The role of rabbit and other invasive herbivore control in reducing Australia's greenhouse gas emissions

Andrew Bengsen
and Tarnya Cox

2014

An Australian Government Initiative

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Andrew Bengsen [1] and Tarnya Cox [1,2]

[1] NSW Department of Primary Industries

Locked Bag 6006, Orange NSW 2800

[2] Invasive Animals Cooperative Research Centre

2014

An Invasive Animals Cooperative Research Centre Project

Invasive Animals CRC

NSW Government Department of Primary Industries

An Australian Government Initiative

CRC Australia

Published by: Invasive Animals Cooperative Research Centre.

Telephone: (02) 6201 2887

Facsimile: (02) 6201 2532

Email: contact@invasiveanimals.com

Internet: http://www.invasiveanimals.com

ISBN: 978-1-921777-74-5

Web ISBN: 978-1-921777-75-2

This document should be cited as: Bengsen, A and Cox, T (2014). *The role of rabbit and other invasive herbivore control in reducing Australia’s greenhouse gas emissions*. PestSmart Toolkit publication, Invasive Animals Cooperative Research Centre, Canberra, Australia.

Acknowledgements: Comments from the Department of Environment’s Vegetation Methodologies Section improved on an earlier draft of this report.

Front cover photo: Wayne Hillier

PestSmart Toolkit

Contents

1. Summary

Controlling feral animals such as rabbits, goats and camels could provide a cost-effective contribution to Australia's greenhouse gas emissions targets while also generating important benefits for agricultural productivity, regional communities and the environment.

Australia has committed to a 5% greenhouse gas emissions reduction target by 2020. The capture and storage of atmospheric carbon in vegetation and soils (biosequestration) is widely accepted as an important means of achieving this target. To date, most attention regarding biosequestration has focused on encouraging tree planting, managing livestock grazing pressure and the adoption of modified agricultural practices. However, it is highly desirable to develop alternative methods that may prove more cost-effective or capable in different contexts, particularly in an uncertain policy environment.

Invasive herbivores, such as feral rabbits, camels and goats can have significant adverse impacts on the biosequestration potential of native vegetation communities and ecosystems. It is possible to reverse many of these impacts by reducing herbivore abundance, and this should increase sequestration rates. There has been some discussion of the potential for directly reducing emissions by reducing the abundance of methane emitting species such as feral camels, but any emissions avoided by this approach could not count towards Australia's targets under current international agreements. Conversely, enhanced biosequestration resulting from increased vegetation growth due to invasive herbivore control would be accountable, but this approach has largely been ignored in Australia.

Examination of the damage caused by feral rabbits, camels, goats and pigs strongly suggests that control of invasive herbivores at large scales has the potential to make significant contributions to emissions reduction targets. However, the likely magnitude of carbon sequestration benefits that could be achieved has not yet been established.

In many cases, herbivore control programs might provide a more cost-effective and practically feasible means of enhancing biosequestration than active tree planting. Rabbits are likely to be the most useful subject for herbivore control programs because many of their impacts on vegetation are well understood; the potential for vegetation recovery after rabbit control has been demonstrated; and a research program to further develop biological control tools that will have continental scale impacts is underway. Importantly, the broadscale suppression of rabbit populations would also have major co-benefits for agricultural productivity, regional communities and the environment. Realisation of these benefits will depend on the development of a sound understanding of the technical and achievable potential for invasive herbivore control to contribute to emissions abatement, and the availability of institutional conditions to promote adoption.

2. Glossary

Biocontrol, Biological control	A method of controlling pests using other living organisms such as pathogens, parasites or predators
Biosequestration	The capture and long-term storage of atmospheric carbon by biological processes, especially photosynthesis in plants
CFI	Carbon Farming Initiative
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
Coalition	Liberal / National Party of Australia Coalition
ERF	Emissions Reduction Fund
GHG	Greenhouse gas
Invasive herbivore	Non-indigenous, free ranging, plant eating mammals, such as feral rabbits, goats and camels
IPCC	Intergovernmental Panel on Climate Change
Kyoto Protocol	The Kyoto Protocol to the United Nations Framework Convention on Climate Change
LULUCF	A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities
Methodology	A process approved by the Domestic Offsets Integrity Committee for implementing and monitoring carbon abatement projects under the Carbon Farming Initiative
MV	Myxoma virus
RHDV	Rabbit Haemorrhagic Disease Virus
TGP	Total Grazing Pressure from domestic, native and feral animals

3. Introduction

Since ratifying the Kyoto Protocol in 2007, Australia has committed to an unconditional 5% reduction in greenhouse gas emissions from year 2000 levels by 2020. Current estimates suggest that this now equates to a target of about 593 Mt carbon dioxide equivalent (CO_2-e) of avoided emissions over seven years (Climate Change Authority 2013). The two key pathways available to achieve this target are reducing greenhouse gas emissions and offsetting emissions by increasing the removal of carbon from the atmosphere.

Biosequestration is the capture and long-term storage of atmospheric carbon by biological processes, especially photosynthesis in plants. Australia has great potential to offset greenhouse gas emissions using biosequestration, particularly through increasing the area of forests and woodlands or increasing the carbon density of existing wooded landscapes (Eady *et al.* 2009). There is also some potential to increase soil carbon storage on agricultural lands, although this capacity may be more limited than previously thought (Lam *et al.* 2013). Biosequestration can provide cost-effective opportunities to reduce emissions without hindering other sectors of the economy and can also provide environmental and productivity co-benefits. Consequently, biosequestration is an important component of current climate change policy in Australia, and is likely to remain so for the foreseeable future.

Current policy focus regarding biosequestration is largely aimed at increasing soil carbon storage through improved agricultural practices and increasing the area of wooded landscapes through active tree planting (Anonymous 2010; Department of Climate Change and Energy Efficiency 2011). However, recent studies have suggested that the control of invasive herbivores such as rabbits, feral camels, goats and pigs could contribute to emissions reductions targets by facilitating the natural regeneration of native vegetation or by reducing greenhouse gas emissions (e.g. Peltzer *et al.* 2010; Holdaway *et al.* 2012). Reducing the impacts of invasive herbivores could also provide important economic and environmental co-benefits.

In some cases, reducing the abundance of invasive herbivores could also directly reduce emissions. Ruminant or pseudo-ruminant species such as goats and camels use enteric fermentation to assist in digestion, and this can produce substantial volumes of methane. The removal of a large number of these herbivores could therefore directly reduce methane emissions under certain conditions (Bradshaw *et al.* 2013). However, this form of emissions reduction has not yet been accepted as an activity that can contribute to Australia's national emissions target under current Kyoto Protocol commitments.

The purpose of this discussion paper is to stimulate informed consideration of the potential for invasive herbivore control to contribute to Australia's carbon pollution reduction targets for 2020 and beyond. The paper provides a synopsis of knowledge relevant to improving biosequestration through invasive herbivore control in the context of recent and potential climate change policy in Australia. It concludes with recommendations emerging from the consolidation and critical review of this knowledge.

4. The policy environment

The unconditional target of a 5% reduction in emissions by 2020, from a year 2000 baseline, is supported in principle by both major political parties. The Climate Change Authority, whose role is to advise Government on reductions targets and abatement initiatives, has argued that this target is inadequate on several grounds (Climate Change Authority 2013). However, recent statements from Government ministers indicate that there will be no increase in the foreseeable future.

4.1 International policy

The Kyoto Protocol makes provisions for parties to include activities relating to land use, land use change and forestry (LULUCF) in their carbon accounting. To contribute to agreed emissions reduction targets, LULUCF activities must be accountable under the Protocol. Most importantly, activities must be verifiable and must meet the conditions of additionality and, for offset activities, permanence. Additionality requires that activities go beyond common practice or ‘business as usual’ to avoid or offset emissions that would otherwise be unabated. Permanence requires that activities aiming to offset emissions, such as reforestation to capture atmospheric carbon, must persist indefinitely. In practice, permanence is assessed over 100 years.

4.2 Previous Australian Government policy

Recent Government policy focussed on using a carbon price, coupled with investment in renewable energy, to induce long-term decreases in carbon emissions. Additionally, the Carbon Farming Initiative (CFI), Carbon Farming Futures program, Biodiversity Fund and associated programs aimed to generate carbon offsets by increasing carbon storage in agricultural and native landscapes (Department of Climate Change and Energy Efficiency 2011).

The CFI has provided a framework for land managers to generate Australian Carbon Credit Units (ACCUs) that can be sold to businesses aiming to offset their own emissions. The list of activities that are eligible to earn ACCUs (the ‘Positive List’) is specified in regulations. The Positive List is dominated by activities that are compliant with the Kyoto Protocol and can therefore contribute to Australia’s emissions reduction targets. These include activities that establish and maintain woody vegetation on land that has not previously supported forest (afforestation) or that has previously been cleared (reforestation). The management of invasive herbivores is recognised as a potential means of facilitating natural regeneration of native vegetation (Anonymous 2013c). Additionally, some activities that are not Kyoto-compliant (such as feral herbivore management to reduce methane emissions) are also eligible to earn non-Kyoto ACCUs that cannot be traded on the international market.

4.3 Current policy

The current Government’s Direct Action Plan identifies biosequestration as an important means of reducing net emissions. The establishment of an Emissions Reduction Fund (ERF) is central to this Plan. The ERF will aim to reduce emissions by investing, through a reverse auction process, in projects that will: 1) reduce CO_2 emissions; 2) deliver additional practical environmental benefits; 3) not result in price increases to consumers; 4) protect Australian jobs; and 5) not otherwise proceed.

The ERF is intended to run until at least 2020, although the Fund’s value will be capped at $1.55 billion for its first three years. These funds will be used to support projects that increase soil carbon storage on agricultural lands, as well as other projects that increase carbon storage or reduce emissions through changes in forestry, mining, waste management, transport and urban development activities (Anonymous 2010). Contracts for payments from the Fund will be valid for a maximum of five years (Department of the Environment 2013). Further details of the Fund’s operation are yet to be determined; a green paper was released in December 2013 and a white paper is expected in early 2014. The first round of the Direct Action Plan is expected to launch in July 2014, and to be reviewed in 2015.

The Government has introduced draft legislation to repeal the Carbon Pricing Mechanism, but there is substantial uncertainty regarding its passage through Parliament in the short term. The legislation would remove the demand for the carbon credits generated under the CFI to be used by liable entities to offset emission under the carbon pricing mechanism. However, the CFI is expected to continue under the Direct Action Plan, with ACCUs being purchased by the Emissions Reductions Fund. The Government has also indicated that it intends to invest up to $300 million over four years to fund a “Green Army” that would conduct environmental management and restoration works, which could include tree planting for carbon sequestration.

5. Biophysical opportunities and constraints

Vegetated landscapes are an important part of the global carbon cycle. Carbon sequestration occurs through the capture of atmospheric CO_2 by plants, and the subsequent transfer of some carbon into plant material and soil for storage. Carbon can thus be stored in five major pools: above-ground biomass, below-ground biomass, coarse woody debris, litter and soil. The rates at which plants accumulate and cycle carbon vary among species, growth stages, environmental conditions and land management or natural disturbance regimes. Storage capacity, accumulation rates and residence times are also highly variable among vegetation communities and soil types. Consequently, some vegetation types and landscapes have greater carbon storage potential than others.

The state of a single land unit can be classified into one of three major categories at any point in time: 1) a carbon source, which contributes carbon dioxide or other GHGs to the atmosphere; 2) a carbon sink, which actively sequesters carbon from the atmosphere; or 3) a carbon store, in which emissions and sequestrations are balanced. The management of land units for increased carbon sequestration can be viewed as a state and transition process, in which management actions are applied to transition a land unit from a state with low or negative sequestration rates and storage capacity to a modified state with greater sequestration rates and capacity (Stafford-Smith *et al*. 1995, Hill *et al*. 2006).

5.1 Carbon sequestration and landscape function

Many of the mechanisms that can transition a unit of land from one state to another are reasonably well understood at a coarse level. In general, for systems that are not intensively managed, mechanisms such as heavy grazing that lead to a decrease in plant biomass or an increase in soil disturbance are likely to cause net carbon losses from a system (Baker *et al*. 2000; Dean *et al*. 2012). Carbon storage in the soil pool is often heavily dependent on continuous input from biomass to counter ongoing losses from soil respiration and erosion (Gifford and McIvor 2009). Mechanisms that facilitate the development of perennial biomass and maintain ground cover and soil stability tend to increase carbon sequestration rates and total storage potential (Baker *et al*. 2000; Dean *et al*. 2012). However, counter-intuitive responses are also possible (Gifford and McIvor 2009).

Several studies have estimated the potential carbon benefits of managing land to improve landscape function and carbon sequestration. Australia's rangelands are thought to have substantial sequestration potential because they cover a vast area (more than 75% of the continent), much of which is thought to be held in a sub-optimal state that might be transitioned to a more productive and functional state with appropriate management intervention. Previous studies have concluded that although the potential carbon benefits per unit area are modest, the benefits accrued over the total area could be substantial (Table 1). However, primary productivity in the rangelands is characterised by high spatial and temporal variability, and the methods used to estimate potential carbon gains have also differed greatly among studies. The estimates presented below should therefore be regarded as being associated with a high degree of uncertainty.

Table 1: Estimated carbon potentials for Australian rangeland systems. Scale refers to the area of rangeland assumed to be in a deteriorated condition that is capable of being remediated to a more carbon intensive state.

Land system	Annual sequestration rate (t CO_2-e/ha/yr)	Scale (M ha)	Per cent of national annual emissions[6]	Estimated total technical potential (Mt CO_2-e/yr) over (x) years
'Grazing land'[1]	0.80	358	51.8	286 (20-50 yrs)
Tropical rangelands[2]	0.67	43	5.2	40 (40 yrs)
Grasslands [3]	0.33	49	2.9	16 (unspecified)
Rangelands [4]	0.51	510	18.7	100 (40 yrs)
Mulga country [4]	0.26	76	3.6	20 (40 yrs)
Eastern mulga country[5]	0.92 - 1.1	0.13	2 - 2.5	11.6 – 14 (40 yrs)

[1](Garnaut 2008), [2] (Ash *et al.* 1996), [3] (Conant and Paustian 2002), [4] (Gifford and McIvor 2009), [5] (Witt *et al.* 2011), [6]2012 estimated annual emissions (551.9 Mt CO2-e, Anonymous 2013d)

5.2 The role of invasive herbivores in landscape degradation

To date, the main mechanisms considered for transitioning land units to states of greater sequestration activity and capacity have been tree planting, the management of livestock grazing, vegetation clearing and fire. However, invasive herbivores such as rabbits, camels, feral goats, pigs, buffalo, horses, donkey and deer (six species) also have major detrimental impacts on plant production that can be expected to reduce carbon sequestration rates and capacity. The impacts of invasive herbivores on the carbon sequestration capacity of Australian landscapes have not been estimated, but expected impacts can be inferred from their effects on vegetation. Some species also produce substantial amounts of methane (CH_4), which has a much greater global warming potential than CO_2, during their digestive process. Here, we consider the likely impacts of four of the most important invasive herbivores: rabbits, feral camels, goats and pigs.

5.2.1 Rabbits

Rabbits have been an important contributor to landscape degradation in Australia since they began spreading across the continent in the late 1800s (Cooke 2012a). Rabbits are now widespread across about 70% of the continent, mainly south of the tropics (Figure 1). Rabbit abundances declined dramatically (up to 99%) in many areas after the introduction of the myxoma virus in 1950, but then increased again as populations developed resistance and the virus attenuated (Fenner and Ratcliffe 1965; Williams *et al.* 1995). The introduction of rabbit haemorrhagic disease virus (RHDV) in 1995 also caused major population crashes (up to 95%) (Bowen and Read 1998; Mutze *et al.* 2008), but populations are now showing resistance and beginning to increase in numbers (Cox *et al.* 2013).

Rabbits predominantly graze on grasses and herbaceous species. In arid rangelands, a small, non-breeding adult rabbit consumes about 80g of vegetation per day (Short 1985). Even at moderate densities, rabbits can contribute an important component of the total grazing pressure on a unit of land (Leigh *et al.* 1989; Bird *et al.* 2012; Cooke 2012a). At high densities, they can be devastating (Figure 2). The reduction in biomass and ground cover caused by rabbits can be expected to reduce the rate of carbon input into the soil, and also to increase the rate at which carbon is lost due to erosion resulting from loss of groundcover.

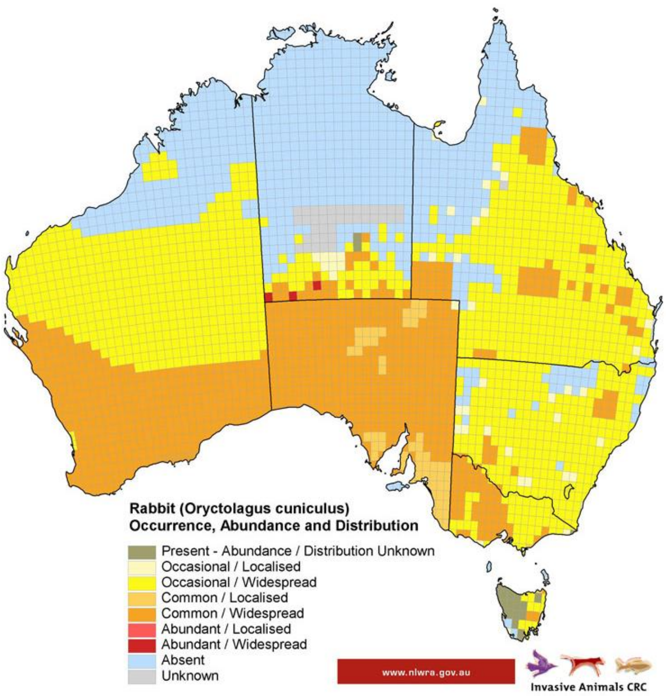

Figure 1: Distribution and occurrence of rabbits in Australia (West 2008).

In addition to the overall increased grazing pressure imposed by rabbits, selective grazing on the most nutritious species can change plant community composition, which could have important implications for carbon storage potential. Persistent grazing by rabbits can greatly reduce the cover of perennial grasses and forbs (Myers and Poole 1963; Foran *et al*. 1985; Wood *et al*. 1987; Cooke 1998). The replacement of perennial species with annuals as a result of grazing pressure is generally associated with a transition to a state of lower or negative carbon sequestration (Stafford-Smith *et al*. 1995; Baker *et al*. 2000; Gifford and McIvor 2009). Moderate to high rabbit densities are therefore likely to inhibit soil carbon storage through increased grazing pressure in general, and on perennial species in particular.

While rabbits are expected to have important impacts on soil carbon storage through grazing on herbaceous vegetation, their greatest impact across much of their distribution might occur through predation on the seedlings of woody trees and shrubs. Many studies have shown that rabbits can drastically inhibit or completely prevent the recruitment of some woody species by destroying most or all of the seedlings or suckers produced by mature plants (Table 2).

Figure 2: Rabbits in Western New South Wales (Image: Mark Fosdick).

Many *Acacia* species that comprise the dominant woody vegetation across much of Australia's rangelands are particularly susceptible because they are selectively consumed by rabbits, even when other feed is abundant (Lange and Graham 1983). They also grow slowly, and therefore take several years to reach an 'escape height' at which they are no longer vulnerable to predation (Mutze *et al*. 2008).

Even low densities of rabbits (≤ 1 rabbit per hectare) are able to prevent regeneration of some of the most vulnerable species (e.g. Mutze *et al*. 2008; Bird *et al*. 2012). Consequently, the dominant woody vegetation layers in many rangeland areas that support rabbits are characterised by age structure gaps and declining cover as mature plants senesce and die with few or no younger individuals to replace them (Friedel 1985; Woodell 1990; Lord 2002). This pattern can also occur in regions where other species favoured by rabbits occur, especially those in the family *Casuarinaceae* (e.g. Cooke 1987; Murdoch 2005; Sandell 2006; Bird *et al*. 2012). The most profound impacts of rabbits in these cases are likely to be due to the lost opportunity for the storage of carbon in above- and below-ground woody biomass. However, Acacias and Casuarinas are also particularly valuable because nitrogen-fixing species such as these can greatly enhance soil carbon storage above that provided by co-occurring non nitrogen-fixing species (Forrester *et al*. 2013).

Table 2: Examples of Australian studies showing complete or substantial inhibition of tree and shrub regeneration resulting from destruction of seedlings or suckers by rabbits.

Region	Species affected
Southern and central rangelands	*Acacia aneura* [1,2,11,12,14]
	A. burkittii [3,10]
	A. carneorum [5,6,15,17]
	A. kempeana [3,13]
	A. ligulata [7,14]
	A. loderi [7]
	A. oswaldii [3,8]
	A. papyrocarpa [3]
	A. rigens [16]
	A. wilhelmiana [16]
	Alectryon oleifolius [7]
	Callitris glaucophylla [18]
	Cassia spp. [12]
	Casuarina pauper [6,7]
	Senna artemisioides [14]
coastal South Australia	*Allocasuarina verticilliata* [4]
central west New South Wales	*Callitris glaucophylla* [9]

[1]Crisp 1978, [2] Mutze *et al*. 2008, [3] Lange and Graham 1983, [4] Cooke 1987, [5] Auld 1993, [6] Denham and Auld 2004, [7] Auld 1995a, [8] Auld 1995b, [9] Allcock and Hik 2004. [10] Woodell 1990, [11]Henzell 1991, [12] Friedel 1985, [13] Foran *et al*. 1985, [14] Munro *et al*. 2009, [15] Lord 2002, [16] Cohn and Bradstock 2000, [17] Auld 1990, [18] Leigh *et al*. 1989

The carbon storage implications of rabbit grazing and browsing have not yet been quantified, but it is clear that rabbits can have dramatic effects on land unit traits that are associated with high carbon capture and storage rates in rangeland systems. The expected implications of these effects are summarised in Figure 3. Landscapes that support moderate to high rabbit densities are almost certainly held in states characterised by low or negative carbon sequestration, and even low rabbit densities are likely to greatly inhibit carbon storage potential in many areas.

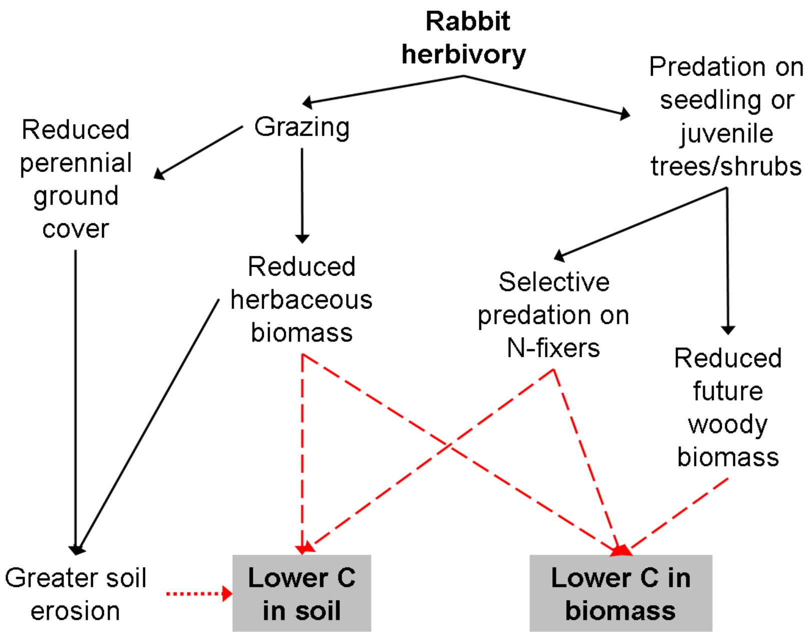

Figure 3: Expected contribution of grazing by rabbits to soil and biomass carbon fluxes in rangeland systems. Dashed red lines represent processes expected to reduce rates of carbon input into the system and the dotted red line represents an expected increase in rates of carbon loss.

5.2.2 Other invasive herbivores

In addition to rabbits, at least 15 medium- to large-bodied herbivore species have established significant wild-living populations in Australia, including: hares, camels, pigs, horses, donkeys, water buffalo, goats, cattle, banteng cattle, and six species of deer. Here, we briefly consider the importance of camels, goats and pigs. These species are included because there is some information available which is suggestive of their likely impacts on greenhouse gas abatement. Other species are excluded for brevity; however, we note that they might also have important impacts.

Camels

Dromedary camels were introduced to Australia in 1840 and are now widely dispersed throughout much of the rangelands, attaining their greatest densities in the arid centre (Saalfeld and Edwards 2010). The total population size is currently estimated at about 300,000 individuals, following the completion of the Australian Feral Camel Management Project (Ninti One Ltd 2013).

Camels have a highly flexible diet that can include most of the vegetation available to them, depending on climatic conditions and the availability of preferred species, such as mulga (Dörges and Heucke 2003). They mainly browse on the leaves of trees and shrubs during dry conditions, and herbaceous vegetation during wetter periods (Dörges and Heucke 2003). Camels can prevent or inhibit the regeneration of many woody species by suppressing flower and fruit production through heavy defoliation of mature trees, or by killing juvenile trees before they can contribute to the reproductive population (Dörges and Heucke 2003). Camels can be so effective at preventing the regeneration of woody species that free-ranging herds have been deliberately established in some areas to reduce the spread of highly invasive shrubs and trees (McKenzie *et al.* 2006; Palmer *et al.* 2012). Selective browsing by camels is likely to threaten the persistence of highly palatable species in some areas, either by directly reducing plant growth and reproduction (Edwards *et al.* 2010, Ninti One 2013).

There are at least three direct pathways through which heavy browsing of woody vegetation by camels can be expected to reduce sequestration potential: by reducing the rates at which mature plants grow and capture atmospheric carbon; by inhibiting the reproductive output of mature plants; and by destroying juvenile plants. In many areas, these impacts will compound or be additional to those of rabbits. For example, both rabbits and camels could reduce or prevent regeneration of woody vegetation, thereby reducing carbon storage potential, but camels could also reduce current rates of carbon capture by slowing the growth of existing mature trees and shrubs. However, unlike rabbits, camels are highly mobile and currently occur at relatively low densities throughout much of their distribution (Saalfeld and Edwards 2010). Consequently, their most profound impacts are likely to occur where their activity is spatially concentrated, such as in fenced holding paddocks, at watering points or in drought refuges (e.g. Dörges and Heucke 2003; Brim-Box *et al.* 2010).

Goats

Feral goats are abundant across large areas of Australia, mainly south of the tropics (West 2008). Like camels, goats are generalist browsers and grazers that will preferentially consume the highest quality forage available. They can eat most plants in the rangelands, including species avoided by sheep and cattle, and can contribute a substantial portion of the total grazing pressure (Parkes *et al.* 1996). Their contribution to total grazing pressure is usually considered to be their most important impact on landscape health and function (e.g. Fisher *et al.* 2004; Grant 2012). Grazing and trampling of herbaceous vegetation by goats can lead to soil erosion, decreased ground cover and shifts in vegetation composition from perennial to annual species (Parkes *et al.* 1996), all of which have negative carbon storage consequences (Stafford-Smith *et al.* 1995). Feral goats can also prevent or severely inhibit the regeneration of some woody species, including mulga, by reducing seed output from mature plants and by consuming seedlings (e.g. Harrington 1976). Goats also compound landscape degradation caused by rabbits (e.g. Figure 4), but rabbits may have the most profound impacts when both species occur together (e.g. Henzell 1991).

Figure 4: Dying mulga tree and narrow-leaved fuchsia bush (*Eremophila alternifolia*) in a rangeland area degraded by goats and rabbits. The narrow-leaved fuchsia in the centre of the picture has been browsed as high as goats can reach (about 1.8 m), leaving only a small tuft of leaves. The grove of bullock bush (*Alectryon oleifolius*) in the middle distance has also been browsed to goat height. Note the absence of regeneration (Image: Robert Henzell).

Pigs

Feral pigs inhabit about 45% of the Australian continent, and are most abundant in the north and east (West 2008). Pigs commonly turn over soil while foraging for subterranean foods, and they can have a wide range of impacts on native vegetation and soils in different environments (Bengsen *et al*. 2014). Some international studies have shown that pigs can have substantial adverse impacts on soil carbon storage in terrestrial environments by physically disturbing the soil or by altering below-ground plant and animal communities (e.g. Risch *et al*. 2010). The only Australian studies that have tested for pig impacts on soil carbon found no observable effect in north Queensland rainforest sites (Elledge *et al*. 2010; Taylor *et al*. 2011), although tropical forest soils tend to store little carbon anyway (Adam 1992). However, wetland soils, which are heavily impacted by feral pigs in northern Australia (e.g. Mitchell 2010), can store large quantities of carbon per unit area (Dixon and Krankina 1995). Repeated physical disturbance of large areas of wetlands by feral pigs could lead to important soil carbon and nitrogen losses by increasing soil respiration and reducing below ground biomass, but this has not yet been assessed.

5.3 Potential benefits of invasive herbivore control

5.3.1 Rabbits

The previous sections have shown that invasive herbivores have adverse impacts on native vegetation that are likely to reduce carbon storage potential of different land systems. Rabbits may be particularly important because of their abundance, wide distribution, site fidelity and their ability to rapidly increase in numbers under favourable conditions. Importantly, the adverse impacts of rabbits can often be reversed. Several studies have shown dramatic increases in the cover of woody or perennial herbaceous vegetation in rangeland or semi-arid systems after rabbit densities were reduced through intensive control programs, or after the arrival of myxomatosis or RHD (Hall *et al*. 1964; Crisp 1978; Henzell 1991; Lord 2002; Murdoch 2005; Sinclair 2005; Mutze *et al*. 2008) (Figure 5). Similar effects have also been demonstrated in south-eastern Australia, where the survival and regeneration of native trees and shrubs increased in conservation areas after rabbit populations were reduced (Cooke 1987; Bird *et al*. 2012). In these cases, reductions in rabbit densities have induced transitions to states associated with higher carbon accumulation rates and storage potential; namely, greater perennial cover in the herbaceous vegetation layer and/or increased woody biomass.

Figure 5: Regeneration of native grasses and shrubs under drought conditions near Broken Hill, following significant rabbit declines due to RHDV and conventional rabbit control (Images: David Lord).

While it is clear that carbon-favourable changes to landscape structure can be brought about by controlling rabbits, the potential magnitude of these changes at local or continental scales is unclear. Most importantly, actual carbon benefits associated with the removal of vegetation suppression by rabbits have not been quantified, and the area of different vegetation types subject to suppression is unknown. Furthermore, patterns of vegetation growth and succession in the rangelands are driven by climate (e.g. Davies 1976; Read 1995; Denham and Auld 2004), fire (Moore *et al*. 2001; Dean *et al*. 2012) and grazing (e.g. Stafford-Smith *et al*. 1995; Dean *et al*. 2012). Consequently, the trajectories of vegetation regeneration after release from suppression will be determined by interactions among these factors, and the nature of those interactions will vary spatially and temporally.

Nonetheless, very crude indications of potential benefits can be produced from specific scenarios using broad assumptions. Mulga woodlands provide a useful case study for several reasons: 1) mulga regeneration can be highly susceptible to suppression by rabbits; 2) mulga trees and shrubs are likely to represent a high proportion of the biomass carbon store in landscapes where they occur; and 3) mulga woodlands cover a large area of the continent, most of which is shared with rabbits (Figure 6). If rabbits suppress the regeneration of woody vegetation across 25% of the area in which they co-occur with mulga woodlands, then the regeneration induced by the removal of rabbit impacts might sequester up to 5 or 6 Mt of CO_2-e per year in living biomass alone (Table 3, estimation method and assumptions outlined in Appendix 1). These estimates are based on extrapolation beyond the geographic range of existing data, and should be regarded as an upper bound. **However**, carbon gains in the soil and coarse woody debris pools could be greater, depending on fire regimes and the intensity of pasture grazing by domestic stock and wildlife (Witt *et al*. 2011; Daryanto *et al*. 2013).

Figure 6: The distribution of rabbits (solid orange) within mulga dominated woodlands (white outline). Dark grey points represent additional mulga observations outside this area. Data adapted from Milton Moore and Perry (1970), West (2008) and Atlas of Living Australia (2013). A more complete rabbit distribution map is shown at Figure 1.

Table 3: Estimated potential carbon sequestration benefits of releasing mulga woodlands from the adverse impacts of rabbits. See Appendix 1 for estimation method and assumptions.

Scenario area affected (%)	Scenario area affected (M ha)	Annual sequestration rate (Mt CO2-e/yr)[1]
1	1.4	0.2
10	14.3	2.2
25	35.8	5.4
50	71.5	10.7
100	143.0	21.5

[1] Assuming a benefit of 0.15 t CO_2-e ha^{-1} yr^{-1} in live, woody biomass alone

5.3.2 Other invasive herbivores

Prior to the commencement of the Australian Feral Camel Management Project, the camel population appeared to be growing at a rate of about 8% per year, with little sign of slowing (Pople and McLeod 2010). Suppression of continued population growth could reduce future methane emissions; a CFI methodology proposal suggested that methane emissions from camels in Australia could generate 1.9 million t CO_2-e per year by 2020 (Northwest Carbon Pty Ltd 2011). However, this can not contribute to Australia's international obligations under current accounting rules. It is difficult to attempt even a crude estimate of the level of control needed to achieve carbon sequestration benefits through reductions in grazing and browsing pressure by camels.

The potential carbon abatement benefits of feral goat or pig control are similarly ambiguous. The Cape York Institute has argued that carbon credits should be provided for feral pig control, based on estimated emissions reductions and offsets of 1.4 t CO_2-e per pig per year (Farrow and Winer 2011), but the origin of this estimate is unclear and it has not been independently evaluated. Other attempts to estimate potential emissions abatements resulting from feral pig control in northern Australia have led to the conclusion that significant baseline data are required before accurate emission reduction estimates can be calculated. In particular, it was clear that direct emission abatement from reduced methane emissions was marginal and it is more likely that a suite of emission abatement values would need to be calculated such as increased carbon sequestration potential by halting wetland degradation. Significant investment in a research project would be required to adequately assess the full suite of emission abatement potential including accurate pig population dynamics, accurate field measurements of methane and carbon sequestration potential of degraded verses intact wetlands (J. Perry, CSIRO, *pers. comm.*).

5.4 Potential to reduce the impacts of invasive herbivores

The management of invasive herbivore impacts generally requires a reduction in their local abundance and distribution, either by excluding them from small areas or, more commonly, by reducing population densities through lethal control.

Exclusion can occur on a variety of scales. For example, herbivores can be excluded or deterred from individual planted seedlings using tree guards (e.g. Bird *et al*. 2012), or from larger areas using fencing (Munro *et al*. 2009). When fencing is used, lethal control or some other means of removal is required to reduce the population inside the fenced area.

Lethal control aims to reduce the density or abundance of a pest animal population to a level at which its impacts are acceptable. For established species, lethal control activities such as poison baiting, fumigating, trapping or shooting are usually applied repeatedly to reduce or counter population recovery. A strategically applied combination of methods is generally needed to achieve the most useful results.

5.4.1 Rabbits

In addition to conventional lethal control methods, rabbits have been subjected to biological control since the introduction of the myxoma virus into Australia in 1950. Biological control may be considered a special form of lethal control, in that it can be applied at a variety of scales. For example, myxoma and RHD viruses spread through rabbit populations across much of southern Australia after their initial releases (Fenner and Ratcliffe 1965; Kovaliski 1998). Both viruses caused severe population reductions at large geographic scales on their initial spread, and they continue to re-emerge naturally in most areas (Saunders *et al*. 2010). However, RHD outbreaks can also be deliberately induced at specific sites and times using baits treated with RHDV in liquid suspension.

It is generally assumed that the impacts of a pest population decline as the density or abundance of animals is reduced. However, the shape of the relationship between density and damage for any given situation is rarely known and is not necessarily linear. A study in south-eastern Australia found curvilinear relationships between rabbit density and woody regeneration: sites with few rabbits showed relatively high levels of natural regeneration, but evidence of regeneration decreased sharply as the density of rabbits approached five per hectare, and there was effectively no regeneration present at sites with 10 rabbits per hectare (Figure 7)(Cooke *et al*. 2010).

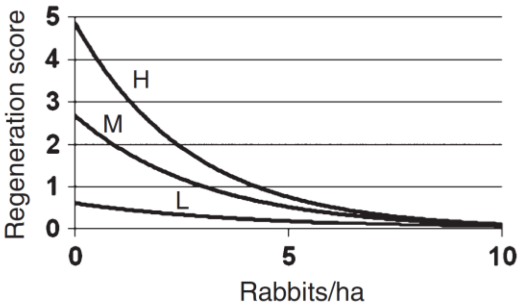

Figure 7: Native plant regeneration in relation to rabbit abundance at sites with (H) high, (M) medium, or (L) low capacity for regeneration in south-eastern Australia (Cooke *et al.* 2010).

Another study in the south east found that regeneration of a rabbit-sensitive shrub increased in areas where rabbit densities were reduced by about 90% to 0.4 rabbits per hectare, but even this level of control was insufficient to release a highly sensitive tree species from suppression by rabbits (Bird *et al*. 2012). In more arid areas, rabbit densities as low as 0.01 per hectare may be sufficient to prevent mulga regeneration, although less palatable shrubs can persist (Mutze *et al*. 2008). Together, these results suggest that areas that support moderate to high rabbit densities will need severe and persistent population reductions to realise the greatest carbon benefits.

To date, the most enduring and effective rabbit amelioration programs have involved the destruction of warrens over large geographic areas in the wake of massive population reductions following the initial dispersal of RHDV (McPhee and Butler 2010). Now that RHDV has become less effective, mechanical warren destruction, combined with direct population control through poisoning or fumigation, generally provides the most useful and efficient means of reducing the impacts of rabbits, particularly when applied after an RHD outbreak (Cooke 2012b). The scale and intensity of control needed to release native vegetation from suppression by rabbits generally requires a broad support base, and is likely to be beyond the capacity of most individual land managers (Cooke 2012b). It is clearly impossible to implement intensive rabbit control across the vast areas of the continent inhabited by rabbits. Alternative approaches are therefore required if potential carbon gains resulting from the amelioration of rabbit impacts on native vegetation are to be realised across large geographic scales (Cox *et al*. 2013).

5.4.2 Other invasive herbivores

Camels

Because of their high mobility and low population density, camel control operations need to cover vast areas. Shooting from helicopters is generally regarded as the most effective, efficient and humane means of reducing population density (Drucker *et al*. 2010). Complementary control methods can include trapping or mustering for commercial benefit in some limited cases. A population modelling study suggested that over 10,000 camels need to be removed each year to suppress population growth (based on projections from 2008, Pople and McLeod 2010). The $19 million Australian Feral Camel Management Project removed about 120,000 camels over its first three and a half years of operation and has one removal season remaining (Anonymous 2013b). Population reductions of this scale can be expected to have substantial environmental, social and economic benefits.

Goats and pigs

Goat populations can be controlled through commercial harvesting (mustering and trapping) or shooting (Parkes *et al*. 1996). The management of goat populations and impacts in rangeland areas is often complicated by their value as a commercial resource, which can result in conflicting management aims. The feral goat population in western New South Wales has been increasing in recent years despite high commercial harvesting rates and lethal control operations on protected areas (Ballard *et al*. 2011). Feral pig populations can be controlled using baiting, trapping shooting or commercial harvesting. However, local population densities will usually recover quickly unless control operations are repeated or maintained (Bengsen *et al*. 2014).

6. Socioeconomic opportunities and constraints

The regeneration of native vegetation resulting from reduced rabbit impacts can clearly contribute to Australia's emissions reduction targets. However, it is important to assess the economic desirability of this method of carbon sequestration, relative to similar alternatives. A detailed analysis of the cost-effectiveness and co-benefits of rabbit control as a means of restoring native vegetation for carbon sequestration is beyond the scope of this paper. However, a simple comparison of the costs of rabbit control to more conventional restoration methods suggests that there may be significant economic advantages in ameliorating the impacts of rabbits and allowing woody vegetation to regenerate through natural growth.

6.1 Costs of conventional rabbit control

The costs of conventional rabbit control operations can vary depending on the situation. Assuming that a combination of poisoning, fumigation and mechanical warren destruction will reduce local rabbit populations to levels where vegetation is released from grazing suppression, vegetation development might be achieved for an initial investment of less than $200 per hectare in areas where rabbits suppress natural regeneration (Table 4). Follow up inspections and treatments would also be needed until vegetation has grown to a size where it is no longer vulnerable to destruction by rabbits, say 16 years (e.g. Allcock and Hik 2004), and also to ensure replacement in the case of short-lived vegetation.

Table 4: Estimated expenses ($ per hectare, in 2012 terms) of rabbit control operations in Australia. Monitoring and maintenance expenses are estimated as 25% of the combined cost of all control methods, biannually for 16 years. Total cost includes initial application of all three control methods plus monitoring expenses.

Source of expense	Initial expense	Monitoring & maintenance	Total cost until establishment
Warren ripping and fumigation			
Murray-Sunset National Park [1]	37	75	$112
Poison baiting, warren ripping and fumigation			
Hattah-Kulkyne National Park [2]	67	143	$210
South-east Australia [3]	128	256	$384
Lameroo case study [4]	161	322	$483

[1] Sandell 2006, [2] Anonymous 2011, [3] Cooke *et al.* 2010, [4] Cooke 2012b

The cost:carbon benefit ratio of carbon gains resulting from rabbit control at any site will be largely determined by biological factors relating to the local rabbit population, which will influence the costs, and factors relating to the local environment, which will influence the benefits. The cost of conventional rabbit control operations is likely to be lowest when the density of rabbits and warrens is low, RHDV is present to inhibit population recovery, control operations are conducted when the population is most vulnerable and the potential for rapid population recovery through immigration from surrounding areas is low. Return on investment, in terms of biomass and carbon gains, is likely to be greatest in vegetation types with the following characteristics (adapted from Sandell 2006; Cooke *et al*. 2010; Peltzer *et al*. 2010; Holdaway *et al*. 2012):

1. A small number of species that are heavily impacted by rabbits contribute disproportionally to the total woody biomass;
2. The vegetation type is widespread within the distribution of rabbits;
3. The vegetation type has high capacity for regeneration if released from rabbits;
4. The vegetation type has large detrital carbon pools and slow rates of litter decay; and
5. The vegetation type has high productivity.

Few, if any, vegetation types will meet all of these criteria. However, studies of vegetation recovery after intensive rabbit control or the initial emergence of RHDV suggest that many rangeland areas may satisfy the first three points (e.g. Hall *et al*. 1964; Crisp 1978; Henzell 1991; Lord 2002; Murdoch 2005; Sinclair 2005; Mutze *et al*. 2008). Decay of woody biomass is also relatively slow in semi-arid or arid rangeland areas, so substantial quantities of carbon can remain stored in fallen timber until they are released by fire or decaying organisms (e.g. Witt *et al*. 2011).

Other factors that will influence the cost-effectiveness of rabbit control as a means of assisting natural regeneration will include the availability of human and other resources, and the physical structure of the landscape. The economic value of carbon sequestration will also be important where the cost of control is to be offset through accumulation of carbon credits or other means.

6.2 Costs of direct vegetation management

There are two broad pathways that have recently been used to encourage the establishment of woody vegetation for environmental benefits: government grant-based schemes such as the Natural Heritage Trust's Bushcare program, and market-based incentives such as the CFI and voluntary carbon markets. Additionally, the Government's proposed 'Green Army' would pay trainees to participate in environmental management and restoration projects, some of which would involve tree plantings that might contribute to emissions reductions targets.

The Bushcare program invested $127 million over five years to address goals relating to the conservation and restoration of native ecosystems across Australia. Most of the funding was directed to on-ground works, such as tree planting and the protection of remnant vegetation, carried out by community groups and state or local governments. The average cost of Bushcare revegetation works carried out across 1,007 sites was $1,378 per hectare [$644 of Bushcare funding (Anonymous 2005) with a leveraged funding ratio of 1:2.14 (Hassall & Associates 2005)], or $1,866 in 2012 terms. The cost of revegetation works varies greatly across different sites and regions, and also with the scale and type of project (Schirmer and Field 2000). Detailed estimates from specific case studies have been substantially greater than those derived from Government grant programs (Table 5). As with rabbit control works, ongoing expenses for monitoring and maintenance are expected to be incurred until plants become established. The expense of monitoring alone has been estimated at about $41 per hectare annually for five years ($30 per hectare in 1999 terms, Schirmer and Field 2000).

In situations where the carbon sequestration benefits of intensive rabbit control are similar to those of conventional revegetation operations, rabbit control clearly provides a substantial cost advantage. The most expensive example of combined poison baiting, fumigation and warren ripping in Table 4 was estimated to cost only a quarter of the least expensive conventional restoration estimate in Table 5. An economic decision model for restoring native vegetation in south-eastern Australia also found substantial cost advantages in conducting intensive rabbit control, relative to conventional tree planting, in areas with high capacity for natural regeneration (Cooke *et al*. 2010).

Table 5: Costs ($ per hectare, in 2012 terms) of revegetation operations estimated indirectly from Government grant programs and case studies. Total cost until establishment includes five years of monitoring at $41 per hectare per year.

Source of estimate	Initial expense	Total cost until establishment
Government grant programs [1]		
One Billion Trees and *Save the Bush*	1,716	$1,921
Bushcare	1,866	$2,071
Case studies [2]		
Assisted regeneration in temperate region	3,328	$3,533
Seedlings in semi-arid region	3,526	$3,731
Tubestock in semi-arid region	3,842	$4,047
Direct seeding in temperate region	4,757	$4,962
Seedlings in temperate region	6,242	$6,447

[1] Anonymous 2005; Hassall & Associates 2005, [2] Schirmer and Field 2000

The primary aim of programs such as Bushcare and the more recent Biodiversity Fund has been the restoration of a broad suite of environmental values, rather than the specific development of carbon sinks. Rabbit control programs for environmental benefit have the same aim. The resulting vegetation communities typically include a diverse range of local species and growth forms that are well-adapted to the local environment, provide a broad range of ecosystem and habitat functions, are resilient to disturbance and require little ongoing maintenance. However, estimation of carbon gains across structurally and floristically diverse communities can be difficult. Conversely, plantings aimed primarily at sequestering carbon should be dominated by a smaller number of high biomass species planted at high density to capture a greater total amount of carbon at a faster rate, and hence provide the greatest returns on investment.

Only 14 environmental planting or reforestation/afforestation projects have been admitted under the Carbon Farming Initiative to date, and only five of these have produced carbon credits (Anonymous 2014). The rate of new forest establishment has declined heavily since

2007, and a greater area of forest was cleared than established in 2012 (Climate Works Australia 2013). The potential expansion of similar projects will depend on several factors, including the price of land, potential returns on investment and returns from existing or competing land uses. A study of the potential for conversion of cleared land to non-harvested carbon forestry indicated that a carbon price of at least $40 per tonne was probably necessary for such projects to be profitable in their own right (Polglase *et al*. 2011). Some on-farm environmental plantings may have a lower break-even point, between about $5 and $20 per tonne, if land value is not considered (Paul *et al*. 2013). However, these types of plantings are likely to be limited to small areas of farms that are unsuitable for more profitable land uses such as cropping and livestock production. Some analysts expect the ERF to pay between $10 and $20 per tonne (e.g. Grossman *et al*. 2013). While there are many types of carbon forestry investors and business models, commercially-motivated carbon forestry projects seem unlikely to make major contributions to Australia's emissions reductions targets at this price.

6.3 Costs and likely benefits of biological rabbit control

Recent estimates value the cumulative benefit of myxoma virus (MV) and RHDV to Australia's pastoral industries at approximately AU$70 billion over the last 60 years (Cooke *et al*. 2013). In environmental terms, significant regeneration of native vegetation occurred after the introduction of RHDV, particularly in the semi-arid areas, despite a period of below average rainfall for the region (Sandell 2002; Murdoch 2005, Figure 8; Mutze *et al*. 2008; Bird *et al*. 2012). In economic terms, RHDV has generated benefits of almost $6 billion to the rural industries alone (Cooke *et al*. 2013). Given that government and industry investment in the initial RHDV release is estimated at $12 million (Cooke *et al*. 2013), the return on investment is unmatched, potentially by any other form of government investment in the last 50 years.

The current RHD-Boost project, which is investigating overseas strains of RHDV for use in Australia has already received an investment of $2 million from Industry and the Australian Government's Caring for Our Country initiative, $1.1 million through the Invasive Animals Cooperative Research Centre, and requires an extra $1.5 million for the rollout and performance monitoring of the impact of the new strain. The impact of this ~ $5 million project has been estimated as a net present value of $840 million over 15 years, excluding any carbon storage value (Agtrans Research 2009). With carbon storage, the net present value was estimated at over $1.45 billion. This was based on a carbon price of $20 per tonne and an increase in carbon storage of 0.005 t CO_2-e storage per km^2, arising from an 85% decline in rabbit abundance over 1.5 million km^2 (Agtrans Research 2009). This estimate considered only the contribution of rabbits to total grazing pressure, not the potential benefits that might be realised from releasing woody vegetation from suppression.

The costs of conventional rabbit control can be prohibitively expensive, particularly in rangeland areas where land size is vast, and the gains in production or carbon sequestration are unlikely to outweigh the costs of control. Biological control is the only economically viable broadscale control tool to manage rabbits across vast arid areas. Without the benefit of existing biocontrol agents for rabbits, it is estimated that the national impact of rabbits would lead to livestock production losses of $2 billion/yr (Cooke *et al*. 2013).

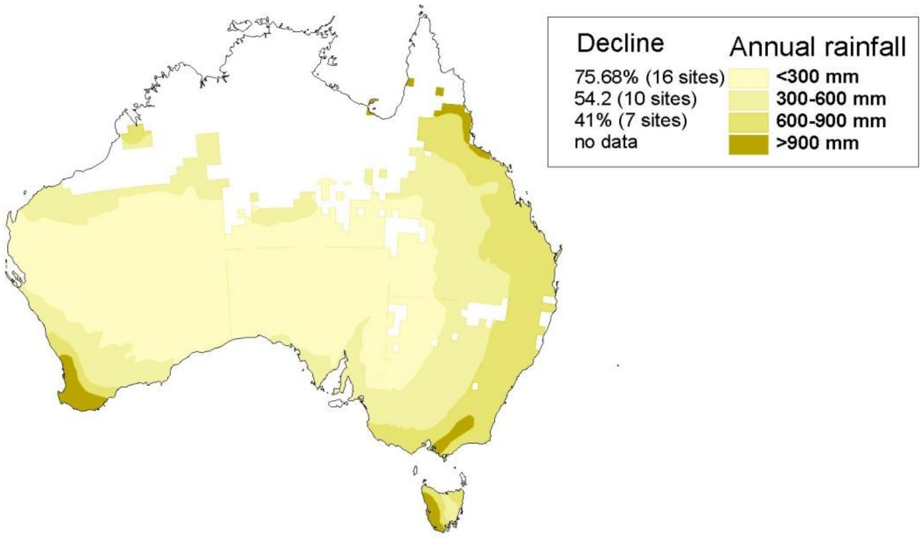

Figure 8: The decline in rabbit populations by rainfall zone after the arrival of RHDV (Cox *et al.* 2013).

6.4 Structural challenges

In order to contribute to Australia's existing emissions reduction commitments, abatement activities must be verifiable, additional and permanent. These requirements present particular challenges to LULUCF activities such as afforestation and vegetation regeneration. Many of these challenges are discussed elsewhere (e.g. Watson *et al*. 2000; Eady *et al*. 2009; Cowie *et al*. 2012). The CFI Positive List, which outlines activities that are eligible for inclusion in the CFI, accounts for these requirements. The Positive List includes human-induced regeneration of native vegetation, on land that is not conservation land, achieved through the management of feral animals (Anonymous 2013c, 2013e).Here, we briefly discuss specific challenges relating to the use of invasive herbivore control to facilitate vegetation regeneration.

6.4.1 Verifiability

Carbon accounting for LULUCF activities requires estimation of changes in carbon stocks from baseline levels or rates of change, based on statistically representative sampling or modelling with appropriate monitoring, reporting and verification. The effects of herbivore control on vegetation regeneration can be expected to vary greatly across different land units depending on factors outlined in section 6.1. Temporal variation is also likely to be high given that many of the rangeland landscapes where this type of activity would be applicable are highly dynamic and herbivore populations can also fluctuate. Volatility will be most acute for herbaceous vegetation and for woody vegetation in arid regions where rainfall is often the major determinant of plant growth and reproduction. Compensatory effects from grazing or browsing by livestock and native herbivores would also need to be estimated as part of a leakage assessment. Furthermore, the carbon benefits of most herbivore control activities are likely to be relatively modest on a per hectare per year basis, so monitoring programs must be able to detect small and variable effect sizes. Consequently, the extent of sampling required to generate reliable estimates of change in carbon stocks is likely to be large and expensive.

6.4.2 Additionality

Carbon abatement projects must demonstrate that measured carbon gains are attributable to a specific management action, and would not otherwise have occurred under a 'business as usual' scenario. This presents two main challenges for projects aiming to increase carbon storage through invasive herbivore control.

The first challenge is establishing baseline rates of change in carbon stocks, as discussed above. Only carbon gains above this baseline rate can be credited. The second challenge is demonstrating that the herbivore control activity itself is actually additional to normal land management practice. Rabbits are a declared pest in all states, and legal requirements exist for their active control, so it could be argued that rabbit control is a universal obligation. However, definitions of 'control' are generally vague, and the intensity of conventional control activities needed to facilitate widespread vegetation regeneration is much greater than occurs in common practice. Biological control of rabbits has been an active field of research for many years, so it might be difficult to claim credit for carbon gains across vast areas resulting from biological control unless investment is specifically tied to carbon abatement objectives. Nonetheless, the Government intends that some projects with incidental abatement benefits will still be able to bid into the ERF (Department of the Environment 2013).

6.4.3 Permanence

The concept of permanence is poorly defined under existing international agreements, but the current accepted timeframe over which sequestration projects must maintain carbon storage is 100 years. This has been the standard for all offset projects under the CFI. However, a 25 year timeframe might be available under for some projects bidding into the ERF, which would then receive a discounted number of credits (Department of the Environment 2013).

Permanence does not necessarily imply that invasive herbivore control must be maintained in perpetuity. Once woody plants reach a stage of growth at which they are no longer vulnerable to attack they can survive, grow and continue to sequester carbon without further animal control activities. Nonetheless, vegetation layers within reach of herbivores will continue to be impacted. The full potential for soil carbon storage and other landscape function attributes will therefore not be realised as long as rabbits or other locally-important pest species persist at damaging densities. It would be particularly difficult to claim credits for herbaceous vegetation at any stage in the project unless the effects of herbivore resurgence could be reliably estimated.

7. Cultural opportunities and constraints

Rabbit control clearly has the potential to provide an effective and economically efficient means of enhancing carbon sequestration through the natural regeneration of woody vegetation. However, it is still possible that these methods and outcomes may not always be socially desirable. Evaluation of the cultural desirability of carbon sequestration opportunities requires assessment of the acceptability of management options and the desirability of the managed state (Stafford-Smith *et al*. 1995).

7.1 Acceptability of large-scale rabbit control

Wild rabbits have had wide-ranging and profound adverse impacts on Australia's biodiversity and agricultural production, and appear to have little or no positive value (Gong *et al*. 2009; Cooke 2012a). Public attitudinal surveys indicate that this is widely recognised, that most people believe that rabbit impacts should be actively managed, and that current control methods are acceptable (reviewed in Fitzgerald *et al*. 2007). Widespread restoration of native vegetation through the control of rabbits should therefore be well-received. The proposed camel control CFI methodology, which would have provided credits for avoided emissions on the basis of numbers of animals killed, was viewed cynically by some (e.g. Black 2012). Moreover, animal welfare groups are likely to oppose the concept of killing animals solely for carbon benefits (e.g. Caraza 2011). However, the range and depth of rabbit impacts is more widely understood and appreciated, and the regeneration of native vegetation is a well-accepted means of abating carbon emissions.

Four biological control agents have been introduced into Australia since 1950: two viral diseases and two insect vectors to facilitate the transmission of myxoma virus. These agents have been highly successful in reducing rabbit impacts, and further research is being conducted to ensure that the benefits are not eroded as rabbit populations develop resistance and disease efficacy deteriorates (Saunders *et al*. 2010; Cox *et al*. 2013). The concept of biological control is generally well-supported by the community (Johnston and Marks 1997; Fitzgerald 2009), and the benefits delivered by myxomatosis and RHD are widely recognised. However, novel biological control agents that are perceived to severely compromise animal welfare or to infect non-target species are unlikely to be acceptable (Henzell *et al*. 2008). Moreover, current CFI guidelines specify that methodologies involving herbivore control must be verifiably humane.

7.2 Cultural desirability of the managed state

Given that rabbits occupy and impact upon a wide range of landscapes and ecosystems across the continent, it is not possible to identify a single landscape state emerging from the release of native woody vegetation from suppression by rabbits. However, some generalisations can be made. Here, we consider only sites where the control of rabbits facilitates natural regeneration.

Most obviously, fewer rabbits will be present, and vegetation types that had been suppressed will begin to regenerate. This may include herbaceous vegetation, particularly perennial species that are important for ecosystem stability and function, and also higher biomass woody species. In time, with continued suppression of rabbits, woody vegetation should develop to maturity and the full range of age classes will be present. Sites that support greater diversity and biomass of native species should have greater landscape function, which provides a more productive and resilient system (Bastin 2008).

The economic impacts of rabbits on the beef, lamb and wool industries have been estimated at about $213 million per annum, mostly through lost production (Gong *et al*. 2009). Widespread reduction in rabbit numbers and increased productivity and resilience of grazing systems is therefore expected to provide substantial economic benefits to individual producers, rural communities and the national economy (Agtrans Research 2009). Importantly, the use of biological control agents to induce vegetation regeneration would have continental-scale benefits. It would also result in reduced or avoided expenditure on conventional rabbit control.

Reduced rabbit densities and increased regeneration of native vegetation would have widespread benefits for environmental and biodiversity values. Many studies have noted that plant species that are highly susceptible to rabbits, such as mulga, could become extinct in many areas if the impacts of rabbits are not ameliorated (e.g. Lange and Graham 1983; Friedel 1985; Mutze *et al*. 2008). The preservation of these species and intact 'outback' landscapes has high intrinsic and social value, and is also important for the maintenance of ecosystem integrity and function. Reduced rabbit densities and the restoration of degraded ecosystems should also benefit native fauna such as the greater bilby (Morton 1990; Cooke 1998; Cooke 2012a). One potentially adverse environmental outcome could be that more productive livestock grazing systems result in increased stocking rates, as occurred after the introduction of MV (Cooke *et al*. 2013), and hence greater methane production. However, in the current context, the main benefits of more productive grazing systems are likely to be realised through greater wool cut per sheep and increased sale weights of cattle and lambs, rather than increased stocking rates (Agtrans Research 2009; Gong *et al*. 2009).

The combined economic and environmental benefits of reduced rabbit densities and increased regeneration of native vegetation can be expected to contribute positively to the well-being of rural and regional communities. Healthy and resilient regional communities, economies and ecosystems are also highly valued by many urban Australians (Heathcote 1994). Consequently, landscapes that support fewer rabbits and greater agricultural and environmental productivity are highly desirable from almost all economic, environmental and social perspectives.

8. Future directions

Recent international research has suggested that herbivore control could provide significant carbon sequestration benefits in some circumstances (Peltzer *et al.* 2010; Holdaway *et al.* 2012; Tanentzap and Coomes 2012), and the preceding discussion shows that the control of rabbits and other invasive herbivores could contribute to Australia's greenhouse gas emissions reduction targets. However, the likely magnitude of any benefits is unclear, and there may be considerable practical and cultural barriers to achieving carbon gains that are admissible under an international carbon accounting framework. Further research is needed to estimate the extent to which invasive herbivore control could contribute to carbon abatement, and also the feasibility of using herbivore control within an internationally acceptable carbon accounting framework. A suitable research program might follow a two-pronged approach to solving these problems using: 1) predictive modelling based on currently available data, and 2) field studies in which rabbit populations are manipulated and changes in carbon sequestration rates estimated. Each side of this program would inform future iterations of the other. Such a program would require significant investment and collaboration among a diverse group of subject matter experts.

8.1 Predictive modelling

A well-constructed model environment should be useful for generating testable predictions about the magnitude and variability of potential changes in carbon accumulation rates for different land types under different herbivore management regimes. This would be a valuable intermediate tool for guiding future work while a more detailed and mechanistic understanding of system dynamics under herbivore management is developed. It would also identify knowledge gaps that would need to be filled in order to develop verifiable models for GHG accounting purposes. However, given the current scarcity of data and the complex biophysical interactions that characterise carbon fluxes in many Australian landscapes, any predictions based on existing data are likely to have low precision. In some cases, even the likely direction of net change in carbon sequestration rates may not be clear.

More detailed and insightful modelling might be possible for some specific locations where data on vegetation responses to changes in rabbit populations are already available (e.g. Flinders Ranges, Mutze *et al.* 2008). These data could be combined with allometric biomass estimation methods for rangeland trees and shrubs (e.g. Pressland 1975; Harrington 1979) to estimate carbon gain in live biomass attributable to reductions in rabbit density. Ideally, models should allow for prediction of carbon fluxes across all pools within an ecosystem including above- and below-ground biomass, coarse woody debris, litter and soil. They would also need to account for climatic variability.

8.2 Field studies

Predictive modelling should be useful for visualising ranges of likely outcomes from different scenarios, generating testable hypotheses and possibly for identifying possible unexpected consequences of management actions. However, effective decision making and carbon accounting will require rigorous estimation of likely carbon gains resulting from herbivore control and a sound understanding of the mechanisms that underlie them. This can only be achieved via direct estimation from intensive field studies.

The design of field studies to estimate the impacts of herbivore control on ecosystem carbon stocks is complicated by the fact that carbon gains are likely to be small (per unit area), driven by complex interactions, and highly variable. Consequently, large sample sizes and long sampling intervals are likely to be necessary for effective estimation of baseline sequestration rates and changes in those rates as a result of herbivore management (Holdaway *et al*. 2012; Marburg *et al*. 2013). Given these constraints, it would be prudent to concentrate initial investment in one or a small number of trial sites to evaluate the biophysical and practical potential to realise meaningful carbon gains from herbivore control. Selection of appropriate sites will be critical for the success of initial field studies (Holdaway *et al*. 2012; Marburg *et al*. 2013).

The most direct way to estimate the impacts of herbivore control on biomass and carbon sequestration would be to manipulate herbivore densities at paired treatment and nil-treatment plots, and compare rates of change over time. With sufficient replication, it may be possible to estimate relationships between rabbit densities and biomass. Herbivore manipulation could be achieved by lethal control at large scale plots (e.g. Bird *et al*. 2012), or by constructing exclusion fences around smaller plots (e.g. Marburg *et al*. 2013). Smaller, fenced plots would allow greater replication, but fencing should allow access to other herbivores that would not be subject to routine control, so that the effects of compensatory grazing can be included. Initial trials would need to consider carbon fluxes in all pools, including carbon emissions from control activities, to allow full description of the carbon budget and to describe the mechanisms underlying any changes.

It may be possible to integrate trials with existing long-term rabbit control programs. This should enhance efficiency and could assist with the leverage of research funding. Also, the inferential capability of field studies might be strengthened by co-locating them with sites used for the release and monitoring of new RHDV strains, under the RHD-Boost Project. This could allow an intervention analysis or incomplete crossover approach to be used, in which the carbon sequestration capacities of treatment and nil-treatment sites are contrasted before and after the introduction of a new biological control agent. However, it may be difficult to establish sufficiently precise estimates before the intervention.

9. Conclusion and recommendations

There appears to be substantial potential for invasive herbivore control to provide cost-effective contributions to Australia's emissions reduction targets. This potential may be increasing as the current uncertainty about the value of carbon services escalates the economic risk associated with conventional biosequestration methods. However, there is much uncertainty about the magnitude and type of benefits that might actually be achieved in different situations. Based on information currently available, the facilitation of native vegetation development through suppression of rabbit populations is likely to provide the greatest and most rapid benefits. However, the control of other widespread and abundant species might also be useful. More effective and widespread control of invasive herbivores, particularly rabbits, would also have important co-benefits for productivity, regional communities and the environment.

Realisation of the potential emissions abatement benefits of invasive herbivore control will depend on the development of:

1. a sound understanding of the technical and achievable potential for invasive herbivore control to contribute to emissions abatement, through facilitation of native vegetation development and/or reduced GHG emissions;
2. awareness among researchers, policy-makers and practitioners of the potential benefits of invasive herbivore control for emissions abatement; and
3. incentives for the adoption of invasive herbivore control for the purposes of emissions abatement, and the identification and reduction of potential barriers.

Realisation of the greatest benefits will further depend on the availability of a means to consistently suppress invasive herbivore populations across vast areas.

We therefore recommend a course of action that would, in the first instance, stimulate research to satisfy the first point noted above, by:

- raising awareness of the full suite of potential emissions abatement benefits of invasive herbivore control with relevant researchers and policy-makers;
- cultivating collaboration to develop a research plan that combines predictive modelling and field trials to evaluate and demonstrate potential carbon sequestration benefits of rabbit control; and
- obtaining financial support to implement the research plan.

We further recommend securing continued support for rabbit biocontrol research to arrest the erosion of RHDV benefits and to enable broadscale suppression of rabbit populations. This will be essential for securing carbon sequestration benefits through invasive herbivore control at sufficient scale to make significant contributions to Australia's emissions reduction targets.

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11. Appendix 1: Mulga carbon benefit estimation

Coarse estimates of the potential sequestration benefits of removing rabbit impacts on woody regeneration in mulga woodlands were produced using the following procedure:

1. The estimated distribution of rabbits (West 2008) was overlaid on a map of mulga woodland distribution (Milton Moore and Perry 1970) to estimate the area of mulga woodlands potentially impacted by rabbits (143 M ha, Figure 6).
2. Estimated carbon gains, in live biomass only, resulting from the removal of grazing pressure in the Mulga Lands Bioregion (Witt *et al*. 2011) were extrapolated across different percentages of the area estimated in Step 1 to represent different levels of rabbit impact across the mulga woodlands.

The following additional assumptions were made:

- Rabbit control is 100% effective in reducing the adverse impacts of rabbits on mulga regeneration
- Other conditions (climate, fire etc) are favourable for establishment and survival of seedlings across the affected area
- Mulga regeneration is consistent across all areas where rabbits are controlled, and follows a pattern similar to that shown in the eastern extent of the mulga woodland distribution (Witt *et al*. 2011; Daryanto *et al*. 2013).

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ISBN: 978-1-921777-74-5 (print)
ISBN: 978-1-921777-75-2 (online)