Geoderma Regional 22 (2020) e00314

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

# Digital soil assessment delivers impact across scales in Australia and the Philippines

Michael J. Grundy [a,*], Ross Searle [a], Elizabeth A. Meier [a], Anthony J. Ringrose-Voase [b], Darren Kidd [c], Thomas G. Orton [d], John Triantafilis [e], Seonaid Philip [f], Craig Liddicoat [g], Brendan Malone [b], Mark Thomas [h], Jonathan Gray [i], John McLean Bennett [j]

[a] *CSIRO Agriculture and Food, St Lucia, QLD, Australia*
[b] *CSIRO Agriculture and Food, Black Mountain Science and Innovation Park, Clunies Ross Street, Canberra, Australia*
[c] *Natural and Cultural Heritage, Department of Primary Industries Parks Water and Environment Tasmania, Prospect, Tasmania, Australia*
[d] *The University of Queensland, School of Agriculture and Food Sciences, St Lucia, Queensland, Australia*
[e] *School of Biological, Earth and Environmental Sciences, UNSW Sydney, Kensington, NSW, Australia*
[f] *CSIRO Land and Water, Dutton Park, QLD, Australia*
[g] *Department for Environment and Water, Adelaide, SA, Australia*
[h] *CSIRO Agriculture and Food, Waite Campus, Urrbrae, SA, Australia*
[i] *NSW Department of Planning, Industry and Environment, Parramatta, NSW, Australia*
[j] *University of Southern Queensland, Centre for Sustainable Agricultural Systems, West St, Toowoomba, QLD, Australia*

## ARTICLE INFO

*Article history:*
Received 26 February 2020
Received in revised form 22 June 2020
Accepted 24 June 2020
Available online xxxx

*Keywords:*
Digital soil mapping
Digital soil assessment
Australia
Philippines
Soil spatial prediction
Soil security
Soil covariates
Soil data systems
Multiple soil classes

## ABSTRACT

Retrospective evaluation has consistently shown that soil information has value beyond the investment used to produce it. Digital soil mapping and assessment (DSMA) is the new paradigm for soil survey and a key source of soil and land information. It promises increased utility and flexibility for the users of soil information. Does DSMA methodology add value? What are some of the outcomes and emerging impacts? Seven examples from the burgeoning use of DSMA in and near Australia have been explored to determine the nature and extent of outcomes and impact achieved. The analysis began with a workshop of key soil scientists, involved a survey of the use of DSMA and attitudes to impact amongst practitioners of DSMA and looked at each of the seven examples in the context of the systems they seek to influence. There is evidence of progress along impact pathways in each case. In the simpler systems, the products of DSMA are being used as envisaged and change is occurring. In more complex systems, the role of soil information meshes with many other influences and impact is harder to discern. Importantly, we find that few practitioners using DSMA explicitly identify impact pathways and design projects at the outset to optimise the chance of more extensive impact. Thus, an approach to planning for impact in DSMA is proposed that could improve the chance of impact and allow for iteration as our understanding of the systems in which change is expected improves through our interaction with them.

## 1. Introduction

Land resource assessment (the mapping of soil and landscapes and an assessment of their level of function) is undertaken to reduce risk by guiding land resource decisions based on better information on the state, capacity, suitability and trajectory of the resource (McKenzie et al., 2008). That soil and landscape information is seen as having value because its use leads to impacts more favourable than would be achieved in its absence or with poorer data and retrospective evaluation has shown that soil information has value beyond the investment used to produce it (eg. ACIL, 1996). This rationale for land resource assessment commonly envisages impact pathways through environmental program design, planning, zoning and infrastructure policy, regional action plans, extension and advisory activities and in land management. More ambitious information systems through the integration of soil mapping with modelling and monitoring aim to broaden that impact. So fundamental is appropriate information on the soil resource it has been described and commissioned as essential national infrastructure (Grundy et al., 2012) and soil survey in its various forms is the key means for the capture and sharing of this information.

Significant advances in soil survey techniques were developed from the 1940s that used aerial photography and soil / vegetation patterns and the observed covariance of soil factors and functions with soil taxonomic units. Such methods were analogous to those used in vegetation

---

[*] Corresponding author at: CSIRO Agriculture and Food, St Lucia, QLD, Australia.
*E-mail address:* mike.grundy@csiro.au (M.J. Grundy).

https://doi.org/10.1016/j.geodrs.2020.e00314
2352-0094/

or geology mapping. This allowed more rapid and effective mapping and became the dominant paradigm for soil survey (Hudson, 1992). However, this form of soil information has some key limitations in achieving the impact required from land resource assessment (Ryan et al., 2000) and has led to a decline in investment in soil survey in Australia and elsewhere (Soils Research, Development and Extension Working Group, 2011). Digital soil mapping (DSM) is a form of soil survey that has emerged after a challenge to traditional soil survey (e.g. Bell et al., 1992) and is partly seen as a useful addition to existing approaches that introduces more objectivity and flexibility to soil mapping practice (McBratney et al., 2003). Its application and use is therefore expected to enable further impacts.

DSM includes a suite of techniques, approaches and data systems and constitutes a replacement paradigm for soil survey. Where an assessment of suitability or condition is included, the term Digital Soil Assessment is used (DSA); we will refer collectively to both DSM and DSA as DSMA for most of this impact discussion. DSA and DSM developed from a series of experiments that explored the application of statistical tools to infer and test the distribution of soil attributes in time and space. The framework for DSMA is now well developed and there are now many instances of use over large areas (Kidd et al., 2020).

The rationale for adopting DSMA includes expectations of enabling decision making that can enhance value in achieving impact. The nature of the impacts suggested does not differ substantially from the earlier paradigms but in this paper, we explore a wider range of pathways to impact that are enabled due to increased connections to data streams, modelling, decision support systems and to the increased access to machine learning and data analytics. Is this impact being achieved? How explicit are soil surveyors in targeting enhanced impact?

The recent substantial use of DSMA in Australia and in the near region (Kidd et al., 2020) provides an opportunity to explore the expectations of impact, the extent to which these impacts are being achieved and suggest ways to optimise the effectiveness of the investment in DSMA. Here we examine a range of significant DSMA projects in Australia and the near region with varied spatial scale, clients and rationale. The breadth of examples provide an opportunity to explore the nature of impact sought, the pathways expected and pursued and the evidence of success. In addition, we look for ways to build impact into project design and implementation so that the promise of DSMA is met.

## 2. Methodology

### 2.1. Approach for assessing impact

Measuring impact from investment in soil information suffers from an attribution challenge, the more factors external to the soil investment are required to achieve impact (ACIL, 1996). It is therefore notable that investment cases for soil assessment rarely specify expected impact beyond either the specific driver for that investment or generalised statements around the use of DSMA for informed decision-making. This is a specific example of a more general challenge for prioritising investment. The literature and practice of impact assessment has gained much momentum and has emerged as one way to guide investment choices and various logic models for impact (eg. W.K. Kellogg Foundation, 2004) have been formulated to guide project design for impact. There are few examples of this form of *ex ante* impact analysis in conventional or digital soil assessment investments, however. Nonetheless, the logic for identifying the classes of change resulting from investment remains valid – whether specified in the case for investment or not. Consequently, in evaluating impact from examples of digital soil information, we have developed a theory of change for soil information against which we can identify pathways to impact and the extent to which it has been achieved.

Expected pathways of change need to be sensitive to the system that they seek to influence. Snowden and Boone (2007) developed the CYNEFIN Framework to guide how interventions in a system can be designed to increase the chances of impact; we use the same framework to explore the extent to which change is likely to be predictable or predicted. The framework recognises four system forms (simple, complicated, complex or chaotic). Each requires a different approach to impact.

In the simplest systems, there is a direct line from the customer and the intended use to the commission of the soil information products; a clear example would be the development of a new irrigation farm layout following the construction of a new dam. A conventional soil survey example is the land suitability mapping used as a direct input to farm design in the Burdekin River Irrigation Area (Day, 1993) and the digital soil mapping analogue is the assessment undertaken as part of the Flinders-Gilbert Agricultural Resource Assessment study (Petheram et al., 2013). Similar examples are specific soil information products for land zoning or reserve allocation.

Complicated systems are characterised by less engaged customers or end-users. For example, soil survey is commonly justified as an input into better soil management by farmers. Best practice survey design will, in this case, engage farmers or farm advisors in the design and delivery of the soil information activity and that will lead to product design that is intended to have wide utility to the farming community. There are, however, logistical limitations to the extent of connection to farmers and the ability to engage sufficient participants in the next stage of information use. In many cases, even a limited level of engagement does not occur. In any case, there are many other drivers of farm soil management and the additional soil information must compete for impact amongst these. In these situations, impact can be assisted for example, by post-survey communication and extension, case studies and decision-support systems.

In complex systems, the nature of the system mitigates against an actionable understanding of how information will achieve impact. In this case, the soil information products may be part of a marketplace of products with varying impact depending on change elsewhere in the system. This seems to apply to a wide range of cases where soil information is described as desired or essential and would include areas such as soil health improvement, gains in agricultural productivity, closing yield gaps or reducing off-site nutrient and sediment movement.

Where chaos occurs in the system (perhaps due to civil war, major natural disaster, economic system breakdown), an *ex ante* impact plan of any sort loses relevance and is not discussed in this paper.

We propose three impact schemas that reflect both the logic model for impact and the varying nature of systems within which the impact is expected to occur (Fig. 1).

To develop the evidence base to test this framework, we held a workshop in July including ~35 global experts and practitioners in DSMA to provide a cross section of projects and impact systems that would allow an initial analysis of outcomes. The workshop also discussed the science outputs and achievements of DSMA (Kidd et al., 2020) and considered future enhancements to DSMA (Searle et al., 2020). Along with the workshop, we polled DSMA practitioners on impact attitudes and experiences, with 97 responses received.

Quantifying impact has major challenges in attribution as local control is lost beyond the production of project products (see discussion in Douthwaite and Hoffecker, 2017 and Rogers, 2014) Additionally, the time frames of impact may be longer than is available within the cases and examples explored here and for much of DSMA. Nonetheless, we consider it instructive and useful to begin a robust process to evaluate DSMA for impact and to identify options that might increase future impact. While many aspects of outcomes and impact are necessarily beyond the direct control of those proposing and delivering DSMA, we propose that it is possible to describe a defensible chain of causation.

With this framework, we evaluate a range of significant DSMA projects - the nature of the system they engage, the *ex ante* expectations of outputs, outcomes and impact pathways, the outputs of the projects, the impact thus far and consider the execution against the system and expected impact. The seven projects are listed in Table 1 and are mapped against the systems in which they aim for impact in Fig. 1.

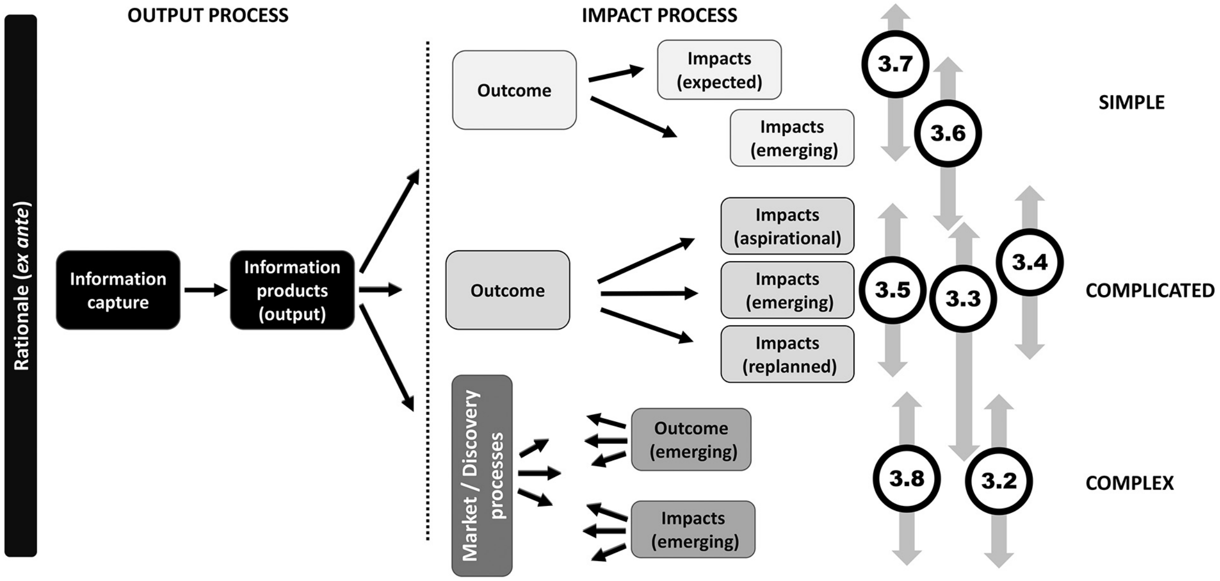

**Fig. 1.** A characterisation of the variable nature of the systems that DSMA aims to impact (derived from the ideas of Snowden and Boone, 2007). Reviewed case studies numbered according to their section within the paper are mapped across the systems where they expect impact.

**Table 1**
The seven project case studies reviewed for impact, numbered by the section within the paper.

| Section | Case study | Scope | Impact system category (CYNEFIN) |
|---|---|---|---|
| 3.2 | Soil and Landscape Grid of Australia | Continental | Complex – a response to many expressed needs |
| 3.3 | Cabulig River Watershed, the Philippines | Large catchment as a regional case study | Complicated to complex – from action within the catchment to system change more broadly |
| 3.4 | Northern Australia | Large catchments (part of a program across key northern catchments) | Complicated (but complex as a changed system is developed) |
| 3.5 | Tasmania | Tasmanian agricultural landscapes | Complicated |
| 3.6 | Australian grain industry | Large region across southern and eastern Australia | Simple to complicated (commissioned work that met the immediate needs) |
| 3.7 | Australian cotton industry | Region within central eastern Australia | Simple |
| 3.8 | Farm decision support | Farmers across Australia (rainfed systems) | Complex |

## 3. Results

### 3.1. Context - a survey of attitudes to impact amongst DSMA practitioners

Ninety-seven respondents from 29 countries (24 from within Australia) responded to a survey on impact and DSMA. The majority of respondents (89%) are using DSMA in an operational context, over a range of scales and most are using both new data collection and repurposed legacy soil data. Over 60% had been using DSMA for 10 years or less. The respondents identified a wide range of areas that they expected to impact with DSMA (Table 2).

The survey also asked where systematic attempts to measure impact had taken place. The results indicated that there were few if any such evaluations and virtually no explicit impact planning beyond the initial project brief.

### 3.2. Application at national scale – The Soil and Landscape Grid of Australia

#### 3.2.1. Nature of the system

National scale soils information is critical infrastructure informing decisions across domains in environment, agriculture, engineering and research. 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 and producing mapping products to meet state and territory requirements that have varied substantially between jurisdictions and frequently within them, leading to locally useful but nationally disparate systems (Searle, 2014). It has thus been difficult to produce nationally consistent soils information across the entire continent that is readily accessible and useful at a range of scales. Each time such a compilation has been attempted, continuous access and improvement has been limited by further disconnected development in the jurisdictions.

**Table 2**
Area that DSMA has had an impact (many respondents identified more than one area of impact).

| Area of DSMA impact | % of responses |
|---|---|
| Environmental monitoring | 18.0 |
| Environmental accounting | 7.9 |
| Systems modelling | 12.9 |
| Future scenarios | 10.7 |
| Government policy | 12.4 |
| Infrastructure and logistics | 5.1 |
| Land suitability or capability | 16.9 |
| Land use planning | 15.2 |

The first version of a comprehensive national map was the Atlas of Australian Soils (Northcote et al., 1960–68), coordinated by CSIRO in the 1960s to provide a consistent description of Australia's soils. This was separate to and disconnected with the state agency surveys that increased in scope and effort through the 1980s and 1990s. Thus, there was an additional need to collate and transform agency soil data to provide nationally consistent soils information connected to the agency effort: the Australian Soil Resource Information System (ASRIS) (Johnston et al., 2003). While they remained disconnected, each was useful and applied to a wide variety of national issues. Both had, however, fundamental limitations in the level of spatial detail, consistency, spatial coverage and accessibility that restricted their utility. Beyond the national context these soil information systems required substantial modification to contribute to global syntheses of the nature and distribution of soil properties.

The impact of an effective national soil information system is potentially large but challenging to specify. A wide variety of economic, environmental, agricultural production and social issues require soil data. The group of potential stakeholders is as large and varied as these issues and they require a diverse range of data and information products in many formats. The impact system is complex.

Despite the difficulty in specifying one clear impact pathway, the need for an improved and flexible national soil information system seems clear. A new approach was needed in the integration and delivery of Australian soils information (Grundy et al., 2012). That required a new way of weaving together the legacy of rich and diverse data available across many different organisations.

### 3.2.2. Ex ante expectations

Sanchez et al. (2009) observed that existing soil maps across the globe (and within countries) do not adequately express the complexity of soils across a landscape in an easily understandable way. They challenged soil scientists to produce a fine-resolution, three-dimensional grid of the functional properties of soils relevant to users that is freely accessible and readily available for land-users, scientists, and policy-makers.

Within Australia, the National Soil Research, Development and Extension Strategy (Dept. of Agriculture, 2014) identified the need to improve quality, availability and access to soil data and information in order to meet unsatisfied user needs.

The response to these challenges and support from the Terrestrial Ecosystem Support Network (TERN) has led to the development of the TERN Soil and Landscape Grid of Australia (SLGA), conceived to generate relevant, consistent, comprehensive, nation-wide data in easily-accessible formats (Grundy et al., 2012). The impact areas identified included, amongst others: 1) shifts in the distribution and intensity of agriculture, 2) arresting the decline of agricultural productivity, 3) improving catchment management in those catchments of national importance and 4) broadening the mix of land use options. In the design of SLGA, access to and use of the system needed to go beyond the current mix of users so that change could be supported across the breadth of these issues. As a result, Grundy (2014) concluded that “The test of the Australian Grid (SLGA) will be the extent to which major stakeholders use it in managing land management issues”.

### 3.2.3. Description / referencing the DSMA activities and outputs

The SLGA uses all the currently available soil data to model the distribution of soil properties across the entire continent (Viscarra Rossel et al., 2015). It provides a nationally consistent set of continuous soil attribute surfaces modelled at 6 standard depths at a 3 arcsecond resolution. The attributes included pH, sand, silt and clay contents, effective cation exchange capacity, bulk density, depth, available water capacity, organic matter content, total P & total N. The SLGA products are based on GlobalSoilMap specifications (Arrouays et al., 2014). In addition, new fine scale terrain derivatives relevant to land management and the depth of the regolith were estimated (Gallant and Austin, 2015; Wilford et al., 2016). A range of assessments has demonstrated an improvement in prediction using the SLGA in model applications, eg. Kearney and Maino, 2018.

The SLGA delivered new and nationally consistent soil datasets freely through an online web portal. It did so using leading web delivery technologies so that they are easily and readily accessible to industry, researchers and the general public.

### 3.2.4. Observed outcomes and description of impact pathways / trajectories

The aim of the SLGA was to have impact at a national level and across a breadth of complex issues. The impacts can be specified in general terms but are difficult to quantify with simple metrics and take time to be realised. The uses and therefore the potential outcomes are broad, many and varied. The published principles behind the design identified broad pathways; here we present some outcomes as indicators of the impacts the SLGA is having.

The openness of the information system means that a chain of access, use and impact is not clear and therefore it is difficult to determine exact uses of the datasets. However, detailed download statistics that provide indicators of users and applications are available and many of the uses leading to impact are known anecdotally and through industry involvement.

The SLGA products are the most downloaded products from the CSIRO data portal, a national, scientific data portal. To date, using the delivery methods implemented by the SLGA, over 168 Terabytes of soil data has been downloaded across Australia (https://www.clw.csiro.au/aclep/soilandlandscapegrid/GetData.html). Over 1.3 million downloads have occurred using the information infrastructure (Fig. 2). The web site supporting the data delivery infrastructure has received 240 visits per week on average since the products were delivered in late 2014.

SLGA data is being accessed by user groups that include Government agencies, agriculture industry advisors, software developers, infrastructure and engineering consultancy firms, environmental consultants, environmental and agricultural researchers, educational institutions and private individuals. This is a breadth of user access that matches and exceeds that expected in the design of the SLGA and on which the impact path was predicated.

Uses for the data products are therefore broad and include soil moisture monitoring and modelling, infrastructure planning, such as pipeline and railway corridor developments, agricultural productivity improvements, ecological assessments, broad scale land development proposals and education.

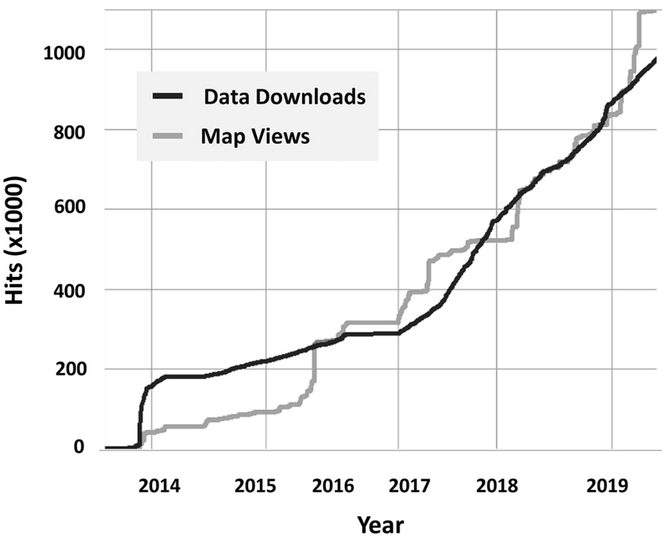

**Fig. 2.** Data download and data view counts pertaining to products from the Soil and Landscape Grid of Australia.

Anecdotally, the success of the SLGA in this first phase since release has been due partly to the consistent and comprehensive nature of the soil information (the same specified attributes on a consistent grid at defined depths) and ease of access and use. Both are features of the DSMA approach.

By developing innovative soil data web APIs, the SLGA has eased the path to impact for a range of purpose built decision support tools. Before the SLGA, if data were at all available for the area of interest, access was often cumbersome and time consuming. Due to the ease of access and extensive coverage and consistent formats, the SLGA has shown a demonstrable surge in the use of soils data in decision making.

In agricultural industries, lack of soil information has often limited the impact of industry decision support tools aimed at assisting productivity improvement and reducing risks for primary producers. Users of these decision support tools are generally required to have a detailed understanding of soil parameters to enable them to get answers to their specific questions such as soil water status or management scenario assessments. Several industry decision support (DSS) tools have now incorporated SLGA data and have reported anecdotally an increase in usage; key examples are discussed in Section 3.8. Although it is difficult to definitively link the cause and effect here, the SLGA has clearly eased the path to this critical data requirement and therefore to broader impact.

Published research suggests a wide range of influence in scientific activity. It includes the use of the SLGA in applications as diverse as continental soil moisture for climate modelling (Kearney and Maino, 2018), agricultural system adaptation (Kath and Pembleton, 2019), landscape change events such as post-fire erosion (Yang et al., 2018) and vulnerability of valued landscapes to extreme events (Zhu et al., 2020), a range of biodiversity applications including broad-scale ecological transitions (Guerin et al., 2018; Guerin et al., 2019) and ecological shift due to aridity (Anderegg et al., 2020), adaptation of birds to heat stress (Medina et al., 2018), habitat of endangered orchids (Reiter et al., 2018) and taxonomic discussions (Hammer et al., 2018), groundwater recharge (Crosbie et al., 2018), soil carbon stocks at a range of scales (Liddicoat et al., 2015; Luo et al., 2019), as well as disease risk in sheep (Taggart et al., 2019) and people (Liddicoat et al., 2018). It is also an important component of Australia's recurring State of Environment Report (Metcalfe and Bui, 2017).

#### 3.2.5. Assessment of impact

Is Grundy's *ex ante* challenge of “the extent to which major stakeholders use it in managing land management issues” clearly met? There is evidence that the likely groups that drive or achieve impact are accessing and using the SLGA. Although measured downloads and dataset views do not directly measure the extent to which the soil attribute data are being used in decision making, communications with end users along with the large number of downloads and views suggest that the data are being used in real world decision making. Informal communications with stakeholders and users identify where the data are being utilised in industry targeted decision support tools and in broad scale policy development.

While the free and public access via anonymous web services enhances access to the soil data, the impact pathways are to some extent hidden. A design feature of such systems that captures the use and intent of data access will increase the understanding of the connection between system design and impact achieved.

### 3.3. Application at regional scale – Cabulig River Watershed, the Philippines

#### 3.3.1. Nature of the system

Population growth and displacement by urban and large-scale agricultural development in the Philippines has led to the increased use of marginal sloping lands for small-holder agriculture with substantial risks of increased soil erosion, degraded watershed function and landscape degradation (Acub et al., 2011; Calalang and Colinet, 2014; Malenab et al., 2016). Essentially, there is a mismatch between land use and land use practice and the capacity of the land to sustain those practices. While the development of the instability issues could be classed as a complicated system, system improvement requires different pathways of repair from an altered system by actors that have, in most cases, limited agency to effect repair (Davila et al., 2018). The DSMA contribution to impact is complex.

#### 3.3.2. Ex ante expectations

DSMA was introduced as part of the solution (and as part of a group of improved land management projects funded by the Australian Centre for International Agricultural Research or ACIAR) in the expectation that new or better land allocation plans would arise, that increased knowledge of the resource would guide the development of locally adapted land management systems and that total factor productivity would increase. The expected impact pathway requires planning instruments based on the products from the DSMA, new land management systems informed by the DSMA, extension programs and, then, widespread adoption of improved systems. In addition, allocation of new land could proceed with better information. It is possible that the DSMA would also allow prioritisation of repair activities amongst options such as terracing, shelter belts, erosion control works (plantings, banks, waterways) and gully remediation.

Less direct pathways from the DSMA were also seen as possible. Installation of infrastructure to improve marketing and market access could be guided by new land use plans opening up a broader range of industry across value chains.

Beyond this immediate influence of the DSMA, outcomes that included improved livelihoods, reduced erosion, more stable watersheds and ultimately fewer flood events, while dependent on the improved soil and landscape information, required additional inputs and initiatives.

#### 3.3.3. Description / referencing the DSMA activities and outputs

The outputs of this project were a digital soil atlas of the Cabulig River Watershed in Mindanao, a mountainous area covering 220km$^2$, together with a land suitability atlas derived from the soil survey with suitability ratings for 40 cropping and agroforestry systems. Both atlases were raster-based with 20 m cells. The soil atlas showed the continuous variation of soil attributes across the landscape (Ringrose-Voase et al., 2019).

DSMA identified areas suitable for diversification into other crops or farming systems. Land use planning activities developed land units with a range of suitable farming systems, with the introduction of agroforestry systems (e.g. based on rubber and cacao) into areas identified as unsuitable for current land uses.

The impact pathway began with rural land use planning that involved stakeholders within the catchment including provincial authorities and authorities from 3 local government units within the watershed together with representatives from farmer groups, NGOs and industry. The soil atlas underpinned the development of a land use plan that recommended broad categories of land use in different land units. Location specific packages of land management practices were developed to overcome land constraints – slope, soil acidity, rockiness, soil depth and low soil fertility. In addition, the project contributed to targeted in-country capability building by increasing skills and tools for optimised sampling design and field sampling approaches and novel soil measurement through soil spectroscopy inference.

#### 3.3.4. Observed outcomes and description of impact pathways / trajectories

Land use plans were developed as envisaged and were used to drive various interventions to improve the state of the Cabulig River catchment in the face of multiple demands on the system. Some specific uses of the project outputs include:

- Planning for an increase in base flow so that more water is available in the dry season for both municipal water supply and electricity generation;
- Advice to influence the smallholder farmers using unsuitable farming systems in steep lands;
- Advice to allow a small hydroelectric company to increase generation, especially in the dry season when flow becomes too low to use both available turbines;
- Planning to allow municipal authorities of the town of Jasaan at the mouth of the Cabulig River who source water for the town from the river to reduce the risk of flooding in the wet season; and
- Support for the village of San Nicolas on the lower floodplain to reduce the risk of flash flooding.

Plans initially identified areas requiring reforestation to reduce flash flooding, but in a compromise to smallholder farmers in the area an amendment suggested agroforestry options using only perennials. In less steep areas, recommended land uses included agroforestry systems with annual crops and in even less steep areas included annual cropping systems with implementation of soil conservation measures.

#### 3.3.5. Assessment of impact

The funding body for Australian agricultural research for development (ACIAR) develops programs of research in countries or regions that then informs which individual projects are funded. These programs, rather than individual component projects, are reviewed as part of the process of refining and building new programs. In addition, it specifically funds projects that provide an *ex post* impact assessment (for example, McMillan et al., 2019). As a result, this DSMA project has not yet been evaluated. Impact pathways that the funding expected have been started, but no data are yet available on their effectiveness. Additionally, without follow up evaluation, the extent to which the power of the DSMA approach is realised is not yet known.

### 3.4. Application at regional scale – Northern Australia

#### 3.4.1. Nature of the system

Agriculture in northern Australia (in areas other than the wet tropical north-east and in relatively small irrigation areas) is characterised by extensive cattle grazing on predominantly native pastures. There has been significant community and political interest in developing more intensive agricultural systems over much larger areas than present – although key areas of vulnerability have been identified and acknowledged (Ash et al., 2017). A review of knowledge of northern systems (Northern Australia Land and Water Taskforce, 2009) concluded that the natural environment and the cultural systems of the current population are interdependent with the region's high natural values and that development, uninformed by the impacts and trade-offs inherent in change, can directly reduce these values. A move to increased land use intensity requires at least effective information underpinnings; including enhanced information on the nature, state, vulnerability and distribution of soil resources with the potential for increased development (Ash and Watson, 2018). Digital soil assessments (as part of a wider systems investigation) were designed to provide these data in key catchments in northern Australia (Petheram et al., 2012).

#### 3.4.2. Ex ante expectations

The immediate impact pathway after the publication and release of soil and land suitability information assumes the use of the information to guide choices in more intensive agriculture. This is expected to include:

1. Design of irrigation options within the existing dominant agricultural land use (mosaics of complementary irrigation activities within grazing leases);
2. Small scale irrigation farms excised from current land uses;
3. Larger scale cropping and feedlot systems drawing water from existing streams or groundwater; and/or
4. New irrigation schemes based around new dams or similar infrastructure.

For the former three options, a change to water access and rights would be evidence that change is occurring. For the latter, more intensive development, business plans, feasibility studies and the like would be the initial steps along an impact pathway. It is also envisaged that the information will inform a decision not to proceed with development; with potential benefits in financial costs avoided and fewer environmental and cultural impacts.

To this point, this could be considered a complicated rather than complex system. Longer term and more systemic impacts are much harder to predict and the system is at least complex. Northern Australian agricultural systems, even the dominant beef cattle industry, require more cost-effective and efficient supply chains and are currently challenged by inadequate infrastructure and transport logistics and the current lack of local processing facilities at scale. Time lags before positive returns on investment are likely and can be exacerbated by climate extremes and variability and other unexpected shocks (Ash et al., 2017). Beyond agriculture (and the intent of the northern Australian resource assessments was to look at the broader sustainability of rural and regional communities), the influence of the DSMA is dependent on decision-making informed by the products of the assessment and other relevant information, tracking of change and measurement of expected and emergent changes and the capacity to intervene where and when needed. This part of the impact system will be realised over decades; the pathways and impact of the Ord River developments, arguably not planned with as much rigour (Graham-Taylor, 1982), remains unclear and debated over 50 years since inception (Davidson, 1982; Greiner, 2002; Turville et al., 2014).

#### 3.4.3. Description / referencing the DSMA activities and outputs

The digital soil assessment of the Flinders and Gilbert catchments in northern Australia (109,000km$^2$ and 46,200km$^2$ respectively) had three key stages:

1. Collection of key data (collation of legacy data and new stratified sampling of the soil environment);
2. Development of fine-grid digital surfaces of soil attributes to depth (Thomas et al., 2015); and
3. Assessment of the suitability of the land thus characterised for irrigated agricultural production with estimates of reliability (Bartley et al., 2013; Harms et al., 2015).

Area of suitable land covering 76 potential irrigation land uses was estimated and for each the key limitations and relevant soil data were released as maps, digital data and reports. This element of the overall assessment was placed in context with reports and data on the broader environmental and economic assessment of the full system study (Petheram et al., 2012). The data and reports are stored on a data repository (eg. doi:https://doi.org/10.4225/08/53041A2A185C1) and the data are accessible and viewable on the "NAWRA-explorer" (https://nawra-explorer.csiro.au/).

#### 3.4.4. Observed outcomes and description of impact pathways / trajectories

The conclusion of the full-system study (incorporating the DSMA) led to widespread communication of the measured potential for more intensive agriculture. The assessment commissioned by the Federal Government was considered both successful and a template for future investigations. The Government allocated AUD$15 m to undertake further assessments in three large areas in Queensland, Northern Territory and Western Australia (since completed) and a new study, recently commenced, in the Roper River catchment in the Northern Territory (AUD$3.8 m).

Accessing water from regulated Queensland streams and groundwater resources (and in general across streams in northern Australia) requires a water entitlement, applications for which are assessed against relevant criteria in the Water Act 2000 (https://www.legislation.qld.gov.au/view/html/inforce/current/act-2000-034; accessed 8 Oct). The Flinders and Gilbert study led to a review of the Gulf Water Resources Plan and identification of additional unallocated water resources. The DSMA provided evidence that was then used by development proponents to apply for increased water allocations, initially for relatively minor increases in extraction from the major streams, and then for large scale developments. An increase in licence fees of about AUD$10 m per year has resulted. Large scale and notable proposals have emerged. Some have lapsed. One led by the Integrated Food and Energy Development (IFED) developed a business case for a AUD$2 billion integrated agricultural system in the Gilbert catchment (Integrated Food and Energy Developments Pty Ltd, 2013). The proposal did not proceed (https://www.dsdmip.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/projects-discontinued-or-on-hold/etheridge-integrated-agricultural-project.html - accessed 9 October). Other lapsed projects of some size include the Three Rivers Irrigation Project (15,000 ha). Subsequently and also based on the DSA study, the Etheridge Shire Council has released a project brief for the “Gilbert River Irrigation Project” aimed at a smaller area of irrigated land and a smaller water storage (20,000 ha and 200,000ML respectively). A smaller project, the 15 Mile Irrigated Agricultural Development project, was approved in July (http://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects/completed-projects/15-mile-irrigated-agricultural-development-project.html - accessed 9 October). The intention is to follow that with a larger irrigation project valued at AUD $300 m (with Federal Government investment of AUD$180 million approved). The data have also been tailored to the needs of potential indigenous enterprise development.

Each project has referenced the DSMA and related studies and these are foundational for the required environmental assessment.

#### 3.4.5. Assessment of impact

To this point, the DSMA has led to pathways anticipated in the *ex ante* justification for the studies. Failure to proceed with large investments is an immediate impact, if and only if the study contributed to a robust assessment. These decisions are rarely publicly available and, in the case of the Flinders and Gilbert River, have not been.

Beyond the current initial responses to the studies, the broader questions remain unanswered and are unlikely to be for many years.

### 3.5. Application at regional scale – Tasmania

#### 3.5.1. Nature of the system

One of the first jurisdictions in Australia to implement operational DSMA was the State of Tasmania, an island off the mainland's south east coast. Its area is approximately 68,000 km$^2$, and population around 0.5 million, with a heavy reliance on agriculture, forestry and tourism. Since 2010, the Department of Primary Industries Parks Water and Environment, Tasmania (DPIPWE), has been developing a DSMA program of Land Suitability. This was initially a pilot project to test and operationalise DSMA and climate modelling technologies in two areas totalling 70,000 ha, as a collaboration between DPIPWE and the University of Sydney (Faculty of Agriculture and Environment) Australian Research Council Linkage Project (Wealth from Water - LP110200731). Considered by the Tasmanian Government and project stakeholders to be a success, the pilot project was expanded State-wide in 2014 to form part of the ‘Water for Profit’ Program (DPIPWE, 2015; UTAS, 2015), a joint undertaking between DPIPWE, the University of Tasmania, and the Tasmanian Institute of Agriculture (TIA). The DSMA involved strategically collecting new soil site information, combined with legacy data, to develop a DSMA resource for Tasmania at 30 m resolution. A temperature sensor-network was also established to integrate with long-term meteorology records and produce 30 m resolution climate grids as part of the suitability rulesets. Suitability rulesets of soil, terrain and climate were developed for 36 crops using existing literature, trial data, and expert input from industry group agronomists and the TIA, which formed the basis for integration of the soil and climate grids into the DSMA (individual enterprise suitability maps).

#### 3.5.2. Ex ante expectations

The Water for Profit Program was a four-year staged venture designed to stimulate impacts such as investment and innovation in Tasmanian agriculture, particularly the primary industry and food sectors which includes ongoing investment in water infrastructure (Tasmanian Irrigation, 2015). The DSMA component of the Program was developed to deliver decision support products across a range of criteria critical for optimal productive agriculture, and capture new and existing information on soils, climate, crop requirements and markets and augment this information with strategic data collection to produce decision-support tools which are consistent with the needs of present and future investors (Agrigrowth Tasmania, 2015). The projected project outcomes were encouragement of rapid land use change to sustainable production of higher-value crops (such as high quality perennial horticulture, therapeutic drug crops, seed crops and wine grapes) based on identified market needs, particularly in newly commissioned irrigation areas and to maximise economic benefits of irrigation at both enterprise level and throughout the wider community. The targeted project outcomes were to develop an improved information resource and decision support to achieve optimal agricultural land use, sustainable management practices and investment decisions. This information provision was expected to facilitate a reduction or mitigation of environmental risks to farmers, investors and landowners associated with shift to higher value, irrigated agriculture. The DSMA outputs and methods are described in greater detail in (Kidd et al., 2020 this issue), Kidd et al. (2015) and Webb et al. (2015).

#### 3.5.3. Description / referencing the DSMA activities and outputs

The DSMA was created using newly-collected and legacy soil site data, and a suite of covariates, using a 30 m resolution SRTM-DEM and derivatives, gamma radiometrics, NDVI, geology and vegetation maps. The geology was obtained from a combination of 1:25,000 (where available) and 1:250,000 maps and integrated into a hybrid geology-gamma radiometrics product, processed to 30 m resolution, as described in Kidd et al. (2015). NDVI was generated from 25 m resolution LandSat (2014), and vegetation mapping using 1:25,000 TASVEG products, a combination of field-mapped and remotely-sensed Tasmanian vegetation communities. It was validated using standard DSM cross-validation approaches for the soil and climate attributes, field-validation, with the final DSMA spatial extents and rule-sets validated in face-to-face consultation with industry experts and grower groups, to ensure the mapping aligns with expert local knowledge, as well as individual industry needs and preferred formats. DPIPWE also provided group training in the use of the DSMA and delivery systems for consultants, growers, Natural Resource Management Groups and relevant Government Departments such as State Growth and Biosecurity. This process ensures appropriate feedback is received and used in aligning DSMA products to end-user requirements in addition to quality control.

#### 3.5.4. Observed outcomes and description of impact pathways / trajectories

An observed outcome of the Tasmanian DSMA is integration of the enterprise suitability mapping into a new State-wide planning scheme, specifically to identify important agricultural and rural resource zones and provide a tool for local government to prohibit non-agricultural development in these areas (Department of Justice, 2018; Macquarie Franklin and Esk Mapping & GIS, 2017). This integration of the DSMA for different crops and existing infrastructure, urban zones, with areal fragmentation and proximity analyses identifies areas that are biophysically and socio-economically important to different industries, ultimately helping to protect agricultural land from the pressures of urban encroachment, and associated losses in agricultural productive land.

### *3.5.5. Assessment of impact*

The full set of expected impacts of the Tasmanian DSA enterprise suitability assessment products includes aspirational influences on Tasmanian agriculture, specifically diversification and intensification, and increase in productivity. Tangible impacts can not yet be evaluated, partly because the latest 30 m resolution DSA was only published and made available online since April 2018, but mainly because the program scope failed to include a system to measure the DSMA impacts; an oversite in many land resource assessment projects. Land use change has resulted from or through consultation of the DSMA suitability products, however, this has only been noted through anecdotal sources; future work will strive to document these instances to get an overall areal estimate of DSMA impact to Tasmanian agriculture.

An indirect metric of the potential for impact is through the cumulative DSMA recorded ‘site visits’ from the online mapping portal (theLIST., https://www.thelist.tas.gov.au/). This does not measure direct impact in terms of the products being used, merely a cumulative indication of anonymous public and professional interest in the suitability maps. It is also acknowledged that some site visits may have been uninformed visits looking for general information, or visits in error. In the period between April 2018 and February 2020, there have been in excess of 330,000 total site visits to the suitability maps, and some discrete soil and climate products. These statistics exclude climate-change land suitability projections, where downscaled climate change scenarios were applied to the suitability maps for the years 2030 and 2050 (Webb, 2015). Of the available online DSMA maps, the two most visited were table wine grape suitability and blueberry suitability (27,782 and 26,199 visits respectively). These figures show that there is a substantial level of interest in the products (relative to the Tasmanian population) and may provide an early indication of the potential for emerging crops and associated land use change. However, it doesn't indicate the maps are actively being used for their intended purpose (Fig. 3); further survey of use is needed.

The DSMA infrastructure that has been developed is also providing originally unintended but desirable outcomes in other areas of government, due to the nature of the DSMA resources developed, for example:

- ad hoc investor suitability mapping for the Office of the Coordinator General;
- mapping wild rabbit habitat for biosecurity planning;
- soil hydrology inputs and flood impact modelling for the Tasmanian State Emergency Service; and
- organic soil mapping in the Tasmanian World Heritage Wilderness Areas for Parks and Wildlife fire management planning.

These DSMA products have only been recently developed, with impact assessment in early stages or additional to the initial project scope.

## *3.6. Application at regional scale – soil constraints in the Australian grain industry*

### *3.6.1. Nature of the system*

The Australian grain industry achieves consistently lower yields than other areas globally and is a relatively high cost producer, although grain quality ensures higher prices on the export market (Herbert, 2018). Yield is challenged by high climatic variability that is being exacerbated by climate change (Hochman and Horan, 2018). In addition, edaphic constraints are widespread in Australian soils and have a direct impact on grain yields in Australia. Yield improvement (while maintaining grain quality) is a current national priority (Robertson et al., 2016). Recent studies have shown that there are opportunities for more effective and profitable management of subsoil constraints (Dang et al., 2010). Digital soil mapping and assessment approaches were seen as an important component in extrapolating paddock and farm level studies of the yield gap caused by subsoil constraints (Dang and Moody, 2016) across the industry to quantify the costs and therefore identify profitable options for management (Clarry, 2015). These constraints, by their nature, are unseen and challenging to measure and map so considerable doubt exists as to whether the cost is realised and if land management effectively manages the threat to production and profitability. This implementation of DSMA was seen as a first and essential step in

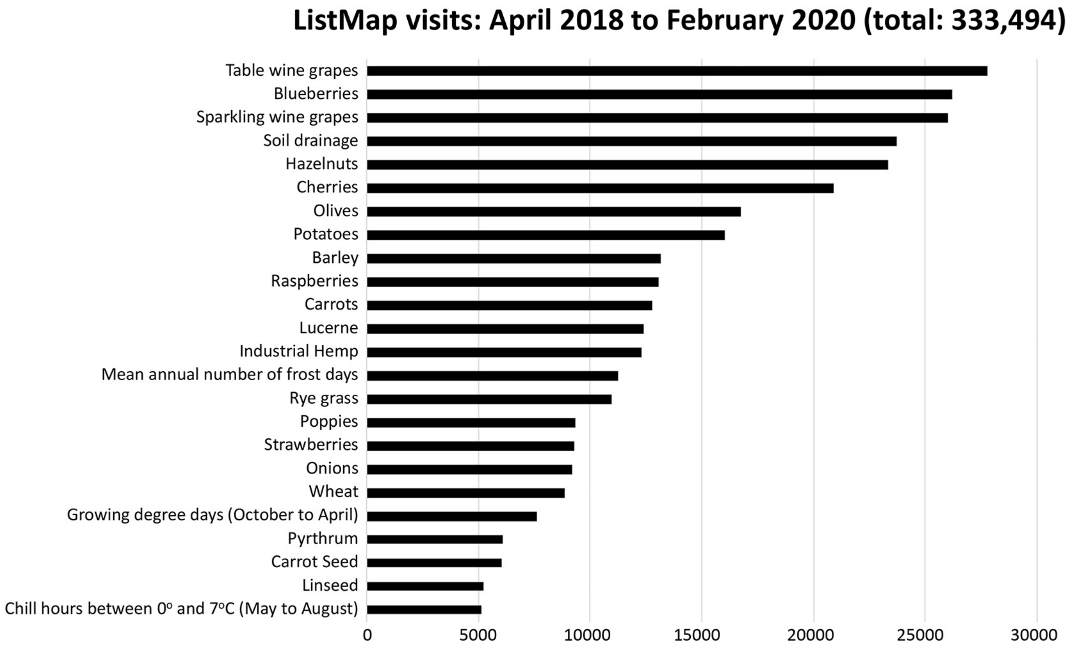

**Fig. 3.** Tasmanian LISTmap DSMA Internet visits.

gauging the extent of the issue and the cost to industry. New approaches to management and then cost reduction were seen as next steps.

#### 3.6.2. Ex ante expectations

The DSMA project aimed to: 1) quantify and develop a national map of forfeited grain yields due to specific soil constraints, and 2) develop a framework for assessing the economic-benefit of ameliorating and/or managing specific soil constraints. The assumption was that the Grains Research and Development Corporation (GRDC) would use the information as a key input into discussions around more targeted investments into amelioration of soil constraints. What are the constraints, where are they expressed, and what would be the potential increase in yields were these constraints to be overcome? The broader impact would then be higher levels of crop productivity. The existing soil map products could not meet these aims.

#### 3.6.3. Description / referencing the DSMA activities and outputs

The DSMA and costing approach accessed data from a variety of sources combined in a series of steps to meet the project objectives (Orton et al., 2018). Broadly, these steps involved:

1. For each soil constraint (soil sodicity, acidity and salinity), a function was developed that represented the impact of the soil constraint on wheat yield at data points across GRDC regions;
2. The developed function was applied to calculate yield gaps due to the soil constraint at soil profile data locations; and
3. Regression kriging was then applied to predict the yield gap due to each soil constraint on a 1 km grid across Australia's wheat cropping land, before predictions were aggregated to the spatial support of SA2 level (a regionalisation of Australia used for multiple statistical reports; there are 2310 regions across the continent) for reporting.

GRDC received project outputs in the form of maps of the spatial distribution of the yield gaps due to sodicity, acidity and salinity (all as averages across SA2 regions), tables summarising the broad-scale results (at state and national level), and a spreadsheet allowing GRDC to access and compare predicted yield gaps for different constraints and in different SA2 regions. The tables and maps were designed to provide GRDC with the information for their discussions around the relative importance of soil constraints in different regions and provide them with information to determine future investment in subsoil constraints. For example, where sodicity was mapped as the major soil chemical limitation to crop yields in a specific region, then further investment into amelioration strategies (gypsum application, deep ripping, selection of resistant cultivars) might be expected as an outcome. The broader system outcome of reduced subsoil constraint effects on production and profitability requires further outputs and implementation.

#### 3.6.4. Observed outcomes and description of impact pathways / trajectories

GRDC have used the various outputs from the study (DSMA approaches allied with economic analysis) to build business cases and key investment targets around potential solutions for subsoil constraints (Hugo Alonso-Cantabrana, Gillian Meppem-Mott; personal communications). They report that the mapping and quantification of yield gaps has provided focus to these cases; the impact of such solutions is, however, dependent on system wide change with a wider set of unknowable influences. The information has also been used by GRDC in strategic discussions on key investment targets related to soil constraints. GRDC investments have since been advertised and funded in the area of spatial diagnosis and ameliorating soil constraints (https://grdc.com.au/research/applying-and-reporting/current-procurement/closed-tenders/9175385).

Broader use, not explicitly planned in the project development, has included a review of the major chemical soil constraints affecting yields in the New South Wales and Queensland grain-growing regions, the relative importance of the constraints, and amelioration options (Page et al., 2018).

#### 3.6.5. Assessment of impact

In this case, the project proposal was explicitly aimed at a clearly constrained subsystem of a broader and complex land management system. The subsystem was essentially to fill an identified information gap, essential but not sufficient to meet the larger need. Within the subsystem however, the DSMA approach met the *ex ante* expectations that could enable longer term impact and delivered additional unforeseen benefits.

### 3.7. Application at field, farm and district scale - estimating deep drainage in the Australian cotton industry

#### 3.7.1. Nature of the system

The northwest slopes and plains of New South Wales, Australia, are highly productive agricultural areas. The dominant soils in the region are cracking clays. The climate is semi-arid (rainfall ~500 mm/year; annual average temperature 27 °C), however water is available for irrigation and is used for cotton production (~ 6 megalitres per hectare per annum). While water use efficiency on the field level is improving, losses from conveyance infrastructure and water storages may be problematic across fields and districts. There is a significant hazard in a small proportion of the landscape (15%) where prior stream channels characterised by more permeable soils are located. Apart from reducing production and profitability, deep draining water can potentially cause salinity in poorly drained (e.g. sodic) soil or mobilise salts held in connate stores deep in the regolith (Buchanan et al., 2017). DSMA approaches provide methods to delineate these risk areas. The DSMA impact system is simple in this case.

#### 3.7.2. Ex ante expectations

In 1998, The Cooperative Research Centre for Sustainable Cotton Production funded an environmental audit to better understand the salinity threat caused by leakage from conveyance infrastructure and water storages. The deliverables to the Cotton Industry were to be case studies of how DSMA could assist irrigated cotton farmers mitigate the salinity threat.

One of the specific sub-projects was to develop methods to map deep drainage risk at the field- (244 ha) and district-scale (40,000 ha) across the Ashley irrigation area using proximal soil sensors (i.e. Geonics EM38, EM31 and EM34).

The explicit *ex ante* objective was that through generating DSMA of deep drainage risk areas, irrigators would be able to identify where irrigation fields might need reconfiguration, where conveyance infrastructure could be re-routed or where water storages should be decommissioned, redesigned or relocated from areas deemed to be at high risk of deep drainage. Targeted cost savings could be made by producers who implement specific works to reduce water losses from the irrigation system. Given the direct links of soil type to potential water losses, the understanding delivered by DSMA provides a relatively simple impact pathway.

#### 3.7.3. Description / referencing the DSMA activities and outputs

To map the areas of potential deep drainage, a Mobile EM Sensing System (MESS) was developed, utilising EM38 and EM31 devices (Geonics. Ltd., Mississauga, ON, Canada), to produce maps from paddock to regional scale. Triantafilis et al. (2002) described how the MESS could be deployed across an irrigated cotton field in the lower Namoi valley to identify causes and manage the problem of minor soil salinization. In the lower Gwydir valley, Triantafilis et al. (2003) describe how equivalent digital data (i.e. EM38) was collected on transects spaced 48 m apart using a MESS. The EM38 data was used to select 81 sampling locations, where samples were collected at four depths including, topsoil (0–0.3 m), subsurface (0.3–0.6 m), subsoil (0.6–0.9 m) and deeper subsoil (0.9–1.2 m). They were analysed for particle size (clay, silt and sand) and exchangeable cations (Ca, Mg, Na and K).

At the regional scale Triantafilis et al. (2004) describe how a similar set of EM38 and EM34 data were collected, but across 40,000 ha and centred on the township of Ashley. Herein, a reconnaissance scale survey was conducted with EM data collected on an approximate $500 \times 500$ m grid in irrigated cotton growing areas and $1 \times 1$ km grid in dryland areas. A total of 105 locations were visited to take soil samples at the same four depths.

To estimate potential deep drainage rates, the soil property data were input into the SaLF version 2.2 salinity modelling program (Carlin and Brebber, 1993); clay (%) and CEC [mmol(+)/kg] at all depths and ESP measured at 0.9–1.2 m. Different irrigation water applications were considered; including, irrigation (600 mm – industry standard) and infrastructure (1500 mm) to simulate conveyance infrastructure and shallow storages. The average annual rainfall ($R =$ 584 mm) and $EC_{iw}$ for Carole Creek (i.e. 0.4 dS/m) were also inputs.

The estimates of deep drainage were coupled to the EM38 data using a three-parameter exponential model. The models were used to develop DSMA of deep drainage risk using the EM data and indicator kriging. The DSMA of deep drainage risk better resolved the network of prior stream channels, which contrasted strongly in potential for deep drainage, with respect to the cracking clays on the clay alluvial plains.

### *3.7.4. Observed outcomes and description of impact pathways / trajectories*

The DSMA of deep drainage risk at the field scale enabled a large corporate farm in the district to make considered judgements on the use of irrigation water. During extended dry periods, the prior stream areas with identified high risk and the surrounding fields were not used for irrigated cotton production. While the elevation of the prior stream areas had water application advantages through allowing gravity feeding of irrigation across the field and farm, the more permeable nature of the soils led to deep drainage and consequent water logging in the lower fields with mainly lower permeability cracking clay soils.

More significantly the corporate farm used the deep drainage map at the district level to decommission an existing dual-cell water storage. Prior to decommissioning, it was estimated the storage lost more than 1500 ML $yr^{-1}$ due to deep drainage because it was located over a prior stream channel. Information from the DSMA enabled both a new location to be identified, as well as the location of suitable clay for construction of walls for the new water storage.

When combined with improvements in design that reduced evaporative losses, losses of water from the storage were reduced by 2500 ML $yr^{-1}$. With wholesale water prices in the district ranging from approximately AUD$1500 to AUD$5000 per ML (Aither, 2019), this is a potential cost saving in the range of AUD$3.75 mil to AUD$12.5 mil. Owing to successes like these, other irrigated cotton growing farmers made modifications to their water storages. To aid decision making further surveys with MESS equipment were used to ensure the selected sites were free of prior stream channels, using EM survey contractors and consultants. One irrigator has since redesigned their single storage into a tri-celled storage to reduce water loss from deep drainage and evaporation based on the risk information.

### *3.7.5. Assessment of impact*

The *ex ante* expectations of impact for DSMA in this project were clearly met in the study areas of the project (CRDC (Cotton Research and Development Corporation), 2007), although the practice change more widely and thus impact across cotton-growing regions has not been evaluated and is unknown. Two factors contributed strongly to the successful outcome. First, the nature of this project provides an example of a simple pathway of change, in which there was a direct line from the funder (CRDC) and map developer (The University of Sydney) to landholders and intended use. There was therefore a large degree of control over the pathway from production to uptake, the period of time between production and uptake was relatively short (< 5 years) and attribution of impact was relatively straightforward.

Despite the simplicity of this pathway, it is unlikely that impact could have been achieved without a second factor involving the development of relationships and ongoing communications with the end-users of the product. This consisted of meetings to develop research projects with two Community Groups and constant updating of progress through annual and final project reports. Plain English articles in the Australian Cotton Grower Magazine communicated results and the development of MESS and its potential applications. While this second factor represents a ‘soft’ quality unrelated to the technical qualities of the DSMA, it was key to uptake (CRDC, 2007). Thus, while the extent of additional impact through practice change is not yet known, this work is well set up to generate further impact. Maps were clearly readable by consultants/farmers (website hits and practice change) and further development is supported by the cotton industry through publication/advertising the work and in establishing and encouraging best management practices.

## *3.8. Application at local scale – DSMA to support decision support tools*

### *3.8.1. Nature of the system*

Agricultural industries contribute significantly to the Australian economy, with total agricultural production for the 2019-20 season forecast to be AUD$60 billion, with grain production contributing approximately AUD$30 billion to this total (Howden and Zammit, 2018). Crop production in Australian agriculture is limited by water supply and water use efficiency (French and Schultz, 1984). Australian rainfall is low and unreliable in much of Australia's dryland cropping areas, requiring well-informed crop management for optimising yield and profit (Freebairn et al., 2018). Major investments in crop production occur at planting time and shortly after, when an uncertain water supply makes prediction of yield and financial return difficult. Financial losses from both under-investing and over-investing in crop inputs are common but having a robust estimate of soil water at sowing time can reduce uncertainty (Thomas et al., 2007).

There are several decision support tools available to the Australian agriculture industry which can model soil water and crop dynamics, providing estimates of soil water throughout the growing season. Yield Prophet (Hochman et al., 2009) and SoilWaterApp (Freebairn et al., 2018) are two of the most widely used of these tools. They use climate, management and soil information to simulate crop dynamics, with a focus on soil water content. These tools are intended to be simple to set up and easy to use. However, defining the correct soil properties to use for a given location has always been problematic, to the point of limiting the potential application of these tools. The developers of Yield Prophet report that “Some users told us that they find it challenging to select the right soil characterisation when setting up a new paddock.” (Van Rees, 2019). In relation to the use of SoilWaterApp, Starasts (2018) states that, “Most users reported that downloading and initial setup were easy, however choosing and inputting appropriate soil types was a drawback… There's a big gap in soil classification knowledge (among the farming community) …. It's not the technology, it's the understanding of soils.” Starasts (2018) also reports “The main limitation to achieving a reliable and trusted estimate of soil water storage from the app for most users is the initial choice of soil type and the initial estimate of soil water, both of which relied on users' own estimation (and both of which for many users were not sufficiently accurate for local use).

Improved yields and profits or reduced financial risk are typically the main focus for better decision making in agricultural production systems. There are many and varied factors influencing agricultural production system outcomes and the interaction of these factors is complicated, thus we consider the contribution of tailored soil information to impact to be a complex system.

### *3.8.2. Ex ante expectations*

Prior to the Soil and Landscape Grid of Australia being made publicly available in 2014, (Grundy et al., 2015) there was no consistent, easily accessible soil information system available across all of Australia upon which a solution to these problems could be developed.

In 2016 the Australian government funded research and development work to further develop the SLGA in order to produce “innovative systems to provide information on soil water status to help farmers make better management decisions (e.g. cropping options, timing of inputs)”. The project specifications state that, “this information will complement existing information sources (e.g. the Apsoil and ASRIS databases) and will be designed to work with cropping systems models such as APSIM and will be incorporated into delivery platforms such as SoilWaterApp and YieldProphet. Farmers will be able to better investigate cropping options and understand the trade-offs between management alternatives.” (Department of Agriculture, 2016).

### 3.8.3. Description / referencing the DSMA activities and outputs

The Soil Data Web API was developed to take soil attribute data contained in the SLGA and provide it in forms specifically required by the decision support tools. The soil parameter information required by the models was made publicly available via a purpose-built application programming interface (API) using industry standard web technologies (Searle and Freebairn, 2018). By providing geographic coordinates for any location within Australia to the web API, app developers can quickly and easily obtain the best available estimate of the soil properties for use in their specific tools. This approach was not possible before the advent of the DSMA products delivered by the SLGA. The Web API is available at https://www.asris.csiro.au/ASRISApi

### 3.8.4. Observed outcomes and description of impact pathways / trajectories

Although the volume of data requests to the web API end-points (Fig. 4) is not in itself an outcome, it does give a strong indication of the uptake of these data services. In the 18 months the web API has been publicly available, there have been more than 550,000 hits across Australia, mostly in the grain cropping regions, which suggest strong uptake in the agriculture industry. There are also distinct peaks in usage in the SoilWaterApp accessing the SLGA data during the planting window of the past 2 growing seasons. This suggests that farmers are using the App to inform strategic decisions at key points in the growing season.

Having this digital soil mapping data now readily available to both Yield Prophet and SoilWaterApp has eased the adoption pathway for agricultural industry users and enhanced the potential impact of these tools. Brown (2019) reports that, “In Yield Prophet you now simply select the location of your paddock from a map and Yield Prophet will do the rest. It is now possible to start using Yield Prophet without current soil test results. Having soil test results for the current season will always provide the most accurate modelling, but we understand that this isn't always possible. This new feature allows users to set up a paddock based on last year's test results, or no test results at all.”

By improving access to digital soil data, the barriers to adoption of Yield Prophet are significantly reduced. A recent economic assessment undertaken by the Wang and Russell (2016) estimates the net present value of the Yield Prophet project to be approximately AUD$26.1 million with a Benefit-Cost ratio of 3.2.

In her review of the SoilWaterApp Starasts (2018) reports that “Use of the App has led to improvements in relation to monitoring and managing soil water and reducing risks. Survey responses indicate that almost half of these users (47%) believed the app had helped to better monitor soil water, 43% believed the app had increased their knowledge about storing soil water and its losses, and similarly had enhanced their decision making (42%). Almost 30% believed use of the app had led to more efficient use of soil water and also had led to decreasing risks of production.”

Adoption of SoilWaterApp is extremely economic compared with the cost of installing a weather station with soil water sensors (estimated at AUD$2–10,000), and Freebairn et al. (2018) identify successful comparisons between app estimates with current sensor technology. It is considered that investment in developing SoilWaterApp is being offset throughout Australian agriculture through more efficient input economies, and more timely management and planning. The app has

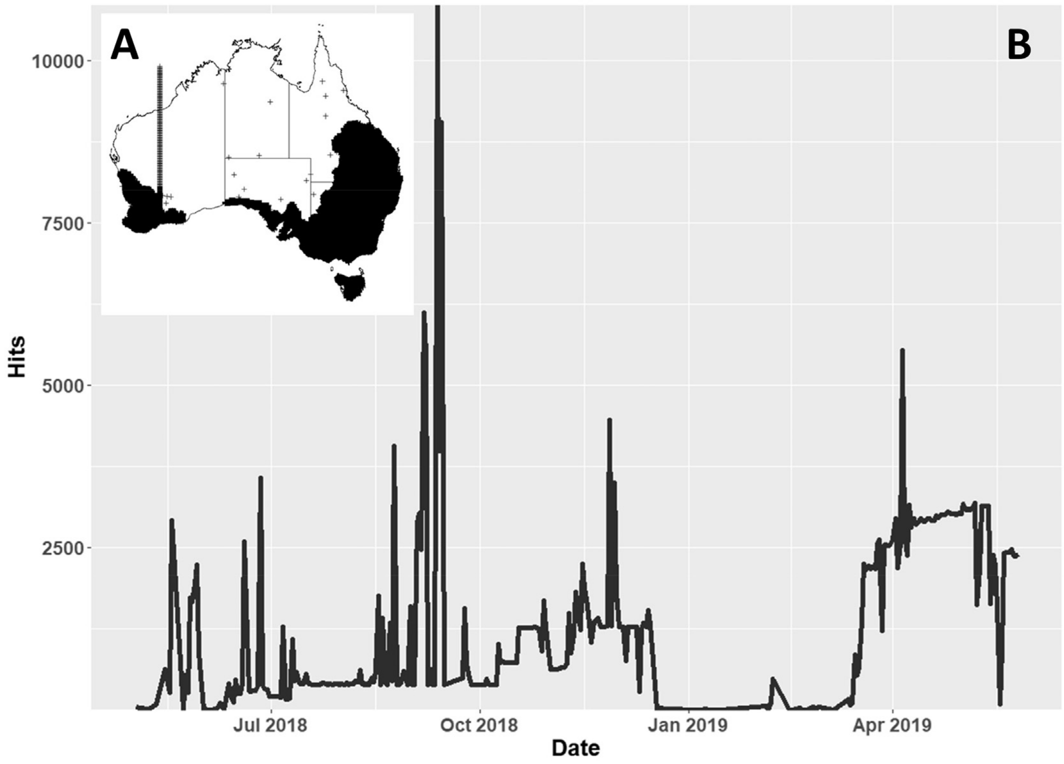

**Fig. 4.** (a) Locations of Soil Data Web API data queries and (b) Number of hits per day on the Soil Data Web API from the SoilWaterApp.

facilitated increased cropping through enhanced confidence to take advantage of opportunity cropping and higher risk cropping scenarios.

Starasts (2018) lists a range of anecdotal measures of impacts arising from the use of the SoilWaterApp. These include decisions by individual farmers around seasonal farm operations and choices and tactical and strategic advice by farm consultants to their clients.

While the anecdotes collected by Starasts (2018) are expressions of impact rather than explicit measurements, they nonetheless demonstrate that the use of the SoilWaterApp when it is enabled by easy access to relevant soils information (the SLGA DSMA product) is having a beneficial influence on the way members of the agricultural industry are conducting their business.

#### 3.8.5. Assessment of impact

The ex ante expectation to “develop innovative systems to provide information on soil water status to help farmers make better management decisions” has demonstrably been met in this work. Given the complex path to impact it is difficult to quantify the impact. The anecdotal indicators of impact presented are strong, but impact in terms of reduced financial risk and or better yields and profits for individual farming systems is not attributable to a single factor and further survey is needed to characterise the specific value of the DSMA component.

The underlying soil data accuracy and its associated uncertainty at the paddock scale will most certainly have an influence on its impact in the industry. As we improve the accuracy of our estimates of soil property values over time using DSA methods, stakeholders will be able to place more confidence in the analysis provided by decision support tools.

## 4. Discussion

The impact from this range of projects, scales, industries and impact systems is not simply characterised. There is a range of impressive outputs, examples of intended outcomes and some serendipitous outcomes but a clear picture of the nature of impact from DSMA is not yet available. The framework and the analysis suggest approaches to both increase the opportunities for impact and to determine where it has occurred.

In the DSMA examples explored here, it was often difficult to find explicit *ex ante* statements of either the major impacts envisaged by the project proponents and funders or the pathways that were expected. In any case, any statement of expected impact is often contained in unpublished project or funding proposals that are challenging to access. In the absence of explicit pathways, any observed impacts might be serendipitous or portrayed as such. More importantly, the capacity to learn from experiments in achieving impact and changes is reduced. In addition, in almost all cases we explored, the DSMA project was seen as a component within a broader approach. Given the complexity of achieving change in land management and agricultural production, individual funded projects rarely stand alone; each project aligns to others in an attempt at interconnected interventions and long-term impact (Williams et al., 2019). Where this does lead to stronger whole-of-system change, attribution to any part of the connected projects becomes more complex.

### 4.1. Preparing for impact

#### 4.1.1. The range of ex ante impact statements and expected achievements

The most constrained example of a DSMA ‘component’ project was the estimation of the extent and production impact of subsoil constraints across the Australian rainfed grain region (section 3.5). The DSMA was to provide the information underpinnings for follow up projects that would be charged with the more complex task of reducing the constraints. If there is success, then the DSMA project will have been crucial but not directly connected.

The more defined the system, the clearer were the expectations of impact and the clarity of the likely pathway. At the most local scale, the cotton industry (section 3.7) invested in DSMA to evaluate and guide water management in storage and irrigation to mitigate salinity. The pathway was inherent in the project and the results and those involved with the project team have already responded to the insights; broader impact will depend upon the incorporation of further mapping and information into farm management. The existence of data-hungry decision support tools already used widely by farmers created a clear pathway for further impact from the SLGA - with alterations for that purpose. There are reported outcomes and early indications of significant impact.

The Soil and Landscape Grid of Australia (section 3.2) is aimed at many such opportunities. Prior to the project commencing, there were documented expectations of impact either directly referring to the SLGA or coming from the discussions surrounding the scoping of the GlobalSoilMap initiative (Arrouays et al., 2014). The expectations matched the scale of the SLGA. They envisaged multi-faceted change from local to continental scale.

The DSMA of the Cabulig River watershed in the Philippines (section 3.3) was predicated on an observation that unplanned land use change created substantial dangers and that planning is more likely with soil information using DSMA. Williams et al. (2019) outline some precursor projects and impact expectation that led to the DSMA and to the need for information underpinning improved planning. There is evidence of new planning; it is early yet to find evidence of consequent better land use.

Similarly, the application of DSMA in Northern Australia (section 3.4) was built on detailed analysis of current and past land use, failed intensification initiatives and the vulnerability of the environmental, social and economic systems of that part of Australia. While a systemic solution requires integrated policy and both public and private investment, it was posited (and accepted in a series of funded projects) that information gathering was an essential first step and a key part of that was the DSMA.

In Tasmania (section 3.5), the DSMA activities have similar and perhaps more ambitious impact plans - to catalyse a state-wide shift in the intensity of agriculture. The initial stated impact pathways were again through plans and supporting policies and progress there is evident. The complexity of change needed beyond that will require a wide range of system adjustments, some of which will be informed by the DSMA. There are indications through access to products and their early use that adjustment is beginning.

### 4.2. The nature of the observed impact

Few of the studies examined had measures of the range of impacts achieved but most had observed a set of outcomes beyond the outputs (products) of the DSMA. In the more complex impact systems, it was not possible to attribute impact only to the DSMA even if measurement were available.

We observed the following outcomes and elements of impact in these studies.

1. Some of the impact arises from the value that the provision of soil and land resource information brings and is therefore indistinguishable from that gained with traditional soil information. The value is that derived from better knowledge of the soil resource and the interaction with environmental and agricultural processes.
2. ‘Connectedness’ – outcomes that derive from the capacity of DSMA-derived data to be part of a modelling and monitoring process – through connection to system models and data streams.
3. Components – outcomes derived from the provision of one essential element (soil and landscape information) within a systems approach to change and improvement.
4. New pathways – where impact derives from new pathways that emerge because of the nature of DSMA information. The digital

data has uses and impacts not initially planned because integration with soil and landscape data from other areas, integration with other environmental data and with economic and social data makes new uses possible.

DSMA products have the additional characteristic of being updateable after the project when circumstances change, or new opportunities arise. It is 'simply' a case of re-focussing the product suite and remodelling to produce the new suite. This only works where the original core data (eg. soil sampling and analytics) were sufficiently comprehensive to allow a broadening of products. The focusing of the SLGA data on its use in decision support apps (section 3.8) is an example.

### 4.3. Improving project design for impact

Explicit design for impact, beyond the expected use of survey products, was not readily discerned in project publications or easily accessible materials; there may be more explicit design in project proposals, but they are rarely available and cannot be easily cited.

We suggest that the opportunity for impact and its reach can be improved if explicit design is part of the project planning and the publications associated with the DSMA outputs. The design would include the following elements:

1. Describe the system within which impact is desired. Who are the key actors, what are the communication channels, what are their key challenges, what is the current state and where is the need and desire for change? Characterise the complexity of the system, perhaps using the CYNEFIN framework.
2. Describe the nature of the impacts that are seen as improvements within the system and connect those impacts with the role of DSMA data products.
3. Draft a theory of change that connects the DSMA project and products with impact pathways and how the DSMA can enable these outcomes and impacts - what are the expected connections, networks and chains and who will be the key actors?
4. Draft a set of expected products, uses and the outcomes sought - so that progress can be measured and, if necessary and possible, adjustments to projects made.
5. Design the project guided by these elements and include, if possible, resourcing for measurement of progress along impact pathways (in many cases, this could be a meta activity that covers a number of related projects).

It is clear from the examined studies that new and/or unexpected impacts and impact pathways are likely to emerge from effective DSMA projects. It is possible to add this element to the design or to run evaluation activities to measure these changes and include them in the evaluation of the DSMA investment.

### 4.4. Complexity and impact

Complex systems may be the norm where soil information is needed. There are simpler subsystems where a connection between survey effort, product release and implementation can be clear, and the salinity and subsoil constraints projects fit this model. But even here, the broader impact becomes complex and multiple actors and other streams of data influence outcomes. The other DSMA examples here play into clearly complex land management systems. So, is the planning, design and explicit *ex ante* statements of limited value?

We think not. A feature of Snowden and Boone's analysis of complex systems is that they are tractable, but the approach differs from more simple systems. Essentially, the nature of change can be understood by probing the system and observing the response - and that response then guides the next step.

The flexibility of DSMA data and products will allow this iterative approach to achieving change. The design then allows both the probing and the further development of products to respond to what is learnt of the system and how people are engaging with and using the DSMA data and products.

The more complex the systems within which impacts are sought, the more useful DSMA approaches are likely to be - if we put the effort into planning for impact at the outset of investments and project design.

## Acknowledgements

The authors wish to acknowledge the support of the Terrestrial Ecosystem Research Network (TERN) to the Australian Digital Soil Mapping Community of Practice.

We thank Uta Stockmann and Larelle McMillan for constructive editorial comment and advice.

We would also like to thank members of the Digital Soil Mapping Community of Practice who attended the Stradbroke Island workshop in 2019, for the input they provided to the initial development of this manuscript. Apart from the authors of this document, they are listed as authors on Searle et al. (2020). Most funding for the workshop came from CSIRO and is appreciated.

## References

ACIL, 1996. The development of an economic framework and instruments for assessing the benefits and costs of land resource assessment in Australia. Report to the Australian Collaborative Land Evaluation Program (ACLEP). Canberra, ACIL Economics and Policy Pty Ltd https://www.clw.csiro.au/aclep/documents/Acil(s).pdf, Accessed date: 17 February 2020.

Acub, R.B., Hebron, I.U., Arazo, R., Cosadio, A.L., Pasco, M.M., Mercado, A., 2011. Rapid hydrological appraisal of Cabulig River in Claveria, Misamis Oriental. J Sci Paper Abstr 1, 78.

Agrigrowth Tasmania, 2015. Tasmania's Sustainable Agri-Food Plan 2016–2018. Department of Primary Industries, Parks, Water and Environment, Tasmania https://dpipwe.tas.gov.au/Documents/Agri-Food%20Plan%202016-2018.pdf, Accessed date: 20 February 2020.

Aither, 2019. Murray Darling Basin Water Entitlement Price Summary Report – June 2019. Aither Pty Ltd. https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/water/market-prices-sum-jun-2019.docx, Accessed date: 20 February 2020.

Anderegg, L.D.L., Loy, X., Markham, I.P., Elmer, C.M., Hovenden, M.J., Lambers, J.H.R., Mayfield, M.M., 2020. Aridity drives coordinated trait shifts but not decreased trait variance across the geographic range of eight Australian trees bioRxiv, 2020.2002.2003.932715. https://doi.org/10.1101/2020.02.03.932715.

Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S.Y., Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonça Santos, M.L., Minasny, B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.-L., 2014. In: Sparks, D.L. (Ed.), GlobalSoilMap: Toward a Fine-resolution Global Grid of Soil Properties. Adv. Agron. Academic Press, pp. 93–134. https://doi.org/10.1016/B978-0-12-800137-0.00003-0.

Ash, A., Watson, I., 2018. Developing the north: learning from the past to guide future plans and policies. Rangel. J. 40, 301–314. https://doi.org/10.1071/RJ18034.

Ash, A., Gleeson, T., Hall, M., Higgins, A., Hopwood, G., MacLeod, N., Paini, D., Poulton, P., Prestwidge, D., Webster, T., Wilson, P., 2017. Irrigated agricultural development in northern Australia: value-chain challenges and opportunities. Agric. Syst. 155, 116–125. https://doi.org/10.1016/j.agsy.2017.04.010.

Bartley, R., Thomas, M.F., Clifford, D., Phillip, S., Brough, D., Harms, D., Willis, R., Gregory, L., Glover, M., Moodie, K., Sugars, M., Eyre, L., Smith, D.J., Hicks, W., Petheram, C., 2013. Land suitability: technical methods. A technical report to the Australian Government from the Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. Brisbane, Australia: CSIRO Water for a Healthy Country and Sustainable Agriculture flagships https://doi.org/10.4225/08/584d97f34ddf4 accessed 20 February 2020.

Bell, J.C., Cunningham, R.L., Havens, M.W., 1992. Calibration and validation of a soil landscape model for predicting soil drainage class. Soil Sc Soc Am J 56, 1860–1866.

Brown, C., 2019. Yield Prophet: Automatic Soil Selection and More! Birchip Cropping Group Newsletter. Birchip Cropping Group Inc. Birchip, Australia https://www.bcg.org.au/yield-prophet-automatic-soil-selection-and-more/, Accessed date: 20 February 2020.

Buchanan, S., Huang, J., Triantafilis, J., 2017. Salinity risk assessment using fuzzy multiple criteria evaluation. Soil Use Manag. 33, 216–232. https://doi.org/10.1111/sum.12301.

Calalang, G., Colinet, G., 2014. A review of soils and crops in the Bukidnon highlands of northern Mindanao, the Philippines. Biotechnol. Agron. Soc. Environ. 18, 544–557.

Carlin, G., Brebber, L., 1993. SaLF: Implementation of the Shaw and Thorburn Model: Program to Calculate Salinity and Leaching Fraction in a Soil Profile. Department of Primary Industries, Natural Resource Management, Indooroopilly, Queensland, Australia.

Clarry, S., 2015. National project brings together soils research. Groundcover 119. https://grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-119-novdec-2015/national-project-brings-together-soils-research, Accessed date: 20 February 2020.

CRDC (Cotton Research and Development Corporation), 2007. Source of water losses found. Spotlight, Spring 2007, p11. https://www.crdc.com.au/sites/default/files/pdf/01795%20CRDC%20Spotlight%20Spring07_0.pdf, Accessed date: 20 February 2020.

Crosbie, R.S., Peeters, L.J.M., Herron, N., McVicar, T.R., Herr, A., 2018. Estimating groundwater recharge and its associated uncertainty: use of regression kriging and the chloride mass balance method. J. Hydrol. 561, 1063–1080. https://doi.org/10.1016/j.jhydrol.2017.08.003.

Dang, Y.P., Moody, P.W., 2016. Quantifying the costs of soil constraints to Australian agriculture: a case study of wheat in North-Eastern Australia. Soil Res. 54, 700–707. https://doi.org/10.1071/SR15007.

Dang, Y.P., Dalal, R.C., Buck, S.R., Harms, B., Kelly, R., Hochman, Z., Schwenke, G.D., Biggs, A.J.W., Ferguson, N.J., Norrish, S., Routley, R., McDonald, M., Hall, C., Singh, D.K., Daniells, I.G., Farquharson, R., Manning, W., Speirs, S., Grewal, H.S., Cornish, P., Bodapati, N., Orange, D., 2010. Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains cropping region of Australia. Aust. J. Soil Res. 48, 105–119. https://doi.org/10.1071/SR09074.

Davidson, B.R., 1982. Economic aspects of the Ord River project. In: Davidson, B.R., Graham-Taylor, S. (Eds.), Lessons from the Ord. Canberra, ACT: The Centre for Independent Studies , pp. 1–22. https://www.cis.org.au/app/uploads/2015/07/pm2.pdf, Accessed date: 20 February 2020.

Davila, F., Dyball, R., Amparo, J.M., 2018. Transdisciplinary research for food and nutrition security: examining research-policy understandings in Southeast Asia. Environ Dev 28, 67–82. https://doi.org/10.1016/j.envdev.2018.10.001.

Day, K., 1993. Irrigated Land Suitability Assessment of Haughton Section - Stage I: Nine Mile Lagoon to Oaky Creek, Burdekin River Irrigation Area. Queensland Department of Primary Industries, Brisbane, Queensland, Australia https://www.publications.qld.gov.au/dataset/8533f947-6ac3-4602-8d04-b566dfb3de0a/resource/83450ab0-e0d3-4965-b6bf-a208e9037b83/fs_download/hts-qo93022-bria-haughton-stage-i-soils.pdf, Accessed date: 20 February 2020.

Department of Agriculture, 2014. Securing Australia's Soil for Profitable Industries and Healthy Landscapes. Commonwealth of Australia, Canberra https://www.agriculture.gov.au/sites/default/files/style%20library/images/daff/__data/assets/pdffile/0012/2379585/soil.pdf, Accessed date: 20 February 2020.

Department of Agriculture, 2016. Soil Sensing – New Technology for Tracking Soil Water Availability, Managing Risk and Improving Farm Management Decisions. Commonwealth Grant Agreement. http://hdl.handle.net/102.100.100/86836?index=1.

Department of Justice, 2018. Tasmanian planning scheme - state planning provisions. Local Provisions Schedules Requirements - Appendix a: 16. State of Tasmania http://www.justice.tas.gov.au/__data/assets/pdf_file/0007/370294/State_Planning_Provisions.PDF, Accessed date: 20 February 2020.

Douthwaite, B., Hoffecker, E., 2017. Towards a complexity-aware theory of change for participatory research programs working within agricultural innovation systems. Agric. Syst. 155, 88–102. https://doi.org/10.1016/j.agsy.2017.04.002.

DPIPWE, 2015. Water for Profit Program. Department of Primary Industries, Parks, Water and Environment, Tasmania https://dpipwe.tas.gov.au/agriculture/water-for-profit-program.

Freebairn, D.M., Ghahramani, A., Robinson, J.B., McClymont, D.J., 2018. A tool for monitoring soil water using modelling, on-farm data, and mobile technology. Environ. Model. Softw. 104, 55–63. https://doi.org/10.1016/j.envsoft.2018.03.010.

French, R.J., Schultz, J.E., 1984. Water use efficiency of wheat in a Mediterranean type environment. I. the relation between yield, water use and climate. Aust. J. Agric. Res. 35, 743–764.

Gallant, J.C., Austin, J.M., 2015. Derivation of terrain covariates for digital soil mapping in Australia. Soil Res. 53, 895–906. https://doi.org/10.1071/SR14271.

Graham-Taylor, S., 1982. A critical history of the Ord River project. In: Davidson, B.R., Graham-Taylor, S. (Eds.), Lessons from the Ord. ACT: The Centre for Independent Studies, Canberra , pp. 25–55. https://www.cis.org.au/app/uploads/2015/07/pm2.pdf, Accessed date: 20 February 2020.

Greiner, R., 2002. Further lessons from the Ord, 46th Annual Conference of the Australian Agricultural and Resource Economics Society, Canberra. https://doi.org/10.22004/ag.econ.125092.

Grundy, M., 2014. The new Australian grid - a multi-institutional template? In: Arrouays, D., McKenzie, N., Hempel, J., Forges, A.R.D., McBratney, A.B. (Eds.), GlobalSoilMap: basis of the Global Spatial Soil Information System. CRC Press, pp. 73–77

Grundy, M., Viscarra Rossel, R., Searle, R., Wilson, P., Chen, C., Gregory, L., 2015. The soil and landscape grid of Australia. Soil Res. 53, 835–844. https://doi.org/10.1071/SR15191.

Grundy, M.J., Searle, R.D., Robinson, J.B., 2012. An Australian soil grid: Infrastructure and function. In: Minasny, B., Malone, B., McBratney, A. (Eds.), Digital Soil Assessments and beyond. Taylor and Francis Group, London, UK, pp. 459–464.

Guerin, G.R., Andersen, A.N., Rossetto, M., van Leeuwen, S., Byrne, M., Sparrow, B., Rodrigo, M., Lowe, A.J., 2018. When macroecological transitions are a fiction of sampling: comparing herbarium records to plot-based species inventory data. Ecography 41, 1864–1875. https://doi.org/10.1111/ecog.03607.

Guerin, G.R., Andersen, A.N., Rossetto, M., van Leeuwen, S., Byrne, M., Sparrow, B., Rodrigo, M., Lowe, A.J., 2019. Consistent sorting but contrasting transition zones in plant communities along bioclimatic gradients. Acta Oecol. 95, 74–85. https://doi.org/10.1016/j.actao.2019.01.006.

Hammer, T.A., Macintyre, P.D., Nge, F.J., Davis, R.W., Mucina, L., Thiele, K.R., 2018. The noble and the exalted: a multidisciplinary approach to resolving a taxonomic controversy within Ptilotus (Amaranthaceae). Aust. Syst. Bot. 31, 262–280. https://doi.org/10.1071/SB17062.

Harms, B., Brough, D., Philip, S., Bartley, R., Clifford, D., Thomas, M., Willis, R., Gregory, L., 2015. Digital soil assessment for regional agricultural land evaluation. Glob. Food Security 5, 25–36. https://doi.org/10.1016/j.gfs.2015.04.001.

Herbert, A., 2018. Australian Wheat Production Compares Well to Global Competitors - an International Benchmarking Comparison, GRDC Update Papers. Grains Research and Development Corporation, Canberra, ACT https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/03/australian-wheat-production-compares-well-to-global-competitors-an-international-benchmarking-comparison, Accessed date: 20 February 2020.

Hochman, Z., Horan, H., 2018. Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. Field Crop Res. 228, 20–30. https://doi.org/10.1016/j.fcr.2018.08.023.

Hochman, Z., van Rees, H., Carberry, P.S., Hunt, J.R., McCown, R.L., Gartmann, A., Holzworth, D., van Rees, S., Dalgliesh, N.P., Long, W., Peake, A.S., Poulton, P.L., McClelland, T., 2009. Re-inventing model-based decision support with Australian dryland farmers. Yield prophet® helps farmers monitor and manage crops in a variable climate. Crop Pasture Sci 60, 1057–1070. https://doi.org/10.1071/CP09020.

Howden, M., Zammit, K., 2018. Australian Agricultural Overview. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. Australia http://data.daff.gov.au/data/warehouse/agcomd9abcc004/agcomd9abcc20180918_xV5mH/AgCommodities201809_AgOverview_v1.0.0.pdf, Accessed date: 20 February 2020.

Hudson, B.D., 1992. The soil survey as paradigm-based science. Soil Sci. Soc. Am. J. 56, 836–841.

Integrated Food and Energy Developments Pty Ltd, 2013. Etheridge Integrated Agricultural Project: Initial Advice Statement. https://www.statedevelopment.qld.gov.au/resources/project/etheridge-integrated-agricultural/eiap-ias.pdf, Accessed date: 20 February 2020.

Johnston, R.M., Barry, S.J., Bleys, E., Bui, E.N., Moran, C.J., Simon, D.A.P., Carlile, P., McKenzie, N.J., Henderson, B.L., Chapman, G., Imhoff, M., Maschmedt, D., Howe, D., Grose, C., Schoknecht, N., Powell, B., Grundy, M., 2003. ASRIS: the database Soil Res. 41, pp. 1021–1036.. https://doi.org/10.1071/SR02033.

Kath, J., Pembleton, K.G., 2019. A soil temperature decision support tool for agronomic research and management under climate variability: adapting to earlier and more variable planting conditions. Comput. Electron. Agric. 162, 783–792. https://doi.org/10.1016/j.compag.2019.05.030.

Kearney, M.R., Maino, J.L., 2018. Can next-generation soil data products improve soil moisture modelling at the continental scale? An assessment using a new microclimate package for the R programming environment. J. Hydrol. 561, 662–673. https://doi.org/10.1016/j.jhydrol.2018.04.040.

Kidd, D., Webb, M., Malone, B., Minasny, B., McBratney, A., 2015. Digital soil assessment of agricultural suitability, versatility and capital in Tasmania. Australia Geoderma Region 6, 7–21. https://doi.org/10.1016/j.geodrs.2015.08.005.

Kidd, D., Searle, R., Grundy, M., McBratney, A.B., Robinson, N., O'Brien, L., Zund, P., Arrouays, D.D., Thomas, M., Padarian, J., Jones, E., McL, Bennett J., Minasny, B., Holmes, K.K., Malone, B., Liddicoat, C., Meier, E., Stockmann, U., Wilson, P., Wilford, J., Triantafilis, J., Payne, J., Ringrose-Voase, A., Bui, E., Slater, B., Odgers, N., Gray, J., van Gool, D., Andrews, K., Harms, B., 2020. Operationalising Digital Soil Mapping – Lessons from Australia this issue.

Liddicoat, C., Maschmedt, D., Clifford, D., Searle, R., Herrmann, T., Macdonald, L.M., Baldock, J., 2015. Predictive mapping of soil organic carbon stocks in South Australia's agricultural zone. Soil Res. 53, 956–973. https://doi.org/10.1071/SR15100.

Liddicoat, C., Bi, P., Waycott, M., Glover, J., Breed, M., Weinstein, P., 2018. Ambient soil cation exchange capacity inversely associates with infectious and parasitic disease risk in regional Australia. Sci. Total Environ. 626, 117–125. https://doi.org/10.1016/j.scitotenv.2018.01.077.

Luo, Z., Eady, S., Sharma, B., Grant, T., Liu, D.L., Cowie, A., Farquharson, R., Simmons, A., Crawford, D., Searle, R., Moore, A., 2019. Mapping future soil carbon change and its uncertainty in croplands using simple surrogates of a complex farming system model. Geoderma 337, 311–321. https://doi.org/10.1016/j.geoderma.2018.09.041.

Macquarie Franklin, Esk Mapping & GIS, 2017. Agricultural Land Mapping Project - Identifying Land Suitable for Inclusion within the Tasmanian Planning Scheme Agriculture Zone - Background Report. Department of Justice, Planning Policy Unit https://planningreform.tas.gov.au/__data/assets/pdf_file/0004/390874/Agricultural_Land_Mapping_Project_-_Background_Report_-_May_2017.pdf, Accessed date: 20 February 2020.

Malenab, M.C., Visco, E., Geges, D., Amparo, J.M., Torio, D., Jimena, C.E.G., 2016. Analysis of the integrated water resource management in a water quality management area in the Philippines: the case of Meycauayan-Marilao-Obando river system. J Environ Sci Manage 19, 84–98.

McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52. https://doi.org/10.1016/S0016-7061(03)00223-4.

McKenzie, N., Ringrose-Voase, A., Grundy, M., 2008. Rationale. In: McKenzie, N.J., Grundy, M.J., Webster, R., Ringrose-Voase, A. (Eds.), Guidelines for Surveying Soil and Land Resources. Australian Soil and Land Survey Handbooks Series. CSIRO Publishing, Canberra, ACT. Australia, pp. 3–13.

McMillan, L., Butler, J., Williams, L., van Wensveen, M., 2019. Reflections and Lessons Learned: Developing Mixed Methods Approaches to Impact Assessment of Philippine Landcare Projects: A Working Paper on Multi-Loop Learning across CSIRO, UPLB, VSU, PCAARRD. CSIRO, Brisbane.

Medina, I., Newton, E., Kearney, M.R., Mulder, R.A., Porter, W.P., Stuart-Fox, D., 2018. Reflection of near-infrared light confers thermal protection in birds. Nat. Commun. 9, 3610. https://doi.org/10.1038/s41467-018-05898-8.

Metcalfe, D.J., Bui, E.N., 2017. Australia state of the environment 2016: land. Independent report to the Australian Government Minister for the Environment and Energy, Australian Government Department of the Environment and Energy, Canberra. https://doi.org/10.4226/94/58b6585f94911.

Northcote, K.H., (compiler), 1960-1968. Atlas of Australian soils. Sheets 1 to 10. With Explanatory Data. CSIRO Australia and Melbourne University Press, Melbourne.

Northern Australia Land and Water Taskforce, 2009. Northern Australia Land and Water Science Review. Department of Infrastructure, Transport, Regional Development and Local Government, Canberra, ACT.

Orton, T.G., Mallawaarachchi, T., Pringle, M.J., Menzies, N.W., Dalal, R.C., Kopittke, P.M., Searle, R., Hochman, Z., Dang, Y.P., 2018. Quantifying the economic impact of soil constraints on Australian agriculture: a case study of wheat. Land Degrad. Dev. 29, 3866–3875. https://doi.org/10.1002/ldr.3130.

Page, K.L., Dalal, R.C., Wehr, J.B., Dang, Y.P., Kopittke, P.M., Kirchhof, G., Fujinuma, R., Menzies, N.W., 2018. Management of the major chemical soil constraints affecting yields in the grain growing region of Queensland and New South Wales. Australia – a review Soil Res 56, 765–779. https://doi.org/10.1071/SR18233.

Petheram, C., Watson, I., Stone, P., Barber, M., Bartley, R., Brough, D., Burrows, D., Crossman, N., Dutta, D., Grundy, M., Hornbuckle, J., Jolly, I., Lerat, J., McJannet, D., Munday, T., Schmidt, R., Waltham, N., Webster, T., 2012. Proposed Project Methods for the Flinders and Gilbert Agricultural Resource Assessment, Hydrology and Water Resources Symposium 2012. Engineers Australia, Barton, ACT, pp. 733–741.

Petheram, C., Webster, T., Poulton, P., Stone, P., Hornbuckle, J., Harms, B., Philip, S., Rogers, L., Eades, G., Brennan McKellar, L., Bartley, R., Holz, L., Kim, S., Schmidt, B., Wilson, P., Tomkins, K., Gallant, S., Marvanek, S., Buettikofer, H., Wallbrink, A., 2013. Chapter 5: Opportunities for irrigation in the Flinders catchment. In: Petheram, C., Watson, I., Stone, P. (Eds.), Agricultural Resource Assessment for the Flinders Catchment. A report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment. CSIRO, Canberra, A.C.T. https://doi.org/10.4225/08/584ee622d70a9.

Reiter, N., Lawrie, A.C., Linde, C.C., 2018. Matching symbiotic associations of an endangered orchid to habitat to improve conservation outcomes. ANN BOT-LONDON. 122, pp. 947–959. https://doi.org/10.1093/aob/mcy094.

Ringrose-Voase, A., Grealish, G., Thomas, M., Wong, M.T.F., Glover, M., Mercardo, A., Nilo, G.P., Dowling, T.I., 2019. Four pillars of digital land resource mapping to address information and capacity shortages in developing countries. Geoderma 352, 299–313. https://doi.org/10.1016/j.geoderma.2017.10.014.

Robertson, M., Kirkegaard, J., Rebetzke, G., Llewellyn, R., Wark, T., 2016. Prospects for yield improvement in the Australian wheat industry: a perspective. Food Energy Security 5, 107–122. https://doi.org/10.1002/fes3.81.

Rogers, P., 2014. Overview: Strategies for Causal Attribution, Methodological Briefs: Impact Evaluation 6. UNICEF Office of Research, Florence.

Ryan, P.J., McKenzie, N.J., O'Connell, D., Loughhead, A.N., Leppert, P.M., Jacquier, D., Ashton, L., 2000. Integrating forest soils information across scales: spatial prediction of soil properties under Australian forests. For. Ecol. Manag. 138, 139–157. https://doi.org/10.1016/S0378-1127(00)00393-5.

Sanchez, P.A., Ahamed, S., Carre, F., Hartemink, A.E., Hempel, J., Huising, J., Lagacherie, P., McBratney, A.B., McKenzie, N.J., Mendonca-Santos, M.D., Minasny, B., Montanarella, L., Okoth, P., Palm, C.A., Sachs, J.D., Shepherd, K.D., Vagen, T.G., Vanlauwe, B., Walsh, M.G., Winowiecki, L.A., Zhang, G.L., 2009. Digital soil map of the world. Science 325, 680–681. https://doi.org/10.1126/science.1175084.

Searle, R., 2014. The Australian site data collation to support the GlobalSoilMap. In: Arrouays, D., McKenzie, N., Hempel, J., Forges, A.R.D., McBratney, A.B. (Eds.), GlobalSoilMap: Basis of the Global Spatial Soil Information System. CRC Press, pp. 127–132.

Searle, R., Freebairn, D., 2018. Soil Sensing – New Technology for Tracking Soil Water Availability, Managing Risk and Improving Farm Management Decisions. CSIRO, Canberra, Australia http://hdl.handle.net/102.100.100/86836?index=1, Accessed date: 20 February 2020.

Searle, R., McBratney, A., Grundy, M., Kidd, D., Malone, B., Arrouays, D., Stockman, T. Zund, Wilson, P., Wilford, J., van Gool, D., Triantafilis, J., Thomas, M., Stower, E., Slater, B., Robinson, N., Ringrose-Voase, A., Padarian, J., Payne, J., Orton, T., Odgers, N., O'Brien, L., Minasny, B., Meier, E., Bennett, J.M., Liddicoat, C., Jones, E., Holmes, K., Harms, B., Gray, J., Bui, E., 2020. Digital Soil Mapping and Assessment for Australia and Beyond: A Propitious Future this issue.

Snowden, D.J., Boone, M.E., 2007. A Leader's framework for decision making. Harv. Bus. Rev. 85, 68–76 URL. https://hbr.org/2007/11/a-leaders-framework-for-decision-making, Accessed date: 20 May 2020.

Soils Research Development and Extension Working Group, 2011. A Stocktake of Australia's Current Investment in Soils Research, Development and Extension: A Snapshot for 2010–11. Department of Agriculture, Fisheries and Forestry, Canberra, ACT. URL https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/natural-resources/land-salinity/overview-soil-information.pdf, Accessed date: 20 May 2020.

Starasts, A., 2018. Evaluation of SoilWater App. A report for the Australian Government's National Landcare Program under project New Technology for Tracking Soil Water Availability. Managing Risk and Improving Farm Management Decisions. Australian Dept of Agriculture and Water URL. https://eprints.usq.edu.au/36507/1/Starasts%20SoilWater%20app%20Evaluation%20Report%202018.pdf, Accessed date: 20 May 2020.

Taggart, P.L., Stevenson, M.A., Firestone, S.M., McAllister, M.M., Caraguel, C.G.B., 2019. Spatial analysis of a cat-borne disease reveals that soil pH and clay content are risk factors for Sarcocystosis in sheep. Frontiers Vet Sci 6, 127. https://doi.org/10.3389/fvets.2019.00127.

Tasmanian Irrigation, 2015. Tasmanian Irrigation Schemes. http://www.tasmanianirrigation.com.au/index.php/, Accessed date: 20 February 2020.

Thomas, G.A., Titmarsh, G.W., Freebairn, D.M., Radford, B.J., 2007. No-tillage and conservation farming practices in grain growing areas of Queensland a review of 40 years of development. Aust. J. Exp. Agric. 47 (8), 887–898. https://doi.org/10.1071/EA06204.

Thomas, M., Clifford, D., Bartley, R., Philip, S., Brough, D., Gregory, L., Willis, R., Glover, M., 2015. Putting regional digital soil mapping into practice in tropical northern Australia. Geoderma 241–242, 145–157. https://doi.org/10.1016/j.geoderma.2014.11.016.

Triantafilis, J., Ahmed, M.F., Odeh, I.O.A., 2002. Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinization in an irrigated cotton-growing field. Soil Use Manag. 18, 330–339. https://doi.org/10.1111/j.1475-2743.2002.tb00249.x.

Triantafilis, J., Huckel, A.I., Odeh, I.O.A., 2003. Field-scale assessment of deep drainage risk. Irrig. Sci. 21, 183–192. https://doi.org/10.1007/s00271-002-0063-1.

Triantafilis, J., Odeh, I.O.A., Jarman, A.L., Short, M., Kokkoris, E., 2004. Estimating and mapping deep drainage risk at the district level in the lower Gwydir and Macquarie valleys. Australia Aust J Exp Agr 44, 893–912. https://doi.org/10.1071/EA02176.

Turville, A., Cullen, S., Tan, P., 2014. Planning for the future: integrated water management in the Ord river catchment: a discussion about the new Ord WAP and how more transparent risk assessment, social input and economic evaluation would assist in water planning. Water 41, 80–86 URL. https://search.informit.com.au/documentSummary;dn=598998257453086;res=IELAPA, Accessed date: 20 May 2020.

UTAS, 2015. Water for Profit Program. University of Tasmania, Tasmania http://www.utas.edu.au/tia/research/research-projects/projects/water-for-profit accessed 5/19/20.

Van Rees, S., 2019. https://YieldProphet.com.au/yp/BlogViewPost.aspx?post=22 accessed 20 Feb 2020.

Viscarra Rossel, R., Chen, C., Grundy, M., Searle, R., Clifford, L., Campbell, P., 2015. The Australian three-dimensional soil grid: Australia's contribution to the GlobalSoilMap project. Soil Res 53, 845–864. https://doi.org/10.1071/SR14366.

W.K. Kellogg Foundation, 2004. Logic Model Development Guide: W.K. Kellogg Foundation. URL. https://www.wkkf.org/resource-directory/resource/2006/02/wk-kellogg-foundation-logic-model-development-guide, Accessed date: 20 May 2020.

Wang, J., Russell, Tanja, 2016. Research Impact Evaluation: Yield Prophet Case Study. Canberra: CSIRO https://doi.org/10.4225/08/58542ea12e355 accessed 20 February 2020.

Webb, M., 2015. Incorporating Climate Futures into Enterprise Suitability Mapping - Technical Report. Department of Primary Industries, Parks, Water and Environment, Launceston, Tasmania URL. http://www.dpac.tas.gov.au/__data/assets/pdf_file/0009/266184/Incorporating_Climate_Futures_Tasmania_into_Enterprise_Suitability_Mapping_Technical_Report.pdf, Accessed date: 19 May 2020.

Webb, M., Hall, A., Kidd, D., Minasny, B., 2015. Local-scale spatial modelling for interpolating climatic temperature variables to predict agricultural plant suitability. Theor. Appl. Climatol. 124, 1145–1165. https://doi.org/10.1007/s00704-015-1461-7.

Wilford, J.R., Searle, R., Thomas, M., Pagendam, D., Grundy, M.J., 2016. A regolith depth map of the Australian continent. Geoderma 266, 1–13. https://doi.org/10.1016/j.geoderma.2015.11.033.

Williams, L.J., McMillan, L., Van Wensveen, M., Butler, J.R.A., Camacho Jr., J.D.V., Lapitan, A., Datoon, R., Gapas, J., Pinca, E., Macavinta-Gabunada, F., Serino, M.N.V., Nunez, L., Recto, A.L., Ruales, J.H., Enerlan, W.C., Ani, P.A.B., Aranas, M.B., 2019. An Integrated Approach to Impact Assessment. ACIAR, Canberra.

Yang, X., Zhu, Q., Tulau, M., McInnes-Clarke, S., Sun, L., Zhang, X., 2018. Near real-time monitoring of post-fire erosion after storm events: a case study in Warrumbungle National Park, Australia. Int. J. Wildland Fire 27, 413–424. https://doi.org/10.1071/WF18011.

Zhu, Q., Yang, X., Ji, F., Liu, D.L., Yu, Q., 2020. Extreme rainfall, rainfall erosivity, and hillslope erosion in Australian alpine region and their future changes. Int. J. Climatol. 40, 1213–1227. https://doi.org/10.1002/joc.6266.