Delta LCA of regenerative agriculture in a sheep farming system

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Abstract

Regenerative agriculture is being used by a small numbers of innovative farmers in Australia and elsewhere, and uses a range of holistic methods that works with the land and climate, such as short duration time controlled grazing with long rest periods for the paddock and higher proportions of above ground biomass, to improve soil health and farm profitability. This paper uses a delta life cycle assessment focusing only on the differences between regenerative and conventional production systems to assess the potential impact of regenerative agriculture on a full range of midpoint impact categories and end point areas of protection for an extensive sheep system in Australia. It assesses the potential improvement to the water, carbon and biodiversity footprints of sheep production, and finds that regenerative agriculture has the potential to improve environmental performance compared to current industrial agricultural practices. In particular, there seems to be considerable potential to offset a significant proportion of the on-farm climate change impacts through a combination of biosequestration in soils and above ground biomass and using harvested biomass to offset fossil fuel use. The assessment highlights the need for additional data to confirm the findings and the potential contribution that regenerative agriculture can make to sustainability of ruminant livestock production.

Keywords: comparative Life cycle assessment, regenerative agriculture, greenhouse gas emissions, carbon sequestration, carbon neutral sheep production

Introduction

Background to regenerative agriculture

Regenerative agriculture is a relatively new term, and there are a number of similar terms, such as carbon farming, agroecology, conservation agriculture, holistic farm management, holistic planning grazing, adaptive multi-paddock grazing and integrated ecological farming (California State University, n.d.; Claughton and Ralph, 2019; Cross, 2013; Duncan and Falloon, 2016; Elevitch et al., 2018; Hawkin, 2019; Hodbod et al., 2016; LaCanne and Lundgren, 2018; Rhodes, 2017, 2013; Rodale Institute, 2014; Shelef et al., 2017; Strong, 2008; Teague and Barnes, 2017; Teague, 2018; Thorbecke and Dettling, 2019). In this paper, regenerative agriculture is defined using a practice-based approach, as extensive agriculture that: uses no-till farming; reduces or eliminates pesticide and herbicide use (e.g. spot spraying rather than broadacre spraying); reduces or eliminates fertiliser use; uses high intensity, short duration time-controlled grazing with frequent rotation of livestock between small paddocks with perennial native grasses (i.e. cell grazing) and long rest periods; increases and subsequently maintains the proportion of land with native vegetation; and reduces or eliminates the use of supplementary feeding by destocking during period of low vegetative primary productivity, rather than operating at a fixed stocking rate. The net impact of these practices is expected to be: an improvement in soil fertility, including increases in soil carbon, soil nitrogen and phosphorus levels; an improvement in the resilience of the system to cope with climate change (including increased water infiltration, soil stability and nutrient cycling); improvements in animal welfare; increases in the levels of biodiversity; and an improvement in the profitability of the enterprise (Ampt and Doornbos, 2011; Ampt, 2013; Ash et al., 2015; Lavorel et al., 2015; Provenza et al., 2007; Stanley et al.,

2018; Villalba and Landau, 2012; Walsh, 2015; Wright et al., 2005). As a consequence of the reduction or cessation of supplementary feeding, regenerative agriculture would generally have a human edible protein required (HEPR, the ratio of the amount of human edible protein consumed in feed by livestock to produce one kilogram of animal protein), of less than one (Wiedemann et al., 2015; Wiedemann, 2018), which limits the system to extensive production systems. A recent report (Ogilvy et al., 2018) which reviewed the profitability and biodiversity of farms using practices consistent with most aspects of this definition of regenerative agriculture, which were part of a 15 year project funded as part of the Australian Government's National Environmental Science Program, found that regenerative farmers were "often more profitable than comparable contributors", particularly in dry years. Similarly, anecdotal evidence of improvements to profitability, animal welfare and biodiversity over extended time periods exist (Claughton and Ralph, 2019; Robinson, 2019).

Life cycle assessment, carbon footprinting and agriculture

Life cycle assessment (LCA) has been widely used in the assessment of livestock products such as meat, wool and dairy products, with much of the focus on the on-farm life cycle stage, as this is the most intensive stage in terms of emissions (Steinfeld et al., 2006). The mid-point impact categories (MIC) assessed in LCA studies reflect the issues of relevance to the production system under assessment, so studies to date in Australia have focused on **fossil fuel use, carbon, water and land-use footprints** (Wiedemann, 2018), with a range of other MIC assessed in other geographical locations, such as eutrophication, acidification and ozone formation (Notarnicola et al., 2012). Earlier Australian carbon footprints tended not to include soil carbon or the impacts of land use change (Wiedemann, 2018). Australian farm dams have relatively high water losses, ranging from evaporative losses of 40 %

(Ridoutt et al., 2012) to water supply losses that are higher than livestock drinking water consumption (Wiedemann et al., 2015; Wiedemann et al., 2016), such as 43.3- 84.7 L for livestock consumption compared to 156.9 – 335 L for drinking water supply losses per kg greasy wool . Regenerative farming increases water infiltration into the soil (Ampt and Doornbos, 2011), resulting in less run off into farm dams and necessitating the installation of bores for livestock watering (Robinson, 2019). A recent research project (Colling and Turner, 2016; Hough, 2015) identified that, with redesign to optimise the surface area to volume ratio to reduce losses and incorporate environmental elements, dams could improve their performance in providing stock water while also improving their provision of ecosystem services. Similarly, a recent successful project (Griffiths, 2018) using floating solar panels on a wastewater treatment pond is currently being assessed for use on farm dams, for both reducing water losses and providing sustainable electricity supply. Land use footprints in Australian systems varied depending on whether the system under study differentiated between land types, namely arable cropping, arable grazing or non-arable (Ridoutt et al., 2014; Wiedemann, 2018).

There have been numerous **carbon footprints** for livestock systems, which highlight the higher emissions of ruminant based systems compared to monogastrics (Steinfeld et al., 2006). Options to reduce emissions from ruminant systems include reducing the emissions per unit of meat produced (increased productivity through a combination of genetics, animal health, reproductive performance and optimising liveweight gains, using feed additives to inhibit methanogenesis in grain fed ruminants) and offset the remaining emissions for ruminant supply chains (Herrero et al., 2016). Intensification, particularly increasing the use of grain finishing in feedlots for beef and lamb production, is often touted as an effective means of reducing the carbon footprint (Peters et al., 2010; Wiedemann et

al., 2015), but it increases the use of arable land for grain production, and increases the HEPR to above 1 (Gill et al., 2010; Wilkinson, 2011; Wiedemann, 2018), effectively shifting the impacts from one MIC to another and increasing the pressure on existing arable land, increasing the risk of further land clearing to create more arable land, which in turn leads to more greenhouse emissions (Henry et al., 2018). There has been significant interest in the recent past in **carbon farming**, which uses an increase in soil carbon to offset emissions from the supply chain (Garnett et al., 2017; Hawken, 2016; Henry et al., 2018; Herrero et al., 2016; Sanderman et al., 2010; Toensmeier, 2016). Several large agribusiness firms have recently made public commitments to substantially reduce their carbon footprint or become climate neutral by 2050 (Arla, 2019; Danish Crown, 2019; General Mills, 2019), and regenerative farming and the resulting increase in soil carbon form part of the strategies. Carbon sequestration in grasslands soils seems promising, as a recent study of regenerative farming (Ampt and Doornbos, 2011; Filippi, 2013) found that the regenerated perennial native grasslands had a significantly higher levels of soil organic matter from litter, a larger active root systems and consequently a larger microbial biomass than the introduced annual grass equivalent, in part because the latter system has been designed to maximise the amount of above ground biomass available for animal consumption relative to the total amount of biomass. The perennial native grassland was found to be at least as productive as the more conventional, heavily fertilised system, and had higher levels of plant litter, which translated into higher levels of soil organic matter, which in turn assisted with conserving moisture and reducing soil erosion (Ampt and Doornbos, 2011; Ogilvy et al., 2018). However, conditions in Australia are generally not favourable to soil carbon sequestration (Henry et al., 2015) and there can be significant inter-annual variability in soil carbon levels (Haverd et al., 2016). Despite the remaining uncertainty regarding soil carbon sequestration,

in March 2019, the first Australian carbon credit units (ACCU) were issued for a soil carbon project as part of the Emissions Reduction Fund, which is linked to Australia's nationally determined contribution target under The Paris Agreement (Corporate Carbon, 2019; Renew Economy, 2019; UNFCCC, 2018). Carbon sequestration in above ground biomass is another option, but unless the above ground biomass is harvested, the sequestration peaks and then declines as trees reach maturity (Henry et al., 2015).

Animal welfare and productivity

Animal welfare may also improve in extensive regenerative agricultural systems and has not traditionally been assessed as part of LCA or life cycle sustainability assessments (LCSA, which include environmental, social and economic issues) (Scherer et al., 2018). Animal welfare definitions vary (Carenzi and Verga, 2010), but generally involve two elements, a **healthy** animal that has what it **wants** (Dawkins, 2017). There is an emphasis on the factors that contribute to good health, such as food, water and shelter, balanced with the wants of the animal, such as the ability to move, physical (thermal) comfort, positive emotional state, interactions with others (Dawkins, 2008) or enrichment (Danish Pig Research Centre (SEGES), 2017). There is some evidence that improved animal welfare can also increase **productivity**, for example through reducing animal mortality, and improving general health and the resistance to disease (Dawkins, 2017). There is also a link between **thermal comfort** and **productivity**. Significant heat is produced during digestion in ruminants due to exothermic methanogenic reactions in the rumen, in addition to thermal energy absorbed from the ambient environment. The two main means by which cattle regulate their body temperature to within the thermal neutral comfort zone is by evaporative cooling (mostly sweating) and increasing their respiratory rate (or panting) (Blackshaw and Blackshaw, 1994;

Kadzere and Murphy, 2002). By considering the link between energy intake and energy use, an overview of how heat stress impacts productivity can be obtained, as outlined in **Figure 1**. In addition to impacts from heat stress, when animals are stressed, their core body temperature increases, and this is now being used to monitor animal welfare using thermal mapping with cameras (Meat & Livestock Australia and Ernst & Young, 2018), which translates into an energy use which does not contribute to weight gain. Once an animal has reached a certain stage and is no longer growing muscle, any excess energy is stored in fat, particularly intramuscular fat, which is what occurs during the finishing stage in feedlots (Blackshaw and Blackshaw, 1994; Meat & Livestock Australia, 2012; Tomkins et al., 2009; URS Australia Pty Ltd, 2006; Wiedemann et al., 2015). Additional information is provided in Supplementary Material 2.

Figure 1: Energy cascade for ruminants (adapted from (Thoma et al., 2013))

Method

Delta LCA

This delta LCA is based on an existing LCA of sheep wool production in three regions in Australia, which used a functional unit of one kilogram of wool (Wiedemann et al., 2016). This delta LCA only models the differences between the conventional system as presented in the existing LCA and the regenerative agriculture systems under study, not the whole system. The results from this delta LCA can then be added to the existing LCA study results, to derive a net result. The system boundaries applied in this study are consistent with the existing LCA, so covered on-farm activities up to the farm gate, as indicated in **Figure 2**. Inventory data from the New South Wales high rainfall zone case study sheep farm (NSW HRZ CSF) was used, as this is a similar location to the farm used in this study, however it was modelled using a functional unit of 1 metric ton of live weight (t LW) instead of 1 kg greasy wool, using 100 % allocation to meat to cover all the emissions (refer to Supplementary Material 1.1 for comprehensive details). Midpoint impact categories in the existing LCA included greenhouse gas emissions, fossil fuel energy demand, fresh water consumption and stress-weighted water use. Stress-weighted water use reported in the existing LCA used water stress index (WSI) factors to reflect different levels of water stress in different geographic regions and reported the results in water equivalents (H_2O_e) (Pfister et al., 2009). Assumptions from a recent article (Robinson, 2019) included: electricity consumption 25 % higher, due to the extra pumping required for supplying troughs for livestock drinking, as less water is captured in dams due to the increased infiltration; electricity was produced by solar photovoltaics, some of which could be floating on dams to reduce evaporative

losses; petrol use increased by 20 %; superphosphate use and supplementary feeding with protein grains ceased, but the use of lime was the same; vet product use reduced by 25 % due to the cessation of wether drenching and this was modelled as a reduction in moxidectin, a milbemycin acaricide insecticide (Wormboss, 2016); herbicide use reduced by 90 %, due to change from broadacre spraying to spot spraying (Scott and Cook, 2016) (refer to Supplementary Material 1.2 for comprehensive details). The resulting delta LCA inventory is included in Supplementary Material 1.3.

Figure 2: System boundary for delta LCA of regenerative farm (compared to conventional farm)

The delta LCA was modelled using openLCA v1.7.4 software and the Ecoinvent 3.2 database. The method and characterisation factors in the Best Practice Guide for Life Cycle Impact Assessment in Australia (Renouf et al., 2016) were used for the climate change, mineral resource depletion, fossil fuel resource depletion, consumptive water use, eutrophication, acidification, photochemical ozone formation, particulate matter formation, ozone depletion and ionizing radiation MICs. The default methods in openLCA were used for the human and ecotoxicity (USEtox) and agricultural land use (ReCiPe H) MICs, and the ReCiPe H method was used for the endpoint areas of protection for human health, ecosystems and resources.

Carbon balance

For the carbon balance, the area of the three categories of land (arable crop, arable pasture and non-arable) from an existing LCA (Wiedemann et al., 2016) were used but converted to the functional unit of 1 metric ton of LW (t LW) with 100 % of impacts allocated to meat production. Varying percentages of non-arable land, up to 20 % in total, were then assumed to be allocated to biomass plantings for biodiversity, bioenergy production or a combination of both. It was assumed that improvements in animal welfare and productivity from using regenerative agricultural practices would offset the percentage of land used for sequestration, as animals would: use less energy to walk to water or feed due to the use of smaller paddocks with watering point; be able to actively seek shade and more shade would be available due to the higher proportion of vegetation. The net impact was assumed to be that the land area required per functional unit was the same, even though up to 20 % of the land was now being used for biomass.

Existing estimates of the carbon offsets available from **above ground biomass** were used (Henry et al., 2015). The energy available from the biomass plantings was used to **replace solid fossil fuels**, whose details were taken from the relevant Australian greenhouse reporting guidelines. The worst case substitution used non-biomass municipal materials (10.5 GJ/t, 88.9 kg CO_{2-eq}/GJ) and the best case substitution used coal coke (27 GJ/t, 107.24 kg CO_{2-eq}/GJ) (Department of the Environment and Energy, 2016). Three different soil carbon sequestration cases were modelled. The base case value of greenhouse gas sequestration in **soil carbon** was taken from the same study for the same system (NSW HRZ CSF) (Henry et al., 2015; Wiedemann et al., 2016), which equated to -0.4 t CO_{2-eq}/t LW. For

the second case, a soil organic carbon level 35 % higher (Ampt and Doornbos, 2011) than the base case was used. For the best case scenario, a multiplier from a study in a Midwestern USA beef system (Stanley et al., 2018) was used, which found that the rate of soil carbon sequestration was approximately 10 times higher in regenerative agriculture grazing systems (Stanley et al., 2018) compared to industrial agriculture. The sum of all three sources of carbon sequestration (above ground biomass, fossil fuel replacement and soil carbon) for the different cases (soil carbon levels, percentage allocated to biodiversity, bioenergy or a combination of both, and fossil fuel substitution) were then calculated, and the totals were compared to the total on-farm emissions from sheep production. The contribution of the total offset from soil carbon and fuel substitution was calculated.

Water Use

As the amount of water infiltration into soil increases in regenerative agriculture, the amount of runoff into farm dams decreases, meaning that water needs to be sourced from alternative sources for stock trough watering, such as bores. Although the surface area-to-volume ratio of water troughs is worse than farm dams, it was assumed that the water troughs in paddocks were only filled when there were stock in the paddock, so that the total volume of water in the trough was less than the total volume of water exposed to evaporative forces in the conventional supply from dams. Additionally, the installation of floating solar panels on farm dams were expected to reduce evaporation from the dam surface. Two cases were modelled, with a 25 % and 50 % reduction in drinking water supply losses and the total fresh water consumption and the stress-weighted water use for regenerative agriculture were then calculated. Both system are rain-fed rather than irrigated.

Results & Discussion

LCA results

Table 1 details the results from the delta LCA for regenerative agriculture, which indicate that the change in production had positive impact on all impact categories reported in the initial study, ranging from small (4 %) in climate change, moderate (22 %) in agricultural land occupation but a very significant in fossil fuel depletion (108 %). The small change in the climate change value is expected, as most of the emissions come from enteric methane production in the sheep, which remains unchanged in this case. The reduction in phosphate fertiliser use provided an overall saving of 97 % of all MIC, with percentages above 100 % for photochemical ozone formation, ionizing radiation and particulate matter formation. The ratio of the savings in emissions from the reduced grid electricity consumption compared to the solar photovoltaic produced electricity that replaced it averaged 6 over all MIC, except for mineral resource depletion, ozone layer depletion and ionizing radiation, where electricity from solar photovoltaics was 7, 1.4 and 2.3 times higher respectively. The reduction in on-farm emissions from pesticides only contributed <1 % to the toxicity MICs (human health and freshwater ecotoxicity).

Water use results

As indicated in Table 2, given that drinking water supply losses account for nearly 80 % of total fresh water consumption in the original LCA study, when the supply losses were reduced by 25 %, there was a corresponding 19 % improvement to the total freshwater consumption and stress-weighted water use. Similarly, when the supply losses were

reduced by 50 %, both water use indicators improved by 39 %. This indicates that the most significant area to target for reducing the water footprint of sheep meat production is the supply system efficiency, which could be achieved in rotational grazing by ensuring that water is only available in paddocks while livestock are present. The reduced runoff that results from improved ground cover in regenerative agriculture means that water is “stored” in the soil and groundwater, rather than being stored in above ground dams, where evaporative losses are significantly higher.

Carbon balance results

As indicated in Table 3, for the case with the lowest soil carbon levels (base case soil carbon), if the biomass grown is all used for bioenergy to replace fossil fuels, then approximately 15 % of the non-arable land needs to be used for biomass production to offset all the on-farm emissions of 12.3 t CO_{2-eq}/t LW. As expected, the total amount of offset is about 10 % higher in the best case substitution, where the biomass is replacing coal coke, compared to the worst case, where the biomass is replacing an equivalent amount of energy from non-biomass municipal materials. Most of the offset comes from the bioenergy, with only a very small portion, 3-7 %, from the soil carbon sequestration. The case using all the biomass for fossil fuel substitution unsurprisingly leads to a lower land area required for sequestration of on-farm emissions (15 %), compared to 8 % for biodiversity and 12 % for bioenergy.

For the case where the soil carbon levels are 35 % higher than the base case, there are only slight reduction in the amount of land required to completely offset the on-farm emissions, because most of the offsets are coming from the bioenergy, not the soil carbon sequestration.

For the case with soil carbon levels ten times higher than the base case, the amount of land required for plantings decreases, to 9.3 % for bioenergy production or 17.5 % for biodiversity (with no bioenergy production). More of the on-farm emissions can be sequestered in the soil carbon, ranging between 31-35 %. Once again, the best case fuel substitution has higher levels of greenhouse reduction (94-104 % offset) compared to the worst case (91-100 % offset), but the proportional contribution of the fuel substitution to reducing on-farm emissions has decreased.

The amount of soil carbon sequestration therefore has a large effect on the overall results, and significantly reduces the overall amount of land required to offset all on-farm emissions.

It should be noted that the results in Table 3 are indicative only, as they do not include emissions relating to the planting, harvesting, transport and use of the bioenergy produced. Rather, they are an indicator of how close to the target of offsetting the on-farm emissions biosequestration and subsequent fossil fuel substitution can come.

Conclusions & Recommendations

This delta LCA was done to identify the potential benefits of regenerative agriculture over its industrial alternative. The analysis indicated that the most significant saving in every category of impact comes from reducing super phosphate fertiliser use. The total impact to climate change was small, but the potential benefit to fossil fuel depletion was quite significant. The reduction in pesticide use had a minimal impact on all midpoint impact category indicators and the ecosystem area of protection. Regenerative agriculture could assist with reducing the water footprint of extensive agriculture, principally by reducing supply losses. The carbon balance provided the most interesting results, indicating that if land is used to produce bioenergy, and the bioenergy is used to offset fossil fuels, then there

appears to be potential to offset all on-farm emissions. In future, remote sensing of vegetation fractionation may be incorporated into the method, to confirm the biodiversity land use gains made by regenerative agriculture (Ogilvy et al., 2018).

However, there were a number of assumptions used in this assessment that need to be confirmed, such as: the savings in water losses from the supply system by moving away from dams to watering points such as troughs; the actual soil carbon sequestration potential of extensive agriculture in Australian soils and climatic conditions, including whether it is a transition effect until the soil reaches a new equilibrium and what that new equilibrium level is; inter-annual variability of soil carbon in regenerative agriculture systems, and whether soil carbon levels are more stable than in industrial agricultural systems; additional emissions relating to the planting, harvest, transport and use of bioenergy; and the link between animal welfare, biodiversity and productivity in regenerative agricultural systems, particularly the impact of increased amounts of above ground biomass on managing thermal comfort and health stress in ruminants.

List of figures:

Figure 1: Energy cascade for ruminants (adapted from (Thoma et al., 2013))

Figure 2: System boundary for delta LCA of regenerative farm (compared to conventional farm)

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Tables

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Table 1: Delta Life Cycle Assessment results for regenerative agriculture per t sheep live weight at farm gate showing the contribution of each source and final value for the 3 MIC included in the initial LCA.

Impact category	Unit	Total	Percentage contributed by each source to regen ag								Value from initial LCA	Final value from this delta LCA	Delta LCA % of initial value
			Phosphate fertiliser production	Grid electricity consumption	Pesticide production	Glyphosate production	Supplementary feed	Solar PV electricity production	Petrol consumption	On-farm emissions			
Climate change	kg CO ₂ -eq	-501	-92	-11	-0.4	-0.2	0.2	0.8	2.4		12,300	11,799	4 %
Mineral resource depletion	kg Sb _{-eq}	-0.0002	-95	-0.1	-4.6	-0.1	0.01	0.7	1.4				
Fossil fuel depletion	MJ	-5,902	-87	-14	-0.4	-0.2	0.1	0.4	0.8		5,463	-439	108 %
Eutrophication potential	kg PO ₄ ³⁻ -eq	-2.43	-98	-1.9	-0.1	-0.1	0.03	0.2	0.2				
Acidification potential	kg SO ₂ -eq	-6.07	-97	-3.5	-0.3	-0.1	0.1	0.4	0.6				
Freshwater ecotoxicity	CTU _e	-5,757	-92	-9.4	-0.3	-0.1	0.05	1.3	0.7	-0.8			
Human health	CTU _h	-0.00034	-94	-8.6	-0.2	-0.1	0.05	1.2	0.6	-0.01			
Photochemical ozone formation	kg C ₂ H ₄ -eq	-0.21	-120	-3.8	-0.6	-0.2	0.1	0.7	23.4				
Particulate matter formation	kg PM _{2.5} -eq	-1.16	-100	-1.3	-0.2	-0.1	0.1	0.6	0.5				
Ozone layer depletion	kg CFC-11 _{-eq}	-0.000061	-98	-1.0	-5.7	-0.3	0.3	1.4	3.1				
Ionizing radiation	kBq U235 _{-eq}	-62.28	-101	-0.3	-0.3	-0.2	0.1	0.7	1.1				
Agricultural land occupation	m ² *year	-31.07	-98	-2.7	-0.4	-0.2	0.1	1.1	0.3		141	110	22 %
Average percentage contribution, MIC			-97	-5.2	-1.0	-0.2	0.1	0.8	2.8	-0.4			
End point - resources	\$	-33.91	-95	-7.0	-0.4	-0.1	0.2	0.8	2.0				
End point – human health	DALY	-0.0017	-94	-8.3	-0.3	-0.1	0.1	0.8	1.3	-0.1			
End point - ecosystems	species.yr	-0.000011	-95	-4.5	-0.2	-0.1	0.1	0.4	1.0	-1.7			

Table 2: Original LCA water values compared to Regenerative Agriculture water values for cases of 25 % and 50 % lower supply losses

Parameter	Unit	Original LCA	25 % lower supply losses	50 % lower supply losses
Supply losses	KL/ t LW	90.9	68.2	45.4
Freshwater consumption	KL/ t LW	117.4	94.7	72.0
Stress-weighted water use	KL/ t LW	3.0	2.5	1.9

Table 3: Regenerative Agriculture carbon balance for three soil carbon cases and two fossil fuel substitution cases , allocating up to 20 % of non-arable land to biodiversity and bioenergy plantings, **compared to on-farm emissions of 12.3 t CO₂-eq/t LW**. Percentages indicate how much of on-farm emissions can be offset and relative contribution from bioenergy substitution of fossil fuel and soil carbon for each scenario.

Scenario	Unit	Base case soil carbon (0.4 t CO ₂ -eq/t LW)			35 % higher soil carbon (0.5 t CO ₂ -eq/t LW)			10x higher soil carbon (4 t CO ₂ -eq/t LW)		
Percentages of non-arable land allocation to biodiversity (B) and bioenergy (E)		5 % B + 5 % E	0 % B + 15 % E	8 % B + 12 % E	5 % B + 5 % E	0 % B + 14.8 % E	8.3 % B + 11.7 % E	5 % B + 5 % E	0 % B + 9.3 % E	17.5 % B + 0 % E
Worst case (substituting non-biomass municipal materials (10.5 GJ/t, 88.9 kg CO ₂ -eq/GJ)										
Carbon offset	t CO ₂ -eq/t LW	5.6	11.7	11.7	5.7	11.7	11.7	11.2	12.0	12.3
Offset	% of total	45 %	95 %	95 %	46 %	95 %	95 %	91 %	97 %	100 %
Bioenergy	% of offset	45 %	64 %	51 %	44 %	63 %	50 %	22 %	39 %	0 %
Soil carbon	% of offset	7 %	3 %	3 %	9 %	5 %	5 %	35 %	33 %	32 %
Best case (substituting coal coke (27 GJ/t, 107.24 kg CO ₂ -eq/GJ)										
Carbon offset	t CO ₂ -eq/t LW	6.1	13.2	12.9	6.2	13.2	12.9	11.6	12.6	12.3
Offset	% of total	49 %	107 %	105 %	50 %	107 %	104 %	94 %	103 %	100 %
Bioenergy	% of offset	47 %	65 %	53 %	46 %	64 %	52 %	25 %	42 %	0 %
Soil carbon	% of offset	6 %	3 %	3 %	9 %	4 %	4 %	34 %	31 %	32 %

Supplementary Materials

1. Data used in modelling

1.1 Inventory data and MIC for NSW HRZ CSF, per t LW, adapted from (Wiedemann et al., 2016)

Parameter	Unit	
On-farm crop land	ha ¹	0
Arable land for pasture	ha	0.3
Non arable land	ha	6.4
Electricity	kWh	58.2
Diesel	L	25
Petrol	L	19.2
Superphosphate	t	0.25
Lime	t	0.7
Protein grains	t	0.31
Admin overheads	\$	84.27
Vet products	\$	159.23
Herbicides	\$	8.30
Transport	\$	50.42

Note – 1) 1 ha = 1 hectare = 10,000 m²

Midpoint Impact Categories		
Climate change	kg CO ₂ -e	12.3
Total fresh water consumption	L	117.4
Stress weighted water use	L	3.0

Midpoint Impact Categories		
Fossil energy demand	MJ	5.5

1.2 Delta LCA inventory – assumptions

Parameter	
Electricity	<ul style="list-style-type: none"> 25 % higher, all from solar PV
Petrol	<ul style="list-style-type: none"> 20 % higher
Vet products	<ul style="list-style-type: none"> 25 % reduction in cost assumed, due to cessation of wether drenching, ie \$72.64 per t LW Modelled as Cydectin Long Acting drench, \$1.38 per animal, 2.5 mL per 50 kg animal, 20 g moxidectin per L, total saving of 2.63 g moxidectin Data taken from http://www.wormboss.com.au/drenches.php
Herbicides	<ul style="list-style-type: none"> 90 % reduction, due to change from broadacre spraying to spot spraying Application rates per ha – 1.2 L glyphosate mix (\$4.70/L), 1.5 L Paraquat mix (\$6.48/L), 1.5 L Spray Seed (\$9.49/L), total cost per hectare \$29.60 Active ingredients – 450 g/L glyphosate in glyphosate mix, 250 g/L paraquat in paraquat mix, 135 g/L paraquat and 115 g/L diquat in Spray Seed mix Paraquat and diquat are specific classes of herbicides Data taken from https://www.dpi.nsw.gov.au/_data/assets/pdf_file/0010/678997/Costs-of-key-iwm-tactics-in-the-northern-region.pdf

1.3 Delta LCA inventory to be modelled

Parameter	Unit	Change to be modelled
Electricity	kWh	-58 grid electricity +73 solar PV
Petrol	L	3.8
Superphosphate	t	-0.25

Parameter	Unit	Change to be modelled
Protein grains	t	-0.31
Vet products	\$	-\$39.81 as -1.44 g moxidectin
Herbicides	\$	-\$7.47, as -75.7 g glyphosate, -43.6 g diquat, -145.8 g paraquat Total pesticides excluding glyphosate = -190.8

2. Supplementary material relating to regenerative agriculture

2.1 Rewilding

In parallel with developments in regenerative agriculture, there is a growing interest in conservation related fields in **rewilding**. In the original context, rewilding refers to the reintroduction of keystone predators as part of conversation management interventions, thereby reinstating top-down trophic cascades, which is one component of ecological restoration (Soule and Noss, 1998). Since that time, the terms has been used in a range of different contexts, such as island rewilding, passive rewilding and ecological rewilding (Hayward et al., 2019). In the regenerative agriculture context, rewilding is unlikely to take the form of the reintroduction of species, particularly not keystone predators, but will be a form of **passive ecological rewilding**, due to the increase in the proportion of native vegetation, particularly if the location of the vegetation is designed to provide interconnected habitats. In turn, suitable habitats are then colonised by species that may contribute positively to farm productivity, such as a recent study of birds (Rayner et al., 2013) which indicated that 54 % of all species ate only invertebrates, with 77 % of all species eating invertebrates. The extent to which ecological rewilding has contributed to a reduction in certain types of parasite infestations of livestock in regenerative agriculture

systems by consuming the parasites is currently unclear, it may instead be due to the diversity of vegetation providing compounds which assist the animals in self-medicative behaviours to self-manage infestations (Provenza et al., 2007; Robinson, 2019; Villalba and Landau, 2012; Villalba and Provenza, 2009).

2.2 Animal Welfare

Central to the concept of managing animal welfare are the ideal states of the five freedoms (Farm Animal Welfare Council, 1993): 1) freedom from thirst, hunger and malnutrition; 2) freedom from discomfort; 3) freedom from pain, injury and disease; 4) freedom to express normal behaviour; and 5) freedom from fear and distress.

2.3 Thermal comfort and productivity

Extensive studies on the link between the welfare and productivity of dairy cattle have been undertaken over several decades, and it is well known that heat stress affects the general health, reproduction and lactation of cows (Atrian and Shahryar, 2012; Cook et al., 2007; Cook and Nordlund, 2009; de Mello et al., 2017; De Rensis and Scaramuzzi, 2003; Hemsworth et al., 1995; Schütz et al., 2009; Schütz et al., 2010; Valtorta et al., 1997; West, 2003; Wise et al., 1988). In terms of the energy budget for dairy cattle, not only does feed (and therefore energy) intake decrease by 10-20 % once ambient temperatures are above 26 °C, but 20-30 % more maintenance energy is required to regulate body temperature (Dairy Australia, 2018). The net impact is that milk production volumes and protein content decreases, which are measured on a daily basis.

Other observable behaviours include reducing the amount of heat absorbed from the environment (e.g. actively seeking shade, grouping with herd mates to create shade,

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aligning their bodies to minimise heat gain), reducing the amount of heat generated internally (reducing feed intake) and optimising heat lost to the environment (avoiding lying down, standing where there is a breeze, increasing water intake, restlessness, drooling) (Blackshaw and Blackshaw, 1994). Cattle “actively seek shade” in hot weather, which “may reduce the radiant heat load by 30 % or more” (Blackshaw and Blackshaw, 1994) but in extensive grazing systems the impacts on production are not observable in the short term. Studies in beef feedlots have indicated that heat stress leads to a reduction in feed intake and weight gain, and the respiration rate is used most frequently as the indicator of heat stress (Brown-Brandl et al., 2005; Eigenberg et al., 2005; Gaughan et al., 2007; Mader et al., 2002; Meat & Livestock Australia, 2012; MLA, 2012; Sullivan et al., 2011).

Sheep are physiologically similar to cattle in terms of how they manage body temperatures, but the presence of wool reduces the effectiveness of sweating, so more heat is lost via the legs and ears (Marai et al., 2007). Sheep adopt similar behavioural modifications in hot weather, such as decreasing or avoiding feed intake, which has flow on effects for production and reproduction.