The relationships between land management practices and soil condition and the quality of ecosystem services delivered from agricultural land in Australia

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Disclaimer

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6. Wind erosion

6.1 Nature of the issues

Soil erosion is the removal of soil particles from the ground's surface. It is usually brought about by wind and/ or water. The extent to which soils are susceptible to wind erosion depends on a range of factors, including climatic variability, ground cover, topography, the nature and condition of the soil, and the energy of the wind.

Soil particles behave differently depending on the strength of the wind and how well the soil surface is protected by ground cover. As wind erosion intensifies, aggregates can break or abrade, releasing dust into the air (Leys *et al.* 2010). Land management can either moderate or accelerate wind erosion rates, largely depending on how it affects the proportion of bare soil, the dryness and looseness of the ground's surface, and structures that reduce the force of wind (i.e., windbreaks). Grazing by stock, native animals (e.g., kangaroos) and feral animals (rabbits, camels, horses, goats) have major impacts on ground cover and soil physical properties. Such impacts have been exacerbated by the establishment of watering points that allow these animals to be active throughout previously dry landscapes in many parts of Australia (James *et al.* 1999; Landsberg *et al.* 2002). The changes in land cover brought about to establish much of Australia's agriculture have led to an acceleration of wind (and water) erosion (Beadle 1948; Yapp *et al.* 1992; Edwards and Pimentel 1993; Ludwig and Tongway 1995; Wasson *et al.* 1996; Campbell 2008; Hairsine *et al.* 2008; Leys *et al.* 2009).

The on-site impacts of wind erosion include soil loss, reduction in soil nutrients and organic matter (including soil organisms), release of soil carbon to atmosphere, undesirable changes in soil structure, reduced water infiltration and moisture-holding capacity, and exposure of unproductive saline and acid subsoils (Morin and Van Winkel 1996; Belnap and Gillette 1998; Pimentel and Kounang 1998; Lal 2001; Leys *et al.* 2009; McAlpine and Wotton 2009). Off-site impacts include negative impacts on the global climate through positive radiative forcing of dust, physical impacts of dust storms on buildings and equipment, and health impacts of dust for people (Leys *et al.* 2009). The limited data available suggest that the off-site costs of wind erosion can be many times greater than the on-site costs. Williams and Young (1999) estimated direct market values for on-site costs of wind ersosion in South Australia to be $1-6 million per year, compared with an estimated $11-56 million cost per year for off-site costs (largely associated with human health). The costs borne by Sydney when hit by the 'Red Dawn' dust storm in 2009, including costs associated with cleaning premises and cars, disruptions to transport and construction, and absenteeism were estimated to be $330.8 million, while losses of soil fertliser and carbon to landholders were estimated at $9 million (Tozer 2012). On the other hand, transport of eroded soil can provide important inputs to nutrient budgets of systems that can trap dust, such as forests and woodlands (McTainsh and Strong 2007).

Several major initiatives have been put in place to improve Australia's ability to monitor wind erosion and to identify priority areas for remedial action (Leys *et al.* 2010; McTainsh *et al.* 2012; Smith and Leys 2009). This will be especially important in the future as climate change is likely to increase the likelihood of soil erosion, due to increased incidence of droughts and reductions in crop production and ground-cover (Leys *et al.* 2009; Soils Research Development and Extension Working Group 2011). Historically, wind erosion has been particularly active in times of drought. In the 1940s and again in 2002 and 2009 there were heightened concerns due to dust storms hitting major Australian towns and cities (McTainsh *et al.* 1990; McTainsh *et al.* 2011). Wind erosion appears to have been reduced substantially since the 1940s, primarily due to better management of vegetation cover on agricultural lands (Australian State of the Environment Committee 2011), but it is expected that the incidence of huge dust storms, like those in 2002, will increase in the future (Leys *et al.* 2009).

6.2 Land management practices in relation to wind erosion

Approaches to reducing wind erosion address three major aspects (Carter 2006):

- Ground cover
- Soil looseness
- Wind velocity

Ground cover is important as it reduces wind speed at the soil surface and captures soils particles mobilised by wind. Soil looseness increases when there is too little vegetation cover, soils are dry, the type of soil contains small particles and/ or the surface is smooth. Maintaining soil moisture, avoiding trampling of exposed or susceptible soil by stock and maintaining rough soil surface are all ways to reduce soil looseness (Findlater *et al.* 1990; Carter *et al.* 1993; Moore *et al.* 2001; Carter 2002; 2006; McTainsh *et al.* 2011). While the velocity of wind is determined by the weather, it can be moderated locally by creating windbreaks.

Cropping and mixed farming

Recent surveys of past soil erosion, using measurement of ^{137}Caesium in soils, have concluded that levels of combined water and wind erosion from cultivated land and rangelands are relatively similar, and as much as eight times greater than from uncultivated areas and forests (Loughran *et al.* 2004; Bui *et al.* 2010). Regions with the largest impacts of wind erosion tend to be focused in arid and semi-arid rangelands of south-western Queensland, western NSW, north-central and north-eastern South Australia and western Western Australia, posing particular challenges for grazing enterprises (Leys *et al.* 2010). The semi-arid agricultural lands of eastern West Australia also have areas of high and very high wind erosion, compared with the generally low erosion levels in the non-agricultural lands of western South Australia, the northern Northern Territory and eastern Western Australia (Leys *et al.* 2010).

The process of cultivation of soil is a key factor affecting potential for both wind and water erosion in broadacre cropping (Freebairn 1992a; b; Freebairn and Loch 1993; Moran 1998; Barson and Lesslie 2004). The effects of cultivation have been likened to a fire passing through ploughed soil, disrupting the activities of soil organisms, oxidising organic matter, reducing soil fertility and often leading to soil structural problems (Australian State of the Environment Committee 2011). Some of these effects can be offset by addition of fertilisers and organic matter, but structural problems are much harder to address. The combination of soil type, moisture, tillage practice, and associated activities like clearing of deep rooted perennials, burning of crop residues, and running of grazing animals on the land can lead to the sorts of structural changes that encourage bare soil (Bartley *et al.* 2006).

The types of land management recommended to reduce wind erosion in cropping and mixed farming zones (McTainsh *et al.* 2011) include:

- Maintenance of adequate plant residue cover for soil erosion protection through the adoption of stubble retention systems;
- The adoption of minimum/ zero tillage systems that protect against erosion and maintain or improve soil structure;
- Avoidance of cultivation in high erosion risk periods;
- Reduction in burning stubbles;
- Use of chemical fallowing rather than tillage;
- Integrated feral fauna and flora control programs, including biological controls;
- Fencing to land class through a developed farm plan;

- Retention of boundary tall perennial vegetation;
- Avoiding grazing erosion-prone areas by fencing these areas;
- Intensive strip grazing/ cropping;
- Land reclamation of degraded areas for both production and conservation uses;
- Involvement of agricultural commodity industries in promotion of better land management practices.

Grazing/ pastoral enterprises

Livestock grazing has been associated with a decline in native perennial cover and an increase in exotic annual cover, reduced litter cover, reduced soil cryptogam cover, loss of surface soil microtopography, increased erosion, changes in the concentrations of soil nutrients, degradation of surface soil structure, and changes in near ground and soil microclimate (Eldridge 1998; Evans 1998; Yates *et al.* 2000; Jansen and Robertson 2001; Landsberg *et al.* 2002; Sparrow *et al.* 2003; Dorrough *et al.* 2004; Hunt *et al.* 2007; Department of the Environment 2009). Recommendations for countering the effects of grazing on soil erosion involve reducing grazing pressure, keeping animals away from riparian areas, and managing movements of cattle using watering points (Andrew 1988; James *et al.* 1999; Dorrough *et al.* 2004; Hunt *et al.* 2007; McTainsh *et al.* 2011). Rotational grazing and cell grazing have been shown to be profitable approaches to managing the impact of grazing on pastures and, therefore, ground cover (McCosker 2000; Southorn and Cattle 2004a; Crosthwaite *et al.* 2008). McTainsh *et al.* (2011) note that pastoral industries have improved in a variety of ways since the 1940s, including better control of total grazing pressure (native, feral and domestic stock).

6.3 Evidence of the effectiveness of management practices for reducing wind erosion

Evidence for the effectiveness of measures to reduce wind erosion come from two types of studies: experimental studies showing relationships between soil movement, wind speed and the state of the soil surface; and evidence of reduced incidence of dust storms as land management practices have improved from the 1940s to the present.

Numerous studies have been performed in Australia, and in comparable ecosystems in other parts of the world, to show that increasing ground cover reduces losses of soil due to both wind and water erosion (Eldridge 1993; Eldridge and Greene 1994;

Erskine and Saynor 1996; Scanlan *et al.* 1996; Carroll *et al.* 2000; Loch 2000; Yates *et al.* 2000; Eldridge and Leys 2003; Durán Zuazo *et al.* 2004; Heywood 2004; Greenway 2005; Bartley *et al.* 2006; Durán Zuazo *et al.* 2006; Raya *et al.* 2006; Silburn *et al.* 2011). Increasingly, evidence is being documented from on-ground initiatives by individual land managers (Jenkins and Alt 2007; Jenkins and Alt 2009).

In semi-arid environments, it has been concluded that ground cover of around 50% is required to keep wind erosion to a minimum (Findlater *et al.* 1990; Leys 1992; Rosewell 1993; Scanlan *et al.* 1996; Leys 1998; Loch 2000; Leys *et al.* 2009; Silburn *et al.* 2011) (Figure 6.1).

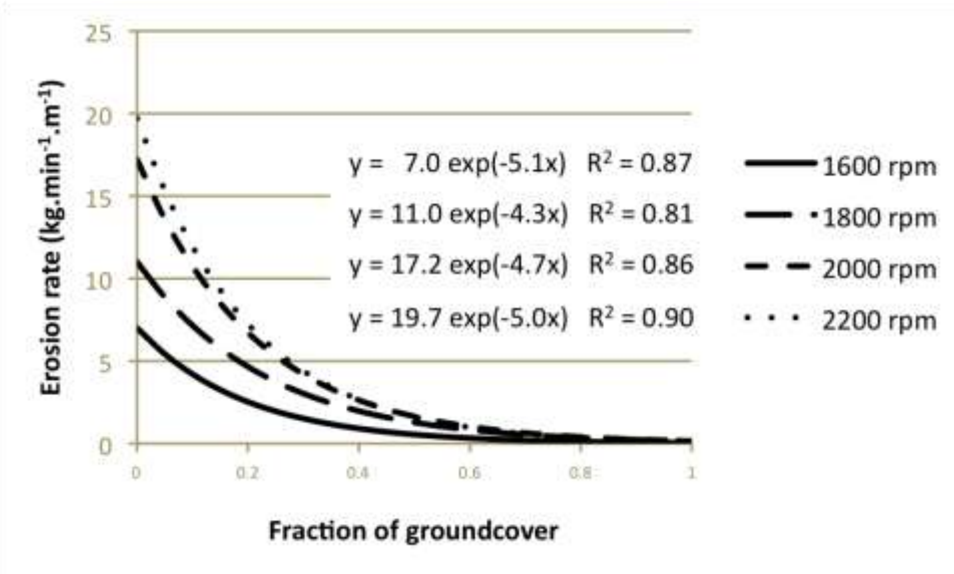

Figure 6.1: Erosion rates in relation to ground cover when four different wind speeds were applied to lupin residues (Findlater *et al.* 1990)

The general relationships between ground cover and soil erosion have been known for over 20 years. The main focus of research and development during the past two decades has been on how to achieve ground cover cost-effectively. This is discussed in the following section on water erosion.

The second line of evidence for the effectiveness of better land management (ultimately resulting in improved ground cover) for reducing wind erosion comes from comparisons of Dust Storm Indices (DSI) between the 1940s and the present (McTainsh *et al.* 2011). DSI provides a measure of the frequency and intensity of wind erosion activity. McTainsh *et al.* (2011) showed that mean on-site wind erosion in the 1940s was almost 6 times higher than in the 2000s, and the mean maximum DSI for the 1940s was 4 times that of the 2000s. There are also significant regional differences: wind erosion in the 1940s was much more active in the Mulga, Riverina and Central Australia than in the SA and WA rangelands, and the decrease in wind erosion between then and the 2000s was much more pronounced in the east and centre of the continent (McTainsh *et al.* 2011). Uptake of measures to improve ground cover was discussed in Section 4 and is also considered in Section 7. Although there have been high rates of adoption among farmers (D'Emden and Llewellyn 2006; Llewellyn and D'Emden 2009; Llewellyn *et al.* 2012), it has not been complete, and so risks of both wind and water erosion remain high in some areas (McTainsh *et al.* 2011).

Box 6.1: Managing wind erosion through a systems approach

System goal
To reduce soil loss from wind erosion.

Considerations
1. Wind speed is reduced by high cover (from soil C actions) and tree windbreaks (probably down fence-lines for operational efficiency). Maintaining ground cover of at least 50% will reduce the risk of soil loss through wind erosion.

2. Particle availability is reduced by limiting concentrated stock movements and tractor operations on very dry surface soils which can generate clay sized particles.

Recommended practices
As for soil C, acidification and water erosion practices.

Performance indicators
Dust monitoring (DEHNSW 2012).

Conflicts
In many cases major changes are needed from traditional practices to ones that build and maintain high levels of ground cover in all seasons and in wet and dry years.

7. Water erosion

7.1 Nature of the issues

Water erosion of soils occurs when soil particles are detached and carried away by water flowing across a landscape. In some cases soil loss is uniform (sheet erosion). In other cases small channels are formed (rill erosion). When the velocity and volume of water are high enough, and the soil surface is vulnerable, deep channels can be cut (gully erosion). Tunnel erosion occurs when the subsoil is removed while the surface soil remains relatively intact, producing tunnels under the soil, which eventually cause the surface to collapse (Coles and Moore 2001).

Like wind erosion (Section 6), the on-site impacts of water erosion include soil loss, reduction in soil nutrients and organic matter (including soil organisms), release of soil carbon to the atmosphere, undesirable changes in soil structure, reduced water infiltration and moisture-holding capacity, and exposure of unproductive saline and acid subsoils (Morin and Van Winkel 1996; Belnap and Gillette 1998; Pimentel and Kounang 1998; Lal 2001; Leys *et al.* 2009; McAlpine and Wotton 2009). Off-site impacts include sedimentation of waterways and impacts on quality of surface water and groundwater (turbidity, nutrient and other chemical loads).

Erosion from hillslopes by water is complex and multifaceted (Figure 7.1). It is determined by the combined effects of:

- the strength of water flow (influenced by the amount and rate of rainfall, the length and steepness of slopes, the degree to which the energy of raindrops is dissipated by ground cover, and whether the water encounters obstacles to its flow)
- the predisposition of soil particles to be dislodged (affected by soil type, ground cover, structural properties of the soil that affect the infiltration rate of water, and the soil's moisture), and
- the presence of obstacles to the flow of sediment from a site (e.g., its roughness and the presence of obstacles such as fallen timber, plant stems or contour banks created to limit erosion).

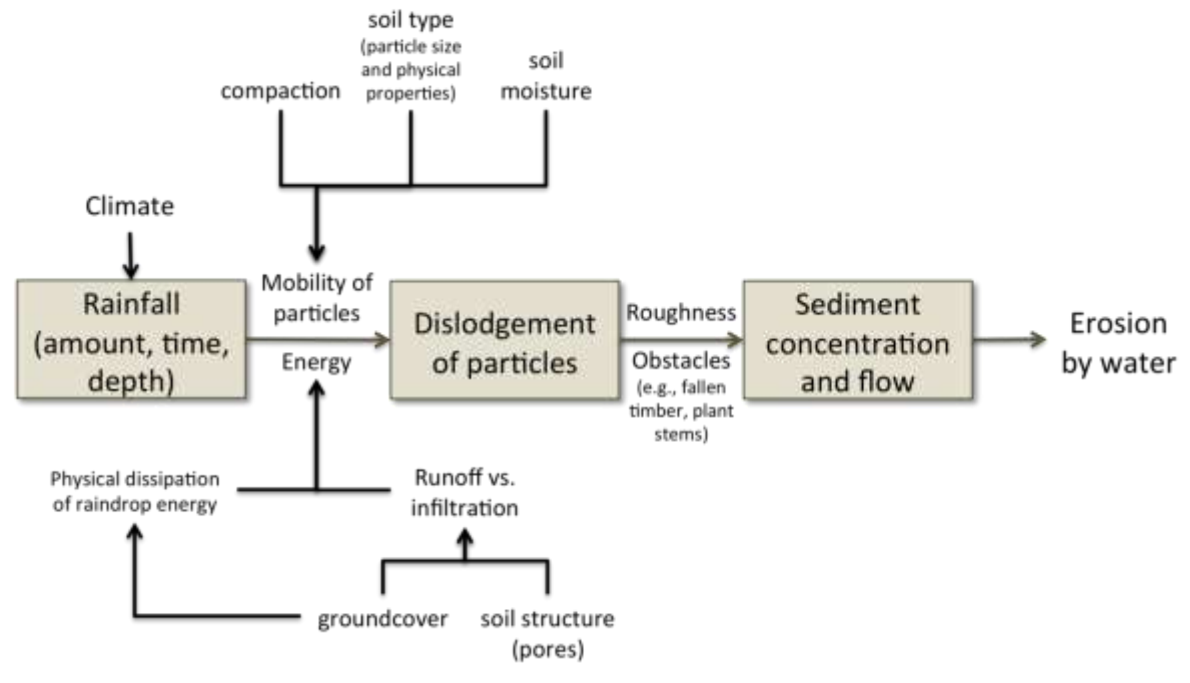

Figure 7.1: Factors influencing soil erosion by water. Figure was derived from various publications cited in the text

By far the strongest factor mitigating water erosion is ground cover: typically, 20-30% cover reduces erosion by 80-90% across a range of soils and land uses (Freebairn *et al.* 1986; Freebairn and Wockner 1986; Freebairn 1992b; Littleboy *et al.* 1992; Freebairn *et al.* 1993; Freebairn 2004; Gerik and Freebairn 2004; Silburn *et al.* 2007; Freebairn *et al.* 2009). Ground cover can be grasses, herbs, trees, dead plants with root systems still intact, dead plant material (especially branches) lying on the surface, or even stones. The mechanisms by which ground covers prevent erosion are a combination of physical binding (by roots), slowing of over-land flows (by plants, fallen timber, litter, and stones as physical barriers) and dissipation of the energy of raindrops (by foliage) (Freebairn and Wockner 1986; Brandt 1988; Hall and Calder 1993; Daily *et al.* 1997; Loch 2000; Phillips *et al.* 2000; Freebairn *et al.* 2009; McAlpine and Wotton 2009).

It is estimated that current rates of soil erosion by water across much of Australia exceed soil formation rates by a factor of at least several hundred and, in some areas, several thousand (Australian State of the Environment Committee 2011). As a result, the expected half-life of soils (the time for half the soil to be eroded) in some upland areas used for agriculture ranges from less than a century to several hundred years. While the time for total loss of soil is estimated to range from 100-500 or more years in different parts of Australia, it is expected that crops and other plants will respond to small changes in depth of topsoil, so that many areas are at risk of critical decline in productivity in much less than 100 years (Bui *et al.* 2010). Areas at highest risk include Coastal Queensland, the Wet Tropics, Mitchell Plains grasslands, New England Tablelands, and Victoria River basin in the NT. The 2011 State of the Environment Report concluded that in 9 of Australia's 22 physiographic provinces, the majority of the landscapes have been eroded (by combined wind and water erosion) to the extent that plant growth and agricultural yields have been adversely affected (Australian State of the Environment Committee 2011). In the other 13, it was concluded that management and monitoring are needed or the system of land use will be threatened in the long term.

Drought predisposes land systems to erosion by both wind and water because of reduced soil cover. Major soil erosion accompanied the intense rainfall events and floods that broke the drought of the late 2000s in southern Queensland (Australian State of the Environment Committee 2011).

7.2 Land management practices in relation to water erosion

Land uses that affect water erosion do so primarily via their effects on ground cover, evaporation of soil moisture, soil structure, compaction by heavy equipment or running of stock, and creation of contours that control water flow (Australian State of the Environment Committee 2011).

Broadacre cropping

Many of the effects of cultivation on susceptibility to wind erosion (Section 6) also apply to water erosion. Water erosion associated with cropping was recognised as a serious issue in the 1930s (Carey *et al.* 2004). Different studies report sediment yields from cultivated basins of between 2 and 21 times those from undisturbed native forests (Neil and Galloway 1989; Neil and Fogarty 1991; Erskine *et al.* 2002), although it should be noted that good land management can keep these figures within the low end of this range (Erskine *et al.* 2002). Soil conservation structures (contour banks and grassed waterways) were designed to reduce the slope length and thus net water erosion. These have been implemented extensively in Australia, but have not been sufficient to bring soil erosion within acceptable limits (Freebairn *et al.* 1993; Freebairn *et al.* 2009).

Management of water erosion on cropping lands has increasingly focused on methods of planting and managing crops and controlling weeds that involve little or no tillage, retention of stubble after harvesting, inclusion of a pasture phase between crops and minimisation of the effects of machinery by controlled traffic methodologies (Freebairn *et al.* 1993; Freebairn 2004; Li *et al.* 2007; Silburn *et al.* 2007; Llewellyn and D'Emden 2009; Llewellyn *et al.* 2012). Creating raised beds for crops in waterlogged areas can create an erosion hazard unless slopes and ground cover are managed carefully (Hamilton *et al.* 2005; Wightman *et al.* 2005)

Over the last 20 years new tillage practices have been developed that maximize water infiltration and reduce runoff; new row spacing and plant arrangement schemes have been developed to reduce soil temperatures and soil evaporation losses. Crop modelling and weather prediction capabilities have been developed to advise farmers on the opportune time of sowing that ensures adequate supply of stored soil water in combination with sufficiently high growing season rainfall probability required to satisfy the crop growth requirements and the farmers' yield goal (Gerik and Freebairn 2004; Australian State of the Environment Committee 2011; McTainsh *et al.* 2011). While including a pasture phase between crops is considered advantageous in managing ground cover, the potential effects of stock on the soil surface during this phase can potentially pose similar problems to those faced on dairy farms, especially if soils are wet (see below).

The uptake of minimum tillage approaches has required two major innovations: equipment capable of planting in stubble; and effective methods for weed control without disturbing the soil (Freebairn 1992; Freebairn and Loch 1993). The advent of better ways to manage heavy vehicles (controlled traffic) has also contributed to reducing runoff-driven erosion (Li *et al.* 2007).

Horticulture

As a form of cropping, horticulture faces many of the same risks as broadacre cropping in terms of encouraging soil erosion. The hardening of soils in many orchards (coalescence) restricts the growth and function of tree roots and infiltration of water to roots (Cockcroft 2012). Two key management innovations in orchards have been control of machinery traffic to minimise soil compaction, and establishment of ground cover plants that both minimise erosion and contribute to the soil ecosystem (Wells and Chan 1996; Dewhurst and Lindsay 1999; Firth *et al.* 1999; Zwieten *et al.* 2001; Reid 2002; McPhee 2009; Loch 2010; Slavich and Cox 2010; HAL 2012a). Increased ground cover is correlated with higher diversity of soil organisms, which has been found to have beneficial effects on water infiltration (and therefore reduced run-off erosion) promotes natural pest control (Colloff *et al.* 2003; Colloff *et al.* 2010).

Dairy

Many dairy farms combine the running of dairy cattle with beef cattle, cropping and/ or irrigated pasture production (Ashwood *et al.* 1993). To maintain high production of milk, pastures are fertilized. Key challenges for such enterprises include controlling sediment (along with nitrogen and phosphorus) losses into waterways, which can be exacerbated by compaction and disturbance of soil by the feet of grazing animals (Nash and Murdoch 1997; Fleming 1998; Fleming and Cox 2001; Fleming *et al.* 2001; Aarons *et al.* 2004; Nash *et al.* 2005; Barlow *et al.* 2007; Chan 2007).

Irrigation itself has the capacity to increase soil erosion by accelerating mineral weathering, transporting and leaching soluble and colloidal material, changing soil structure, and raining the local water table, thereby increasing the risk of salinity (Heywood 2004; Jenkins and Alt 2007; Jenkins and Alt 2009). Irrigation also has the capacity to reverse soil preparation measures such as the tillage that precedes planting.

Grazing

Livestock grazing is the most widespread Australian land use (Section 4). Impacts of livestock grazing on ground cover were discussed in Section 6. These impacts affect vulnerability of landscapes to both water and wind erosion. In addition, as discussed above, grazing during a pasture phase between cropping could increase vulnerability of soils to water erosion by disrupting soil structure and reducing ground cover.

7.3 Evidence of the effectiveness of management practices for reducing water erosion

As mentioned in Section 6, there is an extensive literature showing that increasing ground cover reduces losses of soil due to both wind and water erosion (Eldridge 1993; Eldridge and Greene 1994; Erskine and Saynor 1996; Scanlan *et al.* 1996; Carroll *et al.* 2000; Loch 2000; Yates *et al.* 2000; Eldridge and Leys 2003; Durán Zuazo *et al.* 2004; Heywood 2004; Greenway 2005; Bartley *et al.* 2006; Durán Zuazo *et al.* 2006; Raya *et al.* 2006; Jenkins and Alt 2007; Jenkins and Alt 2009; Silburn *et al.* 2011). Box 7.1 gives an example of how ground cover management, climatic variability and economic pressures can interact to force a region into an 'erosion trap'.

Like wind erosion (Section 6) there is a small number of studies that have focussed on the minimum extent of ground cover needed to avoid soil erosion. While different combinations of cover-types have different effectiveness, largely depending on the proportion and pattern of bare ground (Greene *et al.* 1994; Ludwig *et al.* 2005), some broad guidelines about effective cover have been developed. In general, a higher proportion of cover (70% - Figure 7.2) is recommended to manage water erosion than for wind erosion (50% - Figure 6.1) (Findlater *et al.* 1990; Rosewell 1993; Scanlan *et al.* 1996; Loch 2000; Silburn *et al.* 2011). For environments where rainfall is moderate to high, and/ or slopes are steep, 80-100% ground cover is recommended (Leys 1992; Lang and McDonald 2005). The standard of 70% is being applied widely by catchment management authorities in northern NSW (Central West Catchment Management Authority 2008; Namoi Catchment Management Authority 2010).

Box 7.1: The Gascoyne Catchment – A Case Study of Water Erosion

Three record flooding events in the Gascoyne Catchment, Western Australia, in the summer of 2010–11, resulted in massive plumes of soil spreading into the ocean at the mouth of the Gascoyne River (Waddell *et al.* 2012). The amount of soil lost during one of the flooding events was an estimated 2,250,000 tonnes. Restoration of damaged land in the Carnarvon area after the three floods required 140,000 tonnes of topsoil. It was concluded that the poor state of the landscapes in the catchment resulted in very much higher losses of soil than would have occurred in a catchment with good ground cover, although the extent of the additional losses could not be determined. The flooding also resulted in damage to infrastructure in the Carnarvon horticulture area.

The Gascoyne Catchment is in a typical ‘erosion trap’. Some of the higher country is protected from erosion by a covering of stones, but other parts have been heavily grazed and are highly degraded. This results in the rapid transfer of sediments and large amounts of water into the lower parts of the catchment. Downslope of the upland areas the landscape is dominated by extensive sheet wash plains. These areas are sources of browse for stock and have been over-utilized, leading to soil instability, when water flows from the upland areas, disrupted water flows and nutrient cycles, and erosion where stock have disrupted the soil surface. As the catchment goes through dry periods, grazing pressure in this part of the catchment increases, making erosion risks worse. In the catchment’s lower reaches, saline alluvial plains are stabilised to some extent by buffel grass, but this is susceptible to fire, the risk of which increases in dry periods. As recovery of these sorts of systems is slow, the challenge of returning this catchment to a state that is resilient to the effects of water in the landscapes, and to climate variations in general, is major.

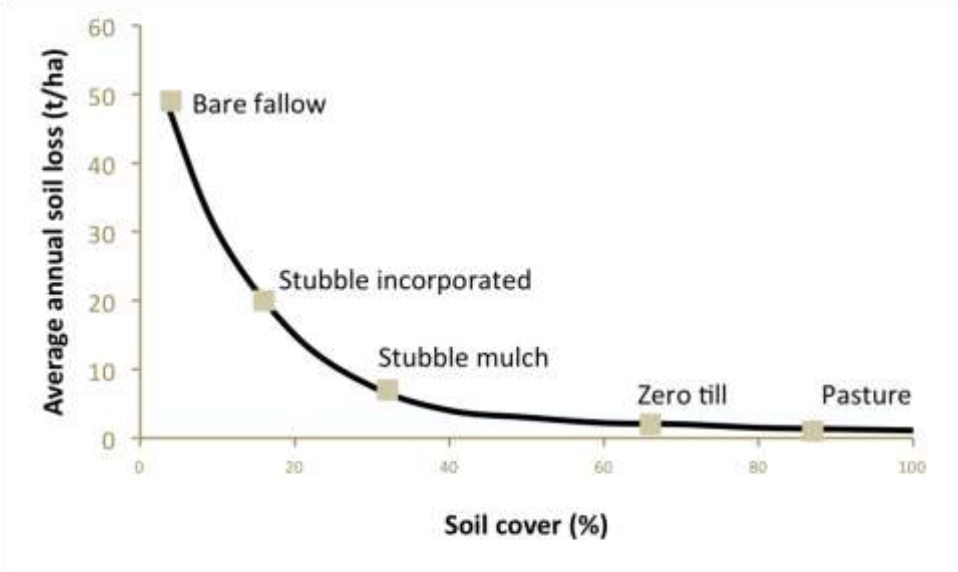

Figure 7.2: Generalised relationship (based on several empirical studies) between ground cover and annual average soil loss from vertisol soils on the Darling Downs, Queensland, with the influence of ground cover management illustrated (Freebairn and Silburn 2004)

The main focus of research and development during the past two decades has been on how to achieve appropriate proportions of ground cover cost-effectively. In grazing systems, removal of stock has been shown to allow recovery of ground cover, if conditions are favourable for regrowth of pastures, but recovery of full soil functionality, especially organic matter content, can take years to decades (Braunack and Walker 1985; Basher and Lynn 1996; Lal 1999; Silver *et al.* 2000) and the short-term and longer-term reduction in financial returns can be a disincentive for graziers (Lilley and Moore 2009). Maintaining a diversity of species, especially native plants and soil organisms, at landscape scales, is argued to be an important component of ground cover strategies in grazing systems, as this provides ready sources of species to re-establish ground cover communities after disturbances such as fires and drought (McIntyre 2002; Colloff *et al.* 2010). Restoring and maintaining plant species diversity and community structure is likely to provide greater resilience of ground cover to climatic and other shocks. This will probably require strategies that capture resources, such as water, seeds, nutrients and carbon, increase their retention on-site, and improve microclimate, in addition to removing stock (Yates *et al.* 2000).

Across Australian states, 30-80% of horticultural businesses reported using alternative or cover crops between main crops or using mulching and/ or matting to provide ground cover between crops in 2009-10 (Barson *et al.* 2012c). The proportion of grazing (beef cattle/ sheep) businesses across Australia monitoring ground cover levels has increased from 70% in 2007–08 to 79% in 2009–10, but the percentage of businesses setting ground cover targets decreased from 40 to 31% in the same period (Barson *et al.* 2011). Similar trends were seen for dairy businesses (Barson *et al.* 2012a).

Detailed research on reduced-tillage approaches has been conducted across Australia (Hamblin *et al.* 1982; Hamblin 1984; Freebairn *et al.* 1986; Hamblin *et al.* 1987; White 1990a; Buckerfield 1992; Freebairn 1992; Kingwell *et al.* 1993; Schmidt and Belford 1993; Schmidt *et al.* 1994; Felton *et al.* 1995; Thomas *et al.* 2007). Conservation tillage has been shown to dramatically reduce soil erosion and provide benefits for production in most areas (Freebairn *et al.* 1986; Freebairn 1992; Radford *et al.* 1993; Thomas *et al.* 2007). No-tillage and reduced tillage (stubble mulch) practices with stubble retention have generally resulted in greater fallow efficiency (gain in soil water during the fallow per unit of rainfall), soil water storage and grain yield, compared with conventional tillage practices, which incorporated stubble into the soil, although lower grain protein content has also been reported for some locations (Freebairn 1992; Radford *et al.* 1993).

These results are supported by around 20 commercial-scale, development and extension experiments across a range of crops and environments in the grain growing areas of Queensland since the 1970s, in which mean grain yield was 9% greater under no-tillage than with stubble incorporation (Thomas *et al.* 2007). There is some evidence that yield responses are likely to be greater where soil water supply limits yield (Freebairn *et al.* 1986; Thomas *et al.* 2007). While it is likely that these general trends will apply in other places with different soil types and production systems, the researchers caution against uncritical generalization without further experimentation (Freebairn *et al.* 2009).

Case studies in Queensland indicate that these benefits can be turned into significantly improved profits from no-tillage compared with traditional tillage, especially when economies of scale can be achieved by applying the same labour and machinery over large areas, and when controlled traffic management is used (Wylie 1997; Gaffney and Wilson 2003).

Some limitations of conservation tillage have been identified. The reduced surface roughness produced by no-till management can lead to enhanced run-off and sediment movement in areas where maintaining high biomass of plants is difficult, or where low cover results from crop failure or grazing (Freebairn *et al.* 2009). In these cases, some tillage might be required to create surface roughness. Since one role of tillage is weed and disease control, crop rotation and other approaches to weed control, such as inversion ploughing every 8-10 years to bury weed-seeds, are especially important in no-till systems (Douglas and Peltzer 2004; Thomas *et al.* 2007).

As discussed in Sections 4 and 5, the adoption of some form of minimum tillage has increased over the past two decades.

In southern Australia, key factors that have influenced adoption of minimum tillage approaches include machinery costs, perceived lack of convincing evidence of results, and concerns about herbicide resistance and weed control (D'Emden and Llewellyn 2006; Llewellyn and D'Emden 2009; 2010; Llewellyn *et al.* 2012). The main reasons given by adopters for limiting their use of no-tillage approaches include herbicide resistance, weed control issues, soil physical constraints, pests and soil disease. Adoption of no-tillage approaches appears to be leveling out at about 90% of farmers in many regions of Australia (Llewellyn *et al.* 2012).

Box 7.2: Managing water erosion through a systems approach

System goal
To reduce water erosion by reducing suspended sediment and transported sediment.

Considerations
1. Maintain ground cover at better than 50% to reduce raindrop impact and production of suspended sediments. Maintaining good ground cover will also increase biomass available for soil carbon.

2. Increase infiltration (reduce runoff) with adequate ground cover, manage soil moisture to avoid excessive decomposition and waterlogging (as for carbon management), and reduce compaction by using Controlled Traffic (CT) approaches.

3. Where appropriate, manage runoff with designed layouts (controlled traffic farming, diversion and contour banks) to prevent flow concentration (spread runoff evenly across the land). Runoff velocity is then unlikely to reach erosive levels in our landscapes. CT wheel tracks are designed to carry runoff to safe disposal areas (typically diversion channels).

Recommended practices
Soil C and acidification practices, controlled traffic and designed layouts, ground cover management.

Performance indicators

Water erosion control (especially percentage groundcover, turbidity of off-flows, water quality) (relevant at local to regional scales), access and timeliness (relevant at farm scale).

Conflicts

In many cases major changes are needed from traditional practices to ones that build and maintain high levels of ground cover in all seasons and in wet and dry years.

8. Ecosystem services and resilience of soils

8.1 The concept of ecosystem services

The concept of ecosystem services evolved to bridge the perceived gap between economics and ecology. To achieve this it has been necessary to consider at some length how to define and classify ecosystem services so that they not only make sense to a range of stakeholders, but also can be used unambiguously in economic valuation and environmental accounting. Because this process has involved multiple disciplines, there have been different views on how to define terms like 'processes', 'functions', 'services', and 'value' (Costanza *et al.* 1997; Daily 1997; de Groot *et al.* 2002; MA 2005; Wallace 2007; Costanza 2008; Fisher *et al.* 2009; TEEB 2009; Dominati *et al.* 2010; Maynard *et al.* 2010; UK National Ecosystem Assessment 2011b; Nahlik *et al.* 2012; Robinson *et al.* 2012). Typologies of ecosystem services have remained fluid with the recognition that services must be identified in relation to those receiving the services, and that this relationship differs with different groups of people, different places and different purposes for considering ecosystem services (de Groot *et al.* 2002; Costanza 2008; Fisher *et al.* 2009).

As our focus in this report is on the links between land management, soil condition and benefits to humans, we have adapted four recent approaches for conceptualising these relationships into the framework shown in Figure 8.1.

Figure 8.1 incorporates several recent conventions designed to reduce inconsistency of terminology and ensure that the direct and indirect contributions of ecosystems are not confused in economic evaluations and environmental accounting:

- Ecosystem services are defined and described (Table 8.1) in terms of what possibilities soil ecosystems make available to humans, without the need for intervention by humans[1]; the benefits to humans are identified separately, and require actions or the articulation of needs by humans (Boyd and Banzhaf 2007; Fisher *et al.* 2009; Haines-Young and Potschin 2009).
- We have avoided distinguishing between ecosystem processes and functions, referring only to processes. Ecosystem processes are defined as transformations of inputs into outputs and ecosystem services are defined as the flows that arise from these processes and are of benefit to humans (Dominati *et al.* 2010).

[1] There are several published definitions that meet these criteria, for example "the aspects of ecosystems utilized (actively or passively) to produce human well-being" (Fisher *et al.* 2009)

- We have distinguished between final ecosystem services (those that can be turned directly into benefits by humans) and intermediate ecosystem services (those that support other services but are not used directly for benefit by humans) (de Groot *et al.* 2002; Boyd and Banzhaf 2007; Fisher *et al.* 2009; TEEB 2009; Bennett *et al.* 2010; Dominati *et al.* 2010; Johnston and Russell 2011; UK National Ecosystem Assessment 2011b).
- For consistency with other typologies, we have adopted the broad organising headings of 'provisioning', 'regulating, and 'cultural' services (Daily 1999; MA 2005; De Groot *et al.* 2010; Dominati *et al.* 2010).

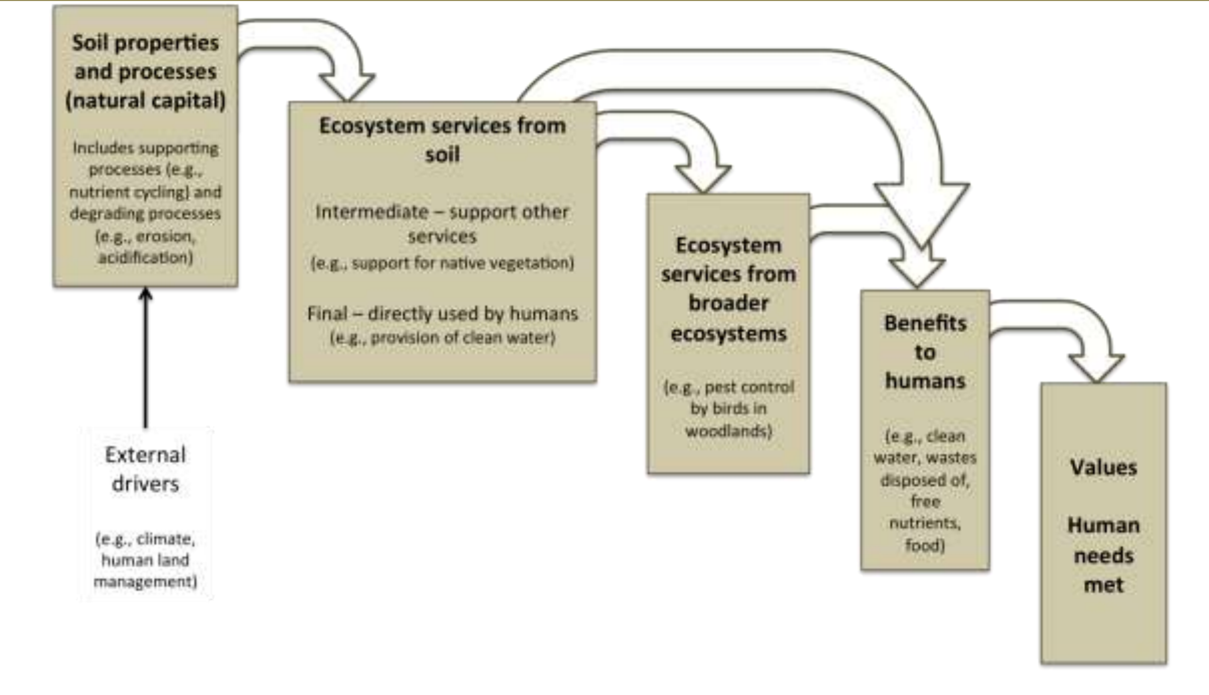

Figure 8.1: Conceptual relationship between land management, soil structures and processes, ecosystem services, benefits to humans and human wellbeing

This diagram draws on several key publications (MA 2005; Haines-Young and Potschin 2009; Bennett *et al.* 2010; Dominati *et al.* 2010)

Although it is potentially confusing to distinguish between final and intermediate ecosystem services, we agree with advocates of this approach that: (i) being strict about final services is essential to avoid double counting of benefits in economic assessments, such as we perform in this report; and (ii) there is a need to recognise a level of aggregation of processes above that of nutrient, water and carbon cycling and the like, by which soils support the final services produced by broader ecosystems.

8.2 Relating soil ecosystem processes to services and benefits

The roles of soils in supporting natural and agricultural ecosystems have been recognised for some time and their importance for providing ecosystem services has been discussed in various recent syntheses (Daily *et al.* 1997; Wall and Virginia 2000; Balmford *et al.* 2002; De Groot *et al.* 2003; Swinton *et al.* 2006b; Dale and Polasky 2007; Kroeger and Casey 2007; Swinton *et al.* 2007b; Turner and Daily 2007; Weber 2007; Bennett *et al.* 2010; Robinson *et al.* 2012). Figure 8.2 and Table 8.1 draw on a number of these syntheses.

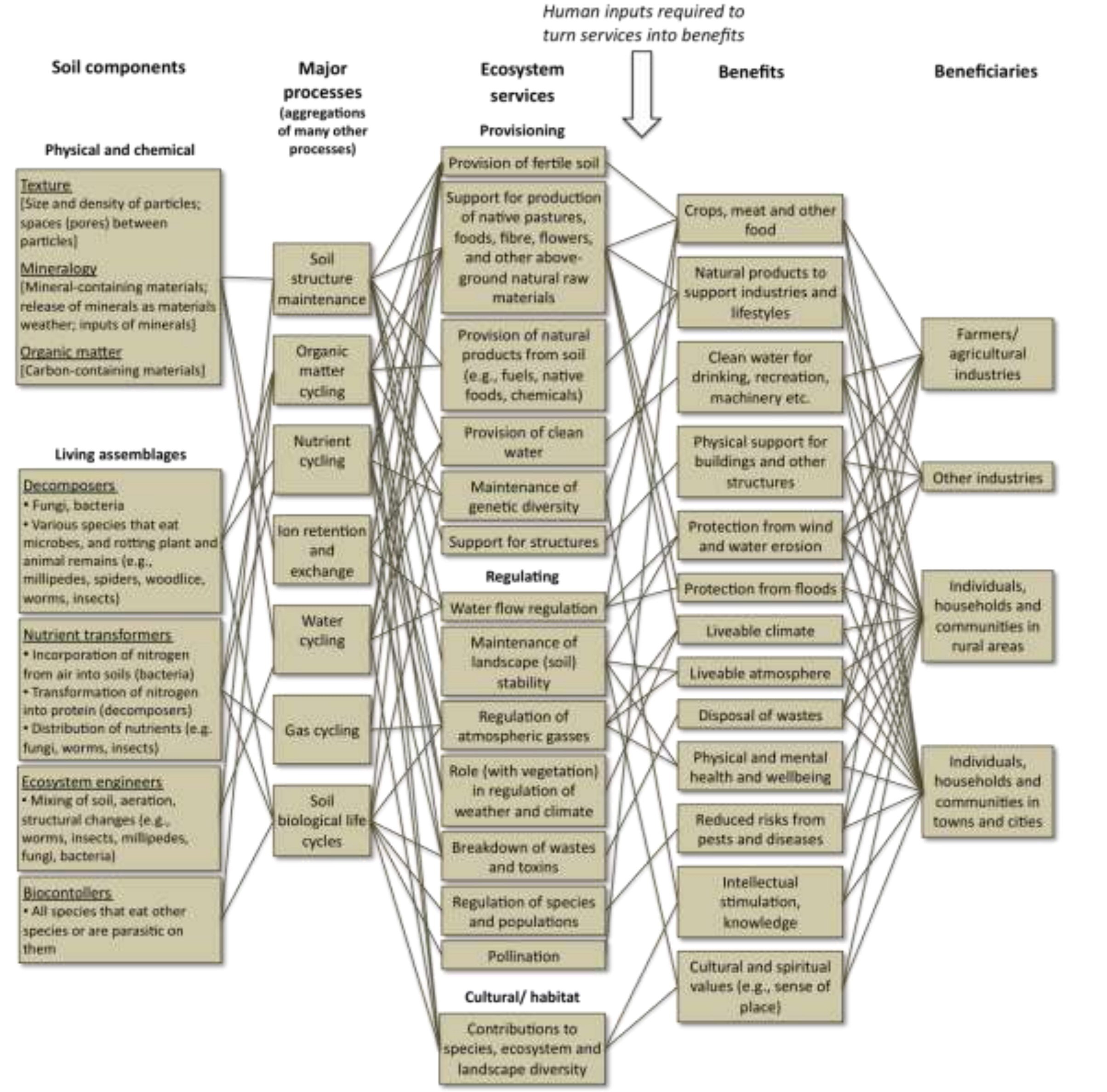

Figure 8.2: Interrelationships between living and non-living components of soils, major processes, ecosystem services, benefits to humans and who the beneficiaries are

The diagram synthesises frameworks by: Palm *et al.* (2007); Kibblewhite *et al.* (2008a); Bennett *et al.* (2010); Dominati *et al.* (2010); UK National Ecosystem Assessment (2011a)

Figure 8.2 and Table 8.1 illustrate the complex interrelationships between the living and non-living components of soil, the processes and ecosystem services these interactions generate and the benefits derived by a range of beneficiaries, and seek to simplify this complexity by identifying a relatively small number of 'final' ecosystem services and benefits. This figure also emphasises the underpinning importance of soil's natural capital (including both living and non-living components), which is the key to long-term sustainable management of soils, and maintenance of soil resilience (Lal 1997; Dominati *et al.* 2010; Sylvain and Wall 2011; Robinson *et al.* 2012).

Table 8.1: Description of the broad groups of ecosystem services provided by soils*

Ecosystem services	Description of services and benefits
Provisioning services Provision of fertile soil, natural products and clean water Support for native vegetation Maintenance of genetic diversity Support for structures	Provision ecosystem services are those that either directly provide products that people value or can be used to produce things of value. Products from soils include clean water, bush foods (e.g., witchety grubs, mushrooms), timber, and chemicals and genetic material that might be developed as pharmaceuticals or used in genetic and other technologies in the future. Fertile soil can be used by humans to grow crops. Soil fertility is maintained by a range of processes, including nutrient cycling (distribution of carbon, nitrogen and phosphorus throughout soils by a range of soil organisms), gaseous exchange with the atmosphere (extraction and release of nitrogen and carbon), and the engineering activities of earthworms, insects, fungi and other species (which maintains soil structure, porosity and water-holding and infiltration capacities). By supporting the growth of native forests, woodland and grasslands, soils contribute to the ecosystem services that native vegetation provides, including the provision of fodder for stock. It is often overlooked that the formation of soil by natural processes provides to foundation for anchoring structures such as houses, other buildings and other infrastructure.
Regulating services Water flow regulation Maintenance of landscape (soil) stability Regulation of atmospheric gases Regulation of weather and climate Remediation of wastes Regulation of species and populations Pollination	Regulating ecosystem services are so named because they control biophysical processes in ways that can be beneficial to humans. The structural properties of soils, determined living and non-living components below ground and the vegetation component of the soil-plant ecosystem above ground, affect how water flows across the surface of the ground or infiltrates underground watertables. This affects erosion and damage to human life and property as well as the access of plants, including crops and native vegetation, to water. In Australia, regulation of watertables by soil-plant ecosystems is a key determinant of whether salinity (rising of salt to the surface) becomes a problem. The above processes stabilise landscapes and prevent negative health impacts and damage to property that can accompany dust storms (including major impacts of dust on weather patterns (Mahowald *et al* 2010; Rotstayn *et al.* 2012)). Along with vegetation, soils affect the amount of radiation (heat, light) reflected from the earth to the atmosphere, which affects weather and climate. Evaporation of water into, via soil and vegetation also influences weather and climatic patterns. Extraction of carbon and nitrogen from the air by soils, and release of these elements into the air, are major mechanisms for regulating the composition of the atmosphere, effecting climate and suitability of air for humans. Soils breakdown organic and non-organic compounds, some of which can become toxic to humans, other animals, or plants. Additional investment in waste disposal is needed when this ecosystem service is exceeded by the rate of production of

Ecosystem services	Description of services and benefits
	wastes by humans. The various species living in soil interact with one another and with species living above ground, by eating one another and competing for food and space. In so doing, they regulate one another's numbers and prevent any species increasing to numbers that might be detrimental to ecosystem functions and/ or human activities. Some of these species also play a role in pollinating plants and moving seeds around in landscapes.
Cultural services Contributions to species, ecosystem and landscape diversity	It has been recognised for some time that people draw a wide range of inspiration and both physical and mental health benefits from ecosystems. People identify with certain landscapes ('sense of place'), gain knowledge by studying ecosystems, and often find spiritual connections with the land. In all of the ways discussed above, and more, soil contributes to the diversity and condition of landscapes. Although these cultural benefits are not always easy to define, they are nevertheless vital for humans to thrive mentally and physically.

*Detailed discussions about the nature of ecosystem services in agricultural and other lands in Australia and globally can be found in the following references: Binning *et al.* (2001); de Groot *et al.* (2002); Haygarth and Ritz (2009); Bennett *et al.* (2010); UK National Ecosystem Assessment (2011a; b).

We have chosen to develop our own framework (Figure 8.2) as we have found existing ones to be inconsistent with regard to some of the principles listed in Section 8.1. The following examples illustrate some of these inconsistencies and explain why we have emphasised them in the context of this report:

- Some other frameworks include 'supporting services' as a separate category. In Figure 8.2, these are considered to be part of the 'major processes'.
- When considering 'provisioning services', several other frameworks for ecosystem services from soils and agricultural land include provision of marketable goods, including food (crops and/ or livestock), wood, fibre and others, as ecosystem services (Bennett *et al.* 2010; Dominati *et al.* 2010; UK National Ecosystem Assessment 2011b). Following the principle of separating the services that ecosystems provide from the benefits that are derived with human input (Boyd and Banzhaf 2007; Kroeger and Casey 2007) (see also Table 8.1), we consider that soil ecosystems provide fertile soil but not crops or livestock (Figure 8.2). We do, however, consider provision of edible products from native soil ecosystems (e.g., edible insects and fungi) to be an ecosystem service. This distinction is important because, if we are to assess the value of better management of soil ecosystems we need to be able to account separately for the human inputs and ecosystem responses.
- It is common in ecosystem service typologies to describe 'cultural services' in terms such as 'spirituality', 'knowledge', 'sense of place' and 'aesthetics'. In our framework we interpret these as benefits that are derived by the ways in

which humans interpret landscapes, including soil landscapes, in terms of human needs and values. This is an important distinction because we need to be able to consider how management of soil ecosystems might affect landscapes separately from how these effects might be interpreted by humans.

- It is also common to include 'control of pests and diseases' as a 'regulatory service'. We prefer to describe the service as 'regulation of species and populations' because whether or not species are pests depends on human perceptions. This is important because improving the control of potential pests, like aphids in orchards, has been achieved through encouraging soil biodiversity rather than targeting pests per se (Colloff *et al.* 2003; Colloff *et al.* 2010).
- We have included pollination as a soil ecosystem service, because some pollinators (e.g., beetles) have a life-stage that occurs in soil and/ or live in soil as adults. We note, however, that pollination is a final service in some situations (e.g., it contributes directly to production of many crops, separately from the contributions of soil fertility) and an intermediate service in others (e.g., it contributes to the support of native vegetation by soil ecosystems).
- Some other studies have identified ecosystem 'disservices', such as salinisation, acidification, erosion and carbon decline (Swinton *et al.* 2007b; Bennett *et al.* 2010). We regard these as symptoms of declines in ecosystem services and we consider them as degradation processes in Figure 8.1, after Dominati *et al.* (2010).

The importance of distinguishing between intermediate and final services was explained in Section 8.1. It can be illustrated in relation to pollination. If this distinction is not made, there is a risk of counting the contribution of pollination more than once in environmental accounting or economic evaluations: one in its own right and again as part of the value of native vegetation. On the other hand, it is important that the contributions of soil biota to fertilising crops are considered in addition to the soil processes that maintain soil fertility, even though the values of both are included in the value of crops produced. This is because the ways in which the benefits are managed by farmers might be different (e.g., farmers might manage soil fertility by addition of fertilisers and might manage pollination by hiring the services of bee-keepers and both of these will be separate items in a farm's accounts).

Our framework identifies 13 major ecosystem services and 12 groups of benefits from soils. Focusing on benefits and beneficiaries is one way to translate complicated scientific concepts and language for other stakeholders (Ringold *et al.*

2009; Ringold *et al.* 2011). Despite the complexity of the interactions involved, it is possible to make qualitative or semi-quantitative assessments of the relative impacts of different management regimes on different ecosystem services (Foley *et al.* 2005; Bennett *et al.* 2010; Gordon *et al.* 2010) (Figure 8.3). If enough information is available then these benefits can be estimated in monetary terms (Section 9). In Section 8.3, we consider the potential effects of better soil management on ecosystems services in more detail, and in Section 9 the economic implications are considered.

We have depicted only broad groups of beneficiaries in our framework (Figure 8.2 and Table 8.2); when dealing with specific situations it is useful to consider beneficiaries in greater detail than we have (Ringold *et al.* 2009; Ringold *et al.* 2011).

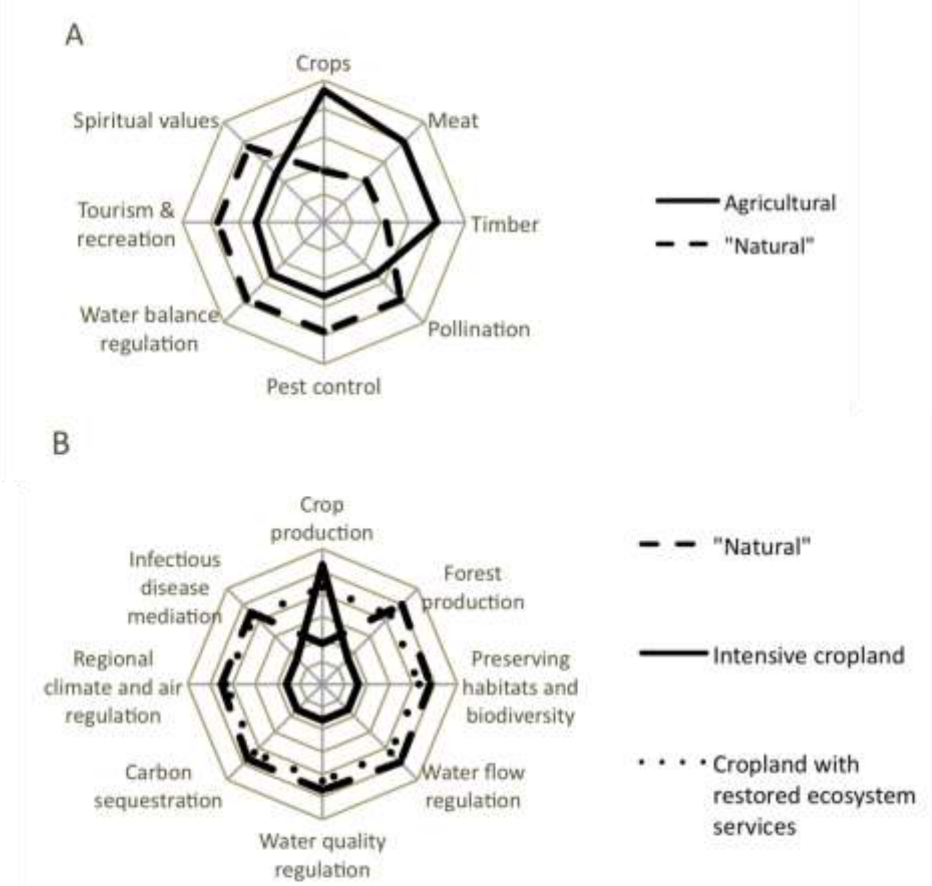

Figure 8.3: Two generalised assessments of differences in ecosystem services from 'natural' ecosystems and agricultural land (Foley *et al.* 2005; Gordon *et al.* 2010)

The further out from the centre the bold line crosses the axis for each ecosystem service the greater the relative production of that service

Table 8.2: Example of the beneficiaries of soil ecosystem services

Beneficiaries	Examples of how they benefit
Farmers and agricultural industries	Production of crops is supported by provision of fertile soil, pollination from animals living in soils and native vegetation, and the role of soil/ plant ecosystems in channelling water into places where it can be used for crops. Raising stock is supported by the role of soils in supporting native (and introduced) pastures and by provision of clean water, filtered and detoxified by soil/ plant ecosystems. Costs of disposing of animal wastes are much lower than they would be if soil ecosystems did not do part of the job. Costs of running machinery are reduced when water has been filtered of sediment by soil ecosystems. Soil provides physical support for farm buildings and structures like dams and levy banks. Stock and crops are protected from heat and floods by native vegetation supported by soil ecosystems, which usually leads to higher yields. The structural components of soils ecosystems, including plant roots, protect against wind and water erosion, reducing costs of replacing nutrients and soil itself and reduced costs of damage. Soil/ plant ecosystems host a range of species that provide pest control by attacking pests of crops. The natural dynamics among species in ecosystems regulated most populations of species and stops them becoming pests or weeds. These processes also control many disease organisms.
Other industries	Industries associated with agriculture, including processors and retailers of food, benefit from the ecosystem subsidisation of food prices – often more than farmers do as profits in these parts of the food supply chain tend to be higher than for farmers. Many other industries rely on clean water and protection from wind and water erosion that could damage infrastructure. Industries that discharge wastes into the environment receive benefits from natural waste breakdown by soil ecosystems. Some industries rely on products from soil ecosystems or ecosystems supported by soil processes (e.g., wildflower harvesting, timber industries, commercial harvesting of fungi or 'bush tucker', peat for fuel).
Individuals, households and communities in rural areas and Individuals, households and communities in rural areas	In both rural and urban areas, individual, households and communities benefit, directly or indirectly, from all soil ecosystem services, but the nature and size of those benefits differs. All Australian households benefit from the production of food and natural products that becomes available in Australian shops. The costs of these products are subsidised by the free soil-fertilisation, water collection, pest control and other services provided to farmers and native vegetation systems by soils. People in both remote and urban areas benefit from water filtration by soil/ plant ecosystems (studies around the world have shown that the cost of providing clean water increases dramatically when catchment areas become degraded). The high health, transport and other impacts and costs incurred by both rural and urban areas during recent dust storms (Leys *et al.* 2011; Tozer 2012) illustrate the benefits of soil/ plant ecosystems controlling soil stability. Soil stabilisation services, which limit erosion by water and help protect against impacts of flooding, also benefit all people, but especially those living near rivers or in urban areas where water flows could affect life and property. All people benefit from the contributions of soil ecosystems to local regulation of climate and to control of the gaseous composition of the air and air quality (through such processes as absorption of heat, reflection of sunlight, contributions to water cycles that influence rainfall, exchange of gases with the atmosphere, and removal of pollutants and particles from the air). Similarly, all people benefit from the absorption of wastes and pest control by soil ecosystems. People in rural areas may make more direct use of such services and benefits, but people in urban areas still reap the benefits through lower costs of waste disposal than would be the case if soils were not in functional condition. Research in heavily urbanised parts of the world has shown that waste absorption

Beneficiaries	Examples of how they benefit
	capacity of soils is being outstripped by waste production, causing major population-management costs and health risks to be incurred (Folke *et al.* 1997). Individuals, households and communities are able to receive intellectual stimulation, education, recreational opportunities and various other cultural and spiritual values from ecosystems of which soils are a part. Often people's 'sense of place' is associated with the type and condition of soils present, for example. Conservation of biodiversity is important to many people and this is supported by soil ecosystems. The ways in which cultural ecosystem services are turned into benefits different considerably between people who live close to these services and those who live remotely. For some people, just knowing that ecosystems and biodiversity are functioning well is value in itself (i.e., 'existence value').

8.3 How better management for soil carbon, pH and erosion might affect ecosystem services

Figure 8.3 shows that agriculture generally shifts the balance of ecosystem services in favour of provisioning services while often degrading the processes that lead to regulatory and cultural services. Similar conclusions have been drawn for the world by the Millennium Ecosystem Assessment (MA 2005), for the UK by that nation's National Ecosystem Assessment (UK National Ecosystem Assessment 2011b) and for Australia by various case studies (Binning *et al.* 2001; Abel *et al.* 2003; Karanja *et al.* 2007; Bennett *et al.* 2010; Maynard *et al.* 2010).

As indicated in Figure 8.3B, the aim of modern agricultural management is to restore this balance as much as possible. This is not simply a response to concerns about conservation of biodiversity. As shown in Tables 8.1 and 8.2, there are many benefits that accrue from soil (and other) ecosystems in agricultural landscapes that are socially and/ or economically important to people across society. In this section, we consider how the sorts of best-practice management of soils discussed in previous Sections might be expected to affect ecosystem services and benefits from agricultural landscapes.

The research reviewed in earlier parts of this report indicates that many of the current and emerging approaches to managing soils in Australia appear to be effective, or have the potential to be effective, at addressing the major concerns of declining soil carbon content, increasing pH in some areas, and wind and water erosion (Table 8.3).

It is not easy to capture interactive effects in a table like Table 8.1. While increasing soil organic matter has many benefits for soil structure and processes, for example, excessive accumulation (e.g., in grazing, diary and some cropping systems) can reduce soil pH (Schumann 1999). Similarly, while inclusion of a pasture phase in crop rotations provides ground cover and potentially reduces wind and water erosion, if too many stock are run on that pasture then there is the potential for adverse effects on the soil surface that could increase susceptibility to erosion.

Table 8.3: Conclusions from this report about the effectiveness of management practices in Australian agricultural lands for addressing declining carbon content of soil, acidification and wind and water erosion[a]

Practice	*Type of agriculture*	*Increases Carbon content*	*Reduces risk of wind erosion*	*Reduces risk of water erosion*	*Reduces risk of soil acid-ification (low pH)*
Soil pH testing	Broadacre cropping	Indirectly	Indirectly	Indirectly	Yes
	Horticulture	Indirectly	Indirectly	Indirectly	Yes
	Dairying	Indirectly	Indirectly	Indirectly	Yes
	Grazing (beef cattle/ sheep meat)	Indirectly	Indirectly	Indirectly	Yes
Soil nutrient testing	Broadacre cropping	Indirectly	Indirectly	Indirectly	Yes
	Horticulture	Indirectly	Indirectly	Indirectly	Yes
	Dairying	Indirectly	Indirectly	Indirectly	Yes
	Grazing (beef cattle/ sheep meat)	Indirectly	Indirectly	Indirectly	Yes
Lime or dolomite applied to reduce soil acidity	Broadacre cropping	Indirectly	Indirectly	Indirectly	Yes
	Horticulture	Indirectly	Indirectly	Indirectly	Yes
	Dairying	Indirectly	Indirectly	Indirectly	Yes
	Grazing (beef cattle/ sheep meat)^	Indirectly	Indirectly	Indirectly	Yes
No cultivation/ tillage apart from sowing	Broadacre cropping	Indirectly	Yes	Yes	
Crop residue left intact	Broadacre cropping	Yes	Yes	Yes	
Reduce fallow	Broadacre cropping	Yes	Yes	Yes	
Monitoring of ground cover	Grazing (beef cattle/ sheep meat)	Yes	Yes	Yes	
Use of ground cover management targets*	Grazing (beef cattle/ sheep meat)	Yes	Yes	Yes	
Pasture phase in crop rotations	Broadacre cropping	Yes	Yes	Yes	
Increasing perennial pastures	Grazing (beef cattle/ sheep meat)	Yes	Yes	Yes	

[a]This table draws not only on the material reviewed in this report but also on Barson *et al.* (2011, 2012a, b, c)

The literature also indicates that levels of soil carbon and acid in soils, as well as the extent of wind and water erosion, affect most of the processes expected to generate ecosystem services and therefore the actions to address them are expected to enhance ecosystem services and the benefits flowing from them. The nature and extent of those enhancements, however, will vary with different land systems, land uses and management regimes (Table 8.4), and improvements cannot be assumed to be linear (see Section 8.4).

Table 8.4: Ways in which actions to address soil condition are likely to affect soil processes and ecosystem services*

Ecosystem services	Practices		
	No cultivation/ tillage apart from sowing/ Crop residue left intact/ Reduce fallow	Managing ground cover above 50%/ Pasture phase in crop rotations/ Increasing perennial pastures	Lime or dolomite applied to reduce soil acidity
Provision of fertile soil	Reduced disturbance is likely to allow soil ecosystems to develop, accumulating soil carbon and nitrogen and engineering soil structure for better water-holding and infiltration capacity	As well as benefits from stabilisation of the soil surface and improved structure and water infiltration, interactions between above ground and below ground ecosystems has the potential to improve carbon and nitrogen cycling.	Reducing acidity will enhance habitat and the activity of many soil organisms. The improvements are likely to be minimal until some pH threshold is reached and soil communities are likely to go through several structural transformations as pH increases.
Support native vegetation	The ability of soils to support native vegetation is likely to be enhanced by reduced use of fertilizers on agricultural land, because fertilizers are likely to change the composition and functioning of native ecosystems. However, if increased use of pest-control chemicals is required then this could have negative impacts on organisms in soils under native vegetation.	Reduced runoff of agricultural chemicals onto soils under native vegetation is likely to be the biggest benefit	Addressing soil acidity on agricultural land might have benefits for soils under adjacent native vegetation by reducing leakage of acid into water tables. However, most cost-effective approaches are likely to only manage topsoil acidity.
Provision of natural products	As above	As above	As above
Provision of clean water	Increased stability of soil, structural involvement of vegetation, and enhanced activity of soil organisms is likely to increase water filtration and detoxification capacity of soils.		To the extent that reduced acidification improves activity of soil organisms and soil structure it will contribute to water filtration and purification.
Maintenance of genetic diversity	Enhancement of the diversity of conditions for soil organisms is likely to improve persistence of genetic diversity both within agricultural soils and in adjacent soils.		As above – reduced acidification is likely to lead to at least small improvements in habitat and genetic diversity below ground.
Water flow regulation	Reduce overland flow of water, reduced evaporation and improved infiltration are all likely to affect hydrological cycles (e.g., increasing recharge of		To the extent that managing acidity improves soil structure and

<table>
<tr><th rowspan="2">Ecosystem services</th><th colspan="3">Practices</th></tr>
<tr><th>No cultivation/ tillage apart from sowing/ Crop residue left intact/ Reduce fallow</th><th>Managing ground cover above 50%/ Pasture phase in crop rotations/ Increasing perennial pastures</th><th>Lime or dolomite applied to reduce soil acidity</th></tr>
<tr><td></td><td colspan="2">water tables, reducing damage from floods)</td><td>infiltration rates and/ or allows better establishment of ground cover, it is likely to affect water flows (impacts likely to be small under realistic acid management approaches at present)</td></tr>
<tr><td>Maintenance of landscape (soil) stability</td><td colspan="2">Improved ground cover and minimisation of soil disturbance contribute to soil stability and reduce risks of dust storms, landslides and water erosion</td><td>As above</td></tr>
<tr><td>Regulation of atmospheric gases</td><td colspan="2">Improvement of carbon capture by soils will affect atmospheric CO_2 (indications are that this effect is likely to be small under most realistic scenarios). Depending on the crops or pastures grown, nitrogen exchange with the atmosphere could be affected (this effects is likely to much more significant for soils than the atmosphere)</td><td>Small impacts on carbon and nitrogen cycles (as above)</td></tr>
<tr><td>Regulation of weather and climate</td><td colspan="2">Vegetation cover has effects on absorption and radiation of radiant energy from the sun, affecting the temperature of the ground (and hence the environment for below ground organisms). It also affects moisture and air movement close to the ground. There are likely to be effects on local weather (evaporation, cloud formation etc.) but these are likely to be small at the scale of most agricultural management. The exception is when ground cover is inadequate (i.e., the ecosystem service of stabilising soil landscapes is not adequate) and wind erosion results in dust storms that can influence weather considerably (Mahowald et al 2010; Rotstayn et al. 2012).</td><td>As above – small impacts to the extent that addressing acidity affects ground cover.</td></tr>
<tr><td>Remediation of wastes</td><td colspan="3">As for provision of clean water</td></tr>
<tr><td>Regulation of species and populations in soils</td><td colspan="2">To the extent that these approaches encourage species diversity, there will be effects on interactions among species. Community structure is likely to change. There is evidence that improving ground cover can enhance control of above ground pests (e.g. aphids) by below ground species (e.g. in orchards).</td><td>To the extent that addressing acidity encourages soil biodiversity (see above) there could be improvements to pest control benefits arising from below-ground population regulation.</td></tr>
<tr><td>Contributions to species, ecosystem and landscape diversity</td><td colspan="3">Improved condition of soils is likely to change the appearance of landscapes and, therefore, the benefits they provide to different groups of people. Perceptions will vary between beneficiary groups. Some will benefit from recreational, spiritual, educational and other cultural aspects of improved condition of native vegetation systems (by experiencing these improvements or just knowing they are occurring). Others will benefit from aesthetic and other cultural aspects of landscapes relating to agricultural productivity. There are likely to be broad cultural benefits from seeing and/ or knowing that degraded landscapes are recovering.</td></tr>
</table>

*This table draws on the rest of this report and, particularly, a number of key synthesis and review paper (Pimentel *et al.* 1995; Seybold *et al.* 1999; Binning *et al.* 2001; Colloff *et al.* 2003; MA 2005; Lavelle *et al.* 2006; Swinton *et al.* 2006a; Barrios 2007; Swinton *et al.* 2007a; Zhang *et al.* 2007; Haygarth and Ritz 2009; TEEB 2009; Bennett *et al.* 2010; Clothier *et al.* 2011; UK National Ecosystem Assessment 2011a; Griffiths and Philippot 2012; Robinson *et al.* 2012)

8.4 Resilience of soils and associated ecosystems

Resilience is a word and a concept that has become increasingly widely used, across many disciplines, over the past decade (Holling 1996; Folke *et al.* 2002; Folke *et al.* 2004; Walker *et al.* 2004; Walker and Salt 2006; Brand and Jax 2007; Cork 2010a). There is still debate about precise definitions and ways to measure this attribute in relation to ecological, social, organisational and other systems, and it is necessary to review some key aspects of this debate in order to consider resilience of soils.

Often, people equate resilience with ‘health’, ‘condition’, or ‘vigour’ – the ability to ‘bounce back’ after shocks. While soil condition is an important aspect of resilience in many cases, there is much more to soil resilience than condition. This section discusses important concepts that have arisen in the soil literature that relate condition (the subject of the rest of this report) to the broader issue of resilience. These concepts include: debate about whether soils have a ‘single stable state that they return to or whether we have to consider a degree of change in state as part of resilience; the idea that resilience might be different at different scales; the different rates of soil degradation versus recovery; the idea that some degraded states can be highly resilient (i.e., resilience is not always a desirable quality); and the important difference between resilience and resistance to change, which affect the short versus long-term responses of soils.

The 2011 State of the Environment Report (Australian State of the Environment Committee 2011) included, for the first time in state of the environment reporting in Australia, a discussion about soil resilience. This discussion focussed on the key aspects of soil condition that allow it to continue to function through perturbations like climatic variation and change and physical disruption by land management practices. It included that good-quality and resilient land has these related features:

- Leakage of nutrients is low.
- Biological production is high relative to the potential limits set by climate.
- Levels of biodiversity are relatively high.
- Rainfall is efficiently captured and held within the root zone.
- Rates of soil erosion and deposition are low, with only small quantities transferred out of the system (e.g. to the marine environment).

- Contaminants are not introduced into the landscape, and existing contaminants are not concentrated to levels that cause harm.
- Systems for producing food and fibre for human consumption do not rely on large net inputs of energy.

The State of the Environment report also pointed to the fact that older, more weathered soils, such as those in most of Australia, are less able to return to their original state after perturbations than younger soils. It discussed the role of clays in allowing some Australian soils (e.g., Vertosols) to recover from compaction. This issue is discussed in relation to resistance versus resilience of soils below. It also discussed the importance of considering thresholds of change, especially with respect to organic matter decline, soil acidity and erosion. The significance of thresholds in relation to soil resilience is also discussed further below.

Since Holling's (1996) landmark paper, a distinction has been made between 'engineering resilience' (return of a system to a previous state after perturbation) and 'ecological resilience' ("the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks") (Walker *et al.* 2004). Folke *et al.* (2002) concluded that resilient ecosystems: "can cope, adapt, or reorganize without sacrificing the provision of ecosystem services".

A key difference between these two approaches is that the former assumes that the system has a single stable state (or if there are alternative states they should be avoided), while the latter assumes that ecosystems can exist in multiple stable states and that resilience is the property of the system that keeps it within the bounds of a particular state (Botton *et al.* 2006).

When considering multiple stable states, the concept of 'hysteresis' becomes important (Lal 1997; Seybold *et al.* 1999; Potts *et al.* 2006). Hysteresis is the difference between degradation and recovery phases, in terms of the rates of recovery and the processes involved. For example, resilient soils often will take much longer to recover their functions than it took to lose them (Lal 1997). This concept is particularly relevant when considering the ability of soils to cope with declining organic matter or increasing acidity. Natural processes or human intervention can help soils rebuild carbon stores and enhance the many processes reliant on carbon and/ or living components of soil when soils have sufficient reserves of minerals and retain sufficient diversity of living components (Seybold *et al.* 1999; Botton *et al.* 2006; Jiang and Patel 2008; Griffiths and Philippot 2012; Kuske *et al.* 2012), but the record of past perturbations is important and recovery can take decades (Kuske *et al.* 2012). Similarly, recovery from acidification can be very long term, especially if sub-soils are affected (Section 5).

Another way to interpret hysteresis is that degraded states often have high resilience and/ or resistance to remediation. The broader literature on resilience has recognised that ecological and/ or social resilience is not always desirable to humans. Apart from highly acidified, carbon-depleted or eroded soils, polluted soils can have high resilience (Botton *et al.* 2006).

The concept of 'panarchy' is also particularly relevant to considering resilience of soils. This is the idea that the resilience of any 'system' is affected by other systems operating at higher and lower scales (Gunderson and Holling 2002). For example, the resilience of the soil ecosystem at a paddock scale will be influenced both by ecosystems operating within the soil and by processes occurring at landscape, regional and even larger scales, including interaction between soils, plants, animals and the atmosphere and interactions between ecological and human social systems. Most soil recovery mechanisms and ecosystem services are biologically mediated, including cycling of nutrients, detoxification of pollutants, and suppression of pathogenic organisms (Seybold *et al.* 1999). Neither recovery of soil organic matter nor rebuilding of resistance to wind and water erosion can be accomplished without considering inputs from plants as organic matter and through their mutualistic associations with soil organisms. Also, as explained below, resilience of soils cannot be considered without reference to human social and economic processes.

Research on ecological and social resilience has emphasised the importance of the question: "resilience *of* what *to* what?" (Carpenter *et al.* 2001). Defining 'essential functions, feedbacks and identify' (*of* what) is essential if we are to judge whether these are being retained. Systems might have resilience to some 'specified' (known, previously experienced) pressures but not others (*to* what). The characteristics that give a system specified resilience can be different from those that give 'general' resilience (Walker and Salt 2006).

Most often, soil resilience has been defined as the capacity of a soil to recover its functional and structural integrity after a disturbance (see reviews by Lal (1997); Seybold *et al.* (1999); Botton *et al.* (2006)). This resembles the engineering concept of resilience, although there has been recent discussion about the concept of multiple stable states applied to soils. For example, research on soil microbial populations indicates that community composition and structure change dramatically with wetting and drying and other perturbations resulting in alternative stable states that exhibit hysteresis (Seybold *et al.* 1999; Botton *et al.* 2006; Potts *et al.* 2006;

Jiang and Patel 2008; Griffiths and Philippot 2012). At the scale of managing agricultural enterprises, however, the essential functions required of soils are defined by the uses that land managers wish to make of the soils. Lal (1997) pointed out that these uses are influenced by: “the socio-economic and political forces that govern land use, land rights, institutional support, and income”.

A related concept of ‘resistance’ refers to tendency of a system’s attributes (e.g., structures and functions) to not fluctuate when perturbed (Lal 1997; Seybold *et al.* 1999; Botton *et al.* 2006). For example, some soils resist compaction and retain their porosity while others suffer compaction but are able to regain porosity after a period of time (Seybold *et al.* 1999). These differences between resistant and resilient soils are important as they affect responses of crops and pastures in the short and long term. Similarly, ground cover above a critical threshold confers resistance to wind and water erosion (Sections 6 and 7), whereas resilience to wind and water soil erosion is a function of the depth and type of soil and the rate of soil formation, which, in many parts of Australia, is many times slower than rates of erosion (Section 7.1).

Often the distinction between resilience and resistance is blurred. For example, different wetlands in the Murray Darling Basin have very different abilities to neutralise acids formed when sediments are exposed by dry periods (Glover *et al.* 2011). This ‘acid neutralising’ capacity confers both resistance and resilience (within the limits of the system’s buffering capacity) on these wetlands.

Research on ecological resilience generally has revealed the importance of considering thresholds of change (rapid, often irreversible changes that take a system into a different state) (Walker and Salt 2006). An important aspect of the resilience of a soil ecosystem is its ability to stay away from such thresholds and, in general, its resilience will be lower the less disturbance is required to push the system through a threshold of change. A range of thresholds have been suggested for soil ecosystems (Lal 1997):

- An organic carbon threshold (varying with soil type but usually 1-2% in surface layers) below which physical and chemical fertility effectively collapse and after which recovery of critical carbon factions can take decades (Baldock and Skjemstad 1999; Australian State of the Environment Committee 2011);
- A soil pH threshold (around 4.2) below which aluminium toxicities emerge and the soil becomes very difficult to remediate (Australian State of the Environment Committee 2011) (Section 4);

- Ground cover thresholds (50-70%) below which soils are vulnerable to erosion by wind and water (Section 6);
- A postulated lower vegetation-cover threshold (20% in Chinese grasslands), below which ecosystems cannot recover by themselves from sustained degeneration of the vegetation community, erosion of the surface soil and declining soil fertility (Gao *et al.* 2011);
- Non-linear changes in many soil properties (e.g., water flux, porosity, mineral dissolution rates, redox potential and acid-base reactions as carbon is added (Chadwick and Chorover 2001);
- Thresholds of inadequate sediment flows (resulting in the loss of beaches, storm protection, nutrient inputs, etc.) or excessive flows (resulting in lake, reservoir and wetland infilling, coral reef smothering, etc.) (Apitz 2012);
- Physical damage to biocrusts (e.g., by grazing), in concert with changing temperature and precipitation patterns, has potential to alter performance of dryland ecosystems for decades (Kuske *et al.* 2012);
- Catastrophic shifts in soil-vegetation systems due to interactions between herbivores, plants and below-ground ecological systems (van de Koppel *et al.* 1997);
- Over-saturation of soil nutrients leading to accelerated leaching to water courses (Heckrath *et al.* 1995);
- Local extinction of certain strains of bacteria when soils become contaminated by toxic pollutants (Chaudri *et al.* 2008);
- Thresholds of suitability of soils when used for sub-optimal purposes (e.g., using soils as raw materials or using soils suitable for growing food as a platform for building upon) (Haygarth and Ritz 2009).

Multiple factors influence soil resistance and resilience (Lal 1997; Seybold *et al.* 1999; Botton *et al.* 2006; Zhang *et al.* 2010; Griffiths and Philippot 2012). They are partly related to soil properties such as organic matter, aggregation, the quantity and quality of carbon inputs, clay content and soil pH. Terrain characteristics, landscape position, parent material, climate, water balance, vegetation and soil biodiversity are also important. Research on the contributions of the living components of soils to soil resilience has focused primarily on microbial populations (Seybold *et al.* 1999; Botton *et al.* 2006; Zhang *et al.* 2010; Griffiths and Philippot 2012). This research reveals no simple general rules but suggests that the diversity of functional traits of species is important, as is the structure of communities (lower resilience when communities have a highly uneven balance between species or are dominated by a few species). There is an expectation that high levels of functional redundancy, i.e., a high number species performing the same function, might act as a buffer against the effect of biodiversity loss on functioning. Resilience and resistance become much more complex issues under extreme perturbations such as contamination of soils with toxic compounds, which select very rapidly for species that can deal with the challenges.

Each of the best-practice management approaches to dealing with soil carbon, pH, and the threat of erosion (i.e., those summarised in Table 8.3) potentially contributes to the requirements for increasing resilience after perturbations. Processes important for returning soil function after perturbation include new soil formation, aggregation, soil organic matter accumulation, nutrient cycling and transformation, leaching of excess salts, and increases in biodiversity, including species' succession (Lal 1997). When applying best-practice management for specific challenges to soil condition, however, it will be important to consider how the range of management practices being implemented interact with one another and to consider the specified as well as the general resilience of the resulting soil ecosystems. For example, managing ground cover to appropriate targets can improve soil carbon status, and reduce wind and water erosion, while managing soil acidity through liming can also overcome a major constraint to building carbon and having adequate ground cover (Table 8.3).

Approaches to assessing soil resilience involve assessing actual functionality through time, or indicators of functionality, in relation to reference states, and considering thresholds of undesirable change (such as those discussed above) and how to avoid them (Lal 1997; Seybold *et al.* 1999; Botton *et al.* 2006).

8.5 Economic values of soil ecosystem services and resilience

Many of the benefits that can come from ecosystem services can be expressed in monetary terms, because they include goods that are sold in markets or involve other financial transactions that reveal people's willingness to pay for the benefits (Costanza *et al.* 1998; Bennett 1999; Bockstael *et al.* 2000; Gillespie *et al.* 2008; TEEB 2009; UK Government 2011). Resilience has been included as a benefit from ecosystems in some recent typologies (TEEB 2008).

The economic values of soil ecosystem services have been estimated in a variety of ways in different studies in different parts of the world. The approach taken depends on the questions being asked. Some studies have estimated the replacement cost of soil ecosystem services. When we consider how processes like large-scale nutrient and water cycling, extraction of nutrients and carbon from the atmosphere, acid-based balance, waste breakdown, regulation of hydrology and pest control could be replaced by engineered alternatives, including provision of fertilizers and other chemical components, the costs are massive (Daily *et al.* 1997; Sandhu *et al.* 2008).

Replacement costs of soil ecosystem services are not, however, relevant to the questions being asked in this report (Section 9). The value that farmers, and others who use ecosystem services in production of goods and services, (i.e., 'producers') might get from better soil management is more appropriately estimated as the difference between what they would be willing to accept as payment for the goods and the price they receive in the markets ('producer surplus'). The contribution of ecosystem services to producer surplus is a function of how much their use reduces production costs. The proportion of total ecosystem service production that is used depends on the time period, from very small over a short time period to total use if an ecosystem is totally degraded in the long term, and the degree to which natural capital is consumed by the production activity. The value that consumers (including the broader public) get from ecosystem services is most appropriately estimated as the difference between what they would be willing to pay for the benefits and what it actually costs them (consumer surplus). Consumer surplus is complex to assess. It can be partly estimated by assessing consumers' willingness to pay for access to ecosystem services (TEEB 2008; MacDonald *et al.* 2011; CSIRO 2012) but this often will not take account of the savings that people make through such benefits as better mental and physical health.

Section 9 considers the economic benefits of better soil management in Australia, by considering the net benefits across a range of case studies. Management practices are not the only factors affecting the adequacy of soil ecosystem services to meet human needs. Climatic factors obviously play a major role, and it is important that soils are managed appropriately for the climate they are exposed to. This is a key component of best-practice management. In Australia, drought should no longer be used as an excuse for degradation of soils as management of soil resilience should include management for wet and dry periods. Apart from factors affecting the supply of ecosystem services, demand for them is an important consideration. Demand for ecosystem services is affected by where and how people live, infrastructure for turning services into benefits, and economic pressures coming from outside a region or Australia. We are unable to take these extrinsic factors into account in this project, but they should be considered as part of broader population planning in Australia in the future (Cork 2010b).

9. Private and public benefits of soils and soil management

9.1 Introduction

This section takes the discussion of ecosystem services in the previous Section a step further and reviews estimates of the value of ecosystem goods and services provided by Australian soils managed for agriculture. It addresses the following questions.

What is the nature of benefits from improving agricultural soil condition?

Who benefits from improving agricultural soil condition?

How significant might these benefits be?

How might Australia realise these benefits?

In this review, we have considered the net benefits that are likely to flow from improved soil condition and better quality soil ecosystem services from agricultural lands. We have not tried to address questions of how to optimise benefits from soil ecosystem services, nor how to balance public and private investment in soil condition.

9.2 What is the nature of benefits from improving agricultural soil condition?

Understanding the benefits from improving agricultural soil condition requires a framework for distinguishing between benefits to human wellbeing; final ecosystem services; the natural capital (or soil condition) which underpins those services; soil depreciation and accumulation processes; and the external drivers which influence soil condition. The framework we use in this report is discussed in Section 8.

In this report, we focus on the marginal change in benefits that ultimately come from a change in land management practices. In the short term, these benefits are generally improvements to agricultural productivity or the reduced cost of impacts off-site from agricultural lands In some cases, the benefit may come from keeping open future options to produce different types of crops in response to changing market demand or climate. In theory, soil conditions which support a wider range of future uses will be reflected in a higher capital value of the land (Gretton and Salma 1996).

9.3 Who benefits from improving agricultural soil condition?

Benefits can improve the wellbeing of private landholders, or the public, or both. They may occur at a local (on-site), regional, national or global spatial scale. They may be realised over short (1-5 year), medium (5-30 year) or long (30-100 year timeframes.

Figure 9.1 shows some examples of who benefits from final soil ecosystem services, where the benefits are realised, and over what timeframe. It also shows whether the value of the benefit is in the form of a flow of services (similar to financial interest), an option to maintain future benefits (similar to insurance) or a stock of soil condition (similar to financial capital).

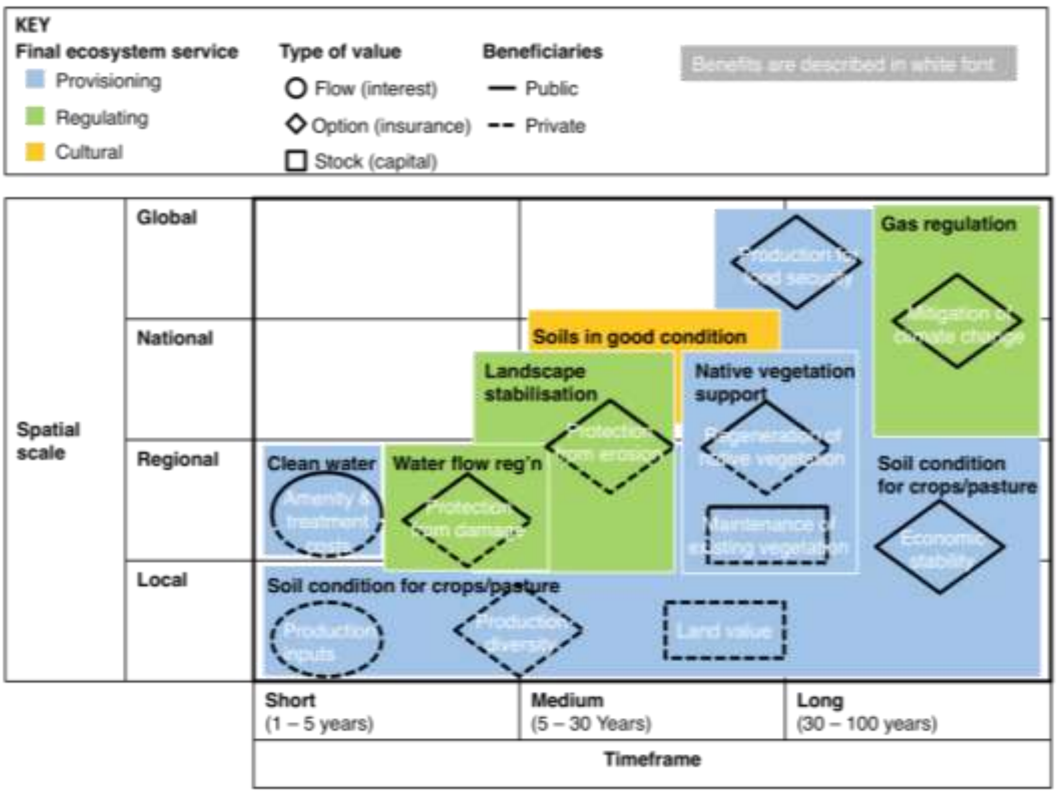

Figure 9.1: Who benefits, where and when?

Soils can provide many different ecosystem services (Figure 9.1). Yet not all services can be provided at once. Land management decisions involve trade-offs between different types of benefits (Robertson 1987). For example, in the short-term, at least, there can be trade-offs between stock production and maintenance of ground cover. The perspectives of different beneficiaries lead to a range of views about which benefits are more important.

For landholders, agricultural systems primarily produce food and fibre. The challenge is to optimise long-term production, and build soil resilience to external drivers such as climate and degrading processes such as erosion or acidification. This means producing stable agricultural returns without compromising the future ability of soil to support crops or livestock, or increasing soil vulnerability to erosion and acidification.

However, the sixty percent of the land mass managed for agriculture is part of the broader Australian landscape. At this scale a number of ecosystem functions are important, for which soils may provide supporting services. For example, soils support the production of native grasses, which are both habitat and food for Australia's diverse range of native fauna.

Australia's agricultural industries are also part of the broader Australian economy, and the global system of food trade. In this context, reliability of agricultural production is important for contributing to Australia's economic stability. As the global population rises, the reliability of Australian agricultural production may also be important for food security. This could become increasingly significant as external drivers such as commodity prices and weather may be more volatile in the future (OECD/FAO 2011).

In this report, we have focused on benefits to land managers at the farm scale- and to the Australian public at a local, regional or national scale.

9.4 How significant might these benefits be?

We have reviewed existing economic studies to assess what is known about the magnitude of benefits from improved land management practices. We selected studies that have a clear link between costs or benefits and soil ecosystem services. However, the economic values estimated are not all attributed to changes in soil condition. Other factors and agricultural inputs also contribute.

Table 9.1: Gross value of agricultural production (ABS 2011a)

Industry sector	Gross value of agricultural production – average 2008 – 2010 ($ billion/yr)
Broadacre cropping	9.6
Beef/sheep grazing	9.8
Horticulture (excluding grapes)	8.4
Dairy	4.0
Other agriculture	9.8
Total	41.2

Australia's total average agricultural production is $41.2 billion per year. The four industry sectors covered in this report, account for around 75% of this production (Table 9.1).

Given the importance of these industries, a number of previous economic studies have examined the links between soil condition, agricultural production and public benefits. Table 9.2 outlines the most relevant previous studies.

The benefits of improving agricultural soil condition need to be calculated against a baseline soil condition. In many cases, the baseline soil condition is on a moving trajectory. The nature of this trajectory, and its likely impact on agricultural production or off-site environmental impacts, is complex. Some aspects of soil condition may be improving, while others may be declining. Both land management practices and external drivers may be responsible for these changes.

The very act of farming alters soil condition (Robertson 1987). Managing land for agriculture shifts soil ecosystem processes toward increased production of crops or pasture, and away from other intermediate or final services (Pretty 2008). In some cases, these other services can be augmented, replenished or replaced by external inputs. For example, adding phosphorus fertilizer can augment the ability of soils to provide nutrients. Trace elements lacking in Australia's weathered soils may be replenished by agricultural practices. Organic matter lost due to erosion or intensive cropping may be replaced by manure or green waste.

However, soil degradation problems occur if land management practices produce short term gain, at the cost of declining soil condition (Robertson 1987). The benefits of improved land management practices therefore depend on improved productivity, calculated against the expected cost of a continuing decline in soil condition. However, improved productivity may be seen in short to medium term, whereas the costs of inaction may only be apparent in longer term.

The complexity of agricultural and natural systems, as well as gaps in knowledge and data, make it difficult to accurately predict the economic impacts of changing land management practices (Gillespie *et al.* 2008; Rolfe *et al.* 2008). Many studies to date have focused on the private benefits of near-term production values; with some estimates of the avoided public cost of damage from erosion or rising water tables; as well as public willingness to pay for environmental benefits. In most cases, these estimated values are specific to a certain region, and may not apply across the diverse range of soil types, conditions, land-use and land management practices found in Australia.

Table 9.2: Existing estimates of the value of costs or benefits related to land management practice (footnotes explained at end of table)

Ecosystem service[2]	Benefits	Time-frame[3]	Net value	Example[4]	Comment
Provisioning services					
Soil condition suitable for growing crops or feed *(through maintenance or improvement against declining baseline)*	Increased nutrients	Short	Positive if private benefits > private costs	$14-$16 per hectare additional production potential from reducing acidity in NSW (Walpole *et al.* 1996). $10.8-$16.5 billion NPV of additional production through lime/ gypsum treatment of the 4% of land at risk of acidity and sodicity where soil treatment is profitable (at a 10% discount rate) (Hajkowicz and Young 2002). It has been estimated that Western Australian farmers face an opportunity cost of lost agricultural production from soil acidity of around $498 million/ year (Herbert 2009).	These figures over-estimate soil ESS as they include benefits from other inputs paid for by farmers. They are not marginal values, as they assume all soil degradation is avoided.
	Greater economic stability	Long	Positive	Avoided cost of 9 cents per household for every 10 persons remaining in regional communities (Hajkowicz and Young 2002).	Choice modelling shows Australians perceive rural depopulation as a cost.
Native vegetation support *(through maintenance of soil condition)*	Maintenance of existing native vegetation	Medium - Long	Positive if public and private benefits > private costs	Willingness to pay $2.90 per household per year over 15 years for a 1% improvement in healthy vegetation in Qld (Windle and Rolfe 2007).	Not all public value can be attributed to soils, as other economic inputs may be required. Private costs will depend on land-management practices, offset to some extent by private benefits e.g. shade for livestock (Fischer *et al.* 2009).
	Regeneration of native vegetation	Medium-Long	Positive if public and private benefits > private costs	Willingness to pay 7 cents per household per year for every additional 10,000 ha of farmland repaired or bushland protected (Hajkowicz and Young 2002).	As above
	Reduced cost of water treatment and equipment maintenance	Short	Positive	Avoided cost of $0.8-$2.0 billion NPV for a 1%-10% decline in water quality based on downstream infrastructure costs of turbidity due to erosion (Hajkowicz and Young 2002).	Not all this value can be attributed to soils as other interventions, like tree planting and erosion control, may be required. Additional public and private benefits would flow from avoiding raised nutrient levels and eutrophication.
Regulating services					
	Protection from	Medium	Positive	$62 m per year avoidable costs of rising water	Not all this value is due to water table

Ecosystem service[2]	Benefits	Time-frame[3]	Net value	Example[4]	Comment
	change in water table levels			impacts on public and private infrastructure based on projections from 2000 to 2020 (Hajkowicz and Young 2002).	levels. Some is due to the avoidable cost of damage from salinity.
Landscape (soil) stabilisation	Protection from erosion	Medium	Positive	Avoided cost of $2 worth of fertiliser lost with every tonne of soil erosion prevented (Raupach, McTainsh, and Leys 1994) Avoidable private costs of $5.72-$8.09 per hectare in net agricultural income in 1989/90, for Lachlan valley and Orange SLA (Mallawaarachchi 1993; Mallawaarachchi, T., Young, M., Walker, P. and Smyth 1994). Estimated public value of $0.5billion PV for erosion control outcomes from National Heritage Trust investments (Gillespie *et al.* 2008). Estimated $23 million per year total off-site wind erosion costs for South Australia. Most of this is health related costs (Williams and Young 1999). Estimated >$400 million cost of 2009 'Red Dawn' dust storm in Sydney. Most of this is cleaning and lost work time (Tozer 2012). Regional dust storm events are more frequent, their economic impacts are likely to be lower because regional populations are smaller and regions have fewer infrastructure assets. Nevertheless, estimates of the offsite impacts of dust erosion on the Mildura region show that costs to the regional economy are approximately $3 million annually (Tozer 2012).	Not all this value can be attributed to soil structure stabilisation. Other interventions, like tree planting and erosion control works, may be required. Health related costs assume asthma rates are linked to wind erosion and dust.
Gas regulation	Reduction in carbon dioxide emissions	Long	Positive if public and private benefits > private costs	Recent research suggests improved management could provide relative gains of 0.2-0.3 tonnes of C per ha/year for cropland, and 0.1-0.3 tonnes of C per ha/year for pasture (Sanderman, Farquharson, and Baldock 2010).	Estimating the market value is difficult as enhanced carbon stocks may be lost due to drought or changes in land management practices.
Cultural services					
Existence of soils in good condition	Environmental health	Medium	Positive	Willingness to pay $3.70 per household per year for 15 years for a 1% improvement in soils in good condition in Qld (Windle and Rolfe 2007).	Choice modelling shows Australians are generally willing to pay for the environmental benefits associated with

Ecosystem service[2]	Benefits	Time-frame[3]	Net value	Example[4]	Comment
					improved soil condition.

[1]Estimates of the potential cost of increased water turbidity were not included as they can't be clearly attributed to changes in soil condition. We have been unable to find published information about whether turbidity is due to soil erosion or sediments already in streams. Estimates of the costs of turbidity, from all sources, are available in Hajkowicz and Young (2002).
[2]This table does not include supporting services, as these generally increase the benefits realised from other ecosystem services rather than directly benefiting humans.
[3]Timeframes are defined as short (1-5 years), medium (5-30 years) and long (30-100 years).
[4]Unless noted otherwise, all estimates of value are in the dollars of the year of the original study.

Nevertheless, some insights can be drawn from consistency of findings across the range of valuations shown in Table 9.2:

- The lost value of crop yields due to soil acidity may be high. Additional production potential of $14-$16 per hectare (1996 dollars) is at least 4% of average NSW broadacre cropping revenue of around $400 per hectare (ABS 2011a; Walpole *et al.* 1996). Compared to an average annual $9.6 billion gross value of production of broadacre crops, an NPV of $16 billion for treating 4% of the land at risk of acidification or sodicity represents a significant opportunity (Hajkowicz and Young 2002). The estimated $498 million/ year of lost production due to acidity in Western Australia was the highest cost of any hazard, followed by salinity ($344 m/yr), surface compaction ($333 million/ year), and water repellence ($251 million/ year), and far exceeding the estimated losses due to wind erosion ($71 million/ year), waterlogging/ inundation ($29 million/ year), soil structure decline ($15 million/ year), and water erosion ($10 million/ year) (noting that these hazards are not independent) (Herbert 2009).
- Aggregate public costs of erosion are high, particularly during intense dust storms. Private costs of erosion may be slightly lower than those of acidity, estimated at $6-$8 per hectare in NSW (Table 9.2) (but note the comparison for Western Australia, above). However, erosion may have more significant long-term impacts as soil-loss is irreversible.
- Willingness to pay estimates indicate Australians recognise the value of public investment to improvement soil condition, regional jobs, and maintenance of farmland vegetation (assuming Queensland residents surveyed by Windle and Rolfe (2007) are representative of the broader Australian population (Table 9.2)).

Recent assessments of the extent and risk of land degradation have also suggested which industries are likely to benefit most from improving soil condition.

- Managing soil acidity is likely to benefit broadacre cropping, of which 36% is at high risk, and intensively managed grazing land, of which 21% is at high risk (Barson *et al.* 2011, 2012b). Tropical horticulture and dairying are also at risk but available data are too coarse to allow accurate assessment to be made for these industries (Michele Barson, DAFF, pers. comm.)
- Reducing soil loss through wind erosion is most likely to benefit beef and sheep grazing in the rangelands, as well as broadacre cropping in WA (Smith and Leys 2009).

- Reducing soil loss through water (sheet and rill) erosion is most likely to benefit broadacre cropping, as well as sugarcane and other horticulture in Qld (Hairsine *et al.* 2009).
- Increasing soil carbon is most likely to benefit horticulture, broadacre cropping and grazing in NSW, Qld and WA (Baldock *et al.* 2009).

9.5 How might Australia realise these benefits? Examples through case studies

Australia's soils, their condition, land-use and management practices, are highly variable. This makes it difficult to present simple conclusions that apply to all soils in Australia. Instead, we have used case studies of specific industries and, in some cases, locations to draw general findings.

We selected four case studies to demonstrate the issues relevant to considering the private and public benefits of improving soil condition. For each case study we have highlighted how land management practices can:

- Improve agricultural production by reducing or removing soil constraints, stabilising profits, or increasing efficiency of resource use
- Reduce or avoid environmental impacts off agricultural lands
- Address land degradation that occurs over different timeframes
- Face barriers to implementation in addition to costs of implementation
- Be widely applied in Australia.

Case study 1: Reducing soil erosion in broadacre cropping – northern NSW

Broadacre cropping is an important agricultural sector for Australia. Australia wide, production of cereals such as wheat and barley, pulses such as lupins and chick peas, and oilseeds such as canola and sunflower, has contributed $9.6 billion per year[2] in gross value of agricultural production from 22 million hectares cultivated across all states (ABS 2011b)[3]. In NSW, 5.8 million hectares produce almost $2 billion per year[4] in gross value of agricultural production (ABS 2011b).

[22] Based on averages for 2008 to 2010

[3] Note that the gross annual value of production for broadacre cropping given in Section 4.2 (around $13 billion) included cotton, hay and sugar cane in addition to the crops included in this section

[44] Based on averages for 2008 to 2010

However, poor structure, low water permeability and soil acidity limit yields in various cropping regions across Australia (Beeston *et al.* 2005). Improving soil condition can increase crop yields, by improving the quality of soil ecosystem services. Maintenance of good ground cover levels results in more stable soils, which reduces wind and water erosion, and therefore the loss of soil nutrients and carbon, which can support crop production. Soils in good condition are also more able to provide nutrients and moisture when crops need it. Where nutrient availability is not a constraint, the level of soil moisture at the time of sowing directly influences the final crop yield (Day *et al.* 2008).

This case study considers the benefits already gained from improving soil structure and water permeability in northern NSW (Table 9.3). Given the benefits of new land management practices are uncertain (due to high variability in soil types, crop types, weather patterns and barriers to adoption), an historical example can offer greater insight than forecasts.

The evolution of farming systems has increased yields in part by improving soil condition, often overcoming negative impacts on soil condition caused by earlier farming practices. Conventional farming systems used before the 1970s tilled the soil, which destroyed the soil structure and increased vulnerability to wind and water erosion (Scott and Farquharson 2004).

Since the 1970s, conservation farming has sought to maintain soil structure and fertility by leaving crop residues on or near the surface. Weed growth is reduced by using herbicides rather than tilling the soil (Barr and Cary 1992). Conservation farming can increase agricultural production, reduce soil loss through wind and water erosion, lower greenhouse gas emissions and improve water use efficiency. Conservation tillage is a key part of conservation farming[5]. Across Australia, 95% of cropped land is now managed with some level of conservation tillage (Barson *et al.* 2012b).

As adoption of newer farming systems increases, significant private benefits from improved soil ecosystem services are often seen. The value of these benefits can be estimated, although it is difficult to separate the contribution of soil ecosystem services from other human and environmental impacts. Public benefits are harder to quantify, but can still be significant.

In northern NSW, existing estimates of net private benefits from conservation farming are significant at an industry level. Between 1970 and 2000, the net present

[5] Conservation tillage involves no-till or minimal till practices, combined with direct drill seeding techniques.

value of increased agricultural production was estimated at over $200 million (Scott and Farquharson 2004). At the farm-scale, returns on capital invested increased by around 3.5% within five years of adopting no-tillage practices, compared to conventional farming as a baseline.[6,7]

A return below commercial investment benchmarks may explain why widespread adoption of conservation farming took several decades. However, conventional farming has shown rapidly declining crop yields and quality in around 20 years (Scott and Farquharson 2004). Using a longer timeframe may therefore show much higher returns on capital invested, compared to business as usual. While these higher private benefits may be clear in hindsight, farmers may be unlikely to take the risk of adopting new practices without some public investment in research, development and extension to prove they work.

Significant public benefits also came from adoption of conservation farming. Soil erosion was reduced by an estimated 18 million tonnes per year (Scott and Farquharson 2004). Public benefits from the increase in gross value of agricultural production would have flowed through increased economic activity at local, regional and state levels.

The key findings from this case study are:

- Private benefits of improved crop yields were apparent within 5 years.
- Public benefits included reduced off-site environmental costs of dust, and possibly greater economic contributions from the broadacre cropping industry.
- Over a 5 year time-frame, private returns on capital invested were below commercial rates. However, over a 20-year timeframe they may be much higher.
- The low 5-year returns on capital invested and risk aversion to adopting new practices may have been barriers to private investment in improving soil condition.
- Conservation farming practices are now widely used within Australia, with current rates of adoption 95%.

[6] This is based on whole farm budget estimates in two locations.

[7] The total private benefits of increased agricultural production across northern NSW were estimated at $224m (no till) and $586m (no till plus reduced tillage). The benefit share due to NSW Government investment was estimated at 35 % of these total figures, giving $78.4m (no till) and $205.4m (no till plus reduced tillage).

Table 9.3: Full range of benefits and beneficiaries – Reducing soil erosion in broadacre cropping

Benefic-iaries	Ecosystem services	Benefits	Costs	Time-frame	Expected net value
Private land-holders	Landscape (soil) stabilisation Soil condition for crops	Avoided cost of lost nutrients and carbon due to erosion Increased soil nutrients over time Increased soil carbon and moisture Avoided cost of lime (reduced need for fertilizers and, therefore, reduced acidity risk)	Short term reduction in production due to nutrients and carbon retained in soil Costs of fertilizers and herbicides	Medium	Positive net benefits from increased farm productivity, profitability and sustainability mean these practices are being rapidly adopted in various regions of Australia (Sanderman *et al.* 2010)
Public	Landscape (soil) stabilisation Soil condition for crops	Reduced risk of erosion and downstream pollution Increased economic activity More stable farm profitability	Incentives for changed land manageme nt, where net private benefits are marginal	Medium	Positive regional and national net value due to avoided costs of erosion and pollution, greater agricultural economic activity, and possibly avoided costs of exceptional circumstances assistance.

Case study 2: Managing acid soils in broadacre cropping - Western Australia

Wheat production in Western Australia was worth $1.8 billion in 2010, measured as gross value of production (ABS 2011a). This is equivalent to 38% of Australia's total crop. The largest wheat producing area is the Avon River Basin, which covers about 45% of the Western Australian wheatbelt (Gazey and Andrew 2010). Other significant areas are the northern and southern wheatbelts. Soil acidity is a significant constraint to increasing wheat yields.

Soil acidity reduces the ability of soil to provide nutrients and moisture for crop production. As Figure 9.2 shows, crop yields decline rapidly as the pH of surface soil drops below a target of 5.5[8]. For subsurface soils, a pH below 4.8 is a significant constraint to root growth. Acidic topsoils reduce the efficiency of nutrient use, leading to higher costs of fertilizers. Acidic subsurface soils can have toxic levels of aluminium which reduce crop root growth, leading to lower nutrient uptake, less efficient water use and lower crop yields.

Vulnerability to soil acidity is widespread in Western Australia's wheatbelt. In the Avon River Basin, almost 80% of topsoil samples are below a target pH of 5.5, while

[8] pH is a measure of potential hydrogen. A higher pH indicates more basic conditions, while a lower pH indicates more acidic conditions.

50% of subsurface soil samples were below the target of 4.8 (Gazey and Andrew 2009). Similar results were found in the northern and southern wheatbelts, where more than 80% of topsoil samples were below a pH of 5.5. Coarse textured sands and gravels account for 90% of all soils affected. (Davies, Gazey, Bowden, *et al.* 2006).

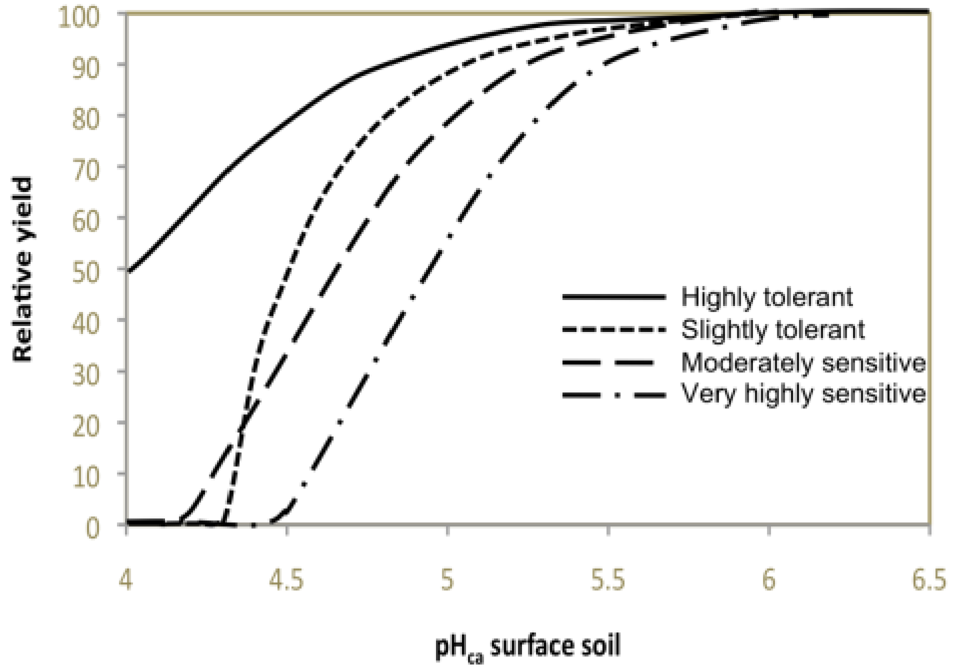

Figure 9.2: Example of output from the acidity relative yield model for four plant tolerance classes within a given Al/Mn solubility class (Dolling *et al.* 2001)

Soil acidity can be reversed by adding lime to soils. However, if insufficient lime is added to agricultural soils at risk they gradually become more acidic. Failure to slow or reverse topsoil acidification generally leads to subsurface acidification. This is much more expensive to fix, and may need special equipment to inject lime deep into the subsurface soil (Davies, Gazey, and Tozer 2006).

Acid soils reduce wheat production in Western Australia by an estimated $300-$400 million per year (Gazey and Andrew 2010).[9] The average loss in wheat yield is 8-12% (Davies, Gazey, and Tozer 2006). Grain yield responses to surface liming are often 10-15% and may increase with time. Subsurface liming can increase yields by 30-40% (Davies, Gazey, and Tozer 2006).

The public costs of acid soils may also be significant. There is speculation that acidification from agriculture might result in acid running off into local streams, with

[9] It has been estimated that the overall cost of lost agricultural production from soil acidity in WA is around $498 million/ year (Herbert 2009).

costs imposed on downstream water users, but evidence is not yet available (Cregan and Scott 1998, Hamblin 1996). Reduction in the quality and quantity of high value wheat grain also has negative impacts on local, regional, state and national economies. While there is little evidence linking off-farm impacts directly to agricultural practices (see Section 5.1), inaction on soil acidity does have public costs. Other public costs of soil acidification are longer term and associated with the risk of wind and water erosion on highly acidic soils which support little ground cover and the possibility of having to take land out of production because subsoil acidification is too costly to remediate.

Applying sufficient surface lime to treat acidity through the soil profile can be a cost-effective way to improve soil condition and the quality of ecosystem services it provides. Recent results from long-term field trials show that significant yield increases can be achieved in both the short and medium term, if sufficient lime is applied. Yield increases can be long-lasting, and may increase over time.

- A trial of 2 t/ha surface lime applied to sandy gravel at Bindi Bindi in the northern wheatbelt showed yield increases of over 10% within the first 2 years. Similar yield increases were still being achieved 8 years after lime was first applied. Net of amortised liming costs, grain income increased by $87/ha (25%) in year 8 (Davies, Gazey and Tozer 2006).
- A trial of 5 t/ha surface lime, followed by a further 1 t/ha 10 years later showed wheat yields were 20% higher 17 years after the initial application. Surface lime was applied to a yellow sandy earth Tenosol at Kellerberrin in the Avon River Basin (Gazey and Andrew 2010).

In addition to improved yields, farmers can benefit from lower fertilizer use and a greater choice of crops to plant in rotations (Table 9.4). This flexibility can allow farmers to take advantage of volatility in international commodity prices, and better manage soil fertility by rotating crops. On-farm environmental benefits can include reduced weed growth, soil degradation and risk of wind erosion of soils (Davies, Gazey and Tozer, 2006; Gazey and Andrew 2010).

However, the amount of lime currently applied is not enough to adequately treat existing and on-going acidification in Western Australia (Hajkowicz and Young 2002). Farmers often cite economic factors (upfront costs, returns and cash-flow constraints) as barriers to applying lime (Fisher *et al.* 2010). Yet focus groups suggest many farmers are convinced of the benefits of liming and need better information on how much lime to apply, and how to make it cost-effective. Others are less convinced and have information needs for how liming works, what the benefits are, how much to apply, and the economics of liming (Fisher *et al.* 2010).

The key findings from this case study are:

- Private benefits of increased crop yields can be seen within 2 years. Gross margins (net of costs of lime) and yield gains are enduring and may increase over 10 to 15 years. A greater range of viable crop choices can allow farmers to better manage soil and respond to climate variability while taking advantage of fluctuating commodity prices.
- Public benefits may include reduced off-site environmental costs of water pollution, although this cannot be confirmed. Higher and more stable long-term economic contributions from the wheat industry may be another benefit, as are longer –term avoidance of soil erosion and loss of productive land.
- The private costs of inaction can rise significantly over time. Unless surface acidity is treated with enough lime, subsurface soil acidity can become an enduring constraint to cropping. Treatment of subsurface soil acidity is more expensive and technically difficult than applying surface lime.
- Barriers to private investment in improving soil condition may be lack of information on how, where and when to apply lime cost-effectively.
- Managing soil acidity by applying surface lime is relevant to around 80% of the West Australian wheat belt.

Table 9.4: Full range of benefits and beneficiaries – Managing acid soils in broadacre cropping

Benef-iciaries	Ecosystem services	Benefits	Costs	Time-frame	Expected net value
Private land-holders	Soil condition for crops	Increased crop yields of >10% Reduced weed growth Wider range of choices for crop rotation Increased fertilizer use efficiency Increased water use efficiency	Purchase and application of lime to soil surface	Short – Medium	Positive and enduring if soil is tested regularly and sufficient lime applied. The longer-term net value should be compared to the cost of deep ripping of soil and injection of lime to reverse the sub-soil acidification that would occur if no action were taken.
Public	Soil condition for crops	Higher crop yields and greater choice of crop rotations increases and	Nil	Medium – Long	Positive

Benef-iciaries	Ecosystem services	Benefits	Costs	Time-frame	Expected net value
		stabilizes regional and national economic contribution of agriculture Reduced offsite impacts of wind and water erosion, long term loss of land from production (intergenerational issue)			

Case study 3: Increasing soil carbon in irrigated horticulture – southern Australia

Horticulture is Australia's third largest agricultural industry, with an average $8.4 billion annual gross value of production over 2008 to 2010 (ABS 2011a). Horticulture includes a diverse range of industries– with fruit and vegetables the largest product sectors (NLWRA 2008). The horticulture industry covers all states and a wide range of climate zones and types of soil. Irrigation is an important contributor to horticultural production, accounting for over 70% of the gross value of production in 2009-10 (ABS 2011b).

Under irrigation, Australian soils with poor structure can harden and significantly constrain horticultural production by restricting the growth of tree roots and their ability to take up water. In general, this is due to the age of Australian irrigated soils. Loams and fine sandy loams, in particular, may lack minerals that maintain soil porosity and structure under irrigation (Cockcroft 2012). Soils with high organic matter, are thought to be less likely to have this problem (Cockcroft and Olsson 2000).

This is a particular problem for commonly irrigated soils in Victoria's Goulburn Valley, the Murrumbidgee Irrigation Area in NSW and the Barossa Valley in South Australia. Red-brown earths account for a large amount of irrigated tree fruit, vines and vegetable production in southern Australia (Cockcroft 2012). These soils are vulnerable to hardening.

The opportunity cost of reduced crop yields due to poor soil condition may be high. An unpublished study suggests that for a fruit crop such as pears, Australian yields of 35 tonnes per hectare are well below the best international yield of 180 tonnes per hectare (Cockcroft 2012). Australian horticultural crops grown on poor soil types can average as low as 10 tonnes per hectare, while those grown on the best soils can achieve yields of 50 tonnes per hectare (Cockcroft 2012).

Increasing soil organic carbon in the root zone can significantly enhance agricultural productivity for a wide range of crops (Lal 2010). As shown in Table 9.5, increasing soil carbon improves the quality of several final ecosystem services from soil: The increase in soil aggregation and available water capacity are among the important benefits of higher soil organic carbon (Lal 2010).

For horticulture, the conventional recommendation is to add organic carbon directly to the soil to supplement minimal till and controlled traffic techniques (Pattinson, *et al.* 2010; HAL 2010). Organic carbon may be in the form of manure, green waste or biochar.

An alternative approach of planting rye grass in fruit orchards has shown economic benefits in field trials in the Goulburn Valley. This method involves growing ryegrass in winter and mulching it onto the roots of trees in summer. The roots of ryegrass are thought to increase soil organic carbon by increasing biological activity within a sheath that protects organic matter from being consumed by worms and other soil biota (Cockcroft 2012). While this mechanism has not yet been fully studied, field results are promising. Preliminary trials suggest soil carbon and structure is reported to increase within a few months, although rye-grass may need to be planted two years ahead of fruit trees to get the best results.

Private benefits for farmers are primarily from higher fruit yields (Cockcroft 2012). In field trials since the 1980's, the best commercial yields have been double those achieved in 1965. However, it is important to note that factors other than increases in soil organic carbon and soil structure may be responsible for some of this increase[10]. Other benefits include trees with stronger and deeper root systems that should be more robust to a wide range of environmental pressures (Murray 2007). Farmers may also benefit from lower operating costs due to more efficient use of irrigation water, fertilizers and pesticides.

Private costs are relatively low, but do involve time and labour (Cockcroft 2012). For the best results, poor soils need to be planted with rye-grass for 2 years before planting trees. Orchards then need to be cultivated every 6 months to build up a bed of soil around the trees. To maximise increases in crop yield, changes to pruning practices and management of leaf to fruit ratio might also be required.

The public benefits from improved soil condition and higher quality ecosystem services are difficult to quantify. Reduced erosion of soil by water and/ or wind would be important if land cover were being increased towards 50%, but above this level of cover the likely off-site impacts on the public are likely to be small (Sections 6 and 7).

[10] This does not account for any increases in crop yield due to other changes in orchard management systems since the mid-1960's. For example, the shift from flood irrigation to spray irrigation, building soil beds around trees, and loosening subsoil before planting fruit trees.

Other public benefits include the reduced pollution of streams and surface water due to greater water-use efficiency by fruit trees and increased removal of carbon from the atmosphere. If higher fruit yields lead to increased total gross value of production for the industry, there will also be public benefits that flow through greater local, regional and national economic activity. With the possible exception of investment in information for fruit growers to encourage building up soil carbon, public costs are nil or very low.

The key findings from this case study are:

- Private benefits of higher fruit yields are related to improved soil structure, nutrient and water conditions.
- Public benefits may include lower off-site environmental costs of water pollution, flowing from improved soil condition and more efficient use of water.
- There may be a lag of several years between action to improve soil condition and higher fruit yields. However, evidence of soil condition is visible within a few months.
- Barriers to private investment may be the availability of labour for orchard cultivation and new pruning practices.

Table 9.5: Full range of benefits and beneficiaries – Increasing soil carbon in irrigated horticulture

Beneficiaries	Final ecosystem services	Benefits	Costs	Timeframe	Expected net value
Private landholders	Landscape (soil) stabilisation Soil with nutrient and water conditions suitable for growing crops	Higher crop yields Increased efficiency of water-use and possibly fertilizer-use	Additional time and labour to plant and mulch ryegrass	Short – Medium	Positive. Field trials indicate fruit crops could be double those achieved with conventional orchard soil management systems not designed to build soil carbon.
Public	Landscape (soil) stabilisation Provision of clean water	Reduced erosion Reduced pollution of streams and surface water	Nil	Medium – Long	Positive

Case study 4: Reducing wind erosion in grazing areas - Rangelands

Australia's rangelands cover 81% of the continent (Bastin and ACRIS Management Committee 2008). They include a diverse range of relatively intact ecosystems, such as tropical savannas, woodlands, shrublands and grasslands. Extensive grazing on native pastures takes place across the rangelands (Australian Government 2012). Much of Australia's $7.4 billion/ year[11] beef grazing industry is located in the rangelands (ABS 2011a). Sheep grazing is also an important industry in some areas.

The causal links between over-grazing, loss of ground cover and soil degradation are well established. In one recent study, spatial comparisons of sites in semi-arid woodlands with different histories of grazing pressure demonstrated reductions in shrub cover and increases in bare soil at the most disturbed sites (Eldridge *et al.* 2011). Reduced soil stability and nutrient levels were obvious at the most disturbed sites, while sites with low levels of disturbance showed no physical or chemical degradation of their soils. Episodes of severe degradation occur when stocking rates remain high during droughts and ground cover declines due to over-grazing[12] (Stafford Smith *et al.* 2007). This decline is essentially permanent. While partial recovery of ground cover can occur during periods of higher rainfall, this requires even lower stocking rates than usual and may be unprofitable (Stafford Smith *et al.* 2007).

However, graziers lack visible signs to indicate when slowly declining soil condition may tip into irreversible degradation. Most of the time, soil condition declines slowly and may still support regrowth of perennial pastures (Ash *et al.* 2002). However, during episodes of drought the vulnerability of soil in poor condition becomes apparent. Impacts of severe soil degradation during drought condition include dust storms, erosion scalds and gullies (Stafford Smith *et al.* 2007). The gap in time between taking action to maintain soil condition and visible evidence of the avoided costs of erosion may be years or decades.

Severe soil degradation can impose significant private and public costs. Degraded soils lose the soil organic carbon, nutrients and structure needed to support perennial grasses on which stock graze (Ash *et al.* 2002). This has private costs, as long-term sustainable stocking rates may be reduced to as little as 40% of the average before degradation (Stafford Smith *et al.* 2007). The costs of rehabilitating land rise significantly for more extreme degradation, as grazing may not be possible for years while soil and pastures recover (Land & Water Australia 2005). Where soil condition is too poor to support the regrowth of perennial native grasses, even with

[11] This is the 2008– 2010 average gross value of agricultural product from livestock slaughtering of cattle and calves.
[12] A common pattern of decline in ground cover and soil condition following over-stocking during droughts has occurred in seven major episodes of land degradation since 1898 (Stafford Smith et al. 2007).

good rainfall, the land may need to be retired unless farmers can afford fertilizers to grow introduced pastures (Ash *et al.* 2002).

Several studies have estimated the off-site costs of dust storms in the order of millions of dollars. The ‘Red Dawn’ dust storm that hit Sydney in September 2009 is estimated to have cost over $400 million in cleaning costs and lost work hours (Tozer 2012). This dust was lifted from the far west and northwest of NSW, and the Lake Eyre Basin, due to drought and extreme wind conditions (Leys *et al.* 2011; Tozer 2012). Earlier estimates of $23 million per year for the cost of less severe dust storms in Adelaide included potential impacts on human respiratory health (Williams and Young 1999). Other public costs for which values have not been estimated include increased nutrient levels in waterways (Leys *et al.* 2011).

Keeping ground cover intact can reduce soil degradation and maintain forage for cattle (Stafford Smith *et al.* 2007). Reducing stocking rates to match pasture cover and condition is the main management practice to achieve this in the rangelands. A large decrease in the frequency of dust storms reaching east coast cities since the 1940’s may be due to graziers monitoring ground cover levels in paddocks and setting targets for ground cover management[13] (Australian State of the Environment Committee 2011; Barson *et al.* 2011). However, recent large dust storms, such as the ‘Red Dawn’ event in 2009, suggest Australia’s management of ground cover is not yet sufficient to avoid wind erosion and soil degradation during extended droughts (Leys 2012).

Reducing stocking rates can provide net benefits to graziers. Although the net economic value may be small in the short-term, the longer-term economic benefits include more stable profits and reduced risk of negative cash returns (O’Reagain *et al.* 2011). Soil ecosystem services contribute to these benefits by providing conditions that allow a diverse range of perennial grasses to thrive (Table 9.6). The magnitude of both short-term benefits and the longer-term reduction in the risk of negative returns due to soil and pasture degradation will depend on the underlying soil type and condition.

More stable profits are likely to be the main private benefit of moderate stocking rates, where soil and pasture condition is not highly degraded (Table 9.6). This assumes the economics of rangelands grazing are similar to other areas of Australia. In northern tropical savanna regions, economic modelling based on the results of long-term field trials suggests that pastures maintained in good condition produce

[13] In 2009-10, 79 % of grazing businesses monitor ground cover and 31 % set targets. Figures are for grazing businesses both within and outside the rangelands. It is worth noting that the number of businesses setting ground cover targets declined from 40 % in 2007 – 08 to 31 % in 2009-10.

slightly higher and more stable cash returns over 25 years than pasture in a deteriorated condition[14] (Land & Water Australia 2005). However, returns were much higher and more consistent than for highly degraded pastures, which produced negative cash returns more than half the time.

By contrast, increasing stocking rates may provide marginal increases in profit, but reduce the resilience of native perennial pastures by driving declining soil condition. According to one economic modelling study in the rangelands for a typical 40,000 ha property in the Mitchell grass plains in Queensland and the Northern Territory, a 3% increase in cattle led to less than 1% profit increase and long term decline in soil condition and hydrology (Macleod and McIvor 2004).

The public benefits of avoiding episodic and ongoing erosion of bare soil are likely to be high (Table 9.6). These include reductions in the annual off-site cost of wind erosion to cities and regional towns, and potentially a lower risk of extreme dust storms. While there are currently no available economic estimates, the value of avoiding water erosion will depend on both management of critical areas of soil and the sensitivity of the catchment receiving sediment (Waddell et al. 2012; see also Box 4 in Section 7). If private profits are more stable, there may also be less need for publicly funded payments to farmers during droughts.

The key findings from this case study are:

- Private benefits of maintaining soil condition and ground cover are primarily more stable grazing profits over time. Using moderate stocking rates to achieve this may have a small positive or negative impact on profits in any given year.
- Public benefits are primarily lower off-site environmental, health and cleaning costs of dust due to wind erosion. On average, these could be worth tens of millions of dollars per year. In some years this may be hundreds of millions of dollars.
- Benefits occur within graziers' decision-making timeframes, but are only visible by comparison to poorly managed areas or during extended droughts.
- Barriers to managing ground cover levels are likely to be the lack of visible indicators of long-term benefits, as well as short-term financial pressure to increase stocking levels.

[14] Cash returns were estimated as a net present value over 25 years using a 6 % discount rate.

- Managing ground cover levels to avoid erosion and maintain soil condition suitable for pastures is relevant to all of the rangelands grazing industry, which covers much of inland Australia.

Table 9.6: Full range of benefits and beneficiaries – Reducing wind erosion in grazing areas

Beneficiaries	Final ecosystem services	Benefits	Costs	Timeframe	Expected net value
Private landholders	Landscape (soil) stabilisation Soil condition for pasture	Avoided cost of rehabilitating or abandoning land Avoided cost of cattle feed during dry periods	Marginal reduction in profits due to lower stocking rate	Short – Medium	Positive due to more stable profits (assuming grazing operation not fully funded by equity, debt levels and interest costs would be lower if profits are stable)
Public	Landscape (soil) stabilisation Soil condition for pasture	Avoided costs of erosion Avoided public costs of drought impacts	Nil	Medium – Long	Positive due to avoided costs of land rehabilitation; health and other costs of erosion; and possibly lower publicly-funded payments to farmers during droughts

9.6 General findings

Australia's soils, their condition, land-use and management practices, are highly variable. This makes it difficult or impossible to present simple conclusions that apply to all soils in Australia.

However, we can draw some general conclusions from the case studies covered in this chapter.

1. The economic benefits from improving soil condition depend on the nature of the soil degradation process. There are three relevant factors:
    - How vulnerable is the soil to crossing a tipping point beyond which agricultural production is constrained?
    - Can the soil be returned to a condition that supports unconstrained agricultural production?
    - How much might this cost and how long will it take?

2. The soil conditions and threatening processes considered in this report vary widely in ways that impact the magnitude, timing and scale of the benefits of improving soil condition, and the costs of inaction:
    - Acidification may be reversible, although the cost of this can increase significantly past certain thresholds of soil condition. The most apparent costs of inaction are at the farm scale, although they may not be visible to land managers.
    - Some forms of soil organic carbon can be replenished within farm planning timeframes. Although the cost of doing so has not been established, private benefits at the farm scale may be visible to land managers where initial soil organic content is low.
    - Erosion causes a permanent loss of soil and associated nutrients that can impose long-term costs on land managers. However, these may not be obvious except during severe droughts or rainfall. Public costs can also be high due to the impact of dust storms.
3. Net private, and public benefits are positive and enduring for the land management practices covered in these case studies. In some cases the private economic benefits are more stable, rather than higher, profits.
4. However, other barriers to private investment may need to be addressed for these land management practices to be widely applied:
    - Conservation farming has already demonstrated improvement in broadacre crop yields in northern NSW. However, slow rates of adoption may have been due to low initial returns on investment.
    - Surface liming to manage acidity can increase and stabilise the profitability of wheat crops in Western Australia. However, land managers may need information about how, when and where to apply lime cost-effectively.
    - Increasing soil organic carbon can improve fruit yields for horticulture on red-brown earths in southern Australia. Barriers to private investment may be the availability of labour for orchard cultivation and new pruning practices.
    - Running moderate stocking rates can provide more stable long-term profits to grazing in the rangelands with impacts on average annual profits likely to be minimal. However, barriers to managing ground

cover levels are likely to be the lack of visible indicators of long-term benefits, as well as short-term financial pressure to increase stocking levels.

5. Over time, the ability to estimate public benefits should improve as data and knowledge about soils, land management practices and ecosystem processes develops. Some high-priority areas for research appear to be:
    - The impacts of soil acidity on surface and groundwater pollution
    - How to encourage strategic approaches to maintaining ground cover above critical thresholds (e.g., 50%) to reduce wind and water erosion from the rangelands during long droughts

10. Summary and conclusions

This project addressed two over-arching questions:

- What evidence exists about how improving land management practices will lead to reduced soil loss (through water and wind erosion) and improved soil condition (especially through reduced impacts of soil acidification and increased organic matter content)?
- How might reducing soil loss and improving soil condition result in improvements in the quantity and quality of ecosystem services and benefits delivered from agricultural lands, including cleaner air, improved water quality, reduced greenhouse gas emissions, and more productive soils?

The answers to these questions are summarised in the following sub-sections.

10.1 Improving the organic matter status of soils

Soil organic matter (SOC) contributes to a range of critical functions of soils, including: holding releasing plant nutrients; involvement in ion exchange; increasing soil water holding capacity; playing a role in building and maintaining soil structure and strength and reducing susceptibility to erosion; influencing water infiltration capacity surface runoff; providing a source energy for soil biota; buffering against fluctuations in soil acidity; and, moderation of soil temperature through its effect on soil colour and reflective capacity (Section 4).

These functions of SOC can be associated with provisioning, regulating and cultural ecosystem services as well as the soil processes that support these services.

The amount of SOC that accumulates is the balance between the amount of carbon added to the soil and the amount lost through degradation. Land-use change (including agriculture) has reduced SOC in many places around the world through both reductions in inputs and increases in losses. In Australia, clearing of native vegetation for primarily agricultural purposes has caused a 40-60% decrease in SOC stocks from pre-clearing levels.

Interpreting research on the effects of soil management practices on SOC is complicated because many studies have not been able to control all variables (e.g., rainfall, soil type, time since last cultivation, and the depth at which measurements are made all affect SOC accumulation). How sustained any increases might be is also subject to conjecture as there are limited long-term studies of these systems across Australia, and rates of accumulation are highest in surface soils, which are also most vulnerable to disturbance.

There is good evidence that management of cropland to reduce disturbance, thereby reducing carbon losses, and increase carbon inputs (e.g., minimising tillage, retaining stubble, and/ or planting pastures between crops) has decreased rates of SOC loss compared with traditional practices, but has so far not resulted in absolute increases in SOC on average across Australia.

The greatest theoretical potential for building SOC is the addition of organic materials such as manure and green waste and the inclusion of a pasture phase in a cropping sequence, and/or transformation from cropping to permanent pasture and retirement and restoration of degraded land. Due to their relatively recent emergence there is very little scientific evidence that associates these sorts of carbon-enhancing practices with increased SOC in Australian broadacre cropping. There are likely to be some tradeoffs involved with such approaches, such as increased nutrient requirements for soil biota as their energy source is enhanced.

For horticulture, dairy and grazing industries, evidence of the efficacy of management strategies to increase SOC is difficult to find in the primary literature.

Horticulture in the past has often involved high losses of carbon to the atmosphere compared with other land uses. Like broadacre cropping, best-practice management of horticultural systems involves minimizing disturbance and compaction of soils (by machinery), maintaining ground cover, and improving inputs of carbon. Limited evidence suggests that these approaches are effective in managing soil carbon as they are for cropping.

Grazing by livestock (e.g. beef and sheep) can impact directly on SOC and nitrogen cycling by modifying plant biomass inputs into soil (shoot and root material) and by reducing ground cover and thereby exposure of SOC-rich surface layers to wind and water erosion, and can also impact indirectly by modifying soil structure. Management options to avoid and overcome these impacts have focussed on increasing carbon inputs (e.g., increasing productivity using irrigation and fertilization and addressing acidification) and reducing disturbance to soils and the potential for erosion (e.g., time controlled or rotational grazing and shifting to perennial pasture species). Research on the impacts of these options on SOC is limited, but a small number of studies in south-eastern Queensland and northern NSW have indicated short-term increases in herbage mass, SOC, nitrogen, and ground-litter, and reduced runoff and soil loss under time-controlled grazing compared to continuous grazing.

Dairy systems generally have high levels of SOC, due to high inputs of manure and fertilizers, but loss of soil carbon can occur and best-practice management seeks to minimize damage to soil from stock and loss of soil by erosion.

Sequestering carbon as way to reduce atmospheric carbon-dioxide is a somewhat separate issue to enhancing SOC to improve soil function. It appears that the potential for reduced or no-tillage (direct-drilling) and stubble-retention to sequester additional carbon and mitigate green house gas emission is limited in low-rainfall areas, in contrast to areas with higher rainfall and greater biomass production.

10.2 Improving the pH (acid-bases balance) of soils

There are several major causes for the acidification of agricultural soils, including: removal of agricultural products; excessive accumulation of organic matter; excessive use of nitrogenous fertilisers; and leaching of fixed, fertiliser and urine-N as nitrate from surface layers to lower layers before plants can utilise it. Impacts of soil acidification on-site and related to plant, animal and soil biological performance or off-site, though the link to stream and groundwater acidification is speculative (Section 5). On-site impacts include aluminium (Al) and manganese (Mn) toxicity affecting plants and plant nutritional problems caused by reduced availability of nutrients such as calcium (Ca), Magnesium (Mg), and Potassium (K). The resulting reduction in plant biomass production reduces the quantity and quality of plant residue entering soils and hence SOC levels.

Acidification occurs in both surface and subsurface soils, the latter being of increasing concern in parts of Australia (e.g., WA). Soil acidification is widespread in the extensive farming lands (cropping, sheep and cattle grazing) of southern Australia, and appears to be getting worse rather than better, and it is common in intensive systems of land use (tropical horticulture, sugar cane, dairying).

The use of high analysis nitrogen fertilisers and a high rate of product removal are features of most horticultural enterprises and about half of the horticultural industries have undertaken research to counter these potential problems. Due to diminishing returns from milk production dairy farmers nationally have intensified and diversified their production to remain profitable. This led to has increased stocking rates, use of irrigated annual fodder crops, use of mixed livestock systems of beef and dairy, and nutrient inputs, resulting in significant acidification, particularly in light textured soils where soil buffering capacity is low (e.g., in south-western Australia). Under grazed permanent pastures, nitrate leaching, as a result of over-fertilization and overstocking, is considered to be the largest risk in relation to acidification

Across most agricultural systems, the primary actions to address soil acidification are to: test soil pH regularly and at a range of depths; add lime at rates that are effective for arresting acidification; add lime at high rates, sufficient to reverse acidification in soils that have already acidified; use acid-tolerant plant species where available (as a short-medium term measure); and, retire land in the extreme. Management of potential acidity in many grazing systems consists of: sowing perennial grass species and/or agroforestry systems, to increase rooting depth and nitrate uptake; and reducing stocking rates on pastures with a high component of native grasses, to maintain vigour of the grasses.

Around 50% of dairy, broadacre cropping and horticulture businesses test for pH regularly (a slight decline over the past few years) and around 30% of grazing businesses (also a decline). Far fewer go on the apply lime or dolomite. It has been concluded that lime applications across Australia is far short of what is needed to arrest, let along reverse, the rate of soil acidification. The use of acid tolerant species, although a relatively straightforward and cost-effective option, does not address the underlying problem, proving a temporary strategy for ‘living with the problem’ and probably making it worse.

There is compelling evidence to show that liming surface soils can increase yields of a wide variety of grasses and legumes (including many broadacre crops such as wheat and barley), so long as strategies are matched to soil type and pH, paddock variability, intended crops grown and fertiliser rates, and soil is tested regularly at a range of depths. These conclusions are based on intensive R&D effort in the 80s-90s on long-term trials in the high rainfall and temperate zones of southern Australia, and more recently in the 1990s-2000s in southern WA field trials. For broadacre cropping and high return industries such as horticulture and dairy, liming can be an effective and profitable management strategy for mitigating surface soil acidification provided appropriate rates are applied that account for regional and local (management) factors of soil and plant type and N-fertiliser regimes. The efficacy of practices to reduce subsoil acidification is less well established and only demonstrated on a small subset of soil types.

10.3 Minimising erosion of soils by wind

The extent to which soils are susceptible to wind erosion depends on a range of factors, including climatic variability, ground cover, topography, the nature and condition of the soil, and the energy of the wind. Land management can either moderate or accelerate wind erosion rates, largely depending on how it affects the proportion of bare soil, the dryness and looseness of the ground’s surface, and structures (stems, leaves, clumps of plants) that reduce the force of the wind. Grazing by stock, native animals (e.g., kangaroos) and feral animals (e.g., rabbits, camels, horses, goats) have major impacts on ground cover and soil physical properties. The changes in land cover brought about to establish much of Australia's agriculture have led to an increase in wind (and water) erosion.

The on-site impacts of wind erosion include soil loss, reduction in soil nutrients and organic matter (including soil organisms), release of soil carbon to the atmosphere, undesirable changes in soil structure, reduced water infiltration and moisture-holding capacity, and exposure of unproductive saline and acid subsoils. Off-site impacts include negative impacts on the global climate through positive radiative forcing of dust, physical impacts of dust storms on buildings and equipment, and health impacts of dust for people. The limited data available suggest that the off-site costs of wind erosion can be many times greater than the on-site costs. Historically, wind erosion has been particularly active in times of drought. In the 1940s and again in 2002 and 2009 there were heightened concerns due to dust storms hitting major Australian towns and cities.

Approaches to reducing wind erosion address three major aspects (Carter 2006): Ground cover; soil looseness; and, wind velocity. Ground cover is important as it reduces wind speed at the soil surface and captures soils particles mobilised by wind. Soil looseness increases when there is too little vegetation cover, soils are dry, the type of soil contains small particles and/ or the surface is smooth. Maintaining soil moisture, avoiding trampling of exposed soil by stock and maintaining rough soil surface are all ways to reduce soil looseness. While the velocity of wind is determined by the weather, it can be moderated locally by creating windbreaks.

Levels of combined water and wind erosion from cultivated land and rangelands are relatively similar, and as much as eight times greater than from uncultivated areas and forests. Management involves: protecting or encouraging ground cover, including avoidance of cultivation; control of pests that destroy ground cover and/or disturb the surface of soil; minimizing the area and intensity of grazing and cropping; and, managing movements of stock in dry areas using strategic placement of watering points.

Numerous studies have been performed in Australia, and in comparable ecosystems in other parts of the world, to show that increasing ground cover reduces losses of soil due to both wind and water erosion. As a general rule, it has been concluded that ground cover of around 50% is required to keep wind erosion to a minimum across a range of climatic conditions and soil types (this level of cover achieves around an 80-90% reduction in erosion compared with bare soil).

The general relationships between ground cover and soil erosion have been known for over 20 years. The main focus of research and development during the past two decades has been on how to achieve ground cover cost-effectively.

Another line of evidence for the effectiveness of better management of ground cover and soil surface properties for reducing wind erosion comes from data showing that Dust Storm Indices (DSI) in the 1940s were on average four times higher in the 1940s than in the 2000s (management of ground cover has improved substantially since the 1940s). Despite these improvements, it is expected that the incidence of huge dust storms, like those in 2002, will increase in the future as parts of Australia go through long dry periods.

10.4 Minimising erosion of soils by water

Water erosion of soils occurs when soil particles are detached and carried away by water flowing across a landscape (Section 7). Like wind erosion, the on-site impacts of water erosion include soil loss, reduction in soil nutrients and organic matter (including soil organisms), release of soil carbon to the atmosphere, undesirable changes in soil structure, reduced water infiltration and moisture-holding capacity, and exposure of unproductive saline and acid subsoils. Off-site impacts include sedimentation of waterways and impacts on quality of surface water and groundwater (turbidity, nutrient and other chemical loads).

It is estimated that current rates of soil erosion by water across much of Australia exceed soil formation rates by a factor of at least several hundred and, in some areas, several thousand. While the time for total loss of soil is estimated to range from 100-500 or more years in different parts of Australia, it is expected that crops and other plants will respond to small changes in depth of topsoil, so that many areas are at risk of critical decline in productivity in much less than 100 years. Areas at highest risk include Coastal Queensland, the Wet Tropics, Mitchell Plains grasslands, New England Tablelands, and Victoria River basin in the Northern Territory.

Many of the effects of cultivation on susceptibility to wind erosion also apply to water erosion. Water erosion associated with cropping was recognised as a serious issue in the 1930s and has been a concern ever since. Horticulture faces many of the same risks of water erosion as broadacre cropping. Reduction of ground cover by livestock grazing can greatly increase vulnerability of landscapes to water erosion.

Key challenges for dairy enterprises include controlling sediment (along with nitrogen and phosphorus from fertilizers) losses into waterways, which can be exacerbated by compaction and disturbance of soil by the feet of grazing animals.

Land management practices designed to minimise water erosion seek to: increase ground cover above a critical threshold; minimise evaporation of soil moisture; maintain soil structure; limit compaction by heavy equipment or running of stock; and/ or, create of contours that control water flow.

There is an extensive literature showing that increasing ground cover reduces losses of soil due to water erosion. Typically, 20-30% cover reduces erosion by 80-90% across a range of soils and land uses. Ground cover can be grasses, herbs, trees, dead plants with root systems still intact, dead plant material (especially branches) lying on the surface, or even stones. While different combinations of cover-types have different effectiveness, In general, 70% ground cover is recommended to manage water erosion, although 80-100% cover is recommended where rainfall is moderate to high and slope are steep.

Reduced tillage has been shown to dramatically lower soil erosion and provide benefits for crop production and improved profits compared with traditional cultivation in a range of climates and soil types. This is especially true when economies of scale can be achieved by applying the same labour and machinery over large areas, and when controlled traffic management is used. Some limitations of conservation tillage have been identified, such as reduced surface roughness and enhanced run-off and sediment movement in areas where maintaining high biomass of plants is difficult or where low cover results from crop failure or grazing, but such issues can be managed cost-effectively.

In grazing systems, removal of stock has been shown to allow recovery of ground cover, if conditions are favourable for regrowth of pastures, but recovery of full soil functionality, especially organic matter content, can take years to decades.

10.5 improvements in the quantity and quality of ecosystem services and benefits delivered from agricultural lands

The living and non-living components of soil ecosystems interact to mediate a range of processes that would require engineering at an unprecedented scale to replicate (Section 8). These processes transform natural resources into forms that are potentially of benefit to humans and in so doing they are said to provide ‘ecosystem services’ (Table 10.1).

Table 10.1: Ecosystem services from soils and the benefits potentially derived (summarised from Section 8)

Ecosystem services	Potential benefits
Provisioning services	
Provision of fertile soil	Crops, meat, and other food
Support native pastures, foods, fibre, flowers and other above-ground natural raw materials	Natural products to support industries and lifestyles, bush food
Provision of natural products from soil	Natural products to support industries and lifestyles, food
Provision of clean water	Water of a quality suitable for drinking, recreation, use in industries, machinery etc.
Maintenance of genetic diversity	Intellectual stimulation, cultural value, moral value, potential for new foods and other products
Support for structures	Physical support for building and other infrastructure
Regulating services	
Water flow regulation	Protection from wind and water erosion and floods, prevention of salinity, storage of water
Maintenance of landscape (soil) stability	Protection from wind and water erosion, including risk to lives from land slippages, protection from damage and adverse health and climatic effects from dust storms
Regulation of atmospheric gases	A liveable atmosphere, physical and mental health and well being, liveable climate
Role (with vegetation) in regulation of weather and climate	A liveable climate
Breakdown of wastes and toxins	Disposal of wastes, health and wellbeing benefits
Regulation of species and populations in soils	Reduced risks of pests and diseases, reduced need for chemicals, health and financial benefits
Pollination and seed dispersal	Contributes to production of crops and native vegetation and the benefits that provides
Cultural/ habitat services	
Contributions to species, ecosystem and landscape diversity	Intellectual stimulation, knowledge, cultural and spiritual values (e.g., sense of place)

Management of land for agriculture dramatically changes the balance among ecosystem services, increasing some provisioning services, decreasing some regulating services and changing the nature of many cultural services. One aim of improved agricultural management is to adjust this balance to meet a wider range of private and public needs.

The research reviewed in this report has shown that best-practice approaches to managing soil carbon, acidity and wind and water erosion are generally effective at addressing those issues and improving soil condition generally. Practices like minimal tillage, maintaining ground cover above 50%, adding organic matter to soil (within limits), and managing the impacts of stock and machinery on soil disturbance and compaction, have beneficial outcomes for all aspects of soil condition. These practices, therefore, potentially enhance most ecosystem services and allow most of the benefits that come from those services to be increased.

The beneficiaries include farmers, agricultural industries, communities, families and individuals in regional areas and in cities. It is possible to estimate the magnitude of these benefits under different conditions in the future, but it is not meaningful to make a single estimate of future value because of the many combinations of management practices, soil types, climatic variations, products, market opportunities, demographic changes, and demands of consumers over the coming decades. Some general conclusions can, however, be made:

- There are achievable opportunities to address declining soil carbon and increasing acidity and reduce wind and water erosion and at the same time improve profitability of agriculture and deliver a range of public benefits (which in some cases will be worth more than the private benefits in terms of health and wellbeing outcomes);
- To do this it will be important to consider the ability of soil ecosystems to cope with ongoing and potential future shocks (i.e., their adaptive capacity and resilience), which cannot be considered in isolation from the adaptive capacity and resilience of the humans who manage agricultural landscapes;
- The resilience of soils in many parts of Australia depends strongly on building and maintaining soil carbon stocks, which affect a wide range of functions, including nutrient cycling and water infiltration and storage, and the ability of landscapes to retain topsoil;
- Another key aspect of the resilience of Australian soils is their ability to avoid passing through thresholds of change, some of which could be, to all intents and purposes, irreversible;
- Such thresholds include critical proportions of ground cover (50-70% depending on factors like rainfall and slope), below which erosion accelerates dramatically, carbon-content thresholds, and thresholds of acidification, especially of subsoil, which currently cannot be addressed economically by most agricultural industries.

10.6 Summary

In summary, this report finds that:

- Efforts by farmers, graziers and governments since the 1970s have achieved many improvements in soil condition.
- Not only farmers, but all people stand to receive major financial and social gains from better management of soils.
- There is a great potential to achieve further benefits from improving soil condition and the quality of ecosystem services.
- Each of the four main indicators of soil condition—soil acidity, soil carbon, wind erosion and water erosion—can be improved by wider adoption of best-practice soil management.
- Appropriate practices do exist, and the benefits of greater adoption are significant to those involved in agriculture and to the wider public.

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