m pixels. Centre, polygonization of despeckled raster data overlain on original raster surface. Right: Final polygons. Despeckling and format conversions were all completed using GRASS-GIS v7 via an R script.

MacMillan (2008), before adopting the approach state-wide as an operational activity.

2.3.2.5.2. Australian Research Council linkages. The Australian Research Council (ARC) Linkage program providing co-funding between universities and partner (industry) agencies worked well and enabled DPIPWE (as a state government agency) to collaborate with the University of Sydney and facilitate their high-level DSM research knowledge to be developed, extended and applied in an operational framework, and passed on to agency land resource assessment staff. This approach accelerated agency uptake of DSM technologies, but also provided the opportunity for agency feedback to the University in terms of DSM application and operational feasibility of processes, allowing these to be adapted and developed for real-world applications. For example, the predetermined sampling approach using conditioned Latin-hypercube sampling (cLHS) (Minasny and McBratney, 2006) was found to be problematic in access-constrained areas, impeding project timeframes, so a new approach was developed and trialled where covariates were clustered as sampling strata, with stratified sites sampled within these clusters with the option of moving within clusters if access was constrained (Kidd et al., 2015a).

2.3.2.5.3. Spectroscopy soil analysis. DSM prediction of soil attributes relies on an adequate sampling density of analysed sites, which can be expensive and prohibitive using conventional 'wet-chemistry' approaches. The application of Mid-Infrared-Spectroscopy (MIR) to predict soil attributes derived good results through wet-chemistry calibration to provide substantially more DSM calibration (and validation) sites than would have been possible within project budgets using a conventional analytical approach.

2.3.2.5.4. Mapping artefacts. Mapping artefacts (visual anomalies) in final DSM products can be caused by the covariates and modelling processes used (particularly 'tree' type modelling, e.g. Cubist Regression Trees (Quinlan, 2005)), where there is 'partitioning' of important covariates. In the Tasmanian work, there was a concerted effort to remove or minimise artefacts, as it was perceived to detract from the end-user's

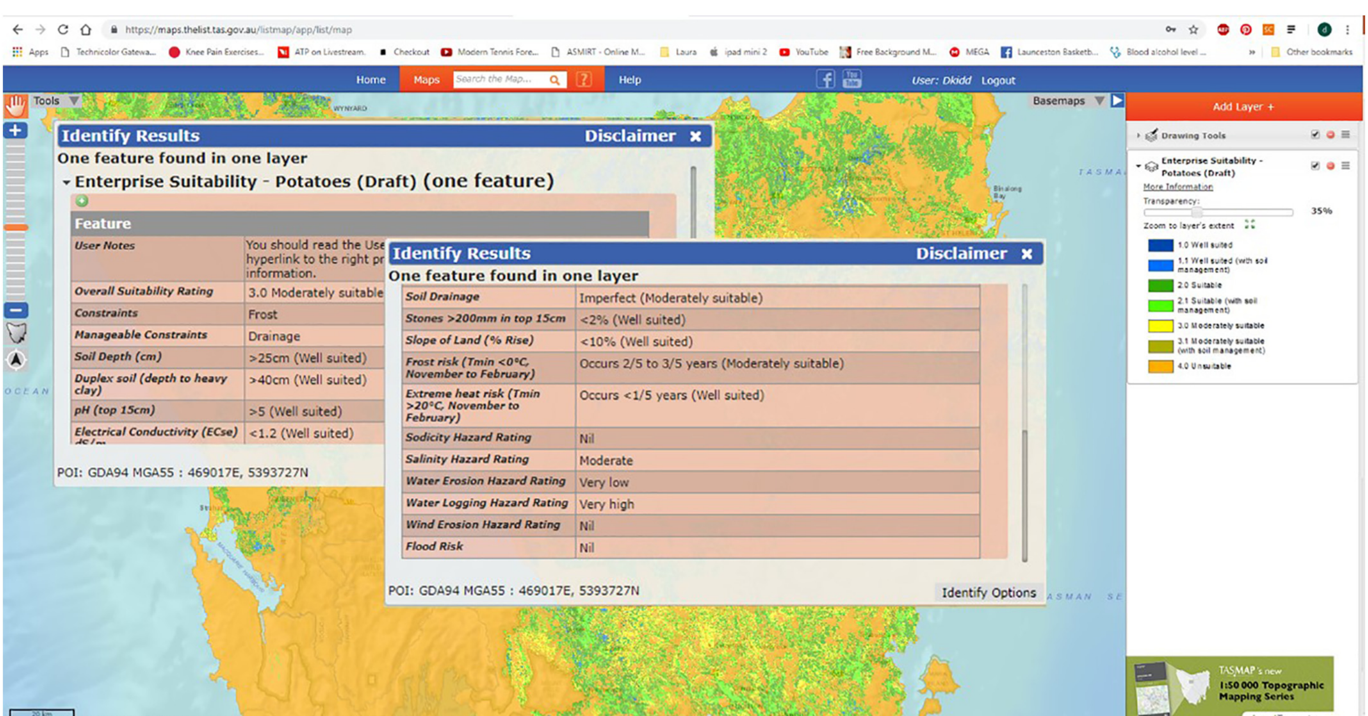

Fig. 7. Tasmanian LISTmap interactive outputs.

confidence in the final products (from anecdotal feedback), especially when the products produced were being vigorously scrutinised. This was achieved by identifying artefact-causing covariates and creating and testing alternative covariates to reduce these artefacts (such as unnatural rainfall isohyet bands), as described in Kidd et al. (2015c).

2.3.2.5.5. DSM modelling infrastructure. Once the Tasmanian DSM/DSA became a state-wide undertaking at 30 m resolution, it was physically necessary to use a cloud-based high-performance computing environment to undertake the different modelling approaches, as most desk-based PCs and applications could not handle the processing and analysis. This was also exacerbated by the memory-intensive cross-validation approaches, and the number of 'pixels' contained in each covariate (around 90-million pixels, 1.2 Gb). The use of open-source software, such as 'R' (R Development Core Team, 2015) also enabled the use of freely available DSM modelling approaches and support from the global 'R' community, and create automated, repeatable models to enable more efficient model-testing, and code-sharing within the Australian DSM community.

2.3.2.5.6. Industry support. Consultation with industry representatives (processor and agronomy experts), grower group professional bodies, as well as industry specialists from TIA was crucial in developing the DSA products, in terms of suitability rule-set development, adaptation and spatial validation and approval of the final mapping products. This ensured that industry (and their potential end-users) were content with and endorsed the final products (having had an opportunity to contribute and edit) and ensure that the final delivery format and features were fit for purpose.

2.3.2.5.7. Delivery systems. The online mapping portal LISTmap (as previously described) was an important resource for delivering the final DSA datasets, metadata, and associated documentation. It enabled end-users to overlay other important spatial datasets for decision-making, in addition to the ESM, and interactively query associated soil and climate constraints and parameter values. By moving away from traditional paper maps, it allowed for the provision of additional information not previously possible by physical (rather than electronic) media.

2.3.2.5.8. Pedo-transfer functions. It was found that when using pedo-transfer functions (PTF) for some soil properties, e.g. 'electrical conductivity of a saturated paste, (Peverill et al., 1999)', better validation and visual results were obtained when the PTF input parameters were modelled as separate DSM surfaces, then spatially calculated using the PTF to produce the final map, rather than applying the PTF to the calibration data and then producing the DSM models. This could be due to removing the PTF uncertainty from the DSM calibration inputs. However, this may not be the case in other areas and would be dependent on the PTF and soil attributes being used.

2.3.2.6. Resources. Combining the initial 80,000 ha pilot study and subsequent state-wide sampling and modelling, the basic resources required per year over the four-year duration are summarised below.

Agency staff (per year);

- 1 x FTE DSM modeller (DSM and DSA development)
- 1 x FTE Climate modeller (suitability climate inputs and DSA development)
- 2 x FTE Soil Surveyors (soil descriptions, sampling, MIR analysis)
- 1 x FTE Field Technical Officer (field assistance, data entry, MIR analysis)
- 0.5 x FTE Project Manager
- 2 x Research Officers (suitability ruleset development)

Academic Staff (Initial ARC Pilot project development), per year;

- 0.2 x FTE Professor/Associate Professor (DSM/climate development and guidance)
- 0.8 x FTE Research Fellow (DSM development and guidance)

There were many others who directly or indirectly contributed, including industry and expert staff from a range of academic, organisations and professional services who assisted in suitability ruleset development and product design and validation.

Soil Sites and Analysis

- 5400 legacy soil sites, multiple depths, full descriptions, full or partial chemical attribute data
- 1300 newly sampled sites, full descriptions, 6 depths, MIR analysis for key soil properties
- 1170 (15% of samples) full chemical and particle-size analysis for MIR calibration

Additional Resources

- 270 non-telemetered temperature sensors, 6 weather-stations (see Webb et al. (2015) for details)
- All covariates were freely available under 'Creative Commons'

2.4. Other Australian operational DSM examples

There have been many other DSM/DSA projects undertaken in Australia, generated for varying purposes, scales, and extents, which would all be defined as 'operational'. These are summarised in 'Supplementary Table 1', an inventory of operational DSM across Australia.

These additional DSM examples include: DSM of soil constraints affecting yield in the grain-growing regions of Australia; disaggregation of legacy maps and characterisation of sand-plain soils in Western Australia; state soil grid mapping to GSM specifications in New South Wales, Victoria and Tasmania; organic soil mapping for fire management in the Tasmanian World Heritage Wilderness areas; soil constraint and erosion potential mapping in Queensland; catchment-based land suitability mapping in the Northern Territory, and soil type disaggregation and property estimations in South Australia.

2.5. Collective lessons learned in progressing operational DSM in Australia

In developing an operational DSM framework across Australia, from the agency-based DSM training, case studies and examples presented here, some common themes were identified, addressed, and adapted to aid the DSM methods to become economically and logistically feasible, while still delivering DSM products that were 'fit for purpose'.

2.5.1. Soil sampling

Prior to about 2010, there had been a modest improvement in new statistically sound sampling technologies that take into consideration the infield contexts when planning and implementing soil sampling campaigns. Soil sampling efficiencies, such as conditioned Latin hypercube sampling and other statistically focused methods such as sampling within environmentally defined clusters (strata), have re-cast the soil survey ideas around sampling the environment. These new sampling methods move away from purposive and ad hoc sampling towards sample placement optimisation that maximally cover the environment space, geographic space, or both. This has resulted in improved confidence in the spatial prediction models that are built using the sampling point data. However, much of the operational project work has focused on developing approaches that remain statistically robust for spatial modelling, while allowing for operational sampling constraints. For example, using the flexible cLHS algorithm developed by Clifford et al. (2014), site samples can be relocated in situations where an original site allocation needs to be moved without deleterious effects on the design of the sample. The fuzzy clustering method that was implemented in Tasmania for the enterprise suitability for locating sites is another example of an optimal yet flexible sampling where sites can be relocated in the field in the event of difficult access (Kidd et al., 2015a).

2.5.2. Soil analysis

Where DSM is collecting new data, rapid soil analysis using, for example, mid-infrared or near-infrared spectroscopy means that soil properties can be measured on all layers at all sampling sites in a way that conventional laboratory analysis cannot due to budget constraints.

2.5.3. DSM training, workshops and conferences

The ACLEP-funded training delivered by the University of Sydney to Australian soil scientists was essential in fast-tracking DSM development and operational uptake across the country. The training was tailored to real-world examples, and R code (R Development Core Team, 2015) was provided to allow trainees to test the DSM processes on their own data when back in their respective offices.

The additional CSIRO funding for Australian and state agency staff to attend national and international workshops and conferences is also considered invaluable in fostering not only Australian collaboration, but also information and idea sharing with international peers, and exposing the latest DSM research for operational consideration.

2.5.4. Some barriers to operational DSM in Australia

The case studies presented are real-world examples that, along with all the other DSM activities undertaken in Australia, have provided valuable lessons. Possibly the most important of these was the need to develop methodologies for real-world applications of previously largely academic science. These lessons also included overcoming various barriers and impediments to operational DSM/DSA. Some of these were previously described fortuitous developments that became enablers, but some other, more persistent barriers are summarised for each jurisdiction below.

3. Uptake of DSM in Australian jurisdictions

Some other jurisdictional observations have been made as to why or why not DSM has progressed across Australia. The application of DSM has been slower in some jurisdictions than others, due to some of the above 'barriers', and for various intrinsic reasons. For individual states, these include;

3.1. Western Australia (WA)

In WA, adoption of operational DSM was slow as the state had a significant investment in edge-matched polygon mapping, while early DSM products were inferior to existing polygon mapping, particularly in the South West of WA. There was interest in DSM, mostly as an interesting academic exercise, but there was not yet a clear benefit. This changed with the NAWRA project, which was done on pastoral land in the Fitzroy catchment, which had previously only had reconnaissance scale 1:250;000 mapping and rudimentary soil descriptions. The DSM mapping was directly driven by the site data, was quantified and demonstrated uncertainty and outputs from early ranger model runs, which followed the rangelands land system boundaries closely, and showed more detail in some areas. Another significant benefit of the process was that, where the mapping looked incorrect, it often highlighted problems with the underlying site data. For example, soil depth persistently started at 10 cm or more as rock outcrops were not included in the site horizons. Similarly, many lower depths and likely substrate materials were not documented, hence the predictions for the lower depths were uncertain, and in these areas, shallow soils were over predicted. By doing model runs during different phases of field work, this even highlighted errors such as misclassified soils. This experience has led to a significant investment in systematic checks of the WA soil profile database, as well as consideration of the rules used to select appropriate sites for modelling. DSM is now being promoted by the agricultural industry in WA, essentially through digital disruption. The newly available high-resolution imagery and readily accessible GIS tools (google earth, industry mapping platforms) are increasing demand for DSM products at high resolution, however, there remains a hiatus between the paddock scale demand and state soil information.

3.2. Victoria

The adoption of DSM in Victoria has been supported in the last two decades through government initiatives and peer support networks such as the ERA program (Grundy, 2001). Digitizing legacy soil site information and existing polygon maps has remained a priority where confidence exists in use of the choropleth model. This could be due to a number of factors. Outputs, inputs and the science used in the choropleth model are well established in soil science and so have inertia not easily displaced: this method of mapping is more than a century in practice. Retooling soil scientists and science infrastructure has proven challenging. Also, the uncertainties in outputs from the choropleth model are seldom communicated to the next users. They may remain unaware that maps from DSM can enable decision making with less risk of failure compared to maps from the choropleth model because uncertainties routinely communicated in DSM studies. In fact, the explicit communication of imprecision in DSM products and its contrasting apparent absence in the products from the choropleth model may create a negative impression for the next user and for funders of DSM research.

New state-wide DSM applications have greatly benefited from the digitization of legacy soil sites and maps, however, future uptake and operationalisation of DSM to deliver regional and locally relevant information will require ongoing support and raising of awareness amongst the potential beneficiaries. Raising awareness of the benefits that can be achieved through DSM (e.g. DSA in Tasmania) will provide confidence in future investment and uptake of DSM in Victoria as a science discipline and the products and services it delivers.

3.3. South Australia

In South Australia, there had been significant investment between 1985 and 2000 in traditional polygon-based soil-landscape mapping under the State Land and Soil Mapping Program (Hall et al. 2009). This mapping was designed to inform State issues and priorities for soil and land management and remains useful for this purpose. However, there are important scale-related limitations of this regional-scale mapping, and, increasingly, there are diverse stakeholders requiring access to more accessible and localised (e.g. paddock scale) soil information. To maximise use of the embodied expert knowledge in the legacy maps, map disaggregation techniques have been a focus in SA, for example, via the application of DSMART as part of the SLGA work. Also, custom disaggregation techniques have been developed to translate legacy wind- and water-erosion potential mapping into fine-resolution products to support new state-wide remote sensing-based assessments of seasonal erosion risk. Environmental correlation DSM modelling has been employed using state-wide legacy soil site data to build local knowledge of the distribution and environmental drivers of soil carbon stocks. However, future progress in DSM will likely rely on either: building available soil site data to feed into future versions of the SLGA; or increased awareness of DSM capabilities across a wider group of stakeholders to facilitate the inclusion of cost-effective soil data and map acquisition capabilities of DSM into future soil-related projects.

3.4. Tasmania

In Tasmania, where uptake and development of DSM at DPIPWE was reasonably rapid in comparison to other states, there were initial barriers that needed to be overcome, including scepticisms of the DSM approach by some of the Tasmanian soil science community, both internally and externally. The need to rapidly acquire the knowledge to undertake an operational DSM approach was also an initial barrier, which was overcome through the previously mentioned training and ARC linkages and ACLEP training. However, Tasmania, being a relatively small state with complex soils and terrain, made a good testing ground for DSM, and an excellent case-study for other Australian Jurisdictions to learn from.

3.5. New South Wales (NSW)

Like most of the other Australian States, NSW continues with polygonal style soil mapping programs, which is where most experience and expertise of staff remains. However, DSM programs are being increasingly introduced, and now State-wide coverages of both conventional and digital mapping products are available through on-line data portals (OEH, 2018).

Outside of national or state agency operational DSM, other barriers to progression exists, especially in localised markets, which include;

- Lack of consultant based operational capability in the private market.
- Difficulties in determining the minimum data set on a per hectare basis with the uncertainty explicitly defined in a useful manner.
- Many landholders are currently interested in interpreted products (DSA), rather than soil attribute information.
- Obtaining soil data is currently viewed as an operational expense, rather than as a capital investment that enhances the value of the land and limits risk for insurance/banks - if we can change the discussion to data as a capital investment the ability to capture sub-paddock scale.
- Developing DSM for use at the farm to sub-paddock extent, which has historically been driven by the private (consultant) market; there is limited operationalisation of DSM at the sub-paddock scale even within countries with the highest levels of DSM adoption and capability.

3.6. Encouraging DSM uptake in Australia

As discussed, operational DSM progression was somewhat slowed by the need to 'prove' DSM theory to the Australian Soil Science community, which is a necessary step in transitioning any new science into operation. This will need to be addressed in transitioning DSM into operation elsewhere. Despite the published research and real-world examples demonstrating the success and benefits of DSM, even enhancements to traditional soil mapping, it was and is still met with resistance by some traditional soil scientists in Australia. Ahrens et al. (2008) compared the introduction of aerial photo interpretation (API) into conventional soil survey as a technological advancement in soil science, which 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" (Ahrens et al., 2008).

In fact, both conventional soil science and DSM approaches effectively use the same concepts to predict soil types or properties where there has been no sampling. 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 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 mathematical processes such as data mining and machine learning.

The benefits of DSM will ultimately depend on the area being mapped, landscape complexity, data density, quality and available covariates. Ma et al. (2019) discussed that for soil class prediction, covariates selected by recursive feature elimination consistently gave the most accurate predictions, while models using covariates selected by expert knowledge consistently had higher uncertainties. This finding appeared counterintuitive as expert judgement from pedologists would seem to be more reliable, given they would have a better understanding of the soil variation and potential reasons and controlling factors for this variation, relative to the tools of a pure data modeller with little soil science knowledge. However, many clinical studies have demonstrated that statistical prediction consistently outperforms expert judgement (Grove et al., 2000). When faced with many variables (covariates), a pedologist might not be able to identify optimal covariates a priori because of the complexity of soil-forming processes (Brungard et al., 2015). However, current statistical approaches for DSM validation lack any consideration of plausible spatial patterns, where DSM maps may have excellent validation statistics, but the spatial distribution of soil property estimates based on pedological experience is questionable (Bui et al. (2020), this issue). Thus, at a minimum, traditional pedology will remain highly relevant in data-limited environments. According to Biggs et al. (2018), the future path for pedology in Australia will be determined by how the soil science community chooses to communicate its requirement and impact. This same point is true for DSM within the internal soil science community and in terms of its stakeholders more widely, where the integration of pedology and DSM in a singular narrative is imperative for operationalising DSM and for the creation and provision of a pedology capacity that services all soil stakeholders.

The Australian DSM community (operational practitioners) have been active in determining optimal approaches to use and engage with pedologists. This has included pre-survey of the project areas to evaluate appropriate covariates, sampling design, sampling and conventional site descriptions, classification, analysis, and most importantly, map evaluation for geomorphological 'reality'. This can also include the development of soil types or profile classes based on discrete mapping of soil attributes, which is still considered important for communication purposes at the farm or paddock scale. In Australia, many of the operational DSM exponents have also come from a pedological background, which is advantageous as the above can be directly factored into DSM development.

4. Operational DSM workflows

From the above operational case studies and examples, 'lessons learnt', and in overcoming barriers to operational DSM development, it is evident that operational workflows have developed for the different type of DSM undertakings that could, in future, be developed into consistently applicable guidelines for use in Australia and elsewhere.

Supplementary Table 2 describes the workflows that are typical of the common steps undertaken in producing DSM of discrete soil attributes or types, after defining the project's objectives and budgets. There are three general workflows in practice,

- DSM of soil properties from point data,
- DSM of soil classes from point data, and
- Disaggregation of legacy polygonal maps (DSMART, (Odgers et al., 2014))

The DSM tasks listed in the supplementary workflow section include standard theoretical DSM processes, however, many of these have had some necessary operational adaptations. These include;

- Adaptive and flexible sampling designs that allow for sampling constraints and limited operational timeframes.
- Spectroscopy of samples to provide enough calibration (and validation) data for large area DSM of soil attributes.
- Using soil and landscape experts to identify locally relevant predictors, provide desktop review of DSM products and ground-truthing.
- Covariate adaptation and development, or 'continuisation' of polygon covariates to reduce to remove or reduce identified mapping artefacts.

5. Impacts of Australian DSM

Australia is a very large country in comparison to its population, which makes conducting and funding soil survey difficult. DSM has enabled Australian soil agencies to continue to provide map products to decision makers in a decreasingly funded milieu. The impacts of Australian DSM are difficult to measure in the short term, as the true value can often be measured through the long-term legacy value, as seen in conventional soil surveys which were used for over 50 years prior to DSM, for example, Burnie, Tasmania (Loveday and Farquhar, 1958). These long-term legacy values not only include the new DSM surfaces that are generated, but also the new land and soil data that have been collected in a standardised way and made publicly available in national or state databases. The impact can also be measured in DSM website usage and download statistics, but this offers little insight into on-ground impacts without factoring this into DSM project scope. The case studies and examples presented above are all currently being assessed in various ways for on-ground impact, however, most of these products have only been available in the short-term, with true impacts yet to emerge. This is discussed further in the associated paper (Grundy et al., 2020, this issue).

5.1. Australian global DSM impacts

Some of the work that has enabled the progression of operational DSM in Australia has also influenced DSM development in other parts of the world. These include;

- The first scientific coordinator of GSM until 2012 was an Australian and was responsible for harmonising the specifications (before being led by Dominique Arrouays in France).
- Developing the proof of concept in collecting a large amount of legacy data, then applying DSM at a country/continental level (Grundy et al., 2015).
- Providing a major input into the development of the GSM concepts, including the initial idea, specifications, and the first continental product) and in the development of the GSP 'pillar 4' theory, (Arrouays et al., 2014a; Arrouays et al., 2014b).
- Spreading knowledge and capacity building through the University of Sydney International DSM training courses (http://www.digitalsoilmapping.com/dsm-training/)
- Developing a collaborative network (Fig. 8)
- Disseminating operational tools and methodologies (e.g. FuzMe, cLHS, Splines, DSMART) in other parts of the world (US, France, NZ, Denmark, Scotland) (Mulder et al., 2016; Roman Dobarco et al., 2019)
- CSIRO have been fostering DSM products in developing countries such as the Philippines and Myanmar, who are either lacking a history of soil survey or capacity and hence few experienced pedologists. DSM has effectively enabled soil mapping in these areas and DSM protocols for other areas with limited legacy data, resources and expertise (Ringrose-Voase et al., 2019).

As a graphical demonstration of Australian DSM collaboration around the world, a SCOPUS database search was conducted to identify academic journal articles and book chapters published between January 2003 and July 2019 that contained the keywords "digital+soil+map" in the title or abstract. These search criteria identified 991 unique publications. Author affiliation information was converted to geographic coordinates using GoogleMaps' Geocoding API, as shown in Fig. 8. Collaborations between agencies and institutions were represented as connecting lines derived from great circle arcs. The opacity of connecting lines increased with the number of publications shared between institutes, however, the opacity of lines for publications with more than five unique institutions was down-weighted to reduce the influence of a small number of publications with exceedingly large numbers of co-authors. This figure demonstrates the active participation of Australia in the global DSM community, and additionally, the international uptake and development of DSM, which is encouraging.

6. The future of DSM in Australia

Some future applications will not be known yet. With ongoing development, each DSM product contains vast amounts of data, and over time could have more measured and inferred values developed; i.e., mining of this data can generate serendipitous outcomes. For example, a study by Liddicoat et al. (2018) showed that soil properties (from mapped DSM grids) had implications for forecasting locations where health could be compromised due to associations between a soil property and the risk of infectious and parasitic disease. Emerging work is also discovering links between exposure to biodiverse soil dust and changes to gut microbiota and mental health (Liddicoat et al., 2020). Such applications for soil data were not envisaged when DSM was first developed. Similarly, such benefits of developing the global DSM resource will increase as the DSM data is developed, improved and mined by data scientists from other disciplines. The nature of the DSM infrastructure (gridded, complete and standard-formatted datasets) enables these and future data-mining exercises.

One of the greatest lessons to learn from the preceding summary of the Australian experience and progression of operational DSM is that fostering a strong community of practice can help overcome systemic institutional barriers that may hinder development. This also aids and fast-tracks testing and operational implementation of new DSM research. The established collaborative DSM community has and will serve Australia to further produce high-quality DSM products, and provides a good template for other countries who are not as well progressed in developing their own operational DSM programs.

Finally, in an environment of diminishing government funding for staff and operational resources, made even more challenging following the 2020 global pandemic, it will be even more important for the Australian DSM and pedological communities to work together to ensure continuation of supply of quality fit-for-purpose spatial soil information.

6.1. Feedback research questions

While the Australian experience provides some good examples of operational DSM development, science adaptation, and lessons learnt, there are some persistent and emergent research questions that will need addressing to progress operational DSM. With operational DSM being widely adopted across the country, it is time for the Australian DSM community to better standardise and produce guidelines for some of the approaches listed in the supplementary workflows, as well as for the following research areas. This could be developed as an accompanying publication to the 'Guidelines for Surveying Soil and Land Resources', (McKenzie et al., 2008a, 2008b).

Searle et al. (2020), this issue provides a comprehensive analysis of the possible future directions for DSM and DSA. Here we present some critical short to medium term challenges we believe are important to address to ensure the continued uptake and application of DSM.

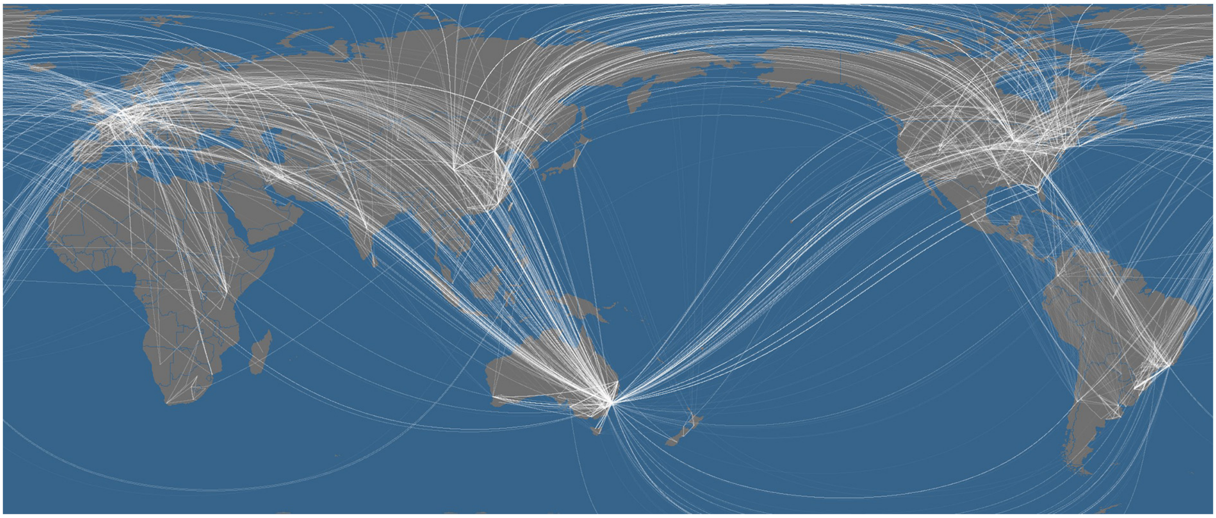

Fig. 8. Global map of collaborative DSM publications.

6.1.1. Operational DSM uncertainties

The ability to provide uncertainty estimates with DSM predictions is frequently touted as one of the main benefits of operational DSM, yet its dissemination to end-users is still problematic. For example, Victorian jurisdictional DSM uptake was described in section 3.2 as somewhat hindered due to criticisms of the explicit uncertainty estimates provided with DSM products. The previously described case-studies all developed measures of uncertainty as part of the DSM processes used. This included upper and lower prediction limit maps for the SLGA, Tasmanian ESM, and the Northern Australian resource assessments, and categorical accuracy validation for the Queensland disaggregation outputs. The SLGA, developed as spatial soil resource to enable national modelling and assessment activities, provides upper and lower prediction limit maps for each soil attribute and depth, and leaves it to end-users to best-determine how to utilise these prediction limits. The Northern Australian assessment products provided 'companion' uncertainty maps to enable end-users to evaluate the quality and reliability of the suitability mapping in their areas of interest.

As part of the Tasmanian ESM work, Malone et al. (2015) developed a method to use the DSM attribute's upper and lower prediction limits, taking multiple random samples between these to determine the number of times each suitability rating is obtained for each soil parameter, providing a measure of probability for each suitability rating. However, end-user and industry group consultation feedback showed that they 'weren't quite ready' for this sort of confidence measure and warned against providing too much confusing detail to end-users. Part of this was likely due to an inability of the end-users to grasp the statistical concepts, but also because the products did not adequately explain this information. Since the main purpose of the suitability mapping was to provide a regional guide, the user-groups were content to rely on the 'best possible predictions' and undertake further paddock-scaled investigations before basing any major investment decisions. Hence, the uncertainty ranges were only provided in the map user documentation and metadata and made available on request.

Improving the evaluation and communication of uncertainties to end-users of operational DSM has long been recognised as a workplan priority for DSM, as well as developing better explanations of various DSM performance indicators (Arrouays et al., 2020a, this issue). While the Malone et al. (2015) method of using prediction ranges in a DSA shows promise, there is a clear need to provide visual maps of uncertainty and user-friendly information on how to use these uncertainties (Arrouays et al., 2020b, this issue).

Field-checking, ground-truthing and determining final mapping accuracy are other areas that need further development, supported by ensuring adequate resourcing for separate validation sampling. Developing uncertainty and validation definitions, reporting metrics, standards and acceptable validation thresholds, along with effective communication to end-users, remains a main area needing improvement to progress Australian operational DSM.

6.1.2. Data quantity and quality

Successful DSM requires an adequate spatial density of good quality calibration (and validation) data. Newly collected qualitative and analytical site data in optimal locations and density is necessary but resource intensive, and many legacy data sites are inappropriate for DSM use due to positional accuracy, 'biased' locations, descriptive and analytical quality, and temporal changes in soil attributes through biophysical processes and land use. Further development is needed in the use of emerging rapid sampling and analysis techniques such as proximal sensing to accompany conventionally acquired soil site descriptions and sampling for calibration, with improved methods and agreed protocols for pruning poor quality legacy data (Biggs and Searle, 2016).

6.1.3. Paddock-scaled operational DSM

From Section 3, a common theme from the jurisdictional DSM uptake is the limitations of current DSM products to aid paddock-scaled decisions. This has historically been the domain of private consultants or academic research trials in Australia, with government land resource agencies operating at catchment, regional or national scales. However, finer scale DSM should be able to better answer paddock-scaled questions as higher resolution covariate data becomes available and the use of rapid sampling approaches such as vis-NIR become ubiquitous. With the development of precision agriculture in Australia, more consultants are using gridded sampling and proximal soil-sensing approaches such as electromagnetic induction (EMI) techniques, which will also enable DSM technologies to bridge the gap between catchment and paddock assessments. Another scale-based research challenge is the need for operational DSM protocols to better define the minimum per hectare calibration dataset to provide a defined level of uncertainty and map quality at different resolutions.

6.1.4. Integration of operational DSM into DSA

In many of the case studies and inventory examples of DSM to date in Australia, it is evident that land evaluation requirements have driven the adoption of DSM to provide the required input soil parameters of a DSA, often due to budgetary constraints. In cases such as the Northern Australia assessment and Tasmanian ESM, this involved coupling DSM parameter ranges into a conventional land suitability approach. In the Tasmanian case study, modelling land suitability directly from the *scorpan* and climatic terrain covariates was tested, and while showing good results, was not deemed effective by end-user groups in identifying manageable soil or climate constraints to suitability and overall productivity. Initially developing the DSM and climate grids, then applying to a DSA framework was able to overcome this, with the advantage of producing a gridded soil and climate resource of various parameters that serves other uses, such as biophysical modelling. The disadvantage was the additional time taken to develop the separate DSA input parameters. Further research is needed to adapt land evaluation and biophysical modelling to take advantage of gridded DSM products, preserving the correlations between soil properties of the DSA input parameters, and DSA uncertainties. Robinson et al. (2015) described many sources of error and uncertainty in DSM; including MIR calibration errors, laboratory and field measurement error, modelling errors, and PTF uncertainties. There is a need to integrate these into the overall estimation of DSM uncertainty, and how these propagate through the DSA process to the final maps.

6.1.5. End-user requirements

DSM can produce raster products that emulate the gradational spatial nature of soil attribute changes, as opposed to crisp polygon boundaries. However, it is important to produce DSM outputs that are tailored to the end-user's needs, for example, the polygon maps requested by the end-users of the Queensland disaggregation case study. For the Tasmanian ESM, raster products with lookup tables were developed for each suitability surface, which allowed end-users to interactively identify soil and climate limitations at any location through the online mapping services. However, the end-users (industry groups) preferred no uncertainty or probability estimates included, and a simplified land suitability framework (as discussed). In this case, while it is up to DSM practitioners to develop products to fit end-user needs, they will also need to better 'sell' some products where the end users might not fully understand how they can be used, fully describe their benefits and deficiencies, and present these in easily understood formats.

7. Conclusions

Australia has developed a strong collaborative Digital Soil Mapping (DSM) community from both government agencies and academic institutions, which has enabled capacity and development of DSM into an operational discipline, used by the state, territory and federal agencies for a range of land resource assessment-based activities. Being such a large country in comparison to its population has historically made funding of soil survey challenging; DSM has allowed Australian soil agencies to continue to provide spatial soil information to decision makers. This has included a national DSM infrastructure for natural resource management and research, and sub-continental and regional land suitability mapping. Australia's unique soil mapping history has influenced how DSM became operational in this country. A series of enablers, drivers, and barriers have been identified which influenced the Australian uptake of operational DSM, along with documented 'lessons learnt' that helped to overcome obstacles to DSM, and the testing and refinement of operational DSM protocols, both in field sampling and modelling. This information provides a useful template for other countries to follow, which can accelerate and enhance their own DSM infrastructure development into operational land resource assessment and analysis. However, the Australian experience also exposes some persistent and emerging research questions that should be addressed to progress operational DSM and further encourage its uptake.

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Declaration of Competing Interest

None.

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