# final report

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# Soil carbon in Australia's extensive grazing lands

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# Soil carbon in Australia's extensive grazing lands

"*Agriculture has always been about farming carbon*." (Dalal *et al*, 2008b)

## 1 Introduction

### 1.1 Purpose and scope

Increasing soil carbon (C) levels in Australia's extensive grazing lands[1] offers both a challenge and an opportunity to graziers and policy makers. While much of the recent interest in soil C is due to its climate change mitigation potential and possible future income from carbon credits, there are multiple co-benefits from improved soil health and ecosystem function.

With projections of a shift to a hotter and drier climate over much of Australia, it is a policy and management imperative to maintain and, where possible, increase C levels for improved productivity, resilience and adaptive capacity as well as climate mitigation benefits, particularly in the drier regions that make up the vast majority of grazing lands (Figure 1).

Graziers who have changed their practices over the past few decades, often as a response to land degradation, are reporting higher soil C levels, improved land condition, productivity and profitability, and greater resilience through use of grazing practices[2] that restore natural processes and build healthy soils. Wider adoption of these restorative grazing practices is slow despite the apparent benefits. Reasons include that these practices can appear counter-intuitive to conventional graziers, with improved ecological literacy likely to improve understanding and facilitate adoption of soil C enhancing grazing practices (King, 2009).

This paper provides a synthesis of knowledge of soil organic carbon[3] in Australia's grazing lands with a view to improving ecological literacy and decision making. It describes the role of C in soil health, and the main biogeochemical processes and grazing practices that affect soil C. Although intensive systems which would require life cycle considerations of inputs are outside the scope of this paper, the main C cycling processes are still relevant. This paper also does not consider greenhouse accounting

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[1] 'Grazing lands' used throughout refers to extensive grazing lands

[2] Two examples are Time Controlled or Cell Grazing, and Pasture Cropping that use high impact/short duration grazing to stimulate plant growth with long periods between grazing to allow full recovery.

[3] 'Carbon' used throughout refers to organic carbon. Inorganic carbon, carbonate-C, is not discussed as, although it affects soil chemistry and structure, the pathways for inorganic C sequestration are poorly understood (FAO, 2004).

policy or carbon trading issues that, although potential drivers of change in grazing practices, do not directly affect the C cycle.

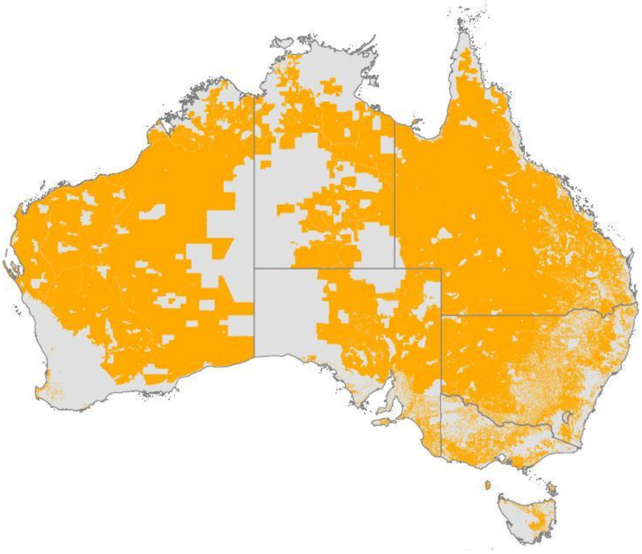

**Figure 1: Australian grazing lands**

*Grazing is a major land use across most regions of Australia. Most grazing is on rangelands with only about 4% on improved pastures in higher rainfall areas, covering 56% and 2.5% of the continent respectively (SOE, 2006)*

C4OC http://www.nrm.gov.au/business-plan/10-11/priorities/sustainable/pubs/map-2-4-9.pdf

## 1.2 Greenhouse accounts

While this paper does not cover greenhouse accounting in the main discussion, this summary of emissions is provided as context. The two main sources of greenhouse gases accounted for from grazing lands are methane ($CH_4$) from enteric fermentation[4], and $CH_4$ and nitrous oxide ($N_2O$) from savanna burning. The other main agricultural source accounted for is nitrous oxide ($N_2O$) from agricultural soils which is mostly from fertilisers used in cropping and intensive grazing systems. Carbon dioxide ($CO_2$), although emitted from savanna burning and agricultural soils, is not accounted for as it is assumed to be taken up by vegetation growth within an accounting period. Australia does not account for C sequestration in soil or vegetation in grasslands or croplands[5].

In accounting for greenhouse gases, carbon dioxide equivalents ($CO_2$-e) are used as a common measure to compare and aggregate greenhouse gases with different global warming potentials (GWP)[6]. $CO_2$ is the reference gas with a GWP of 1, methane ($CH_4$)

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[4] Enteric fermentation is part of the digestive process of ruminants. Methane released as a by-product of digestion

[5] It is mandatory to account for forest land under Article 3.3 of the Kyoto Protocol, whereas accounting for other managed lands (croplands, grasslands, wetlands, settlements, other lands) is optional under Article 3.4. Australia has elected not to account for Article 3.4 activities.

[6] GWPs incorporate a gas's capacity to absorb and hold heat (radiative efficiency) and its atmospheric lifetime.

has a GWP of 25 and nitrous oxide ($N_2O$) a GWP of 298 (Forster *et al*, 2007), meaning that 1 *t*$CH_4$ or 1 *t*$N_2O$ in the atmosphere is responsible for the same amount of warming as 25 or 298 *t*$CO_2$ respectively. In converting between C and $CO_2$-e, 1 *t*C is equivalent to 3.67 *t*$CO_2$-e.

The agriculture sector contributed 87.4 M*t*$CO_2$-e or just over 14% of Australia's total emissions of 618.1 MtCO2-e in 2008 (Table 1). Of these emissions, 55.5 M*t*$CO_2$-e was $CH_4$ from enteric fermentation, accounting for 64% of agricultural emissions and almost 9% of total emissions and 9.5 M$CO_2$-e of $CH_4$ and 4.1 M*t*$CO_2$-e of $N_2O$ was from prescribed burning of savannas. Other agricultural emissions are $CH_4$ and $N_2O$ from manure management and $N_2O$ from agricultural soils. Conversion of forest to grassland (land clearing), reported under the Land Use, Land Use Change and Forestry sector, contributed another 50.6 M*t*$CO_2$-e, mostly $CO_2$, or 8% of total emissions (DCCEE, 2010).

**Table 1: Agriculture sector CO2-e emissions, 2008**
(DCCEE, 2010)

| Greenhouse gas source and sink categories | $CO_2$-e emissions (Gg) | | | |
|---|---|---|---|---|
| | $CO_2$ | $CH_4$ | $N_2O$ | Total |
| AGRICULTURE | N/A | 67138 | 20257 | 87395 |
| Enteric fermentation | N/A | 55552 | N/A | 55552 |
| Manure management | N/A | 1804 | 1542 | 3346 |
| Rice cultivation | N/A | 43 | N/A | 43 |
| Agricultural soils | N/A | N/A | 14557 | 14557 |
| Prescribed burning of savannas | N/A | 9549 | 4065 | 13615 |
| Field burning of agricultural residues | N/A | 190 | 93 | 282 |

# 2 Carbon stocks and benefits

## 2.1 Carbon in grazing lands

Australia's grazing lands (Figure 1) are widespread and diverse, covering temperate, high rainfall regions in the south and east, to semi-arid inland, and semi-tropical and tropical regions in the north; across different landforms, soils and climates. Woodlands, grasslands and savannas have evolved and adapted in response to these different environmental factors resulting in a diversity of ecosystems with widely variable carbon carrying capacities. Above and below ground C are interrelated and integral to the land's capacity to provide ecosystem services, with soil C an indicator of soil health.

Australian soils are inherently infertile (Sanderman *et al*, 2010) and, since European settlement, land clearing, primary production and erosion that have altered vegetation (Figure 2) and depleted C stocks. Loss of soil C has diminished productivity, resilience and adaptive capacity – a significant loss of natural capital to grazing enterprises, with release of C also contributing to climate change. However, many studies (Conant *et al*, 2001; Conant and Paustian, 2002) show that improved grazing management can increase soil C levels and have potential to restore productivity and ecosystem function. Conant and Paustian (2002) found that light to moderately degraded soils respond best (Figure 3), with soils furthest from C saturation having the greatest C sequestration potential (Stewart *et al*, 2007).

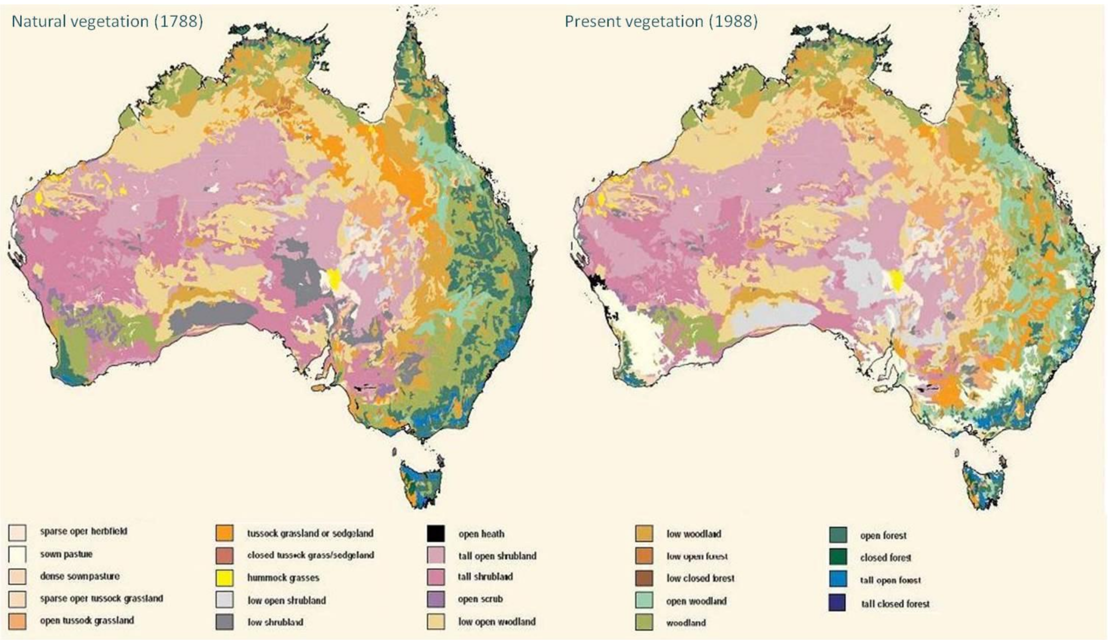

**Figure 2: Vegetation change 1788 to 1988**

*Land clearing since European settlement has depleted carbon stocks*

SOE (1996)

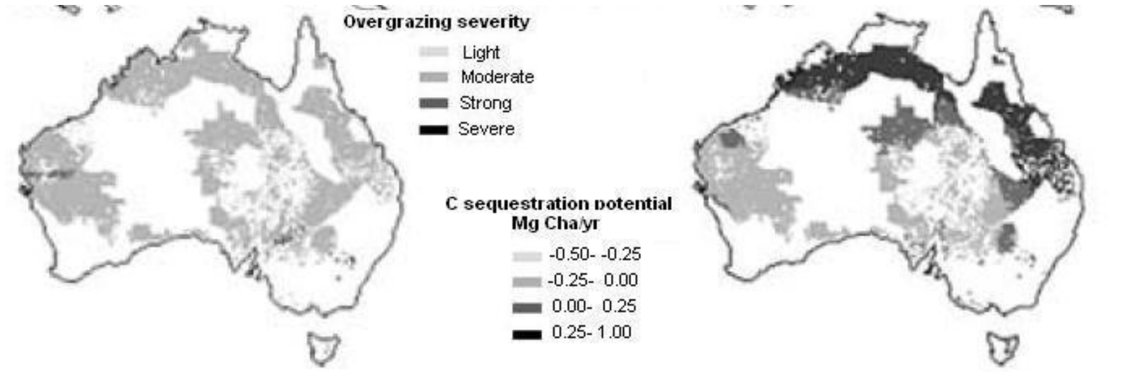

**Figure 3: Overgrazing and carbon sequestration potential in grassland ecosystems**

*Most of Australia's rangelands are lightly to moderately degraded with potential for carbon sequestration and recovery.*

Conant and Paustian (2002)

C stocks in Australia's grazing lands vary widely (Figure 4), due both to the natural diversity of landforms and climate, and the effects of different land management practices. Natural variability is also a determinant in soil C levels Figure 5, ranging from 5 to 250 *t*C/ha (Bruce *et al*, 2010). C stocks are lower in the north despite high rainfall and productivity due to rapid decomposition of organic matter in warm, moist conditions (Raupach *et al*, 2001). The highest density of both above and below ground C is in the south-eastern Australia and the south-west reflecting the higher productivity of higher rainfall, temperate regions, while soil C is the major stock in grazing lands due to grasses being the dominant vegetation type. This can be seen in Figure 6 where in a predominantly grazing area in the NSW Northern Tablelands region with an average annual rainfall of about 800mm, 86% of C is in the top 30cm of soil. Other organisms, such as livestock, also represent a C stock and play an important role in C cycling but are considered a fast turnover stock and are not included in C accounting.

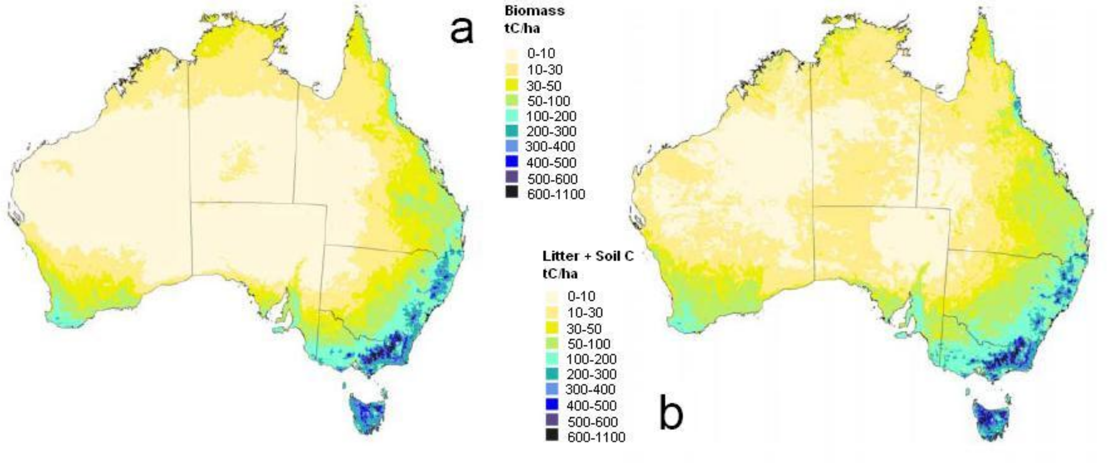

**Figure 4: Carbon stocks**

*a. Biomass carbon including leaf, wood and root pools. b. sum of litter and soil carbon pools*

Raupach *et al* (2001)

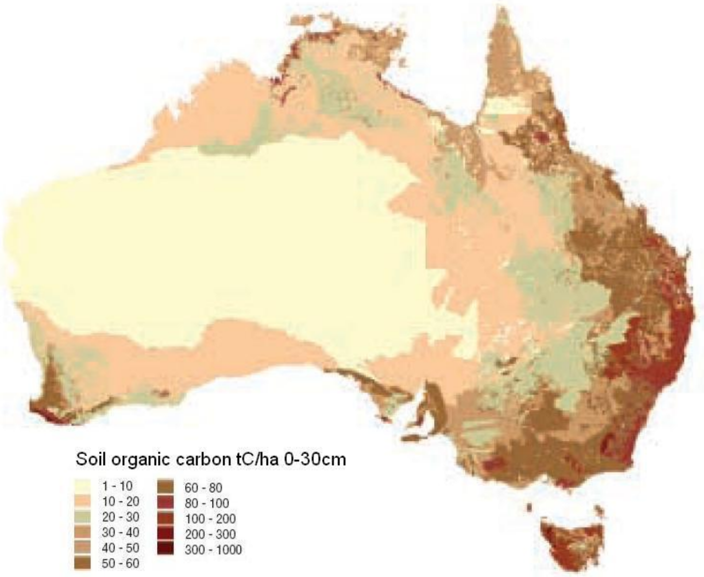

**Figure 5: Soil organic carbon levels pre European settlement**

*Soil carbon levels vary greatly due to different environmental factors across Australia*

AGO (2002)

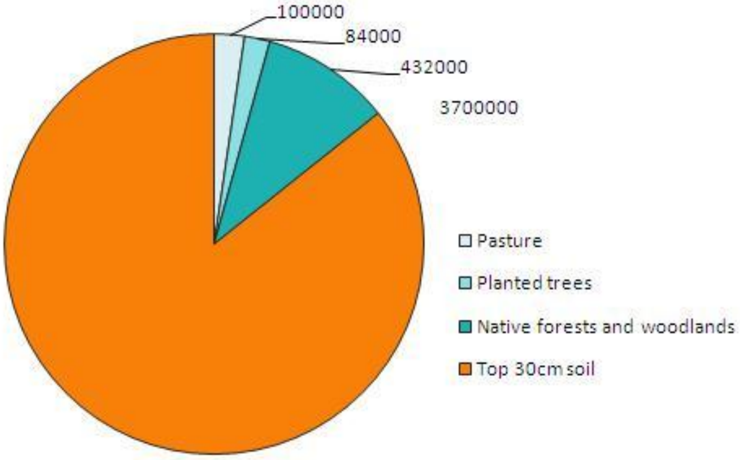

**Figure 6: C stocks in the Lower Apsley River Landcare Group region 2009 ($tCO_2$-e)**

*The estimated total amount of carbon contained in the soils and vegetation of the Lower Apsley = 4,316,000 tonnes of CO2-e (16,500 ha)*

Andrews (2010)

## 2.2 Ecosystem Services

The amount of C and its cycling is integral to ecosystem function and an ecosystem's[7] capacity to provide the services needed to maintain life and human wellbeing (Box 1). The supporting ecosystem services of primary productivity, nutrient cycling and soil formation are also fundamental processes within the terrestrial C cycle. Together, the supporting ecosystem services enable the regulating services, such as water, pollination

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[7] "An ecosystem is a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit." (MEA, 2005)

and climate regulation to operate, that in turn enable the provisioning services, such as food and fibre to be produced.

As well as being the major C stock in grazing lands, soil C is an indicator of soil health (Box 2). As C is a critical component of healthy soil, soil is degraded when C losses exceed C inputs (Lal, 2002). The health of a soil determines its capacity to support all other ecosystem services, with soil processes regulating productivity and decomposition, “the two main life-supporting processes on planet Earth” (Brussaard *et al*, 2007). While all C contributes to ecosystem services throughout the C cycle, the role of soil C in processes that regulate primary productivity nutrient cycling, and soil formation (Box 3) demonstrates its critical nature for land condition, production and environmental outcomes.

Dynamic processes within the terrestrial ecosystem (Figure 7) create positive feedback loops[8] that drive the system in the same direction as a change in one of the variables. For example, an increase in vegetation provides more organic matter, leading to an increase in nutrient cycling and soil biota, and an increase in soil C. More soil C increases the soils capacity to hold moisture; making it more productive which leads to more vegetation growth, driving the system in a virtuous cycle. Conversely, a decrease in vegetation means less organic matter for nutrient cycling and soil organisms, decreasing soil C and the soil’s productive capacity in a vicious cycle, leading to less vegetation growth. While past loss of soil C has degraded grazing lands’ capacity to provide ecosystem services and store C, the positive feedback in the system means that an increase in soil C or other variable establishes conditions for further increases in C until a limiting factor such as water or nutrient availability is reached.

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[8] A positive feedback loop drives the system in the same direction as the initial change, leading to a virtuous or viscous cycle. An increase (or decrease) in one variable results in an increase (or decrease) in another variable that results in an increase (or decrease) in the first variable and so on until a limiting factor stops the cycle. Negative feedback is where an increase (or decrease) in one variable results in a decrease (or increase) in another variable, limiting the extent of the cycle and maintaining the system in a dynamic balance.

### Box 1: Ecosystem services

adapted from MEA (2005)

| Provisioning Services<br>*Products obtained from ecosystems* | Regulating Services<br>*Benefits obtained from regulation of ecosystem processes* | Cultural Services<br>*Non-material benefits obtained from ecosystems* |
|---|---|---|
| ▪ Food<br>▪ Fresh water<br>▪ Fuel wood<br>▪ Fibre<br>▪ Biochemicals<br>▪ Genetic resources | ▪ Climate regulation<br>▪ Disease regulation<br>▪ Water regulation<br>▪ Water purification<br>▪ Erosion regulation<br>▪ Pest regulation<br>▪ Pollination | ▪ Spiritual and religious<br>▪ Recreation and ecotourism<br>▪ Aesthetic<br>▪ Inspirational<br>▪ Educational<br>▪ Sense of place<br>▪ Cultural heritage |

Supporting Services

*Services necessary for the production of other ecosystem services*

- Soil formation
- Nutrient cycling / decomposition
- Primary productivity

### Box 2: Healthy soil characteristics

Moody (2010)

Soil health: "the ability of a soil to provide ecosystem functions to its full capacity"

- *ability to provide ecosystem services*
- *robustness – ability to resist temporary stress*
- *resilience – ability to 'bounce back' after stress*

### Box 3: Services provided by organic soil carbon

adapted from Bruce *et al* (2010)

*Carbon storage* – Increasing the amount of organic carbon in the soil may decrease atmospheric carbon

*Food and habitat for biodiversity* – Soils are home to many organisms that, together with plant roots, form the living organic matter, and often use the organic matter as food. They include earthworms, insects (for example dung beetles, ants and termites, cicadas, locusts, millipedes and centipedes), spiders, mites, snails, nematodes and even some mammals (for example, mice, rabbits, platypus and wombats). In addition, there are many microorganisms – bacteria, fungi, algae and protozoa – that actively contribute to carbon cycling in soils.

*Nutrient storage and supply* – Soil organic matter can form up to half of the sites for nutrient storage and exchange in some soils.

*Aggregate formation and stabilisaton* – Soil organic matter stabilises other parts of the soil, binding soil particles into aggregates that are more resistant to erosion.

*Buffering capacity* – Soil organic matter increases the soil's ability to buffer against changes in pH and may adsorb many pesticides.

*Soil moisture* – Soil organic matter helps to increase soil aeration, allowing water and air to move more easily through the soil, thus increasing the infiltration rate (so that rainfall takes a shorter time to enter the soil) and water holding capacity of the soil.

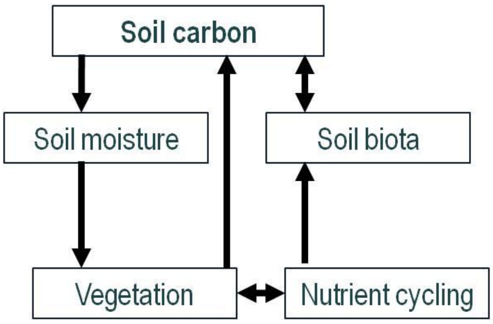

**Figure 7: Conceptual feedback loop**

*Conceptual feedback loop between soil carbon, soil moisture, soil biota and vegetation condition. Arrows represent both self-reinforcing systems (positive feedback) and negative reinforcing ones (negative feedback)*

Colloff and Baldwin (2010)

# 3 Carbon and nutrient cycles

## 3.1 Global carbon cycle

All living or once living things contain carbon which is continually recycled by biological, physical and chemical processes between and within the terrestrial biosphere, atmosphere and oceans, and on a geological timeframe, the deep ocean and the Earth's crust (Figure 8). Terrestrial carbon was in a dynamic equilibrium before industrialisation, with C uptake from the atmosphere (120 G*t*C) balancing losses from erosion and leaching (0.4 G*t*C) and respiration (119.6 G*t*C). The main terrestrial C stocks are in vegetation and soils, with the soil storing about three times as much C as vegetation and about double the C in the atmosphere. Since industrialisation, the terrestrial biosphere has been a source of C as $CO_2$ to the atmosphere, with more C lost from land clearing and degradation (140 G*t*C) than uptake (101 G*t*C), although it is currently a sink, taking up more C (2.6 G*t*C) than it is losing (1.6 G*t*C) (Denman *et al*, 2007).

The C cycle is global due to atmospheric mixing, with impacts from changes in the C cycle often being geographically dislocated from the source. Depletion of the terrestrial C stock contributes to climate change[9] and represents lost productivity and resilience. Regenerating degraded land and rebuilding C stocks therefore has significant co-benefits for climate change mitigation, adaptation and production.

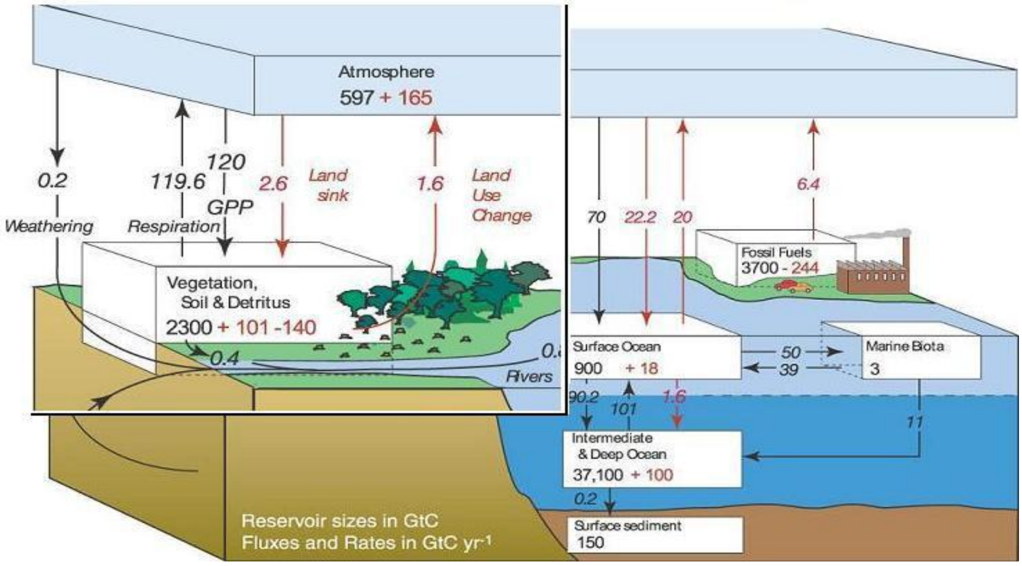

**Figure 8: Global carbon cycle**

*Global carbon stocks and fluxes showing pre-industrial 'natural' fluxes and stocks in black and 'anthropogenic' fluxes and stock changes in red*

adapted from Denman *et al* (2007)

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[9] Examples of ways a depleted terrestrial C stock contributes to climate change are through emissions from deforestation, land degradation and land use, reduced capacity to take up C from the atmosphere, changed albedo, and changed hydrological cycle.

## 3.2 Terrestrial carbon cycle

The terrestrial C cycle is the flow of C between stocks, with the C balance a function of inflows and outflows, globally between the terrestrial biosphere and the atmosphere and oceans, or between different C stocks at a paddock, property, catchment, region or national scale.

The C cycle does not operate in isolation but is one of many interrelated biogeochemical processes and reactions in the flow of energy and nutrients within the terrestrial ecosystem (Figure 9). Although simplified and usually described separately, it is important to keep in mind that C and nutrient cycles are dynamically linked through the creation and decomposition of organic matter. Elements are essential for life, with plants obtaining C as $CO_2$, oxygen (O) and hydrogen (H) from the atmosphere and water and mineral nutrients from the mineral soil and decomposed organic matter. The major nutrients are nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S); with trace elements of boron (B), copper (Cu), chloride (Cl), iron (Fe), manganese (Mn), molybdenum (Mo) and zinc (Zn) required only in micro amounts. The C, N and P cycles are briefly outlined to illustrate the interaction of biological, geological and chemical processes involved in making nutrients available to plants and other soil organisms, and sources and sinks of $CH_4$ briefly discussed.

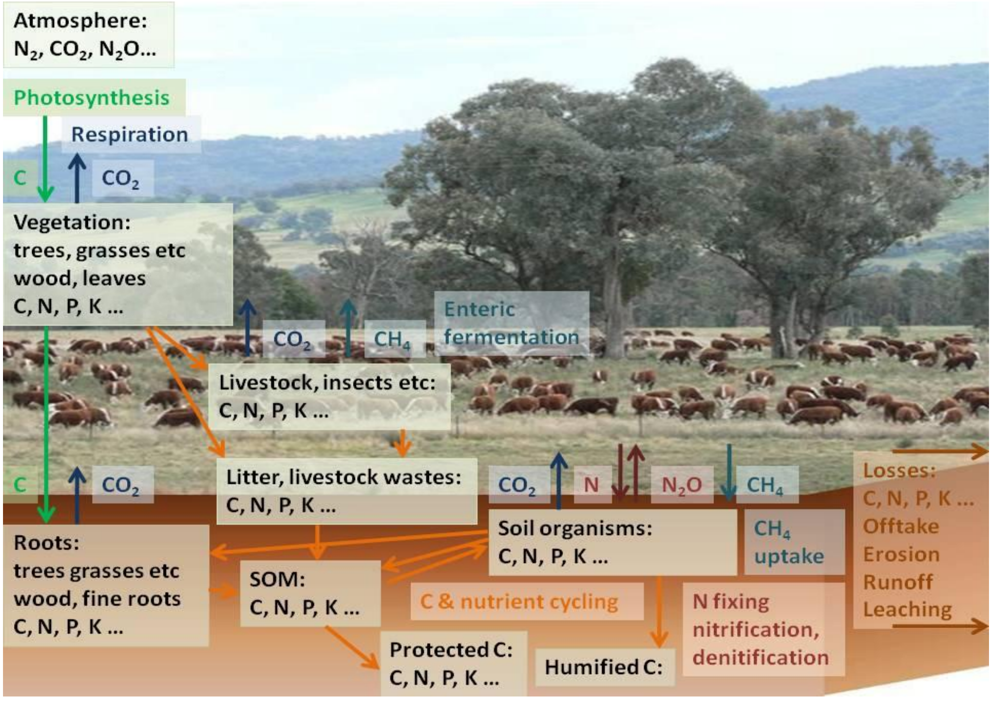

**Figure 9: Carbon and nutrient cycling (using N, P and K as examples)**

*Dynamic ecosystem processes cycle carbon and nutrients through the atmosphere and terrestrial biosphere through the creation and decomposition or organic matter.*

King (2010)

Living plants start the C cycle with photosynthesis and the creation of organic matter and continues through disturbance and decomposition as C flows between stocks, for example from grass to livestock, to manure, to dung beetles and fungi, to soil microorganisms. Above ground, C stocks are in living trees, shrubs, forbes and grasses; in animals, insects, fungi and microorganisms; and in course woody debris, litter and detritus[10]; and below ground in roots, soil macro and microorganisms, and soil organic matter[11] (SOM) including stabilised C in protected organic matter and humic substances..

As autotrophs, plants create their own food through photosynthesis with most other organisms[12] (heterotrophs) directly or indirectly reliant on plants for C and nutrients to meet their metabolic needs. This forms a complex above and below ground food web where organic matter created by plants is consumed and decomposed by other organisms recycling C and nutrients through their bodies and wastes. Most of these decomposition processes occur within the soil with plants obtaining dissolved nutrients from soil solution.

Using solar radiation, plants assimilate C by taking $CO_2$ from the atmosphere and water ($H_2O$) from the soil to create carbohydrates ($C_6H_{12}O_6$), returning excess oxygen ($O_2$) to the atmosphere. Plant respiration returns C as $CO_2$ to the atmosphere as the carbohydrates are broken down for metabolic energy and to build biomass in leaves, stems and roots. The amount of C captured by photosynthesis is termed gross primary productivity (GPP) with net primary productivity (NPP) the C stored in biomass after respiration.

Organic matter, above and below ground is physically and chemically broken down through a complex food web, recycling C and nutrients through the bodies and waste products of multiple organisms. Respiration of $CO_2$ by organisms releases most of the C captured by plants, with C also lost by wind and water erosion, photodegradation, fire and leaching. In natural ecosystems, C inflows tend to exceed outflows, the net uptake of C making the terrestrial biosphere a C sink (FAO, 2009). A small proportion of C obtains a stable state that resists further decomposition; which over millennia of gradual accumulation has resulted in soil C being the largest terrestrial C stock (Sanderman *et al*, 2010).

Most decomposition processes occur within the soil, with SOM in varying stages of decomposition and humification, and with different decomposition rates depending on its composition (Guggenberger and Zech, 1994). Soil C is broadly classified into three conceptual pools (Figure 10). Fresh organic matter that provides C and nutrients to soil organisms is turned over quickly, in years or less, and is termed the active, labile or fast

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[10] Detritus is the debris formed from the decay of organisms

[11] SOM contains between between 40% to 60% carbon by mass (Sanderman *et al*, 2010)

[12] Algae and some bacteria are also autotrophs.

pool. Some SOM, termed the slow or protected pool, is encased in soil aggregates or bonded to clay particles making it less accessible to soil organisms, with a residence time from decades to centuries. The passive, recalcitrant or inert pool is comprised of humic substances or char which are chemically resistant to decomposition and which can have a residence time of centuries to millennia (Bruce *et al*, 2010; Sanderman *et al*, 2010).

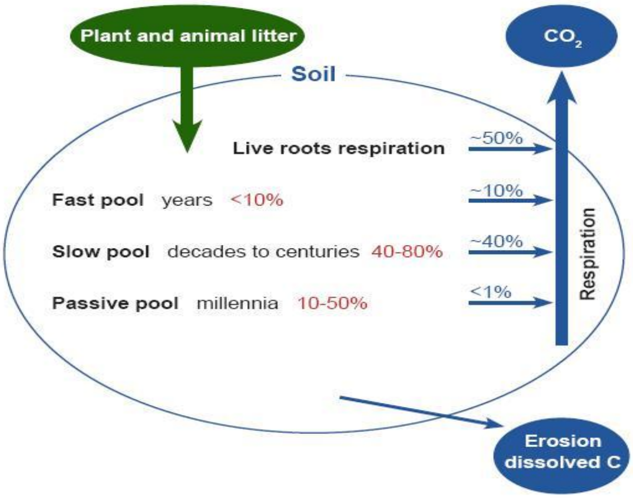


**Figure 10: Conceptual soil carbon pools**

*Soil carbon in varying stages of decomposition is classified into three conceptual pools depending on the turnover or residence time.*

Bruce *et al* (2010)

## 3.3 Nitrogen cycle

As a major nutrient, N is integral to plant growth and the C cycle. However, although N (as $N_2$) is abundant as the major component of the atmosphere, atmospheric N is extremely stable and must be converted to another form to be available to plants and other organisms. In nature, N fixing bacteria free in the soil or in symbiosis with plants, convert $N_2$ to ammonium ($NH_4^+$). N is also input to the soil as SOM is decomposed, and from animal manure and urine. Synthetic fertiliser uses an industrial process to convert $N_2$ into ammonia ($NH_3$). Nitrifying bacteria convert these N inputs to nitrate ($NO_3^-$) that is available to plants and other soil organisms, and through denitrification, other bacteria reverse the process to form nitrite ($NO_2^-$) and nitrous oxide ($N_2O$). Good soil conditions promote nitrification while anaerobic conditions and water-logging promote denitrification and result in higher $N_2O$ emissions. If not taken up by plants, excess N results in emissions of $N_2O$ while $NO_3^-$ lost in run-off or leeched can lead to water quality issues.

## 3.4 Phosphorous cycle

Unlike C and N, phosphorous (P) does not have a gaseous state under normal environmental conditions. P stocks are held in the Earth's crust as rock phosphate ($PO_4^{3-}$) and P is released by weathering, the process that breaks down rocks to form the mineral fraction of soil. Without an atmospheric stock, the P cycle operates at a local or regional scale, with the exception of P fertiliser that is mined elsewhere. Rock phosphate is mined and converted into a mineral fertiliser using an industrial process or used as a clay mineral formed as a by-product of mining. P is also recycled back to the soil by decomposition of SOM and in animal manure and urine. Like N, excess P not taken up by plants can be lost in run-off or leached, which can lead to water quality issues. Australian soils are generally deficient in P making it a limiting factor for primary productivity and C cycling (Chan *et al*, 2010).

## 3.5 Methane-C cycle

As methane ($CH_4$) is a compound of C and hydrogen (H), it does not cycle itself but is formed and broken down as part of the C cycle. The main sources of $CH_4$ emissions in grazing lands are as a by-product of ruminant digestion (enteric fermentation), termites and fire. Soil can be a source or sink of $CH_4$.

### 3.5.1 Enteric fermentation

Cellulose is the main component of leaves that provides structural strength; however, the atomic structure that provides strength also makes it difficult to break down. Mammals do not produce the enzymes needed to digest and release the nutrients from cellulose which is decomposed by microorganisms (methanogenes) living in the digestive tract.

In ruminants, the rumen is effectively a large anaerobic fermentation chamber (Figure 11) that holds ingested material while cellulose is broken down, with portions being regurgitated, chewed as cud and either returned to the rumen for further fermentation or passed to the second stomach when it is sufficiently degraded. Methanogenes in the rumen create methane ($CH_4$) as a by-product that is breathed or burped out.

While $CH_4$ is lost energy that would otherwise be available for production, foregut digestion of cellulose is relatively efficient as the bodies of cellulose-processing microorganisms pass through the third stomach where most nutrients are extracted. In hindgut fermenting animals such as horses, cellulose is fermented in the caecum after food has passed through the stomach, meaning that C and nutrients in the bodies of microorganisms are not available to the animal. Like ruminants, kangaroos are foregut fermenters and chew cud, however they have bacteria that utilise the $H^+$ precursor to $CH_4$, with very little $CH_4$ emitted.

Factors such as feed digestibility and feed conversion efficiency, health and nutrition influence the amount of $CH_4$ produced by livestock.

**Figure 11: Bovine rumen and contents**

http://matronofhusbandry.wordpress.com/2009/06/11/i-want-to-die-with-my-cud-in-my-mouth

### 3.5.2 Termites

Termites and other arthropods, millipedes, cockroaches, and scarab beetles for example (Hackstein and Stumm, 1994) also emit $CH_4$. Termites play an important role in C and nutrient cycling and are a keystone group in savannas (Ndiaye *et al*, 2004), recycling C and nutrients through their bodies and wastes and incorporating it into the soil as SOM. They forage and consume grass, litter and wood that contain cellulose and lignin, another hard to break down substance that provides the strength in wood. Like mammals, termites do not produce the enzymes needed to breakdown the cellulose and lignin which are decomposed by microorganisms in the digestive tract, with methanogenes releasing $CH_4$ in the process.

### 3.5.3 Fire

Fire is an important C cycling process in Australian grazing land, providing both a natural disturbance that decomposes organic matter and recycles nutrients, and management tool to reduce fuel load or stimulate fresh vegetation growth. The net effect on C stocks depends on the extent of damage and speed of recovery, which depends on the intensity and frequency of burning.

Emissions of $CH_4$ and $CO_2$, reduce C stocks although some C that remains in residues and as char adds to the soil C pool. Low intensity fires mostly burn leaves and litter which are a small proportion of the total C stock and recover quickly, taking up C in the process. More intense or frequent fires reduce photosynthetic capacity over longer timeframes, reducing NPP and C inputs to the soil. Loss of vegetation and organic matter through fire can also make the land vulnerable to erosion with further C lost from the soil.

### 3.5.4 Soil

The soil organisms that emit or take up $CH_4$ are ubiquitous (Dalal *et al*, 2008a) and the soil can be a source or sink of $CH_4$ depending on soil conditions, primarily air flow and soil water. Methanogenes, organisms that emit $CH_4$, require anaerobic conditions, with waterlogged or compacted soil providing the environment for emissions, while methanotrophs, microorganisms that take C from $CH_4$ for energy require aerobic conditions, with healthy soil providing the environment for $CH_4$ uptake.  Soil air flow is the main factor that facilitates $CH_4$ uptake as it provides an aerobic environment and diffuses atmospheric $CH_4$ within the soil.  SOM for nutrients and soil water, as long as the soil remains aerobic, are also important, while soil acidification and salinity, fertilisers, soil amendments depending on their C:N ratio, pesticides and herbicides inhibit $CH_4$ uptake (Dalal *et al*, 2008a).

# 4 Atmospheric carbon to soil carbon

As the major C stock in grazing lands is in the soil, the main option for increasing C stocks is to raise soil C levels, while increasing trees in the landscape will increase C stocks in woody biomass. Both improve an ecosystem's capacity to provide a range of ecosystem services utilised by grazing enterprises in the production of food and fibre.

The potential of a soil to build soil C depends on environmental and management factors, and current soil C levels as degraded soil has more potential to build C than one close to its carbon carrying capacity (Baldock *et al*, 2009; Follett and Reed, 2010; Sanderman *et al*, 2010). Baldock *et al* (2009) has identified areas with high, medium and low potential to enhance soil C based on current soil C level relative to carbon carrying capacity, capability to increase SOM inputs, ability to stabilise and retain C, and environmental and past land use and land clearing factors (Figure 12). The low potential across most of Australia's grazing lands reflects both the lower productivity of low rainfall areas relative to more intensively farmed agricultural areas, and that less C has been lost under pasture and extensive grazing than under cropping.

The soil C balance is a function of inflows and outflows. As most soil C originates from plants, increasing inflows will come from increasing NPP and input of SOM; whereas reducing outflows will come from improving the soil physical, chemical and biological properties and the soil's capacity to cycle, stabilise and store C and reduce soil loss. Although not usually stated as a C input, methanotrophs take up C from atmospheric $CH_4$ and most well drained soils are a significant $Ch_4$ sink (Lal, 2004b; Dalal *et al*, 2008a).

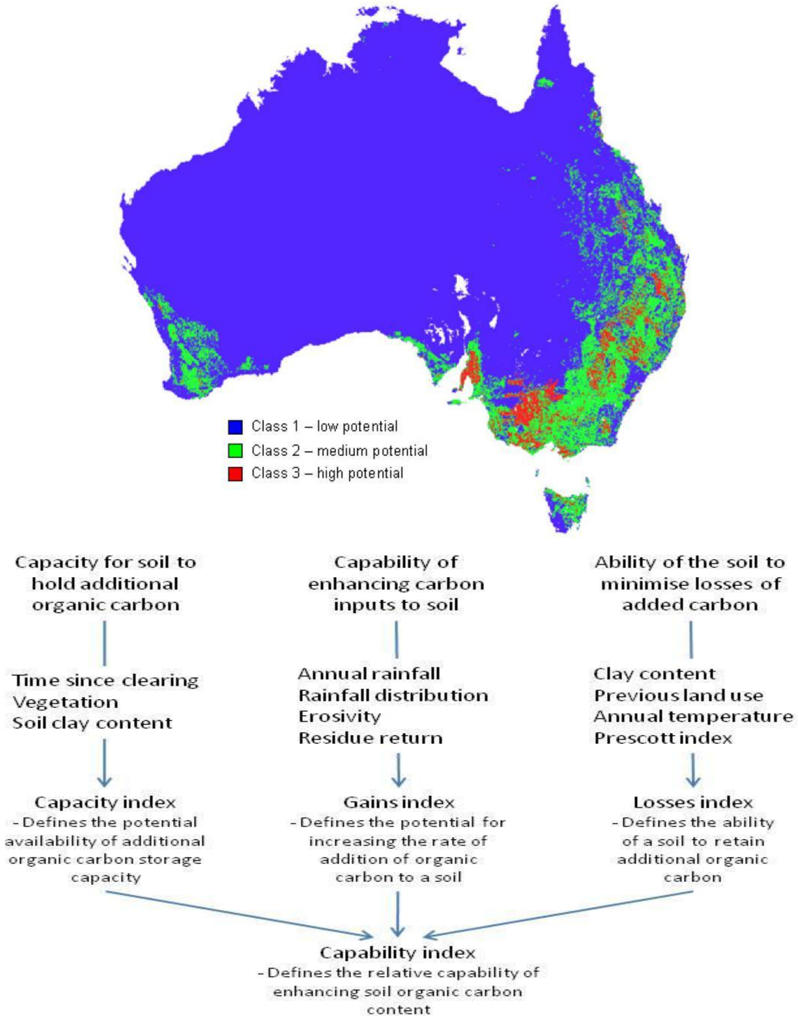


**Figure 12: Soil carbon capability schematic**

*Multiple factors determine a soil's potential to enhance soil carbon levels. Prescott index relates to availability of water combining rainfall and evapotranspiration*

Baldock *et al* (2009)

## 4.1 Primary productivity

The inflow of C to the terrestrial C cycle is from $CO_2$ in the atmosphere taken up by plants through photosynthesis (GPP) which is used to produce biomass in leaves, stems and roots (NPP) or respired as CO2 back to the atmosphere. While an ecosystem's carbon carrying capacity is determined by environmental conditions such as climate and soil type, NPP sets the maximum C inflow (Sanderman *et al*, 2010), which is determined by the resources needed for photosynthesis, including solar radiation, water, nutrients and atmospheric $CO_2$.

### 4.1.1 NPP determining factors

The amount of sunlight available for photosynthesis is affected by the amount of photosynthetically active radiation (PAR) available to plants and the light use efficiency (LUE) of plants to utilise it. PAR varies with latitude due to the angle of the sun, with more radiation closer to the equator, with cloudiness due to albedo reflecting sunlight away from the Earth's surface, and with light intensity with more diffuse light reaching more of the canopy[13]. LUE is affected by canopy shape, either blocking or allowing light through, the amount of living green leaves, termed the leaf area index (LAI), available to undertake photosynthesis and the photosynthetic pathway, with C4 plants able to capture more $CO_2$ than C3 in hotter, drier conditions (Mercado *et al*, 2009; Sanderman *et al*, 2010). While solar radiation is not normally a limiting factor in Australia, managing to increase NPP and maintain LAI is important to increasing C in grazing lands.

Soil water, required for photosynthesis and transport of nutrients, is affected by rainfall and potential evaporation. The combination of high temperatures and low rainfall in Australia mean that effective rainfall, the rainfall that infiltrates the soil and is available for NPP, is less than actual rainfall over most of the country for most of the year. The rainfall deficit can be seen by comparing actual and potential evapotranspiration (ET) (Figure 13). Good soil condition and ground cover improves infiltration and soil water holding capacity, reducing run-off and increasing effective rainfall. Effective use of soil moisture is also reduced by dry air as it reduces the water use efficiency (WUE) of plants and therefore NPP (Raupach *et al*, 2001). Water is the primary limiting factor in Australia, making managing to maximise the efficiency of rainfall critical to maximising NPP. The variation in NPP across Australia (Figure 14) reflects effective rainfall, showing it is the main limitation to NPP in Australia. NPP is highest in the temperate high rainfall areas in the south-east and south-west, and lower in the north where higher temperatures and evaporation make effective rainfall low despite high rainfall (Raupach *et al*, 2001).

Nutrients predominantly come from recycling of organic matter, with NPP largely determining the litter and fine roots that is the main input to the soil and soil C (Janssens *et al*, 2001). SOM is decomposed by processes within the soil, recycling nutrients that are taken up by plants in soil solution and used in photosynthesis for NPP. These interdependencies represent a series of positive feedbacks (Figure 7) creating a virtuous (or vicious) cycle whereby an increase (or decrease) in NPP leads to a further increase (or decrease) in NPP until a limiting factor such as the soil's capacity for nutrient cycling is reached. Australia's low nutrient soils and dry climate are natural limitations to NPP which is exacerbated by land degradation and reduced soil C levels.

Although NPP is the only natural inflow to the C cycle, additional inflows can come from, for example, livestock, fodder or compost brought in from another location. Conversely offtake such as livestock or fodder is an outflow of C when removed from an ecosystem. As these flows increase or decrease organic matter available as an input to soil C, it effectively transfers 'virtual NPP' between locations. In the same way, cutting and storing fodder is a way of transferring 'virtual NPP' between time periods.

---

[13] Canopy is any layer of vegetation, eg. grass, shrubs or trees, elevated from the ground

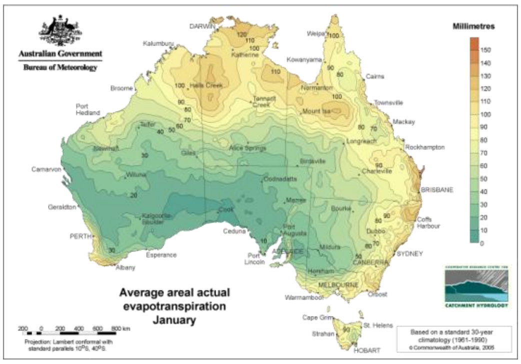
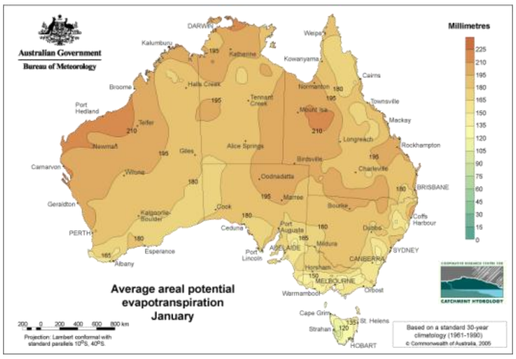
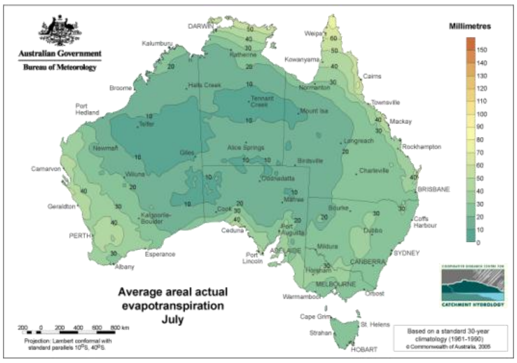
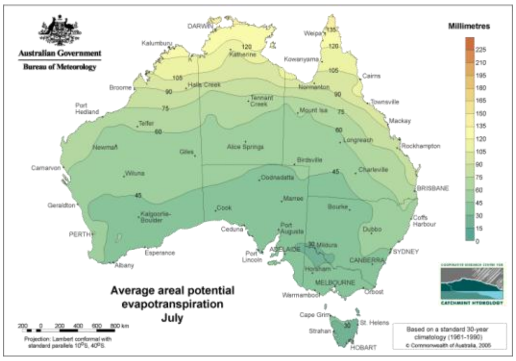
|  | **Actual evapotranspiration (based on actual rainfall)** | **Potential evapotranspiration (based on unlimited rainfall)** |
|---|---|---|
| **January** |  |  |
| **July** |  |  |

**Figure 13: Actual and potential evapotranspiration (30 year average 1961-1990)**

*Evapotranspiration is a function of rainfall, humidity, evaporation and transpiration. Potential evapotranspiration is greater than actual over the whole country in summer (January) and most of the country in winter (July). In this situation, any rainfall that does not infiltrate will be evaporated, increasing the rainfall deficit and further limiting NPP.*

BOM (2010)

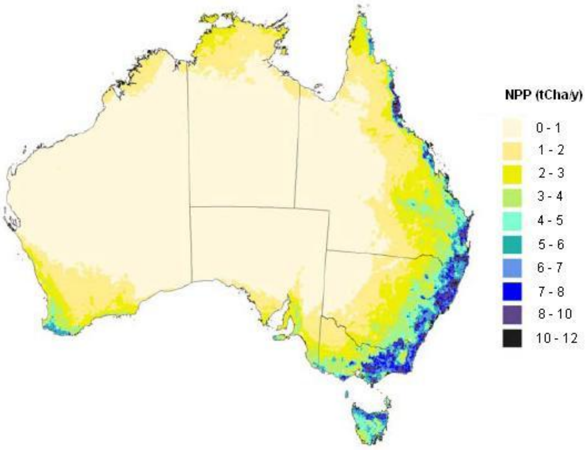


**Figure 14: Mean annual net primary production (tC/ha/yr)**

*Variation in net primary productivity reflects effective rainfall*

Raupach *et al* (2001)

### 4.1.2 Carbon allocation to above and below ground biomass

With soil C the main C stock in grazing lands, the allocation of plant material from photosynthesis into above and below biomass is an important mechanism in determining soil C stocks (Zhu and Miller, 2003). While all plants capture C, the extensive roots, high SOM and microbial biomass C of perennial grasses may be more important in the C cycle than annuals (Al-Kaisi and Grote, 2007), and should increase soil C due to improved ground cover and addition of roots, root exudates and mycorrhizal fungi deeper in the soil profile where decomposition is slower (Sanderman *et al*, 2010). As annuals die off each year and regenerate from seed, they do not develop large root systems, whereas perennial grasses can invest up to 80% of NPP in below ground biomass (Figure 15). As well as contributing more C directly to the soil, perennials' deeper roots enable them to access water and nutrients that are not available to annuals, making them more productive and resilient in harsh and variable conditions (Olupot *et al*, 2010) than annuals which are reliant on suitable seasonal conditions for survival and seed germination.

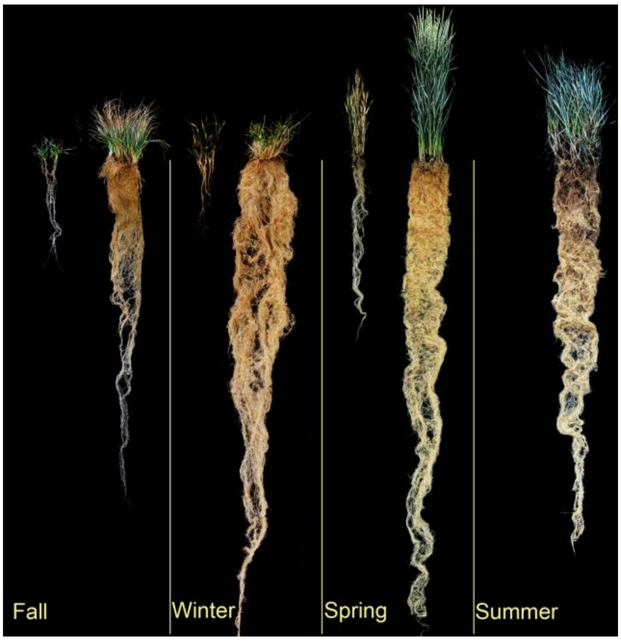


**Figure 15: Roots of annual wheat vs perennial intermediate wheat grass**
Glover *et al* (2010)

### 4.1.3 Disturbance

Disturbance is a normal and necessary part of a dynamic ecosystem with a key role in the C balance in grasslands (Soussana *et al*, 2007). Without disturbance, an ecosystem would reach its notional carbon carrying capacity based on environmental conditions such as soil and climate, and C uptake would slow or cease as plants reach maturity and senesce. Grazing is an example of disturbance that contributes to decomposition and recycling of organic matter, fire recycles some nutrients but loses C in emissions, and erosion and drought result in loss of soil and soil C from an ecosystem. The effect of a disturbance on the C balance depends on its extent, duration and frequency and the resilience of the ecosystem. Severe or frequent disturbance, such as when forest is cleared for agriculture, intense frequent burning, and activities that affect soil health can degrade land beyond its capacity to recover, effectively resulting in a permanent shift to different ecosystem with a lower carbon carrying capacity. Managing fuel loads with grazing and timing burns for cooler periods can reduce the frequency and intensity of fires and retain LAI for recovery and C in biomass and litter that would be burned in a more intense fire. Climate change is another form of disturbance that may result in a permanent shift due to different environmental conditions.

The factors determining an ecosystem's resilience and ability to recover from disturbance relate to the supporting ecosystem services that also determine the capacity to capture cycle, stabilise and store C. NPP will be largely determined by LAI, the amount of green leafy material remaining for photosynthesis, and plant available nutrients after a disturbance, which largely depends on the amount of SOM, the soil's capacity to provide the decomposition and nutrient transport processes; and plants' ability to access the nutrients.

## 4.2 Soil processes

Most of the processes that support primary productivity and nutrient cycling occur in the soil and are regulated by soil organisms (Brussaard *et al*, 2007), making soil health and an active biological community critical factors in a soil's capacity to cycle and store C. Soil C is also an important component and indicator of healthy soil as it provides C storage, food and habitat for biodiversity, nutrient storage and supply, erosion control, buffering capacity and soil moisture (Bruce *et al*, 2010).

As all organic matter originates from plants, the notional maximum inflow of C to the soil is determined by NPP, with inputs including surface litter and detritus that is broken up and incorporated into the soil by trampling and insects or leeched into the soil as dissolved organic carbon (DOC), fine roots as they die and are sloughed off, and root exudates (Sanderman *et al*, 2010). While environmental conditions such as climate and landform determine an ecosystem's carbon carrying capacity, within that, soil physical, chemical and biological properties determine a soil's capacity for NPP and ability to cycle, stabilise and store C, with soil biological activity contributing to each property.

### 4.2.1 Soil biology, carbon and nutrient cycling

The main source of nutrients for NPP comes from decomposition of organic matter by living organisms in the soil, consuming organic matter and recycling C and nutrients through their bodies, exudates and waste products, by fragmentation and by leeching (Sanderman *et al*, 2010). Biodiversity is a key factor in C and nutrient cycling due to the range of biophysical, biochemical and biological processes needed to decompose different types and stages of organic matter. Starting with plants as the foundation, C and nutrients flow through an intricate community of diverse, above and below ground organisms from plants, to grazing animals and predators, to insects, fungi and bacteria.

Although the above and below ground environments are generally considered separately with primary productivity above ground and decomposition below (Brussaard *et al*, 2007), the two domains are inextricably linked (Figure 16) (De Dyne and Van der Putten, 2005). Above ground NPP and nutrient cycling provide Inputs of organic matter to the soil, and below ground processes sustain above ground life. For example, plants allocate a significant proportion of NPP to roots and add C to the soil in root exudates that provide food for soil organisms, grazers such as livestock consume and break down leafy vegetation through their digestion, adding partially humified C to the soil in manure (Sanderman *et al*, 2010), and fragment and incorporate litter into the soil surface by trampling, providing food for soil organisms. Termites are also grazers and foragers of grass, litter and wood, shredding and incorporating C in fragments of plant material with their secretions into their runs, tunnels, galleries and mounds (Ndiaye *et al*, 2004) .

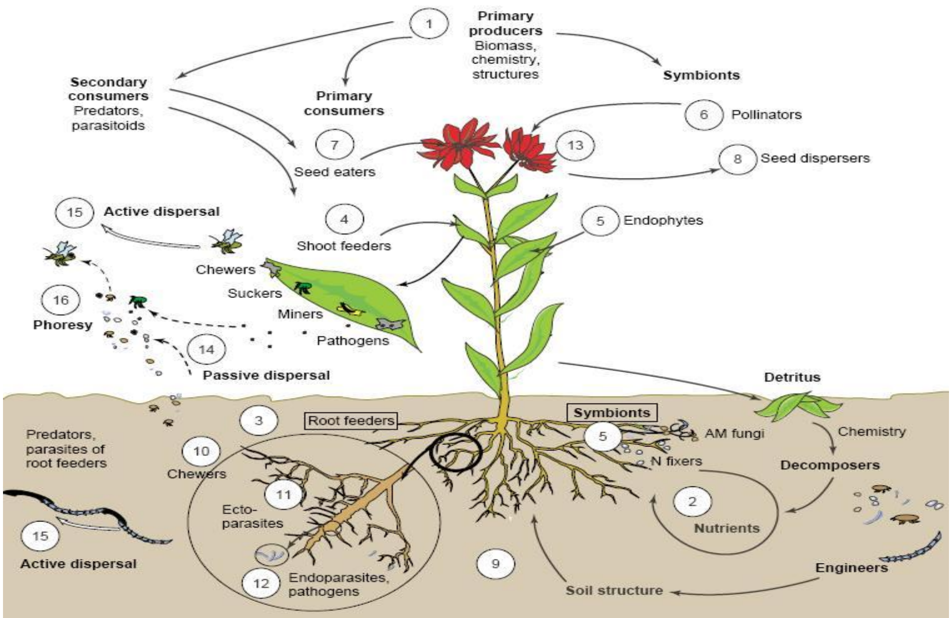


**Figure 16: Food web: interdependency of above and below ground biodiversity**

*Aboveground plant community biomass and chemical and structural composition (1) drive the abundance and diversity of aboveground higher trophic levels, although these aboveground plant characteristics depend upon the net activity of soil functional groups, such as decomposers and symbionts (5), which make nutrients available (2), and on aboveground and belowground herbivores and pathogens (3,4), which reduce plant growth [17]. Heterotrophic organisms that interact with plants affect plant metabolism, potentially altering litter, shoot and root biomass production, distribution and chemical composition by feeding on roots (3) or shoots (4) or living symbiotically in shoots, leaves or roots (5). In the longer term, pollinators (6) as well as seed eaters (7) and seed dispersers (8) affect the persistence of the plant species and, thus, the specialist organisms associated with it. Soil organisms are constrained in their mobility and, as a result, organisms interacting with a single plant root system are subsets of the total species pool present in the direct surrounding soil (9). Depending on their size and mobility, these organisms occupy microhabitats of different sizes and might have different effects on plant growth. Although active roots have high turnover rates and are distributed throughout the soil, root herbivores and pathogens (3) can account for this 'unstable food' source by being relatively mobile generalist feeders (10,11), similar to many aboveground chewing insects and free-living suckers, by adapting a specialized endoparasitic plant association (12) or by having an aboveground life phase enabling targeted active dispersal (15). Aboveground plant structures might be easier to find than are roots, and although the availability of more-specific aboveground plant tissues [e.g. buds, flowers, fruits or seeds (13)] is often brief, these can still affect the aboveground diversity of plant-associated organisms owing to the large active range sizes of aboveground organisms. Large aboveground and belowground organisms might disperse actively in a directional way (15), by flying, walking, crawling or borrowing, whereas smaller organisms (or small structures of larger organisms, such as seeds) disperse more randomly via passive dispersal (14) by air, water or via phoresy (16) (i.e. using other organisms as transport vectors).*
*Abbreviations: AM fungi, arbuscular mycorrhizal fungi; N-fixers, nitrogen-fixing microorganisms.*

De Dyne and Van der Putten (2005)

Most of the Earth's biodiversity is in the soil, with organisms in the soil food web (Figure 17) providing most of the processes that support ecosystem services (Gupta and Ryder, 2003; Brussaard *et al*, 2007; Hinsinger *et al*, 2009). Although microorganisms such as bacteria and fungal hyphae make up less than 5% of SOM, they are a labile source of C and nutrients, as well as making C and nutrients available to plants and other organisms by decomposing SOM (Dalal, 1998).

Plants also form symbiotic relationships with soil microorganisms that provide nutrients directly to the plant, such as legumes with nitrogen fixing bacteria, and most plants with mycorrhizal fungi. Mycorryzal fungi play a critical role in C and nutrient cycling by effectively extending the reach of roots (Figure 18), with plants exchanging from 3-20% of C from photosynthesis for nutrients making an additional input of soil C. (Treseder and Cross, 2006). Treseder and Cross (2006) found that temperate grasslands have the greatest mycorrhizal biomass, which should be a reflection of total root biomass, and savannas as a percentage of root length colonised, reflecting a higher proportion of C allocated to mycorrhizal fungi and the cost-benefit tradeoff of gaining access to nutrients in low nutrient environments . Mycorrhizal fungi increase the host plant’s nutrient and water capturing ability by increasing the absorbing root surface area, modifying transpiration rates and increasing the host plant’s drought tolerance, and also form interconnecting networks, facilitating nutrient transfer between plants (He, 2003). Other soil organisms may also aid mycorrhizal colonization and networks, for example, termites translocate spores in soil and some cultivate fungi in their galleries, potentially mediating a flow of nutrients from the mound to the host plant (Duponnois *et al*, 2006).

Other fungi also play a major role in soil C cycling and stabilization due to their ability to decompose recalcitrant SOM and explore the soil with mycelium, accessing and distributing C and nutrients through the soil space and synchronising nutrient flow with plant requirements, effectively mediating a SOM bank mechanism that may contribute to long term soil C stores (Fontaine *et al*, 2011).

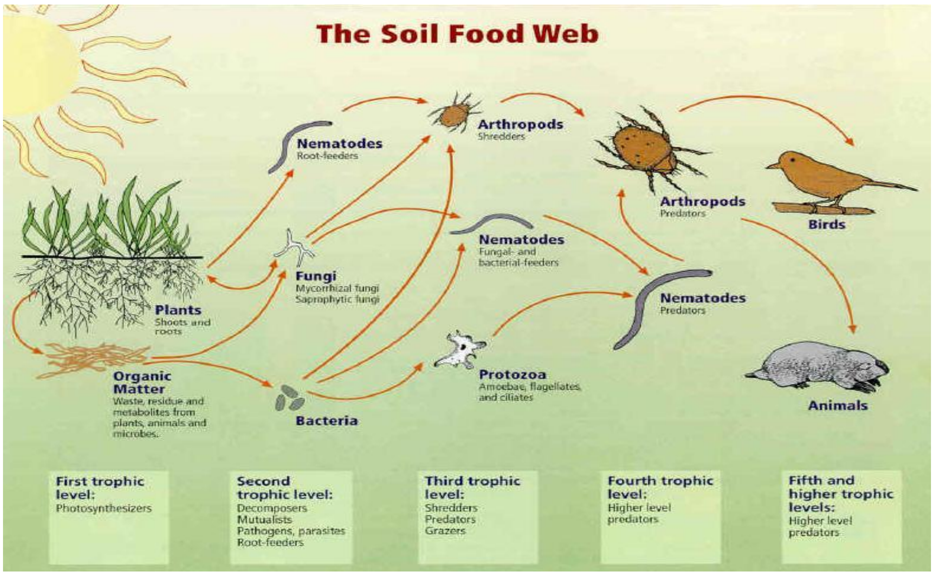


**Figure 17: Soil Food Web**

http://soils.usda.gov/sqi/concepts/soil_biology/soil_food_web.html

*Pine seedling roots colonized by mycorrhizal fungi*

*Redwood seedlings without and with mycorrhizal fungi*

**Figure 18: Mycorrhizal fungi symbiosis**

www.morning-earth.org/graphic-E/Biosphere/Bios-C-PlantsNew.html

### 4.2.2 Soil biology and soil properties

In addition to being the main mechanism for C and nutrient cycling, soil biological activity is one of the five soil forming factors[14], with soil organisms making up the soil biological properties also contributing to soil physical and chemical properties. They fall broadly into three main functional groups of ecosystem engineers, biological regulators and chemical engineers (Box 4). Through these functions, soil organisms convert mineral soil and organic matter into living soil capable of supporting primary productivity and nutrient cycling that lead to higher levels of soil C. This makes maintaining a large, active and diverse community of organisms especially important for soil health and productivity in low input systems (Gupta and Ryder, 2003) that make up the major proportion of Australian grazing lands.

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[14] The 5 soil forming factors are parent material, climate, topography, biology and time.

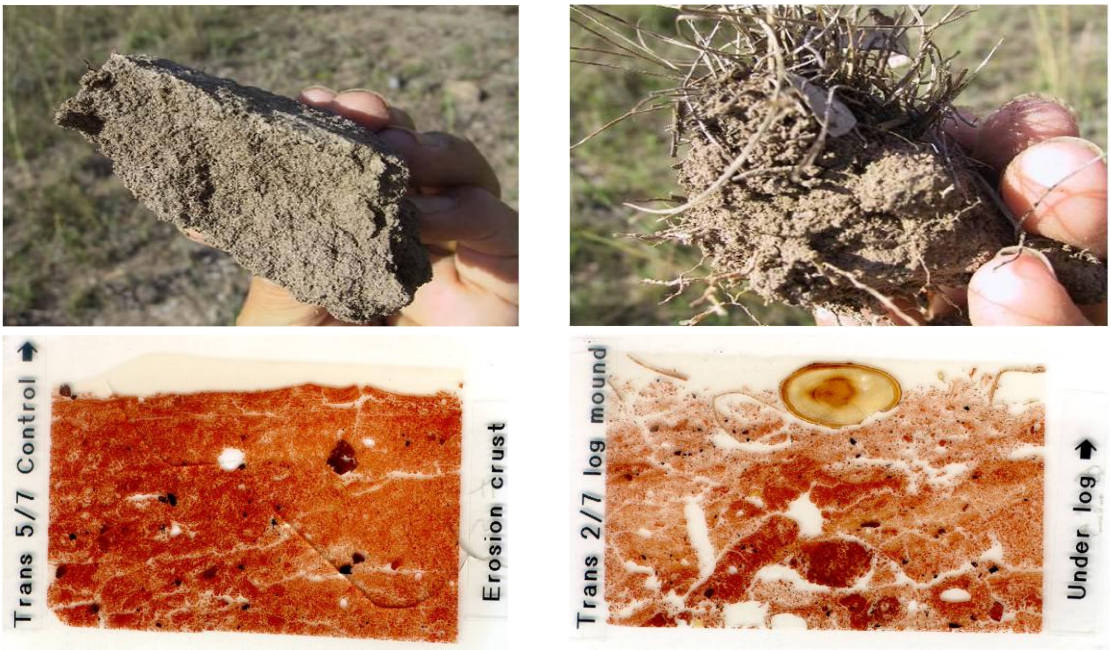
**Box 4: Characteristics of soil functional groups**

adapted from Turbe (2010)

| Characteristics | Ecosystem engineers | Biological regulators | Chemical engineers |
|---|---|---|---|
| Main organisms | Ants, termites, earthworms, plants roots | Protists, nematodes, mites, springtails (collembolan) | Bacteria, fungi |
| Function | Creation and maintenance of soil habitats; transformation of physical state of both biotic and abiotic material, accumulation of organic matter, compaction of soil, decompaction of soil, soil formation | Regulatoion of microbial community dynamics, faecal pellet structure, mineralization, nutrient availability regulation (indirect), litter transformation and organic matter decomposition | Organic matter decomposition, mineralization + nutrient release, pest control, toxic compounds degradation |
| Body size | 0.1-5 cm (ants)<br>0.3-7 cm (termites)<br>0.5-20 cm (earthworms) | 2-200 µm (protists)<br>500 µm (nematodes)<br>0.5-2 mm (mites)<br>0.2-6 mm (springtails) | 0.5-5 µm (bacteria)<br>2-10 µm (fungal hyphae diameter) |
| Density in soil | $10^2$-$10^3$ $m^2$/soil (ants)<br>10-$10^2$ $m^2$/soil (earthworms) | $10^6$ g/soil (protists)<br>10-50 g/soil (nematodes)<br>$10^3$-$10^5$ $m^2$/soil (mites)<br>$10^2$-$10^4$ $m^2$/soil (springtails) | $10^9$ cells/g of soil (bacteria)<br>10 metres/g of soil (fungal hyphae) |

The physical structure of soil determines the spaces available for the flow and storage of soil air, water and nutrients; and soil aggregates as habitat for soil organisms, for protection of SOM from decomposition, and to stabilise soil (Figure 19). Compressed or crusted soil lacks pore spaces and aggregates, limiting its capacity for NPP and biological activity resulting in low soil C levels, while well structured soil enhances soil C cycling and storage. Ecosystem engineers such as plant roots, burrowing animals, earthworm, termites and ants create structure and aid soil aggregation with their exudates, secretions and wastes, leaving pore spaces for habitat for other organisms such as fungi and bacteria (Ndiaye *et al*, 2004), and roots and mycorrhizal fungi hold soil aggregates in a mesh or ‘string bag’ like effect (Figure 20) (Oades and Waters, 1991; Sanderman *et al*, 2010).

The soil tunnelling activities of termites and ants are important for soil structure and decomposition, especially in arid and semi-arid regions that do not support earthworms (Lobry de Bruyn and Conacher, 1990; Ndiaye *et al*, 2004), where their subterranean structures have been shown to significantly increase water infiltration and storage (Dawes, 2010a). SOM also improves soil physical and chemical properties and contributes to soil aggregation and water holding capacity (Dalal, 1998; Sanderman *et al*, 2010).



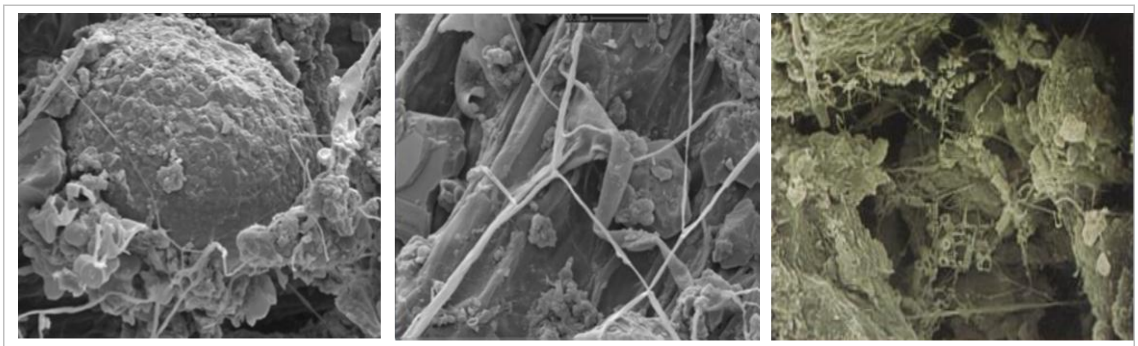
*Compacted soil showing few spaces and no visible organic matter. Surface crusting prevents water infiltration resulting in run-off and erosion. Seeds find it difficult to germinate.*
*LFA indices: Stability 43.3, Infiltration 24.0, Nutrient cycling 11.5*

*Friable soil shows large spaces for soil atmosphere and root penetration. The surface crust has been broken by soil organisms allowing water infiltration and germination.*
*LFA indices: Stability 69.1, Infiltration 39.8, Nutrient cycling 31.7*

**Figure 19: Compacted and friable soil**

*Landscape Function Analysis (LFA) indices provide relative measures of soil function*

David Tongway (pers comm., 2009)



*a. Soil aggregate with organic matter, fine roots and fungal hyphae*

*b. root sheath with soil particles and fungal hyphae*

*c. soil pore with fungi and fungal hyphae within a soil aggregate*

**Figure 20: Soil macro aggregates**

John Field (pers comm., 2009)

Soil chemical properties also contribute to soil structure and biological activities, and are important in providing an environment conducive to C cycling and stabilisation. Soil pH affects solubility of minerals needed for transport of micronutrients, if too high or too low, some minerals are locked up, and if too low others become available at toxic levels. SOM contributes to cation exchange capacity (CEC), buffering and soil stability (Baldock and Skjemstad, 2000). Soil texture affects decomposition rates, with high clay mineral content soils having a higher CEC and the clay better able to protect C from decomposition than more sandy soils. Organic compounds in root exudates, secretions and wastes of soil organisms alter soil chemistry, as do organic acids formed through decomposition of SOM.

The balance of nutrients in the soil affects biological activity, decomposition rates and C cycling and stabilisation. Soil organisms require a balance of C, N and other nutrients. Fontaine *et al* (2004) found that fresh SOM increases the soil microbial biomass if there are sufficient nutrients, whereas with excess N, such as synthetic fertiliser greater than plant needs, soil microbes consume old C for energy to maintain their C:N ratio, resulting in a transfer from a more stable to a labile C pool. Khan *et al* (2007) also found that excess synthetic N depletes organic N as well as soil C, resulting in lower NPP. Chemical inputs affect soil properties but little is known about their effect on soil organisms. Seymour (2005) found species diversity and population size (Box 5) was affected by different chemicals, mostly detrimentally although some effects are temporary and some delayed. The review did not include the effect of fungicides on mycorrhizal fungi which would be expected to have a detrimental effect.

**Box 5: Herbicide and pesticide effect on soil organisms**

Seymour (2005)

| **Effect or impact on non-target species** | |
|---|---|
| Herbicides | |
| Nitrifying and denitrifying bacteria | Prosulphuron inhibited $N_2O$ and NO production by bacteria (*Kinney et al 2005*) |
| Mycorrhizal fungi | Decreased in some situations. Reductions due to recommended rates of 2,4-D, simazine, diuron, monuron and cotoran (*Dodd and Jeffries 1989*) |
| Protozoa | As herbicide is decomposed, increases in protozoa attributed to stimulation of bacteria and fungal populations (*Gupta 1994*) |
| Earthworms | No effect in top 10 cm (*Mele and Carter 1999*) |
| Microarthropods and microflora | Paraquat and glyphosate altered activities and reduced decomposition of crop residues (*Hendrix and Parmalee 1985*) |
| Collembola and mites | Adverse effects of atrazine and simazine for up to four weeks (*Gupta 1994*) |
| Insecticides | |
| Bacteria | Chlopyrifos reduced numbers (*Pandley and Singh 2004*) |
| Fungi | Chlopyrifos significantly increased numbers (*Pandley and Singh 2004*) |
| Protozoa | Diazinon decreased populations (*Ingham and Coleman 1984*) |
| Earthworms | Extremely sensitive to organophosphates and carbamates, less sensitive to organochlorins although can be affected over time due to persistence of these chemicals (*Fraser 1994*) |
| Fungicides (effect on mycorrhizal fungi not in review) | |
| Nitrifying and denitrifying bacteria | Mancozed and chlorothalonil inhibited $N_2O$ and NO production (*Kinney et al 2005*) |
| Earthworms | Copper oxychloride very toxic to earthworms (*Lee 1985*) |
| P Fertiliser | |
| Mycorrhizal fungi | Increasing P concentration to very high levels decreases colonisation of roots and/or spore numbers in soil (*Jensen and Jacobsen 1980, Seymour 2002*) |
| N Fertiliser | |
| Mycorrhizal fungi | Spore numbers and root colonisation decreased (*Hayman 1970*) |
| Protozoa | Significant increases, stabilisation and decreases have all been reported (*Gupta 1994*) |
| Actinomycetes | No effect on total count (*Zaitlin et al 2004*) |
| Earthworms | Increases due to long-term applications of N fertiliser to wheat and barley (*Fraser 1994*) |
| Root lesion nematodes | *Pratylenchus thornei* increased with long-term use of N fertiliser on wheat crops (*Thompson 1992*) |
| Lime | |
| Mycorrhizal fungi | Little effect on colonisation/change (*Wang et al 1985*) |
| Earthworms | Often increases populations – probably due to raised pH (*Fraser 1994*) |
| Sulphur | |
| Bacterial feeding protozoa | 30-71% decline in populations (*Gupta and Germida 1988*) |
| Fungal feeding amoebe | More than 84% decline in populations (*Gupta and Germida 1988*) |
| Fungi | Reduced biomass (*Gupta and Germida 1988*) |

Soil organisms also affect soil biological properties.  For example, exudates released from roots glue soil particles together, forming sheaths of soil around living roots that are hotspots of biological activity, increasing decomposition to release nutrients close to the root surface and C input to the soil (Figure 21) (Hinsinger *et al*, 2009; Sanderman *et al*, 2010).  Termites create fertile islands of relative resource richness around their mounds by transporting nutrients and enhancing mycorrhizal fungi symbiosis (Duponnois *et al*, 2006).  Termite mounds also contain large microbial populations that are active throughout the year, probably due to the almost constant temperature and moisture levels inside the mound, increasing decomposition and C cycling (Holt, 1987).  Termite mounds have been found to have improved soil properties, greater diversity and density of trees, shrubs and forbs than outside the mound area due to higher nutrients and improved soil water, with the increase productivity also increasing litter and detritus for the termites and C input to the soil (Moe *et al*, 2009; Dawes, 2010b)

**Figure 21: Root sheaths are hotspots of biological activity**
Hinginger *et al* (2009)

## 4.3 Losses

Loss of C from ecosystems is a normal part of the C cycle through respiration and leaching, wind and water erosion, photodegradation, fire and drought.  In natural ecosystems which tend to have a positive C balance (FAO, 2009), disturbance stimulates primary productivity and new growth draws down atmospheric C until the C balance is restored to its carbon carrying capacity.  However, soil formation is slower than loss, with full recovery likely to take years to decades (Balesdent *et al*, 2000).  The increased loss of C since European settlement through removal of vegetation by land clearing, overgrazing and fire has changed the C balance significantly and lead to land degradation and erosion.  Although grazing enterprises are in the business of converting C in vegetation into animal production, resulting in C removal in offtake, the net effect depends on the grazing effect on C and nutrient cycling in the balancing or adding to C offtake.

Erosion occurs when living vegetation, litter and SOM that protect and bind the soil are removed and soil is exposed to wind and water. Inappropriate land management has resulted in significant volumes of soil loss from grazing lands since European settlement (Figure 22). Erosion rates are highly variable, with erosion risk being determined by a range of interacting factors including, living vegetation and ground cover, slope length and gradient; soil health and SOM; climate such as drought, dry seasons and rainfall intensity; and management. Erosion of grazing lands on native pasture across Australia is estimated at 2-3 the natural rate, or 5.4 t/ha/yr on average, and up to 10 times in savanna woodlands (Lu *et al*, 2003), significantly higher than average soil formation rates of less than 1 t/ha/yr (SOE, 1996). Erosion is estimated to be responsible for up to 50% of historical soil C losses as even when eroded soil is re-deposited, it may have been depleted of up to two-thirds of its soil C in the process (Lal, 2004a).

*North western Victoria*
http://calidore.wordpress.com/2010/09/22/walkies

*Central western NSW*
Photo: Zoe Read, 2010

*South eastern NSW*
Photo: Helen King, 2009

**Figure 22: Soil loss from erosion since European settlement**

C is also lost by photodegradation, a chemical decomposition process that breaks down dead organic matter by solar radiation. Photodegradation is driven by direct solar radiation and emits C directly to atmosphere, a loss of C that would otherwise be incorporated into soil as SOM and food for soil organisms (Austin and Vivanco, 2006). Austin and Vivanco (2006) found that photodegradation is the dominant decomposition process in arid and semi-arid areas, and that C residence time is more than doubled when litter is shaded under a canopy.

## 4.4 Principles for soil carbon enhancement

While environmental factors such as climate and soil type determine an ecosystem's carbon carrying capacity, management factors also affect the processes that cycle and stabilise soil C and detemine a soil is building or losing C. For example, rainfall is outside management control, but management can increase or decrease effective rainfall and WUE by its effect on groundcover and infiltration. Soil type is also an environmental factor but management can improve or degrade soil physical, chemical and biological properties. Management also affects photosynthetic capacity through the LAI remaining after grazing and the time allowed for recovery. King (2009) summarised nine key principles based on the biogeochemical processes that drive the C cycle, with a tenth principle that incorporates the socio-economic dimension of grazing enterprises (Box 6). If the principles are followed, grazing practices would be expected to enhance C cycling and soil C, or if not, would be likely to lose soil C and lead to land degradation.

**Box 6: Key principles for soil carbon enhancement**

King (2009)

| Principles | Recognising the interrelationships between principles, does the practice: |
|---|---|
| 1. Enhance photosynthesis | provide year round green plants for continuous photosynthesis to capture solar power and build biomass?<br>for example by increasing plant diversity to take advantage of different growing cycles |
| 2. Stimulate vegetation and root growth | provide appropriate disturbance to stimulate vegetation growth, especially roots?<br>for example by perennial plants, grazing or mulching |
| 3. Maintain and break up litter and detritus | minimise export of organic matter, enable accumulation of litter and detritus and facilitate its incorporation as soil organic matter?<br>for example by trampling or mulching |
| 4. Conserve soil and prevent erosion | protect the soil from wind and water erosion?<br>for example by shelter belts, continuous ground cover, perennial plants, soil organic matter, landscape patterning and riparian zone protection |
| 5. Maintain soil structure and soil ecology | protect the soil from compaction, maintain a healthy soil ecology and stimulate soil biological activity?<br>for example by continuous ground cover, perennial plants, soil organic matter, carbon and nutrient balance, short rotation grazing, minimising soil disturbance, synthetic fertilisers and pesticides |
| 6. Improve hydrology, infiltration and reduce runoff | facilitate infiltration and water holding capacity and reduce runoff?<br>for example by trees planting, continuous ground cover, soil organic matter, perennial plants, landscape patterning, restoring and maintaining wetlands and riparian zone protection |
| 7. Stimulate and support biodiversity | encourage biodiversity and stimulate species balance?<br>for example by diverse native vegetation and perennial grasses, continuous ground cover, landscape patterning, poly-culture, habitat, food source and natural predators, minimising synthetic fertilisers and pesticides |
| 8. Maintain carbon and nutrient balance | provide the right nutrients in the right place at the right time for the right purpose?<br>for example by minimising export of organic matter, nutrient inputs, diverse native vegetation and perennial grasses, soil organic matter, continuous ground cover, landscape patterning, and minimising synthetic fertilisers and pesticides |
| 9. Remediate and avoid further degradation | repair existing and avoid further degradation (eg. salinity, acidity, sodicity, gullying)?<br>for example by tree planting, perennial plants, soil organic matter, continuous ground cover, landscape patterning, protecting wetlands and riparian zones |
| 10. Provide financial viability and build natural capital | provide a sufficient economic return for financial viability, personal health and wellbeing, support and social structure, and build natural capital?<br>for example by integrated farm planning, financial and risk management, support networks |

# 5 Grazing

Results of research into the effect of grazing on soil C levels are varied and often ambiguous due to the complexity and variability of ecological and management factors (Lecain *et al*, 2000; Briske *et al*, 2008). Connant and Paustian (2002) identified that ceasing overgrazing and grazing at moderate intensity has substantial potential to rehabilitate overgrazed grasslands and increase soil C levels. However, although grazing pressure is widely identified as a key factor, research is usually based on stocking levels, often referred to as high, medium or low grazing intensity, rather than different grazing practices.

In an extensive review of experimental data, Briske et al (2008) was unable to find evidence for ecological benefits of rotational grazing compared to continuous grazing. He proposed that grazing experiments using conventional research protocols may not be able to mimic the subtle differences in the way grazing practices are implemented and adapted by successful managers, suggesting that human factors may explain inconsistencies between experimental and anecdotal evidence.

In paired site experiments of soil C in south eastern New South Wales, Chan et al (2010) found no significant difference under rotational grazing compared to continuous grazing and pasture cropping compared to a control . He identified high levels of heterogeneity between farms and within sampling areas, residual effects of past land use, inadequate time for changes in soil C to be detectable, and sampling methods such as paired sites and insufficient sampling depth as likely to be masking small differences between practices.

Some studies of Time Controlled Grazing / Cell Grazing have identified benefits. Earl and Jones (1996) found increased perenniality, more desirable/palatable species and increased ground cover compared to continuous grazing on the Northern Tablelands of New South Wales. Sanjari *et al* (2008) found increased NPP, increased soil C and N, increased litter, improved soil physical and chemical properties and reduced N and P in runoff compared to continuous grazing in south eastern Queensland. Sanjari *et al* (2009) found significantly reduced sediment loss compared to continuous grazing in south eastern Queensland. Kahn *et al* (2010) found higher NPP, more stable litter cover, less bare ground and increased perenniality with an estimated 78% increase in stocking rate under high density short duration grazing based on herbage mass thresholds compared to continuous grazing in April-December, June-December, April-August and nil livestock grazing in mid-northern South Australia .

## 5.1 Grazing effect

Grazing effects soil C in complex ways (Pineiro *et al*, 2010) due to the dynamic interaction of grazing and C cycling processes (Figure 23). If the grazing effect stimulates vegetation growth, improves soil structure and increases nutrient cycling (green arrows) the positive feedback in the system should increase soil C, improve land condition and potentially support more grazing. If it inhibits vegetation growth, degrades soil structure and reduces nutrient cycling (red arrows) soil C will be depleted and the land will support less grazing. The positive feedback (black arrows) between these variables and soil C mean that an increase or decrease in will drive the system in the same direction resulting in an increase or decrease in soil C.

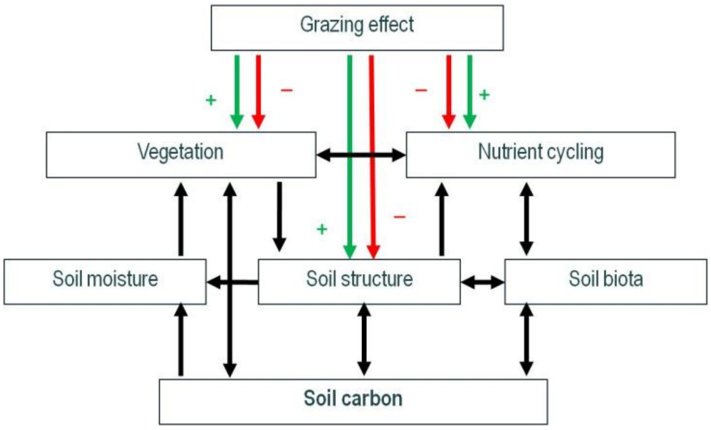


**Figure 23: Conceptual feedback loops with grazing effect**

Grazing in dynamic interaction with ecosystems processes and positive feedbacks within the system show that grazing can potentially enhance or deplete soil carbon levels

adapted from Colloff and Baldwin (2010)

Overgrazing reduces LAI to the extent that roots are negatively impacted, reducing NPP and root and litter input to the soil, whereas grazing at appropriate levels stimulates plant growth and litter and root turnover, contributing more SOM (Conant *et al*, 2001). Conant and Paustian (2002) found that decreasing grazing intensity in overgrazed grasslands is likely to increase soil C levels across all ecosystem types and that this is directly related to root biomass; with soil C increasing with heavier grazing pressure when grazing practices led to a species mix with more deep rooted grasses. Importantly, many studies found that grazing led to higher soil C when compared to ungrazed sites due to more perennial grasses in the species mix, rapid root and shoot turnover, and organic matter incorporated into the soil with grazing. In sites where grazing was removed, dead standing organic matter and litter with low nutrient levels built up and species shifted to annual grasses and forbes without dense roots and less input of SOM (Reeder and Schuman, 2002; Pineiro *et al*, 2010), and where grazing was reduced, soil had lower nutrient levels and pH (Marriot *et al*, 2011).

Grazing stimulates root growth to access more nutrients for recovery (Fisher *et al*, 2007), initially drawing on stored energy until leaves regrow and restore a plant’s photosynthetic capacity. If grazed again before the reserves are replenished the plant is overgrazed and will be unable to grow roots and fully recover. This effect of grazing on plant growth can be seen in Figure 24 which shows the almost constant relationship between LAI and root biomass, termed the root:shoot ratio. The plant on the left represents a continually grazed plant that is unable to capture sufficient C through photosynthesis to maintain a vigorous root structure (Fisher *et al*, 2007), limiting its ability to access nutrients and soil moisture. The plant on the right which has been grazed and allowed to fully recover has a high LAI, giving it a high photosynthetic capacity to capture sufficient C to support an extensive root system. The deeper roots are able to reach more soil and have greater access to nutrients, also adding more C deeper in the soil where decomposition is slower (Sanderman *et al*, 2010).

**Figure 24: Grazing effect on roots**

*Continually clipped leaf and related root length, versus fully recovered leaf and root*

http://www.firstmillimeter.com/2010/02/26/overgrazing-defined

Uneven distribution of nutrients is another effect of continual grazing that reduces soil C cycling and stock. Excess nutrients from manure and urine in areas where livestock congregate result in high losses while the remaining pasture receives insufficient and uneven distribution of nutrients, resulting in low NPP, bare patches and pasture degradation (Fisher *et al*, 2007).

## 5.2 Grazing practices

Grazing practices can be broadly categorised as continuous grazing, rotational grazing or planned grazing (Box 7). Under continuous grazing or set stocking, paddocks are grazed for extended periods and rested only occasionally, for example to provide fresh pasture in a lambing paddock, and animal numbers are generally maintained at a constant level and supported with supplementary feeding when required. Rotational grazing also maintains fairly constant animal numbers and may use supplementary feeding, however stock are rotated through a group of paddocks which are each grazed for a set period and rested between grazes. Under planned grazing, animal numbers are flexible to match anticipated conditions, with paddocks grazed by large numbers in short intense grazes with long rest periods based on the physiological needs of the plant for recovery.

The primary emphasis is on restoring soil health and productivity with grazing animals used as a management tool. Guidelines for different practices are shown in Box 8.

In practice, there is an infinite variety of grazing practices as graziers adapt to prevailing conditions and meet diverse management goals. They range from pure set stocking where paddocks are grazed indefinitely to planned grazing with two or more moves a day; and the primary emphasis from animal production to ecosystem function. Names of practices are also problematic as they are often loosely defined and multiple names ascribed to what is effectively the same practice (McCosker, 2000) (Box 9). This variation makes a grazier's practice in use and how the principles are applied more relevant than what it is called in considering if a grazing practice is likely to maintain, increase or decrease soil C levels (King, 2009).

The conceptual diagram in Figure 25 shows the relative effect on soil C of set stocking, rotational grazing and planned grazing based on how well their characteristics (Box 7) meet the key principles for soil C enhancement (Box 6), although the position of practices in use would change depending on how they are implemented. For example, a set stocking grazier that proactively adjusts stock levels for anticipated conditions may be more beneficial to soil C than one rotationally grazing who does not anticipate and adapt to environmental conditions. Grazing practices that meet all of the principles (top right quadrant) would be expected to restore the land's capacity to capture, cycle and stabilise C, resulting in increased productivity and soil C levels; while those that don't (bottom left quadrant) are likely to be losing soil C with resulting land degradation.

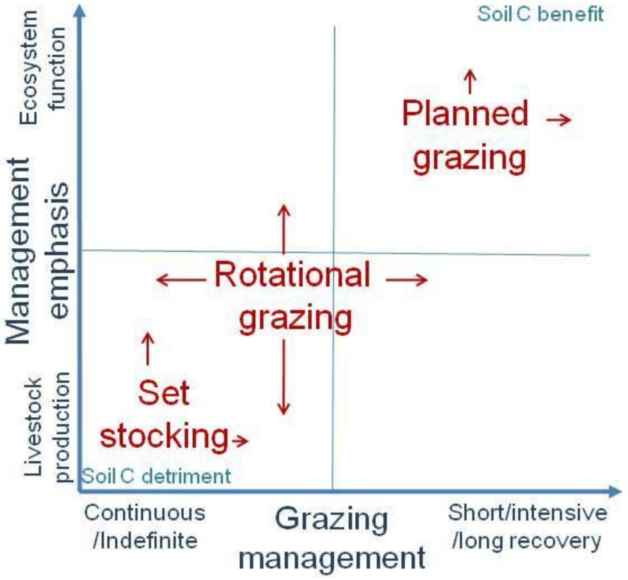


**Figure 25: Conceptual grazing effect matrix**

*Notional relative positions of grazing practices based on their characteristics (Box 7) and key principles for soil carbon enhancement (Box 6). In practice, the grazing effect on soil carbon varies with implementation and ranges from depletion in the lower left quadrant to enhancement in the upper right quadrant.*

**Box 7: Grazing practice characteristics**

adapted from Nicholls *et al* (2007)

| **Continuous grazing / set stocking** | **Rotational grazing** | **Planned grazing**<br>**eg. Time Controlled Grazing, Cell Grazing** |
|---|---|---|
| Few paddocks, many mobs spread through paddocks | Few to many paddocks, few to many mobs | Many paddocks, one to a few large mobs |
| Graze periods are based on feed availability or a set time period | Graze periods may be based on a set time period, remaining biomass, animal demand or pasture recovery periods | Graze periods are flexible based on required pasture recovery periods |
| Rest periods are few and may be for a specific purpose such as a lambing paddock or to be spelled | Rest periods are the remaining time when paddocks are not being grazed | Rest periods are flexible based on required pasture recovery periods |
| Stock numbers kept relatively constant and may be based on a notional long term carrying capacity. Supplementary feeding common | Stock number may or may not be adjusted and supplementary feeding may be used | Stock numbers flexible based on anticipated pasture and adjusted well ahead of expected feed shortages |
| Stock density* is low (e.g. 2-4 times stocking rate) | Stock density* may be high or low | Stock density* is high (e.g. 10–100 times stocking rate) |
| Grazing is not often planned to adjust to seasonal conditions | Grazing may or may not be planned to adjust to seasonal conditions | Grazing is planned at least 6 months in advance on the basis of anticipated conditions and required plant recovery periods. Animal management needs are planned in advance |
| Animals graze paddocks for long periods mostly until the feed runs out | Animals may graze paddocks for longer periods but are removed before the pasture runs out | Animals graze paddocks for short periods and are moved well before feed runs out |
| The possibility of drought is not actively planned. | The possibility of drought may or not be actively planned | The possibility of drought is routinely planned |
| The option of using the management of animals for the purpose of land regeneration is not considered | The option of using the management of animals for the purpose of land regeneration may be considered | The use of animals as a tool for land regeneration is planned |
| No or little monitoring of pasture quantity, quality or ground cover. | No or little monitoring of pasture quantity, quality or ground cover | Regular monitoring of pasture quantity, quality and ground cover and use of this information in grazing plans |

** Stocking rate is the number of animals per hectare across an area of land, or the property.*
*Stock density is the number of animals per hectare in a paddock at a given time.*

**Box 8: Grazing practice guidelines**

Simple Rotational Grazing
http://www.mla.com.au/Publications-tools-and-events/Publication-details?pubid=3753

- Divide paddocks into 2 or 4 and combine mobs
- Move stock every 2 weeks allowing six weeks rest
- Speed up rotation to 1 week moves in spring and after the autumn break

Intensive Rotational Grazing
http://www.mla.com.au/Publications-tools-and-events/Publication-details?pubid=3754

- Move stock frequently (1-3 days) through a large number of paddocks (20-40)
- Slow down rotations to increase duration of rest periods in slow growth periods
- Speed up rotations to reduce the grazing periods in fast growth periods
- Adjust stock levels accordingly

More Beef from Pastures – Key actions
http://www.mla.com.au/Research-and-development/Extension-and-training/More-Beef-from-Pastures

| Tactical stock control | Pasture growth | Pasture utilization |
|---|---|---|
| • Predict monthly pasture growth in kg DM/ha/day for a range of weather patterns.<br>• Continually match animal feed demand to predicted feed supply.<br>• Use partial budgets to assess the benefits and costs of options to match supply to demand. | • Map land into zones based on land capability and primary land use.<br>• Predict the potential annual pasture production using long-term rainfall records<br>• Understand the water cycle on your farm<br>• Improve and maintain water use efficiency<br>• Build and maintain soil nutrients and healthy soils<br>• Manipulate pasture composition and productivity | • Aim to use 50% or more of green pasture growth<br>• Base grazing management on plant growth rate and growth stage<br>• Use tactical grazing to meet different animal and pasture objectives at various times<br>• Manage pastures to ensure adequate rest and regrowth before the next grazing |

Cell Grazing / Time Controlled Grazing principles
McCosker (2000)

In priority order:

1. Control rest to suit the growth rate of the plant
2. Adjust stocking rate to match carrying capacity
3. Plan, monitor and manage the grazing
4. Use short graze periods to increase animal performance
5. Use maximum stock density for the minimum time
6. Use diversity of plants and animals to improve ecological health, and
7. Use large mob size to encourage herding,

**Box 9: Summary of grazing systems and methods**

McCosker (2000)

| System/ method | Common names and/or sub-methods | Definitions | Comments |
|---|---|---|---|
| Continuous | - Continuous grazing<br>- Set Stocking | Plants are continuously exposed to animals | At high stocking rate, it causes widespread overgrazing of plants, is drought- and erosion-prone, and has fluctuating animal performance due to variation in quantity and quality.<br>At ;low stocking rate, it causes undergrazing in patches and overgrazing in the remainder. May lead to woody weed ingress and overuse of fire. Animal performance is high and relatively stable. |
| Rotational resting systems | - Spelling<br>- Deferred rotation<br>- Deferred grazing<br>- Merrill systems | One or two more paddocks than there are herds or flocks. Rest may vary from weeks to years | May defer effects of overgrazing. Leads to undergrazing and can reduce animal performance. Common reasons for use include: burning, drought reserve, special animal needs, allowing plants to seed. |
| Rotational grazing systems | - Rotational grazing<br>- High intensity, low frequency grazing (HILF)<br>- Short duration grazing | 3-7 paddocks per herd on fixed calendar-based moves | There are many approaches using rest periods of 30-365 days. Suffers from lower animal production than continuous grazing in 43% of cases studied. Perpetuates patch grazing and consequent under- and overgrazing effects. Can slow degradation in about 50% of cases. Can be used only on sweet country due to the effect of a long rest period on quality. |
| Multi-camp rotational grazing systems | (a) High utilisation grazing (HUG)<br>- Acocks/Howell system<br>- Short duration grazing<br>- Non-selective grazing<br>- Crash grazing<br>- Mob grazing<br>(b) High performance grazing (HPG)<br>- Controlled selective grazing | (a) HUG > 7 paddocks/herd. Each paddock is severely grazed before moving to the next, generally on fixed calendar-based moves.<br>(b) HPG >7 paddocks/herd. Each paddock is lightly grazed for a short period so that only the most palatable plants are grazed. Ungrazed undesirable plants eventually die out. Calendar-based moves. | (a) Will reverse land degradation. High stock density and long grazing periods can lead to high utilization and good animal impact. Suffers from very low animal performance. Usually uneconomic due to low gross margins.<br>(b) Will reverse land degradation. Designed to increase palatable species. Has a short graze period and high animal performance. Has low stocking rate and is hence more wasteful of rainfall and sunlight energy than HUG. Usually uneconomic due to reduced turnover. |
| Time-control grazing methods | (a) Production focus<br>- Block grazing<br>- Strip grazing<br>- Rational grazing (Voisin)<br>- High density, short duration grazing<br>(b) Holistic focus<br>- Savory grazing method (SGM)<br>- Cell grazing<br>- Controlled grazing<br>- Management Intensive Grazing (MIG)<br>- Planned grazing<br>- Ultra-high density grazing | > 7 paddocks/herd, but usually 20-40. Moves are based on the growth rate of the pasture and its physiological requirements for rest. It is not calendar-based. Requires high stock density.<br>(a) Production: Focus on maximising plant and animal production.<br>(b) Holistic: Focus on ecosystem sustainability and maximizing profit | Recovery period is determined by plant growth rate. Paddock number and recovery period then determine graze period. Varying recovery period protects the plant. A short graze period maintains high animal performance. Combines the best features of D(a) and D(b). Makes more effective use of rainfall and sunlight energy than other approaches. |

# 6 Conclusions

Australian grazing lands have potential to increase soil C levels through changed grazing practices, with multiple co-benefits for grazing enterprises and the environment including improved productivity and resilience, restoration of degraded land, climate change mitigation and greater adaptive capacity.

Planned grazing with its emphasis on soil health and restoring ecosystem function should have the greatest soil C potential based on understanding of biogeophysical processes, with anecdotal evidence of increased soil C and improved productivity and profitability from successful graziers. However, little research has been done to provide rigorous evidence that the grazing practice is driving changes in soil C levels or explain gains in soil C. Enhancing soil C stocks requires a combination of increasing net primary productivity to increase input of soil organic matter, improving soil properties and function to enhance infiltration, C cycling and stabilisation, and protecting the soil from erosion to reduce soil C losses. Grazing practices that do this should result in higher soil C levels (Sanderman *et al*, 2010)

Continuous or rotational grazing practices with adaptive management that adjusts stocking levels for anticipated conditions and applies the principles summarised in Box 6 should also lead to improvement in soil C levels. However, marginal changes within a practice are unlikely to result in the same magnitude of change in soil C as a change from one grazing practice to another (Sanderman *et al*, 2010).

Improving ecological literacy should help to demystify and facilitate wider adoption of planned grazing and should also lead to improvements in continuous and rotational grazing practices in use. Simple principle based guides such as the ecological principles summarised in Box 6 are also likely to lead to more informed decision making (King, 2009).

Research is needed to improve understanding of the effect of grazing practices on soil C dynamics, however methods used should address shortcomings in past research and include studies of successful graziers and their decision making (Briske *et al*, 2008; Chan *et al*, 2010). Knowing which grazing practices are likely to enhance soil C, what they can reasonably be expected to achieve, their limitations and how they may be affected by climate change is also important to ensure that, as far as possible, gains are sustained and to reduce the risk of future land degradation.

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