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Offsets required to reduce the carbon balance of sheep and beef farms through carbon sequestration in trees and soils

Natalie Doran-Browne[A,C], *Mark Wootton*[B], *Chris Taylor*[A] *and Richard Eckard*[A]

[A]Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville, Vic. 3010, Australia.
[B]Jigsaw Farms, 1874 Hensley Park Road, Hensley Park, Vic. 3301, Australia.
[C]Corresponding author. Email: n.doran-browne@unimelb.edu.au

Abstract. The sustainability of farming is important to ensure that natural resources remain available into the future. Ruminant livestock production generates more greenhouse gas emissions than other types of agricultural production and most livestock mitigation options to date have a modest greenhouse gas reduction potential (<20%). Trees and soils, by comparison, can sequester large amounts of carbon depending on the availability of land. Previous studies on carbon neutral livestock production have shown that farms with a stocking rate of 8 dry sheep equivalents (DSE)/ha can be carbon neutral or carbon positive by sequestering more carbon than is emitted from the farm. However, the carbon offsets required by farms with higher stocking rates (>20 DSE/ha) has yet to be studied in Australia. The challenge is to sequester enough carbon to offset the higher level of emissions that these higher stocked farms produce. This study calculated the carbon balance of wool, prime lamb and beef enterprises using a range of stocking rates (6–22 DSE/ha) and levels of tree cover in two agroecological zones. Emissions from livestock, energy and transport were offset by the carbon sequestered in trees and soils. Additionally, the carbon balance was calculated of a case study, Jigsaw Farms, an intensive sheep and beef farm in south-eastern Australia. The methods used to calculate emissions and carbon stocks were from the Australian National Greenhouse Gas Inventory. The majority of stocking rates were carbon positive over a 25-year period when 20% of the sheep or beef enterprises were covered with trees. This study demonstrated that substantial reductions can be made in greenhouse gas emissions through the use of carbon sequestration, particularly in trees. The results showed that from 2000 to 2014 Jigsaw Farms reduced its emissions by 48% by sequestering carbon in trees and soil. The analysis of different stocking rates and tree cover provides an important reference point for farmers, researchers and policy analysts to estimate the carbon balance of wool, prime lamb and beef enterprises based on stocking rate and the area of tree cover.

Additional keywords: agricultural systems, animal production, global climate change, greenhouse gases, sustainable grazing systems.

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Introduction

The sustainability of farming has become an important focus of research to ensure that natural resources remain available, underpinning food production into the future (Pretty 2008). One focus of this research is the contribution that ruminant livestock make to greenhouse gas emissions (GHGE), increasing by ~1% each year (Lamb *et al*. 2016). The carbon (C) balance of a farm can be defined as the amount of carbon dioxide equivalents (CO_2e) from farm emissions (livestock, fuel, energy, the production of fertiliser and supplementary feed), less any C stored in trees or soil. The term C neutral is used when the farm emissions are offset in their entirety by an equal amount of C sequestration or the mitigation of GHGE, and the term C positive is when more C is stored than produced on-farm.

Ruminant livestock production generates more GHGE than other forms of agricultural production (Garnett 2009). Although animal emissions can be reduced by up to 30% (Gerber *et al*. 2013), many mitigation options have a mitigation potential of less than 20% (Waghorn *et al*. 2006; Alcock *et al*. 2015; Browne *et al*. 2015; Doran-Browne *et al*. 2015). Trees and soils can sequester large amounts of C depending on the availability of land, rainfall and the effect that tree planting has on the land available for agricultural production.

The time period analysed is of utmost importance when calculating the C balance of a farm. The highest rates of C sequestration in Eucalyptus tree species in south-eastern Australia occurs ~20–25 years after the tree is planted, depending on the tree species and environment (Unwin and Kriedemann 2000). The C balance will appear favourably if this time period is analysed in isolation. However, any livestock on the farm will be emitting GHGE over the initial 20–25-year period and these emissions need to be included in the analysis. For this reason, although annual emissions can still be considered, cumulative emissions over a specified time period should be presented when analysing the C balance of a farm (Doran-Browne *et al*. 2016).

Doran-Browne *et al*. (2016) showed that farms with a stocking rate of 8 dry sheep equivalents/ha (1 DSE = 8.8 MJ/day, the energy required to maintain the liveweight of a 50-kg non-lactating sheep) or less required less than 15% of the farm to be covered by trees to be C neutral. However, the C stocks required on farms with a higher livestock stocking rate have yet to be studied. Intensive sheep and beef farms have higher stocking rates (18–22 DSE/ha) than less intensive farms (McEachern *et al*. 2010; DEDJTR and Rural Finance 2015). Therefore, the challenge on intensive farms is to sequester enough C to offset the additional emissions from these higher stocking rates.

This study aimed to: (1) evaluate a range of stocking rates by percentages of tree cover options required for livestock enterprises in temperate regions of south-eastern Australia to be C neutral or positive and (2) determine the C balance of a wool, prime lamb and beef enterprise with a relatively high (20–22 DSE/ha) stocking rate.

Methods

Modelling C sequestration in trees and soils

The FullCAM model, version 4.00 (Richards and Evans 2004) was used to estimate C sequestration in trees, as well as soils for the case study farm. The FullCAM model used SILO data drill climate files (see http://www.longpaddock.qld.gov.au/silo/, accessed 14 April 2015) from the nearby Hamilton Airport (37°39′S, 142°04′E) on a monthly time step. The FullCAM model was run from 1870, the point of initial tree clearing, and projected forward to 2090, so that the changing rates of C sequestration in trees from plantation to future growth could be estimated. The SILO climate data were interpolated in FullCAM to generate climate data beyond 2014, by merely repeating the historical climate sequence.

Two different groups of trees were modelled. The first group were planted for environmental benefits and were represented in FullCAM using the default recommended species mix for the location based on ‘environmental plantings’ (see Paul *et al*. 2015 for further details on environmental plantings tree species). These trees were calibrated to match measured rates of C sequestration at Jigsaw Farms for trees that were 4 and 7 years old and sequestered 0.7 t C/ha and 1.7 t C/ha, respectively (as measured by Greenfleet, Melbourne, Vic., Australia; M. Wootton, pers. comm.). The second group of trees consisted of *Corymbia maculata* agroforestry plantings that were defined in FullCAM with a mature aboveground biomass of 196.7 t DM/ha, assuming a medium quality site (Ximenes *et al*. 2005), and a faster growth rate than environmental plantings, determined by the species multiplier for the aboveground biomass in FullCAM being set at 2. These settings produced C sequestration outputs of 19.5 t C/ha when the trees were 10 years old, consistent with C density measurements of *C. maculata* by Walsh *et al*. (2008), being 19.1–23.3 t C/ha.

Calculating the C balance of wool, prime lamb and beef enterprises at different stocking rates and levels of tree cover

Two different agroecological zones were used to analyse the C balance of wool, prime lamb and beef enterprises. The first zone in Hamilton, Victoria, was more suitable for more intensive farming (14–22 DSE/ha (DEDJTR and Rural Finance 2015)) due to higher rainfall and more fertile soils. These enterprises were based on Jigsaw Farms and are described in the following section. The second zone in Yass, New South Wales, was more appropriate for less intensive farms (6–10 DSE/ha (McEachern *et al*. 2010)) and was based on the modelling case study detailed by Doran-Browne *et al*. (2016). The characteristics of the Yass farm are in Table 1 and further information is available in Doran-Browne *et al*. (2016). The Yass case study was expanded from the wool enterprise to also include prime lamb and beef enterprises.

The livestock systems were represented using the whole-farm, mechanistic, biophysical model, GrassGro (Freer *et al*. 1997). GrassGro includes modules for soil water and nutrient balance, pasture production, and animal production. The GrassGro model has been validated in other studies, particularly the pasture and animal production modules (e.g. Clark *et al*. 2000; Cohen *et al*. 2003) and in the study regions specifically. GrassGro uses a daily time step and, as a mechanistic model, performs complex interactions between the various modules that are influenced by climate data and farm management options.

The C sequestration potential of trees modelled in FullCAM was different for the two agroecological zones. The default environmental planting in Hamilton produces a 20-year average annual C sequestration rate of 2.5 t C/ha in trees, whereas in Yass the 20-year average annual C sequestration

Table 1. The size, stocking rate, sale information and supplement fed on wool, prime lamb (crossbred) and beef enterprises modelled at Yass, NSW using stocking rates of 6 and 10 dry sheep equivalent (DSE)/ha (based on Doran-Browne *et al*. 2016)

B = Barley; H = Hay; M = Mixture of 50% Barley, 20% Lupin, 20% Vetch, 10% Molasses; S = Silage

Enterprise	Wool		Crossbred		Beef	
Year	6 DSE/ha	10 DSE/ha	6 DSE/ha	10 DSE/ha	6 DSE/ha	10 DSE/ha
Stocking rate (ewes or cows/ha)	3.4	6.1	3.3	5.7	0.4	0.7
Weaning percentage (%)	76	74	107	104	90	89
Month of calving/lambing	Sept.	Sept.	July	July	Aug.	Aug.
Young stock sale age (months)	12–14	12–14	5–8	5–8	13–15	13–15
Ewe/heifer sale weight (kg liveweight)	50	48	45	45	340	331
Wether/steer sale weight (kg liveweight)	45	41	46	46	391	379
Supplementary feed (t/ha)	0.03	0.16	0.25	0.65	0.8	1.7
Type of supplement fed	B	B	B/M	B/M	H/S	H/S

rate is 1.6 t C/ha (Doran-Browne *et al.* 2016). Different percentages of tree cover were modelled with 10%, 20%, 30% and 40% of the enterprise area being covered with trees. This sensitivity analysis also included pre-farm emissions from the production of fertiliser and supplementary feeds, but excluded C sequestration in soils.

Soil C levels under the long-term permanent pastures at Hamilton were considered as largely stable, based on the work of Robertson and Nash (2013). Therefore, given the lack of soil C sequestration potential, as well as the variability in soil C estimations in other areas of Australia (Young *et al.* 2005; Robertson *et al.* 2016), soil C was assumed to be stable at Hamilton and was excluded from the comparison of stocking rates and tree cover.

The C balance of the farm enterprises was calculated by subtracting the C sequestered in trees and soil from the on-farm and pre-farm emissions. The C balance was calculated over 35 years from when the trees were planted to include the peak rate of C sequestration in trees ~25 years after being planted and to then incorporate declining rates of C sequestration beyond 25 years.

The case study farm, Jigsaw Farms

Jigsaw Farms is a 4900-ha wool, prime lamb and beef farming enterprise in south-west Victoria (37°35′27′S, 142°2′9′E) that was used as the case study for this research. Jigsaw Farms was named due to the numerous parcels of land that the farm consists of, having gradually been purchased to expand the farm area. The farm is split into two main sections by location and the Hensley Park portion was used in this study. Hensley Park has both sheep and beef enterprises but the focus of the farm has changed from 2000 to 2014. In 2000–2004 wool production was the main enterprise, then beef from 2005 to 2007 and more recently prime lamb was predominant from 2008 to 2014 (Table 2). Jigsaw Farms receives an annual average rainfall of 675 mm.

The majority of the original farmland was cleared in 1880 and trees subsequently planted from 2000 to 2006 with a total of 380 ha of permanent environmental plantings and commercial tree plantations (Table 3). Additionally, tree plantings were modelled with all environmental plantings and forestry plantings occurring in 2000 to allow a comparison between the C balance from staggered plantings versus a single planting activity.

Modelling sheep and beef on Jigsaw Farms

The livestock systems at Jigsaw Farms were represented using the GrassGro model (Freer *et al.* 1997). The same SILO climate files for the Hamilton Airport were used as in FullCAM (37°39′S, 142°04′E), only using a daily time step. The model was run from 2000 to 2014 because data from Jigsaw Farms was available for these years to validate the GrassGro model. The C balance of the case study farm was projected forward to 2035 to maintain consistency with the FullCAM analysis on a range of stocking rates and tree cover.

The predominant pasture, Phalaris (*Phalaris aquatica*), was modelled with a fixed legume content of 35% to represent the white clover (*Trifolium repens*) and subterranean clover (*T. subterranium*) at Jigsaw Farms. As the amount of land dedicated to each enterprise changed in 2000, 2001–2004, 2005–2007 and 2008–2014 (Table 2), separate model simulations were used for each enterprise to model these blocks of years. The models were run from 1990 so that carryover effects between years could be included, then outputs for the relevant years were extracted. GrassGro was calibrated for Jigsaw Farms by comparing the model outputs with wool, crossbred and beef farm data from 2000 to 2014 to ensure that Jigsaw Farms was accurately represented by the model.

Calculating greenhouse gas emissions using the IPCC methodology

The IPCC methodology (IPCC 2006), as detailed in the Australian National Greenhouse Gas Inventory (DIICCSRTE 2013), was used to calculate GHGE. The on-farm GHGE modelled were methane (CH_4) from livestock enteric digestion and excreta, nitrous oxide (N_2O) from soil cultivation, dung and urine deposits, indirect N_2O from leaching, runoff and ammonia volatilisation, and CO_2 emissions from diesel, petrol and

Table 2. The size, stocking rate, sale information and supplement fed on wool, prime lamb (crossbred) and beef enterprises at Jigsaw Farms
B = Barley; H = Hay; M = Mixture of 50% Barley, 20% Lupin, 20% Vetch, 10% Molasses; S = Silage; n/a = not applicable

Enterprise	Wool		Crossbred		Beef			
Year	2000	2001–2004	2005–2007	2008–2014	2000	2001–2004	2005–2007	2008–2014
Enterprise size (ha)	510	850	205	1150	70	120	1240	120
Stocking rate (dry sheep equivalent/ha)	20.7	20.7	20.9	20.7	21.2	20.7	25.6	21.2
Stocking rate (ewes or cows/ha)	8.5	8.3	12.4	10.8	1.5	1.4	2.5	1.5
Weaning percentage (%)	73	73	105	126	88	93	93	93
Month of calving/lambing	Aug.	Aug.	July	July	Aug.	Aug.	Aug.	Aug.
Young stock sale age (months)	24	24	5–8	5–8	13–15	13–15	13–15	13–15
Ewe/heifer sale weight (kg liveweight)	52	54	45	45	363	365	164	349
Wether/steer sale weight (kg liveweight)	62	66	45	46	418	420	172	402
Meat sold (kg liveweight/ha)	322	316	470	436	290	325	323	322
Wool sold (kg clean fleece weight/ha)	46	46	39	40	n/a	n/a	n/a	n/a
Fibre diameter (µ)	18.3	18.4	25.2	26.6	n/a	n/a	n/a	n/a
Supplementary feed (t/ha)	0.43	0.05	0.88	0.70	3.13	1.25	5.68	2.38
Type of supplement fed	B	B	B/M	B/M	H/S	H/S	H/S	H/S

Table 3. The permanent revegetation, agroforestry planting activities and livestock areas at Jigsaw Farms

Year	New areas of environmental plantings (ha)	New areas of forestry planted (ha)	Total area used by livestock (ha)
2000	8.3		580
2001	22.1		970
2002	31.8	56.8	970
2003	28.8	34.8	970
2004	38.3	60.2	970
2005	14.6	60.1	1445
2006	7.6	16.9	1445
2008–2014	0	0	1270
Total in 2014	151.5	228.8	1270

electricity. The included pre-farm emissions were the production of feed barley at the rate of 0.30 t CO_2e/t grain and the production of SuperPhosphate fertiliser at 0.23 t CO_2e/t SuperPhosphate (Christie *et al*. 2011). The CH_4 and N_2O emissions were converted and presented in t CO_2e using the global warming equivalent for each gas, being 21 and 310, respectively (DIICCSRTE 2013). The GHGE were projected forward to 2035 by using the average annual emissions from 2007 to 2014, to provide an indication of the net C balance as the rate of C sequestration changed in trees into the future.

Results

The analysis of C balances for a range of tree cover and stocking rates combinations showed a similar pattern for wool, prime lamb and beef enterprises across a 35-year period (Fig. 1 and Fig. 2). Wool, prime lamb and beef enterprises with stocking rates of up to 22 DSE/ha were C positive when more than 20% of the farm enterprise was under tree cover over a 25-year period (Fig. 1). When 10% of the farm was under trees, only the lowest stocking rate analysed (6 DSE/ha) was C positive (Fig. 2).

The net C balance of the case study farm decreased from 2000 to 2007, while the trees were first being established and then remained relatively constant from 2008 to 2030 at around –35 000 to –45 000 t CO_2e (Fig. 3*a*). In 2014, 48% of GHGE were reduced through sequestration, increasing to 67% in 2020. Trees stored around eight times more C than soils in 2014. If all trees had been planted in 2000 instead of staggered plantings from 2000 to 2006, then 75% and 79% of emissions would have been reduced through C sequestration by 2014 and 2020, respectively (Fig. 3*b*). The effect between staggered plantings and single plantings levelled out over time and by 2035 there were 70% and 74% of emissions offset through C stocks in staggered and single plantings, respectively.

An estimated 37 000 t CO_2e was sequestered in trees between 2000 and 2014 on Jigsaw Farms (Fig. 4). Over this period, C in soils remained relatively stable with a modest increase of 200 t CO_2e estimated by the FullCAM model. At 77 800 t CO_2e, total farm emissions were higher than C stocks over the same period, producing a C balance of –40 600 t CO_2e from 2000 to 2014, whereas if the trees had all been planted in 2000,

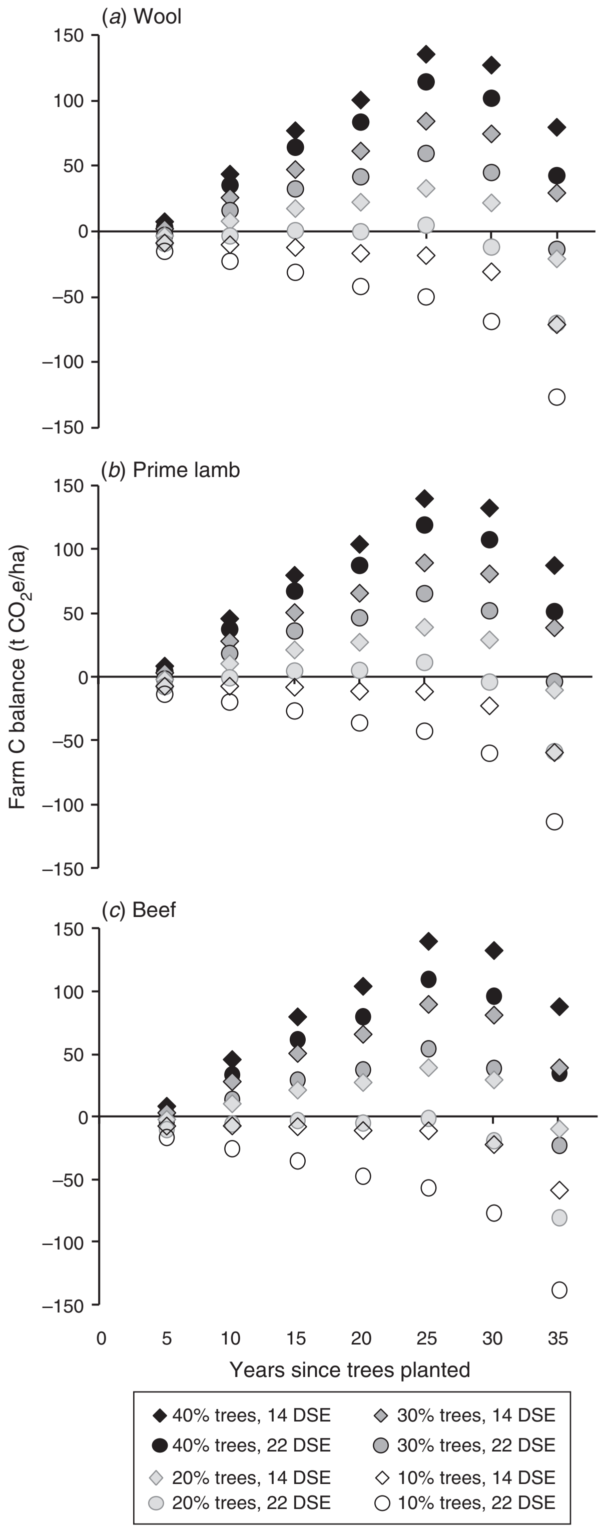

Fig. 1. The carbon balance of (*a*) wool enterprises, (*b*) prime enterprises and (*c*) beef enterprises at stocking rates of 14 and 22 dry sheep equivalents/ha when between 10% and 40% of the farm area has environmental tree plantings for carbon sequestration, based on the Jigsaw Farms case study.

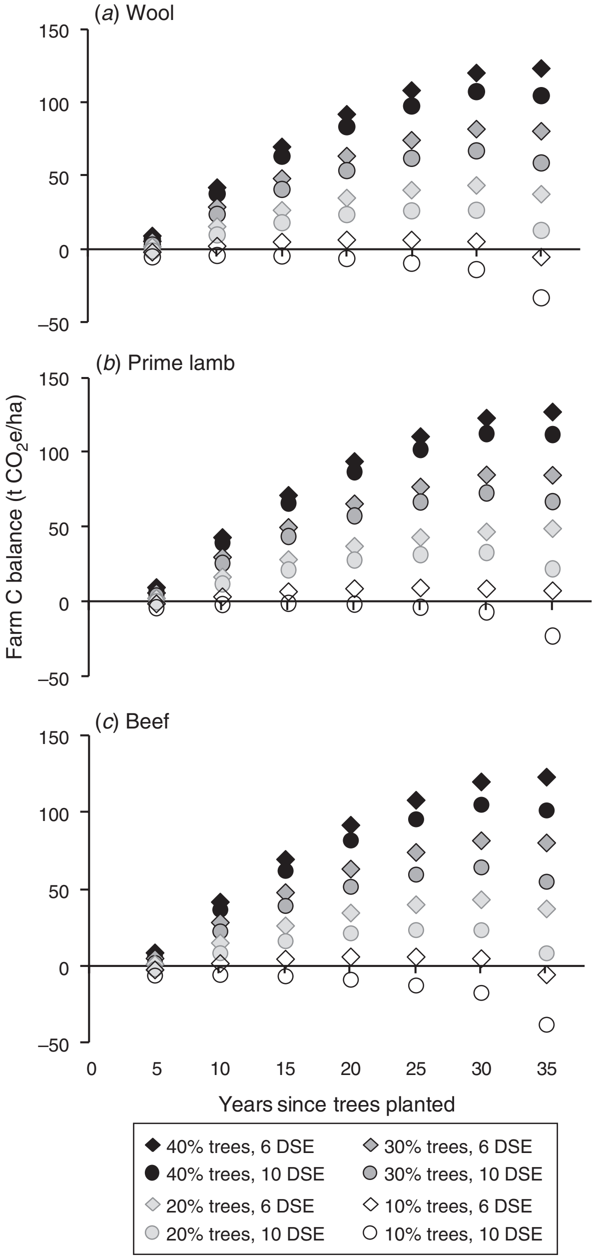

Fig. 2. The carbon balance of (*a*) wool enterprises, (*b*) prime enterprises and (*c*) beef enterprises at stocking rates of 6 and 10 dry sheep equivalents/ha when between 10% and 40% of the farm area has environmental tree plantings for carbon sequestration, based on the Yass case study (Doran-Browne *et al*. 2016).

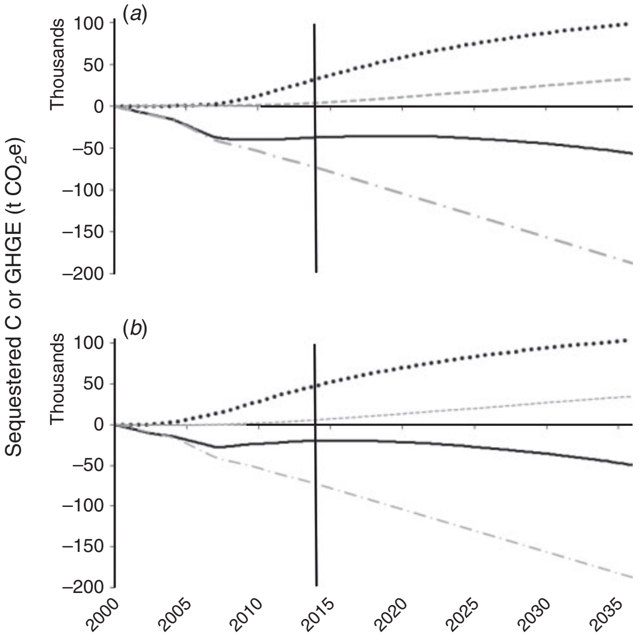

Fig. 3. (*a*) Jigsaw Farms with staggered tree plantings, (*b*) Jigsaw Farms with all trees hypothetically being planted in 2000. The cumulative carbon balance (CO_2e) from 2000 to 2035 (—) is shown, including farm emissions from CH_4, N_2O, CO_2 and pre-farm emissions (–··), as well as carbon stocks in trees (·····) and soil (····). The vertical line is at 2014 and greenhouse gas emissions are projected to 2035 using the annual emissions from the 2007 to 2014 scenario.

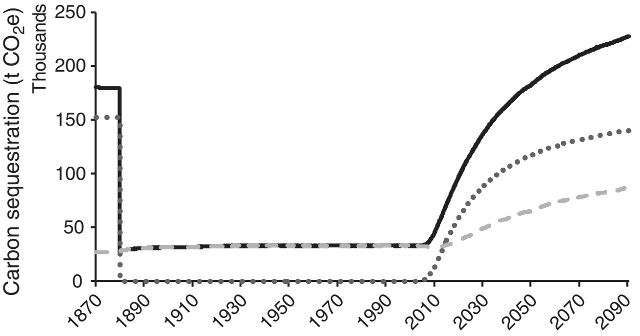

Fig. 4. Estimation of total carbon (C) stocks (—), carbon stocks in soil (----) and carbon stocks in trees (·····) at Jigsaw Farms, following land clearing in 1870 and subsequent tree plantings from 2000.

the C balance would have been –19 600 t CO_2e. The average C sequestration rate in trees over the 20-year period from planting was 2.3 t C/ha.year for environmental plantings and 2.7 t C/ha.year for *C. maculata* forestry. When individual years were analysed, the C balance of Jigsaw Farms was –2251 t CO_2e in 2000 and 920 t CO_2e in 2010 (Table 4) and the farm then remained C positive until C sequestration rates declined around 2030.

Farm emissions were predominantly driven by livestock numbers and consequently fluctuated according to stock numbers (Table 5). The majority of farm emissions (69–77%) were in the form of CH_4. Pre-farm emissions consisted of a small percentage of total emissions (1–9%) in most years with the exception of 2005–2007 when pre-farm emissions represented 27% of total emissions. The bulk of pre-farm emissions (68–99.5%) were from the production of supplementary feed.

Discussion

Analysis of C balances under various stocking rates and levels of tree cover

When 20% or more of the enterprise area was covered by trees, the three livestock enterprises, with stocking rates of up to

22 DSE/ha, were C positive for over 25 years after the trees were planted. This analysis assumed that the trees were planted at the beginning of the time period and results would differ if trees were planted over several years, as shown in the case study of Jigsaw Farms.

Table 4. Carbon balance (CO_2e) of individual years at Jigsaw Farms from 2000 to 2014 including farm emissions (including pre-farm emissions), as well as carbon stocks in trees and soil

Year	C in trees (t CO_2e)	C in soil (t CO_2e)	On-farm emissions (t CO_2e)	Pre-farm emissions (t CO_2e)	Annual C balance (t CO_2e)
2000	0	85	2204	132	–2251
2001	5	207	4034	65	–3888
2002	37	91	3948	22	–3843
2003	189	114	4010	72	–3779
2004	426	48	3854	80	–3461
2005	868	41	5915	1777	–6782
2006	1177	49	5949	2571	–7293
2007	2326	119	6062	2259	–5876
2008	3716	205	3958	589	–626
2009	3609	284	3687	406	–200
2010	5101	257	4169	269	920
2011	5104	616	5441	118	161
2012	4733	683	4295	378	742
2013	4907	903	3899	529	1382
2014	4805	983	4297	629	862

When enterprises at the same stocking rates (DSE/ha) were analysed, the C balance from least to most were prime lamb, wool then beef enterprises, although the differences were small. This is consistent with other research (Browne *et al*. 2013) where GHGE from beef enterprises were slightly higher than emissions from sheep enterprises with similar stocking rates.

The C balance of farms with 10 DSE/ha at Yass and 22 DSE/ha at Jigsaw Farms and 40% tree cover was similar up to 30 years from tree planting. Although the greater rainfall at Jigsaw Farms allowed high stocking rates it also meant greater tree growth to offset these emissions. This effect disappeared at lower levels of tree cover because there were not enough trees to offset emissions when farms were more intensively stocked. Regions of dryland farming that are able to support higher stocking rates commonly have greater rainfall and soil fertility than areas with a lower carrying capacity, therefore this is likely to be a realistic effect.

Analysis of the case study farm, Jigsaw Farms

Despite the study site not being C neutral from 2000 to 2014, nearly half the farm's GHGE were offset in 2014 and almost 70% of emissions offset by 2020 (assuming stocking rates were maintained at 20–22 DSE/ha). This was a significant accomplishment, given that most direct livestock mitigation options reduce GHGE by less than 20% (Henry and Eckard 2009). The C balance changed depending on whether the trees had staggered plantings (as actually occurred) or if all the trees

Table 5. Annual average greenhouse gas emissions (GHGE) produced by wool, prime lamb (crossbred) and beef enterprises at Jigsaw Farms

Year	Unit	2000	2001–2004	2005–2007	2008–2014
		Sheep-Merino		*Sheep-Crossbred*	
Area	Ha	510	850	205	1150
CH_4 emissions	t CO_2e/year	1370	2425	447	2791
N_2O emissions	t CO_2e/year	571	1085	155	851
Pre-farm emissions	t CO_2e/year	67	15	88	302
Total GHGE	t CO_2e/year	2008	3525	690	3944
GHGE per ha	t CO_2e/ha	3.9	4.1	3.4	3.4
		Beef			
Area	Ha	70	120	1240	120
CH_4 emissions	t CO_2e/year	196	326	4032	327
N_2O emissions	t CO_2e/year	59	120	1341	96
Pre-farm emissions	t CO_2e/year	66	45	2114	115
Total GHGE	t CO_2e/year	321	491	7487	538
GHGE per ha	t CO_2e/ha	4.6	4.1	6.0	4.5
		All livestock			
Area	ha	580	970	1445	1270
CH_4 emissions	t CO_2e/year	1566	2751	4479	3119
N_2O emissions	t CO_2e/year	630	1205	1497	947
CO_2 emissions	t CO_2e/year	3	3	3	3
Pre-farm emissions	t CO_2e/year	132	60	2202	417
Total GHGE	t CO_2e/year	2332	4019	8181	4486
GHGE per ha	t CO_2e/ha	4.0	4.1	5.7	3.5
		Carbon sequestration			
C sequestration – trees	t CO_2e/year	0	169	1451	4697
C sequestration – soil	t CO_2e/year	10	75	38	493

were planted in 2000. When all trees were planted at the beginning of the analysis, 75% of the emissions were offset in 2014 instead of 48%. In reality it may be difficult for farmers to plant large sections of land in the same year instead of staggered plantings due to the labour and capital expense. The different levels of emissions offset over time highlight the importance of selecting an appropriate time period to analyse.

When individual years were analysed, the years from 2010 were C neutral due to increased rates of C sequestration that occurred ~8 years after tree planting (Table 4), which can be seen in the way the cumulative C balance levels out from around 2008 to 2030 (Fig. 3*a*). Reporting on emissions cumulatively is a comprehensive method of including all emissions and C stocks that are part of the system for a particular time frame. Again this emphasises the importance of how the reporting period is defined.

A recent review by Herrero *et al*. (2016) showed the livestock sector had the technical potential to reduce GHGE by 1–13% through the following methods: grazing management to improve C sequestration in soils (2–13%), improved feed digestibility (9–12%), feed additives (3–5%), animal productivity and health (1–4%), the use of legumes (2%) or better manure management (1%). However, the economic potential of these mitigation options is below 10% of their technical potential due to implementation constraints, costs, and trade-offs between practice and interactions with other sectors (Herrero *et al*. 2016). Although a full cost-benefit analysis would need to be undertaken before committing to environmental plantings, from a mitigation perspective, these findings are very promising. As C sequestration rates decline in trees after ~25 years, for the species modelled in this case study, more trees would need to be planted at Jigsaw Farms to maintain a C balance of around –40 000 t CO_2e beyond 2030.

The average C sequestration rate for environmental plantings over 20 years in this study (2.5 t C/ha.year) was higher than the 20-year C sequestration rates (1.6 t C/ha.year) estimated for environmental plantings in the Yass case study (Doran-Browne *et al*. 2016), due to higher rainfall and more fertile soils at the Hamilton case study site. Similarly, environmental plantings in southern Queensland with a rainfall of 682–955 mm/year also sequestered an estimated average of 2.5 t C/ha.year (range of 1.0–4.1 t C/ha.year) over a 20-year period (Maraseni and Cockfield 2015). The differences in the C sequestration rates in the study by Maraseni and Cockfield (2015) were also attributed to edaphic and climatic reasons. Differences in C sequestration rates per hectare can also be ascribed to the variability in environmental plantings where different combinations of native trees and stocking densities are commonly found.

A study by Paul *et al*. (2008) found that the C sequestered in *C. maculata* was also dependent on the rainfall at the sites (509–755 mm/year) and was predicted to be 73–90 t C/ha for 32–45-year-old trees and sequestered C at a rate of 3.0–3.3 t C/ha.year. The maculata trees in this study sequestered a similar amount of total C over a similar time period at 78–87 t C/ha, although with a more modest annual rate of sequestration (2.7 t C/ha.year). The rates of C sequestration are, however, influenced by the agroecological zones where the trees are planted, especially the amount of rainfall and the fertility of the soil. The projected C stocks in the future were higher than before land clearing in 1880 at Jigsaw Farms. This is most likely due to maculata being planted, which has a higher rate of C sequestration than the historical woodland plantings in this region.

Although the C in soils is sensitive to management changes, soil C sequestration rates are usually between 0.05 and 0.8 t C/ha.year (Sanderman *et al*. 2010; Robertson and Nash 2013). The soil C sequestration modelled at the study site fell within this range at an average of 0.3 t C/ha.year from 2000 to 2014.

In the dry years between 2005 and 2007, stock were moved from other parts of the farm to Hensley Park, creating higher beef cow stocking rates (25.6 DSE/ha) and a corresponding increase in GHGE during these years. As a result, beef cows required more supplementary feed between 2005 and 2007 (1.2 t/head.year) compared with other years (0.4–0.8 t/head.year). From 2005 to 2007 pre-farm emissions contributed significantly to farm emissions, accounting for 27% of total emissions, compared with 1–9% in other years. It is not expected that stocking rates and pre-farm emissions from feed would increase on farms elsewhere, as it is more common to destock under drought conditions to help manage costs.

Conclusion

This study analysed the C balance of wool, prime lamb and beef enterprises at various stocking rates versus tree cover in south-eastern Australia and showed that storing C in trees can create considerable C offsets against livestock GHGE. When 20% of the farm enterprise was covered with trees, the majority of stocking rates were C positive over a 25-year period. This research provides an important reference point for farmers, researchers and analysts to estimate the C balance of wool, prime lamb and beef enterprises based on the stocking rate and the area of tree cover.

This study also calculated the C balance on Jigsaw Farms in south-eastern Australia, with an average stocking rate of 20–22 DSE/ha and found that from 2000 to 2014 nearly half the GHGE produced by livestock, fuel and energy were offset through C sequestration in trees and soil. This is a noteworthy reduction in emissions, given that most greenhouse gas mitigation options from livestock tend to reduce emissions by less than 20%. Although a full cost-benefit analysis would need to be undertaken before committing to planting trees to offset GHGE, from a mitigation perspective, these findings are very promising, particularly as this is a case study using actual farm data.

A comprehensive economic analysis is required of the C balance of farms at various stocking rates and levels of tree cover, particularly in situations where agricultural land is taken out of livestock production in order to plant more trees. Future research could include the ecological value of environmental plantings, as well as the economic potential of harvested forests, including the storage of C in harvested wood products.

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