Save Our Soils

Supporting document

Soil Science Australia

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VALUES AND SERVICES OF AUSTRALIA'S SOILS

Soils are one of our most valuable resources in Australia, supporting our food, fibre, and water supplies. Soil underpins our agricultural production, directly contributing approximately $63 billion AUD per year to Australia's economy (Jackson et al. 2018). Soils are also an important resource for their ability to store and filter water. These abilities sustain vegetation and human uses such as irrigation and stock watering across Australia, while also absorbing contaminants and purifying our water resources. Soil water storage helps to mitigate flooding.

Soil contains and directly supports the overwhelming majority of our terrestrial biodiversity from microscopic organisms such as fungi and bacteria to macroscopic organisms such as earthworms and wombats. These soil organisms play critical roles in important ecosystem processes including organic matter decomposition, nutrient cycling, enhancing plant nutrient uptake, carbon and nitrogen fixation from the atmosphere, and improving soil structure and aeration (Colloff 2011). Many of these ecosystem functions are vital to the indefinite sustainable use of our soils.

Our soils are also a vital player in global climate change mitigation as Australia's soil store large amounts of organic carbon, last determined as 3.5% of the total global stocks in the 0-30 cm layer (Viscarra Rossel et al. 2014). However, native vegetation clearance and poor soil management have and continue to result in the loss of soil organic carbon and in enhanced greenhouse gas emissions. Capturing and retaining carbon in soil (sequestration) helps mitigate against climate change also improves soil health and productivity. Soil carbon sequestration is an accredited method under Australia's Emissions Reduction Fund (ERF), thus storing carbon in soil can also produce direct economic benefits in addition to the improvements to soil function.

When considering all the above soil functions and services, Australia's soils provide an estimated value of $930 billion AUD per year. This number is based on analysis of McBratney et al. (2017) were they determined that soil provides an average value of $121,022 AUD per square kilometre per year. Hence the value of soils far exceeds the value of the land itself which, while by far the most valuable Australian environmental asset (90% of total), is valued at $5.8 billion AUD (ABS 2018).

Soils are threatened by a number of degradation issues that result in large direct costs, indirect costs, and in lost economic opportunity for Australia as will be described further below.

URBAN AND INDUSTRIAL ENCROACHMENT

Urban encroachment occurs when population growth and land values in cities and urban areas puts pressure to develop surrounding peri-urban and rural regions, which may contain high value agricultural soils. Industrial encroachment occurs when land becomes more economically valuable for industrial uses than other uses (for example, coal mining) (Williams 2015). The areas that urban and industrial developments encroach upon are often valuable in their current state or were previously deemed unsuitable for urban development. Valuable soils include those used for agriculture, ecosystem services, and conservation, whereas unsuitable sites include floodplains and contaminated land (NSW EPA 2015, Metcalfe and Bui 2017). Urban encroachment is a serious global issue; two thirds of the world's population is projected to be urban by 2050 (ITPS 2015). In addition to the agricultural benefits, preventing urban encroachment into peri-urban and rural areas also yields social benefits such as recreation, biodiversity, visual amenity, flood mitigation and other ecosystem services (Metcalfe and Bui 2017).

Due to the historic situation of Australian cities near soils suitable for horticulture and agriculture, and water, urban expansion into the peri-urban fringe has led to capping of these soils. It appears unlikely that these good-quality soils will ever regain their biological function (State of the Environment 2011 Committee 2011, Metcalfe and Bui 2017). Urban developments also affect yield and water regimes (Campbell 2008). Pressure to sell also affects nearby agricultural landholders as new occupants in the expanded urban area put pressure on growers to change or cease farming practices that cause odour, noise or dust (Metcalfe and Bui 2017). Urban encroachment causes an iterative loss of strategically valuable agricultural lands in local government areas and is a significant challenge across most states and territories (State of the Environment 2011 Committee 2011, Metcalfe and Bui 2017). Although urban encroachment occurs nation-wide, prevention against it occurs at local government and State levels through city boundaries and state development policies. Some states have introduced legislation to protect key soil-agricultural areas from urban encroachment (e.g. Barossa and McLaren Vale Character Preservation Bills in South Australia), but this is not the case for many other regions.

EROSION

Soil erosion is the removal of soil particles from one place to another via the movement of wind or water. It is a natural process that is greatly enhanced by human activities; this acceleration makes it one of the greatest threats to soil function globally as soil is essentially a non-renewable resource (ITPS 2015, Metcalfe and Bui 2017). It is particularly of concern in Australia where soil formation rates are well below the global average (Bui et al. 2010, Metcalfe and Bui 2017). The loss of topsoils and exposure of subsoils results in reduced agricultural productivity and health of native vegetation (WA EPA 2007). Soil movement can also undermine infrastructure, fill drains, and contaminate water supplies and inland waters (WA EPA 2007). Severe erosion leads to a loss of soil functional capability. The loss of organic carbon and other topsoil resources due to wind and water erosion are significant causes of soil condition decline over time (Tozer and Leys 2013, NSW EPA 2015).

Globally, soil water erosion transports 23 to 42 million tonnes of N and 15 to 26 million tonnes of P off agricultural land, often causing eutrophication of waterways receiving nutrient rich sediments (ITPS 2015). Replacing these nutrients costs an estimated $33-60 billion USD for N and $77-$140 billion USD for P (ITPS 2015). In catchments flowing to the Great Barrier Reef, the waters contain 5 times as much sediment, 2 times as much nitrogen, and 3 times as much phosphorus compared to pre-development conditions (Waterhouse et al. 2017). In addition, the 2015 rate of crop yield losses per annum due to soil erosion was 0.3% (more than 10 million hectares per year); if this rate continues, a 10% loss of potential crop yield would occur by 2050 (NCST 2013, ITPS 2015). The cost of soil erosion within Australia is difficult to quantify but undoubtedly substantial, particularly as up to 10 million hectares of land have less than 500 years until the soil's A horizon (generally the most productive/valuable layer) will be lost (WA EPA 2007, Bui et al. 2010, Metcalfe and Bui

2017, Waterhouse et al. 2017). The cost of dust storms in New South Wales alone is estimated at $9 million AUD per year (Tozer and Leys 2013).

Soil erosion can be prevented by maintaining adequate groundcover, protecting soil from particle detachment and transport. Climatic variation is a major concern for erosion management however, as erosion risk is determined by climate and vegetation interactions; drought, climate change, fire, and severe weather events all contribute to increased erosion risk (Metcalfe and Bui 2017, WA DAF 2017, VIC EPA 2018). Conservation agricultural practices are a key preventative measure for soil erosion, and are increasing in Australia (Metcalfe and Bui 2017); however, adoption rates are low or have decreased in some key Murray-Darling Basin catchments (Metcalfe and Bui 2017). As such, current rates of soil erosion by water across much of Australia continues to exceed soil formation rates even though there is an improving trend in erosion management through improved land management practices (ITPS 2015, Metcalfe and Bui 2017).

Strategies to prevent erosion often present an opportunity to improve soil condition and therefore soil sustainability. Promoting vegetation leads to an increase in soil organic matter, which can improve soil structure and therefore soil nutrient content and water holding capacity. A significant challenge facing erosion prevention however is the scale at which most prevention activities occur; that is, most prevention takes place at the landholder scale. Social and economic pressures on landholders can prevent the activities that might lead to effective erosion prevention.

ACIDIFICATION

Acidic soils occur naturally in some areas but human activities have accelerated soil acidification which is having negative consequences on agricultural production in many regions. Negative effects of acidification include changed soil biology, accelerated nutrient leaching, nutrient deficiencies and toxicities (Metcalfe and Bui 2017). Agricultural acidification is caused by adding acidifying fertilizers (such as some nitrogen fertilizers) and removing alkalinity (through removing plant products or leaching). Other localised acidification can be caused by sulfide oxidation, acid deposition from industrial pollutants, and land contamination. Because the addition and leaching of nitrogen fertilisers are associated with acidification, acidification risk increases when land use changes from low nitrogen inputs to high nitrogen inputs (Eugenio et al. 2018, VIC EPA 2018). An example of this land use change might be converting unimproved pasture into cropping, or cropping into intensive horticulture. Treatment of surface acidity is relatively simple and usually involves adding crushed lime sand, limestone, or dolomite; subsoil acidity is significantly more difficult and expensive to remediate. As always, prevention is generally less expensive than remediation and can be achieved to an extent by managing the type, rate, and timing of fertilizers and irrigation (WA EPA 2007).

Soil acidification affects about half of Australia's agricultural soils (c. 50 million hectares), mostly in Western Australia and New South Wales (Metcalfe and Bui 2017). In the Western Australian wheatbelt alone, between 8 and 27 million hectares are estimated to have been affected by moderate to severe soil acidity in 2001; this area is likely to have expanded (WA EPA 2007). Acidification is accompanied by yield decreases; productivity losses in South Australia and Victoria due to acidity and acidification have been estimated at $88 and $470 million AUD per year, respectively (DEW 2018, VIC EPA 2018). Unfortunately, liming is expensive, and is not occurring at a rate that will prevent further acidification (Metcalfe and Bui 2017, VIC EPA 2018). However, precision agriculture provides an opportunity to prevent soil acidification through improved fertiliser regimes, and also to improve the management of acidity through variable rate liming (VIC EPA 2018). The lost opportunity in Australia associated with soil acidity for wheat production is estimated to be worth A$400 million per annum (Orton et al. 2018).

SALINISATION & SODIFICATION

Salinisation and sodification are processes that involve salts in the soil. Salinisation is the accumulation of salts whereas sodification is an accumulation of sodium on clay exchange sites leading to structural decline. Soil salinisation occurs when salt stored underground is drawn into topsoils and subsoil by the movement of water (dryland salinity), or when land is irrigated with saline water (irrigated salinity), or if excessive amounts of fertiliser is applied (Eugenio et al. 2018). Irrigation-driven salinity is a particular issue for areas with poor drainage conditions which prevent salt removal from the profile (WA EPA 2007, ITPS 2015). Depending on an individual species salt tolerance, soil salinisation can negatively affect plants/crops via osmotic stress leading to a reduction of plant water intake (Rengasamy 2016). Sodic soils also have negative effects on plant growth as they disperse when wet with low salinity water (such as rainfall). Dispersion is a degradation of clay structure and causes clay microaggregates to break apart and the clay particles to 'disperse' into the soil water. Clay particles then block soil pores, leading to poor infiltration, waterlogging when wet and hardsetting when dry. Due to their poor hydraulic and structural properties, sodic soils are vulnerable to water erosion via gullying (Wong et al. 2010, Rengasamy 2016); gullies in sodic subsoils are particularly difficult to stabilise.

The movement of salt into the root zone in dryland salinity is driven by rising water tables; this is often caused by a change in the vegetation from deep rooted perennial species to shallow rooted annual species. This land use change allows groundwater to rise to a point (approx. ≥1.5 m depth) where capillary action due to evaporation draws the water (and the salt) to the soil surface (Rengasamy 2016). This process can take several decades before being detected and local geology, topography and groundwater aquifer characteristics also play an important role in groundwater upwelling (WA EPA 2007). The loss of deep rooted perennial species continues in Australia through both natural (fire, drought) and human induced pathways (disease, urban development), furthering the spread of salinisation into susceptible areas (WA EPA 2007, Rengasamy 2016). Although drought decreases the number of deep rooted perennial plants, it can also have a positive effect on salinisation rates by decreasing groundwater recharge (WA EPA 2007, Campbell 2008).

Salinisation and sodification are widespread issues in Australia. Although no accurate and recent statistics are available, about 16% of Australia's total cropping area has been estimated to be affected by dryland salinity; it is expected to increase from 5.7 million hectares to 17 million hectares by 2050 (ITPS 2015, Rengasamy 2016, Metcalfe and Bui 2017). Approximately 75% of Australia's dryland salinity occurs in Western Australia, including about 1.1 million hectares of land in the South West; over 14 000 hectares of land is lost to land salinisation each year in Western Australia (WA EPA 2007). About 40% of the Swan Coastal Plain (Western Australia) is at risk of salinisation (WA EPA 2007). The extent of soil salinisation in Victoria is currently unknown as it has not been mapped since the Millennium Drought (VIC EPA 2018). Although it hasn't been recently estimated for the nation, salinity costs to water, infrastructure and agricultural land within the Murray-Darling Basin have been estimated at $305 million AUD per year (Campbell 2008). The lost opportunity in Australia associated with soil sodicity and salinity for wheat production is estimated to be worth A$1,300 million and A$200 million per annum respectively (Orton et al. 2018).

CONTAMINATION

Soil contamination occurs when a pollutant is present at higher than background concentrations and is causing, or has the potential to cause, adverse effects on society or the environment (WA EPA 2007, ITPS 2015). These contaminants may adhere to soil particles, air, or water and their transport can lead to both on-site and off-site issues; the toxicity and persistence of soil contamination is a serious concern (WA EPA 2007). Contamination is a large and complex topic though, as the effects of soil contamination depend on soil properties as these control their mobility, bioavailability, and residence time (Eugenio et al. 2018). It is clear though that severe contamination degrades the ecosystem services provided by soil and reduces agricultural production capacity by limiting the end market opportunities of contaminated produce (Eugenio et al. 2018).

Contaminated sites are usually associated with past land uses of industry and agriculture where inadequate action was taken to prevent contamination (WA EPA 2007). The discovery of contaminated land in or near residential areas causes significant community concern and distress (WA EPA 2007); consider for example, the increasing attention that per-and poly-fluoroalkyl substances (PFAS) are receiving (VIC EPA 2018). Severe contamination can render land uninhabitable and significantly constrain land use options over the mid to long term (WA EPA 2007, ITPS 2015). As such, the economic costs of contaminated land generally outweigh the costs of remediation however rural sites can prove more difficult to remediate without external support due to their low land values (WA EPA 2007, NSW EPA 2015). Even though legacy sites continue to exist, soil contamination is improving in Australia due to improved regulation and remediation of contamination producing activities and contaminated sites (ITPS 2015).

Unfortunately, soil contamination continues to occur and actions that landholders take to improve one aspect of their business can have negative effects on other aspects. For example, pesticide and herbicide use is increasing in production systems, particularly in association with the adoption of no-till and minimum-till cropping (WA EPA 2007); these contaminants can raise significant public concerns (ITPS 2015). Agricultural contaminants usually involve build-up, leaching or transport of agricultural chemical and fertilisers (WA EPA 2007). Accidental release of contaminants also occurs, often due to inappropriate storage, transport, or handling; deliberate dumping of wastes due to economic pressures are also sources of environmental contamination (WA EPA 2007). Inappropriate mine management or closure is frequently associated with contaminated soil and water; these sites are likely to remain unsuitable for other uses without extensive rehabilitation (WA EPA 2007, ITPS 2015). Contamination of land and water resources, regardless of intent, often causes conflict between the landholders affected (Fergusson 2017, Metcalfe and Bui 2017).

CLIMATE CHANGE

The combination of Australia's climate, landscape, and soils mean that only about 10% of the continent is suitable for crops and improved pasture (Orton et al. 2018). In addition to the small amount of productive land, Australia is vulnerable to climate change, and in particular to changes in rainfall. Rainfall is projected to decline in southern Australia and change in other areas of Australia (DAFF 2014). Small decreases in rainfall can be exacerbated by increased evaporation rates and increasing aridity can also reduce soil structural stability and increase salt accumulation (DAFF 2014, Rengasamy 2016). As such, improving water use efficiency and increasing sustainable use of Australia's soil are key requirements for climate change adaptation (DAFF 2014). Soil management itself also contributes to climate change as poor soil management potentially releases large greenhouse gas emissions whereas conservation soil management can prevent the release or sequester carbon (Campbell 2008).

Climate change will exacerbate existing pressures and impacts; these pressures include shorter growing seasons, increased heat stress, an increase in extreme events, and a decrease in water availability (Burdon et al. 2017, Metcalfe and Bui 2017). Exacerbating existing pressures is likely to lead to an increase in soil degradation from processes such as erosion (both wind and water), salinisation and sodification from irrigation waters, and organic matter breakdown. It is likely that some production systems will become economically unviable in some regions; climate change is likely to reduce the global production of key commodities, with Australian production of some commodities decreasing by up to 19% by 2050 (Campbell 2008, Burdon et al. 2017). Furthermore, Australia is projected to be one of the most adversely affected countries due to climate change and may suffer declines of up to 79% in export commodities by 2050 (Campbell 2008).

Climate change adaptation will be vital for the sustainable management of Australia's soil resources as it increases the risk of carbon losses, erosion, and desertification, salinisation, and natural disasters such as severe droughts and floods (Campbell 2008, ITPS 2015). In addition, increasing energy costs will affect landholder management options (Campbell 2008). Finally, climate change effects are disproportionately felt by large landholders and low socio-economic groups, further affecting landholders capacities to address changing conditions (Metcalfe and Bui 2017).

OPPORTUNITIES

CLIMATE CHANGE

Australia is one of 186 countries to ratify the Paris Agreement; this agreement is on the reduction of climate change, limiting global warming to <2ºC warmer than pre-industrial global temperature, and ideally pursuing a change of no more than 1.5ºC (United Nations 2015, UNFCCC 2019). The two methods available for preventing enhanced global warming included preventing carbon emissions and sequestering carbon emissions. Soil contains a significant carbon pool, containing between two and three times as much carbon as the atmosphere (Minasny et al. 2017); the prevention of emissions and sequestration of carbon into soil via agricultural management has been strongly suggested as a method to mitigate against climate change (Minasny et al. 2017).

Agriculture is a significant emissions sector in the Australian economy, releasing 13.1% of Australia's emissions during the last accounting quarter (DEE 2018b); however, emissions from agriculture have decreased slightly since 1990, with most of the change driven by livestock management (DEE 2018b). Australia already has a framework for carbon sequestration in agricultural systems via the Emissions Reduction Fund (ERF) method for 'measurement of soil carbon sequestration in agricultural systems' (Commonwealth of Australia 2013, DEE 2018a). Few projects have successfully enacted this method however, due to a number of economic and administrative constraints (Burke 2016).

Australia as whole also has a number of physical constraints to soil carbon sequestration as many of the soils contain naturally low carbon contents (i.e. arid soils) or are often water limited (Minasny et al. 2017). The largest losses of soil carbon due to agricultural management have occurred under conventional cropping with stubble burning, with >50% of carbon lost in the top 10 cm (Luo et al. 2010). This is similar to the global average of almost half of soil carbon lost due to agricultural activities (Paustian et al. 2000). There is an opportunity, therefore, for substantial carbon emissions sequestration through global agricultural best practice and a small opportunity for increased soil carbon sequestration in Australian agricultural areas.

SOIL SUSTAINABILITY AND SECURITY

Soil is essentially non-renewable and needs to be managed in a sustainable manner (Bui et al. 2010). As such, soil sustainability is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations (United Nations 1998). Sustainable management is difficult however if human activities can place substantial demands on soil resilience, often leading to a decline in soil function and productivity over time (e.g. from poor agricultural practises) (Bennett and Cattle 2013). There are a number of soil characteristics that indicate soil condition, such as (Metcalfe and Bui 2017):

- carbon and nutrient contents,
- acidity (pH) and acidification trends,
- soil structure and porosity,
- topsoil thickness, and
- salinity.

Historically, poor soils management has led to significant losses in soil carbon, nutrients, and organic matter and subsequent negative changes in soil structure, acidity, and salinity (Bui et al. 2010, Metcalfe and Bui 2017). The retention of these positive characteristics and the prevention of soil degradation is therefore an important land management goal to ensure soil sustainability (Bui et al. 2010).

However, sustainable land management can only occur when the land's capability is understood and the land is managed within that capability and although soils (NSW EPA 2015). It is also important to note that even though soils and their interactions underpin effectively all plant and animal production systems, our understanding of soils continues to be patchy (Burdon et al. 2017). Therefore although appropriate land management is vital for the sustainable use of soils, economic pressures can drive landholders into unsustainable production habits or prevent landholders from choosing more sustainable methods (NSW EPA 2015). These economic conflicts occur because systems that maximise yearly income are often not the same systems that maximise soil longevity (Bennett and Cattle 2013). Therefore, sustainable soil management requires approaches where long term soil condition is a core consideration (Campbell 2008).

A vital component of sustainable soil management and agricultural best practice is the availability of accurate and relevant soil information for landholders. In addition to the data generated by industry, research, and the government, landholders themselves generate data during their activities. Soil information is primarily in the form of geographical information systems (i.e. spatial data and mapping) and is spread between a large number of agencies, preventing efficient access and collaboration of interested parties. An important gap in Australia's data infrastructure is therefore the lack of a single entity for the collection and curation of soils data.

Rather than a single-dimensional land assessment approach, such as land capability mapping of soil and landscape biophysical features, the Soil Security concept incudes consideration of other allied soil facets, including societal connections, education, policy, legislation, current land use, condition, and the economic and environmental value of our soils (Soil Science Australia 2018). Soil Security does not simply identify discrete soils, rather aspires to quantify additional stimuli which could result in soil becoming unsustainable, or not secure, and in quantifying this provide a framework for realising the potential for improved productivity, function, and ecosystem services. In this way, Soil Security is a broader concept than soil health, condition or quality.

Our food production in Australia is underpinned by the soil resource. Food exports are a significant sector in the Australian economy and indefinitely producing national and global food supplies will only be possible in agricultural systems that are managed sustainably (Orton et al. 2018). In this sector, industry driven sustainability goals are potentially an important driver in improving soil sustainability (VIC EPA 2018). However, it is important to realise that land that cannot be managed sustainably while being economically viable indicates that that land use is unsuitable for the capabilities of the site (Campbell 2008). Although both industry and individual landholders are responsible for enacting sustainability measures, governments also have a responsibility to support sustainable management through the provision of soil resources, community awareness, professional support, incentives, investment, and extension (Campbell 2008). Governments also have a responsibility to discourage unsustainable management by preventing inappropriate projects, and by maintaining regulations and compliance capabilities (Campbell 2008).

PRIORITIES FOR ACTION

The below recommendations are drawn from the Soil Science Australia 2019 Expert Panel Survey. This survey was administered by Soil Science Australia and included 48 responses from 75 invited members wherein members were chosen to reflect a range of career histories and progress.

ADOPT A NATIONAL INTEGRATED APPROACH TO SOIL MANAGEMENT

National level strategic planning

- Develop a national policy framework such as a National Soils Strategy.
    - Ensure this document is confined to evidence based management and contains measurable milestones and targets.
    - Ensure this document includes strategic approaches to urban planning and industrial development.
- Integrate environmental and agricultural priorities in all landscape decision making processes.
- Develop long term strategies for soil contamination.

Local level strategic planning

- Encourage realistic expectations of land capability; support landholder actions to change land use to align with those expectations.
- Encourage consumer cultural change to better align with sustainable soil systems.

DEVELOP LINKS BETWEEN SOIL SCIENTISTS, RESEARCHERS, POLICY MAKERS AND FARMERS

Communication

- Improve dialogue between landholders, industry, government, and research.
    - Improve collaborations between research and other stakeholders.
    - Improve strategic planning between government and other stakeholders.
    - Improve engagement with already developed soil policies.
    - Develop improved tools to deliver soils information to stakeholders to meet their needs.
- Improve extension on the value of soils and soil conservation.
    - Provide support for preventative measures against soil degradation.
    - Provide support for mitigating actions and adaptation for climate change, including soil carbon sequestration.
    - Develop and release community fact sheets on soil issues, solutions, and opportunities. Raise public awareness of the value of soils.

IMPROVE SOIL INFORMATION SYSTEMS TO SUPPORT SUSTAINABLE LAND MANAGEMENT

Investments

- Invest in the development of a publicly funded entity (e.g. a National Soils Bureau) with the aim to improve conservation, management and productive capacity of Australia's soils.
    - Invest in the production, storage, and communication of soils data and information.
    - Facilitate improved data sharing and communication between the States and Territories
    - Increase community soils awareness.
    - Increase investment in soils research, development and extension (RD&E).
- Increase the efficiency and certainty of current funding initiatives.
- Improve support resourcing for preventative actions against soil degradation.

- Improve resourcing and infrastructure for contamination management and remediation.

Agricultural best practice

- Improve farming systems management (including strategically locating agriculture).
  - Improve stock management.
  - Improve soil organic matter content.
  - Prevent the inappropriate storage and use of irrigation water.

- Improve preventative degradation measures.
  - Encourage soil testing to promote best nutrient application practices.
  - Encourage chemical handling certification to prevent agricultural contamination.

Landscape management

- Improve development controls to prevent erosion.
  - Prevent soil degradation through meaningful design and implementation of infrastructure and development.
  - Review land clearing and development guidelines and enable effective enforcement.
  - Encourage whole landscape management for weeds and pest species.

Government capability

- Improve governmental flexibility to short term challenges.
- Support the development of soil best practice management plans.
- Promote soil stewardship with landholders.
- Support innovative ideas and new adaptive management strategies.

FOCUS ON PROFESSIONAL ACCREDITATION, EDUCATION AND TRAINING IN SOILS

Education and training

- Support soils education programs in schools and tertiary institutions.
- Invest in soils training (or employing professional soil scientists) in land management agencies.

Accreditation

- Mandate the use of Certified Professional Soil Scientists (CPSS) for all development projects involving soils.
- Encourage and support the accreditation of non soil scientist professionals working with soils.

ABS. 2018. 4655.0 - Australian Environmental-Economic Accounts, 2018. Australian Bureau of Statistics.

Bennett, J., and S. R. Cattle. 2013. Adoption of soil health improvement strategies by australian farmers: I. Attitudes, management and extension implications. The Journal of Agricultural Education and Extension **19**:407-426.

Bui, E. N., G. Hancock, A. Chappell, and L. J. Gregory. 2010. Evaluation of tolerable erosion rates and time to critical topsoil loss in Australia. CSIRO, Canberra.

Burdon, J., T. J. Higgins, J. Pratley, R. Leigh, B. Gibson, A. McNeill, R. Gleadow, S. Powles, B. Gillanders, B. Woods, and S. Hatcher. 2017. Grow. Make. Prosper. The decadal plan for Australian Agricultural Sciences 2017-26. Australian Academy of Sciences.

Burke, P. J. 2016. Undermined by adverse selection: Australia's direct action abatement subsidies. Economic Papers: A journal of applied economics and policy **35**:216-229.

Campbell, A. 2008. Managing Australia's soils - a policy discussion paper. Prepared for the National Committee on Soil and Terrain (NCST) through the Natural Resource Management Ministerial Council (NRMMC).

Colloff, M. 2011. The role of soil biodiversity in providing ecosystem services. Report prepared for the Australian Government Department of Sustainability, Environment, Water, Population and Communities on behalf of the State of the Environment 2011 Committee. DSEWPaC, Canberra.

Commonwealth of Australia. 2013. Emissions Reduction Fund green paper.

DAFF. 2014. The National Soil Research, Development and Extension Strategy, securing Australia's soil, for profitable industries and healthy landscapes. Canberra.

DEE. 2018a. Measurement of soil carbon sequestration in agricultural systems. Commonwealth of Australia - Department of Environment and Energy.

DEE. 2018b. Quarterly Update of Australia's National Greenhouse Gas Inventory: September 2018 - Incorporating emissions from the NEM up to December 2018. Commonwealth of Australia - Department of Environment and Energy, Canberra.

DEW. 2018. Tracking changes in South Australia's environment - 41 trend and condition report cards. Government of South Australia Department of Environment and Water, Adelaide.

Eugenio, N. R., M. McLaughlin, and D. Pennock. 2018. Soil pollution - a hidden reality. Food and Agriculture Organization of the United Nations, Rome.

Fergusson, L. 2017. Anthrosols and Technosols: the Anthropogenic Signature of Contaminated Soils and Sediments in Australia. Water, Air, and Soil Pollution **228**.

ITPS. 2015. Status of the world's soil resources technical summary. FAO - Intergovernmental Technical Panel on Soils, Italy.

Jackson, T., K. Zammit, and S. Hatfield-Dodds. 2018. Snapshot of Australian Agriculture. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Luo, Z., E. Wang, and O. J. Sun. 2010. Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis. Geoderma **155**:211-223.

McBratney, A., C. Morgan, and L. Jarrett. 2017. The value of soil's contributions to ecosystem services. Page 227 *in* D. Field, C. Morgan, and A. McBratney, editors. Global Soil Security, Progress in Soil Science. Springer International Publishing Switzerland.

Metcalfe, D. J., and E. N. Bui. 2017. Australia state of the environment 2016: land. Australian Government Department of the Environment and Energy, Canberra.

Minasny, B., B. P. Malone, A. B. McBratney, D. A. Angers, D. Arrouays, A. Chambers, V. Chaplot, Z. S. Chen, K. Cheng, B. S. Das, D. J. Field, A. Gimona, C. B. Hedley, S. Y. Hong, B. Mandal, B. P. Marchant, M.

Martin, B. G. McConkey, V. L. Mulder, S. O'Rourke, A. C. Richer-de-Forges, I. Odeh, J. Padarian, K. Paustian, G. Pan, L. Poggio, I. Savin, V. Stolbovoy, U. Stockmann, Y. Sulaeman, C. C. Tsui, T. G. Vågen, B. van Wesemael, and L. Winowiecki. 2017. Soil carbon 4 per mille. Geoderma **292**:59-86.

NCST. 2013. Establishing the Australian Soil Assessment Program (ASAP).

NSW EPA. 2015. New South Wales State of the Environment 2015. New South Wales Environment Protection Authority, Sydney.

Orton, T., T. Mallawaarachchi, M. Pringle, N. Menzies, R. Dalal, P. Kopittke, R. Searle, Z. Hochman, and Y. Dang. 2018. Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat. Land Degradation and Development **29**:3866-3875.

Paustian, K., J. Six, and E. T. Elliott. 2000. Management options for reducing CO2 emissions from agricultural soils [J]. Biogeochemistry **25**:430-440.

Rengasamy, P. 2016. Salt-affected soils in Australia. GRDC, Adelaide.

State of the Environment 2011 Committee. 2011. Australia state of the environment 2011. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. DSEWPaC, Canberra.

Tozer, P., and J. Leys. 2013. Dust storms - What do they really cost? Rangeland Journal **35**:131-142.

UNFCCC. 2019. Paris Agreement - Status of Ratification. United Nations Framework Convention on Climate Change.

United Nations. 1998. Kyoto Protocol to the United Nations framework convention on climate change. Page 21.

United Nations. 2015. Paris Agreement. Page 16.

VIC EPA. 2018. Victorian State of the Environment 2018 scientific assessments. Authorised by the Commissioner for Environmental Sustainability, Melbourne.

Viscarra Rossel, R., R. Webster, E. Bui, and J. Baldock. 2014. Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. Global Change Biology **20**:2953-2970.

WA DAF. 2017. Report card on sustainable natural resource use in the rangelands: status and trend in the pastoral rangelands of Western Australia. Department of Agriculture and Food, Western Australia, Perth.

WA EPA. 2007. State of the Environment Report: Western Australia 2007. Perth.

Waterhouse, J., B. Schaffelke, R. Bartley, R. Eberhard, J. Brodie, M. Star, P. Thorburn, J. Rolfe, M. Ronan, B. Taylor, and F. Kroon. 2017. 2017 scientific consensus statement - land use impacts on gret Barrier Reef water quality and ecosystem condition. Queensland.

Williams, J. 2015. Soils governance in Australia: challenges of cooperative federalism. International Journal of Rural Law and Policy **Special edition 1**:12.

Wong, V. N. L., R. S. B. Greene, R. C. Dalal, and B. W. Murphy. 2010. Soil carbon dynamics in saline and sodic soils: A review. Soil Use and Management **26**:2-11.