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Greenhouse gas abatement on southern Australian grains farms: Biophysical potential and financial impacts

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ABSTRACT

The agricultural sector generates a substantial proportion of global greenhouse gas (GHG) emissions through emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O). Changes to agricultural practices can provide GHG abatement by maintaining or increasing soil organic carbon (SOC) stored in soils or vegetation, or by decreasing N_2O emissions. However, it can be difficult to identify practices that achieve net abatement because practices that increase SOC stocks may also increase N_2O emissions from the soil. This study simulated the net on-farm GHG abatement and gross margins for a range of management scenarios on two grain farms from the western and southern grain growing regions of Australia using the Agricultural Production Systems sIMulator (APSIM) model. The soils and practices selected for the study were typical of these regions. Increased cropping intensity consistently provided emissions reductions for all site-soil combinations. The practice of replacing uncropped or unmanaged pasture fallows with a winter legume crop was the only one of nine scenarios to decrease GHG emissions and increase gross margins relative to baseline practice at both locations over the 100-year simulation period. The greatest abatement was obtained by combining this practice with an additional summer legume crop grown for a short period as green manure. However, adding the summer legume decreased farm gross margins because the summer crop used soil moisture otherwise available to the following cash crop, thus reducing yield and revenue. Annual N_2O emissions from the soil were an order of magnitude lower from sandy-well-drained soils at the Western Australian location (Dalwallinu) than at the other location (Wimmera) with clay soil, highlighting the importance of interactions between climate and soil properties in determining appropriate GHG abatement practices. Thus, greatest abatement at Dalwallinu was obtained from maintaining or increasing SOC, but managing both N_2O emissions and SOC storage were important for providing abatement at Wimmera.

1. Introduction

The rate of climate change has increased since the 1950s (IPCC, 2014a), linked with substantial (10–30%) increases in atmospheric concentrations of the GHGs CO_2, N_2O and methane (CH_4). While increased concentrations of CO_2 can improve crop productivity, increased concentrations of these GHGs in combination have increased temperatures and altered rainfall distribution, and it is very likely that they will also cause an increase in heat waves and extreme rainfall events. These climate changes are predicted to decrease crop productivity in many regions globally (IPCC, 2014a). However, this decrease in capacity to produce food coincides with a predicted increase in world population of a third by 2050 (FAO, 2009). Thus there is a risk that global food deficits may occur if GHG abatement measures are not adopted.

The agricultural sector contributes 25% to the global GHG inventory (IPCC, 2014a), and thus decreasing agricultural emissions is important to provide GHG abatement. The potential for agriculture to contribute to GHG mitigation is less in developed countries, where agriculture typically forms ~10% of national GHG inventories (Eurostat, 2015; US

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EPA, 2015). However, there are some developed countries (e.g. Australia and New Zealand; Thorburn et al., 2013) where agriculture is a relatively important part of the GHG profile (14 and 49%, respectively), and so a focus on GHG abatement is a high priority (DoE, 2016; Ministry for the Environment, 2016a). In both Australia and New Zealand, economic incentives are available to businesses in the land sector to voluntarily enter projects that deliver GHG abatement (Clean Energy Regulator, 2016a; Ministry for the Environment, 2016b). Funding is available on a project basis, which effectively delivers on-site emissions reductions. In order for projects to be eligible, they must comply with an approved method focusing on management of forestry in New Zealand, or on forestry, livestock, pastures or irrigated cotton in Australia. However, farmers could also mitigate on-farm GHG emissions from cropping systems by maintaining or increasing SOC stocks and decreasing N_2O and CH_4 emissions from soils (IPCC, 2014b). Emissions of CH_4 from cropping systems other than rice are minor (DoE, 2016). Therefore additional strategies for mitigating GHG emissions from the soil in grain farming systems would focus on maintaining or increasing stocks of SOC and decreasing N_2O emissions.

A range of agricultural management practices can contribute to SOC stocks and thereby provide GHG abatement (Luo et al., 2010; Stockmann et al., 2013). Such practices include, for example, increasing cropping intensity, reducing tillage, retaining stubble, and changing nitrogen fertiliser and irrigation management. However, other studies suggest that the contribution of SOC storage to climate change abatement is likely to be modest (Baldock et al., 2012; Lal, 2004), and that the potential for increasing the stocks of SOC in Australian soils is limited (Lam et al., 2013; Robertson and Nash, 2013).

The potential for soil N_2O emissions to occur is greater in environments that favour N_2O-producing microorganisms. These include: water-filled pore space between 40 and 80%, increasing temperatures up to 37 °C, pH values of 7–8, and a supply of nitrate and decomposable carbon (Dalal et al., 2003). There is potential for these conditions to occur widely, so many management practices aim to limit soil nitrate loss by matching the supply of nitrate with the demand for nitrate by crops. Practices include matching the rate, timing and placement of nitrogenous fertiliser or other inputs with plant requirements, replacing nitrogenous fertiliser with nitrogen sourced from legumes or manure, and managing irrigation and drainage to avoid anaerobic conditions (Cameron et al., 2013; Li et al., 2013; Rees et al., 2013). These practices may conflict with practices aimed at increasing SOC storage. For example, retaining instead of burning crop stubble can increase stocks of SOC. However, it can also decrease evaporation of soil moisture and thus increase the likelihood that the soil will attain a water filled pore space that favours N_2O production.

The tradeoff in abatement from different GHGs, and the influence of site-specific conditions makes it difficult to generalise about the contribution that different practices could make to climate change abatement. The purpose of this study was to identify (a) additional practices that could decrease the net on-farm GHG emissions arising from SOC storage and N_2O emissions from cropping systems on Australian grain farms, and (b) the extent to which financial objectives are needed to prompt adoption of practices that provide abatement. To achieve this, we describe the biophysical properties, net GHG abatement potential, and average gross margins for a range of on-farm practices for two grain farms from contrasting locations in Australia.

2. Methods

2.1. Case study farms

Two case study farms were defined for the western and southern regions of the Australian grains industry. The researchers collaborated with local farmer groups and agronomists to describe representative soils and typical practices on farms in those regions. The soil types represented were among the most commonly occurring soils in the Western Australian-North and South Australian-Victorian Bordertown-Wimmera GRDC agro-ecological zones (GRDC, 1998; Western Australian Department of Agriculture), and findings were intended to be relevant to a broader region than the immediate farms. For example, the Dalwallinu farm in Western Australia was designed to represent a larger region of > 1 million ha in the local area (Liebe Group, 2015), and be representative of other low rainfall grain farming environments across Australia, e.g. the Eyre Peninsula in South Australia.

Table 1
Biophysical properties, management practices and GHG emissions for baseline conditions at the Dalwallinu and Wimmera case study farms.

Description	Case study farm		
	Dalwallinu, Western Australia		Wimmera, Victoria
General information			
Location	30.1°S, 116.6°E		36.6°S, 142.6°E
Area (ha)	6000		2300
Management			
Crop 'rotations' representative of typical sequence and proportion of crops	'Legume rotation' (canola/wheat/lupin/wheat/wheat) 'Cereal rotation' (canola/wheat/wheat/barley) 'Pasture rotation' (canola/pasture/wheat/wheat/barley)		'Average rotation' (chickpea/canola/wheat/barley/faba bean/wheat/barley/oaten hay/fallow/wheat)
Target N inputs (supplied by fertiliser and soil mineral N)	40 kg N ha^{-1} (tonne of harvested grain)$^{-1}$		5–80 kg N ha^{-1} $crop^{-1}$
N fertiliser splits	60% at sowing; 40% at 40 d after sowing		5–10 kg N ha^{-1} at sowing; 0–70 kg N ha^{-1} after sowing
Tillage	Minimum tillage		Minimum tillage
Soils			
Soil types[a]	Texture contrast (Chromosol)	Sand (Tenosol)	Medium clay (Vertosol)
APSsoil number[b]	487	613	746
Total soil C (%, 0.0–0.3 m)	1.6	0.4	2.0
Predicted C after 100 yr (%, 0.0–0.3 m)	1.4	0.5	1.6
Soil pH (0.00–0.15 m)	5.3	5.8	5.3
Plant available water (mm)	66	90	203
Rooting depth (m)	0.8 m	1.5 m	1.6
Drainage	Moderate	Free	Slow
Mean GHG emissions[c] *(100 yr)*			
SOC sequestered (kg C ha^{-1} yr^{-1})	− 94	25	− 175
N_2O emitted (kg N_2O-N ha^{-1} yr^{-1})	0.12	0.07	1.25
Net GWP (kg CO_2e ha^{-1} yr^{-1})	401	58	1229
Mean gross margins ($AUD ha^{-1} yr^{-1})[c]	185	226	497

[a] Isbell (2002).

[b] Holzworth et al. (2014).

[c] Average from 100-year simulations (described in Section 2.5).

2.1.1. The Dalwallinu case study farm

The Dalwallinu case study farm was conceptualized in collaboration with a local farming group (www.liebegroup.org.au; Table 1). The farm is located in a grassland climate zone which is characterised by hot dry summers (Stern et al., 2000) and cooler winters with winter-dominant rainfall (Table 2). The soils represented in the model farm were based

Table 2
Selected weather data[a] at the Dalwallinu and Wimmera case study farms.

Description	Case study farm	
	Dalwallinu	Wimmera
SILO weather station	Wubin (#8139)	Rupanyup (#079075)
Rainfall (mm yr^{-1})		
Annual	307	414
Growing season (April–October)	261	279
Average min-max temperature (°C)		
January	18–35	13–30
July	6–17	4–13

[a] Average climate measurements from 1965 to 2014 reported in SILO (Jeffrey et al., 2001).

on two of the dominant soils of the region (Schoknecht and Pathan, 2013): a deep sand (Tenosol; Isbell, 2002 or Entisol; USDA, 1999) and a texture contrast soil (Chromosol; Isbell, 2002 or Alfisol; USDA, 1999). The properties of these soils were obtained from profiles recorded in the APSIM model (Section 2.3).

The three crop rotations used on the Dalwallinu farm (Table 1) were assumed to be grown in the same proportion on all soils and the results from all rotations were averaged for each soil. Wheat and canola were grown in all of the rotations. In addition, the 'cereal' rotation included barley; the 'legume' rotation included lupins; and the 'pasture' rotation included a pasture grown for approximately 17 months between harvesting canola and sowing the next crop. This pasture consisted of volunteer grass and weed species and was not grazed. The purpose of the unmanaged pasture phase was to break disease cycles for other crops in the rotation. Crops were sown between 25 April and 15 June. Usual farm practice was to not grow crops during the summer months; weeds were controlled at all times by spraying. Non-legume crops were supplied with a target amount of nitrogen of 40 kg N ha^{-1} for each tonne of expected grain yield based on average farm yields, taking into account mineral nitrogen present in the 0.0–0.1 m soil layer as per usual farm practice. Zero tillage was practiced at the farm but crop residues were burned in March each year to destroy weed seeds prior to sowing the next crop.

2.1.2. The Wimmera case study farm

The Wimmera case study farm (Table 1) was based on the properties, practices and farm records of an existing farm (van Rees et al., 2014). The farm is located in a temperate climate zone with moderately dry winters and warm summers (Stern et al., 2000; Table 2); these conditions limited commercial cropping to the winter period only. Farm soils were relatively uniform and were represented by a single clay soil (Table 1). An average rotation was based on advice from farm consultants and represented the sequence and proportion of crops grown at the farm. Nitrogen fertiliser was applied according to the farmer's usual practice at the rate of 5 kg N ha^{-1} crop^{-1} at sowing and 0, 40 or 70 kg N ha^{-1} of additional fertiliser depending on soil mineral N (0.0–0.25 m) and seasonal outlook. Other fertiliser blends were applied to supply adequate phosphorus and zinc. Zero tillage with was practiced and weeds were controlled by spraying.

2.2. Scenarios

A set of farm management scenarios was modelled at both farms (Table 3). The baseline practice (Scenario S1) was defined as having typical N-fertiliser application rates and low organic matter inputs. Practices that could potentially provide GHG mitigation by increasing SOC stocks and/or decreasing soil N_2O emissions relative to the baseline were defined in the remaining scenarios. These practices included modifying nitrogen fertiliser rates (S3–S6), increasing inputs of carbon to the soil by retaining stubble instead of burning it (all scenarios except S3 and S4), applying manure (S7), or increasing cropping intensity (S8–S10). Scenarios 8 and 10 increased cropping intensity by including a summer cowpea crop in the dry summer period when crops are usually not grown (WANTFA, 2015). This practice was applied in all years for these scenarios to maximise potential inputs of SOC. Scenario 9 increased cropping intensity by including a winter field pea in place of unimproved pasture in the Dalwallinu pasture rotation or the bare fallow in the Wimmera rotation (S9). The crops in scenarios S8–S10 were retained as a mulch to increase SOC and were not harvested for grain.

2.3. The APSIM model

The SOC storage, N_2O emissions and crop production from the different cropping practices was determined with the Agricultural Production Systems sIMulator (APSIM) v7.5 model (Holzworth et al., 2014). APSIM was configured with modules for soil nitrogen (APSIM-SoilN; Probert et al., 1998; Thorburn et al., 2010), soil water dynamics (APSIM-SoilWat; Probert et al., 1998), soil temperature (APSIM-SoilTemp2, following Campbell, 1985), residue (APSIM-SurfaceOM; Probert et al., 1998; Thorburn et al., 2001) and crop growth. Climate data was obtained from the SILO data base (Jeffrey et al., 2001) for weather stations close to the case study farms (Table 1).

APSIM-SoilN and APSIM-SoilWat were set up with the specified soils (Table 1). This data was site-specific and included soil water characteristic information, hydraulic conductivity, SOC (including the allocation of SOC to microbial biomass, humus and inert SOC fractions), soil pH, runoff curve numbers and coefficients for first and second order evaporation. Full details for each soil are provided in the APSIM model soil database 'APSoil' (Holzworth et al., 2014).

The crop modules were parameterised using default information for commonly used local varieties or, where these were not available, for varieties that produced comparable yield. Crop management information (e.g. plant density, sowing depth and sowing window) were provided by local stakeholders.

Each combination of soil and rotation in each study area was modelled over a 100-year period. Each combination was run for 10 different starting years (1906 to 1915) to prevent any potential cyclical patterns in the climate data interacting with the patterns in crop rotations. The results were then averaged over the relevant simulation periods and rotations.

2.4. Model testing

APSIM is an established cropping systems model with a proven capacity to simulate grain farming systems (Holzworth et al., 2014; Carberry et al., 2009) including those considered in this study, i.e. the Dalwallinu (Asseng et al., 1998) and Wimmera (van Rees et al., 2014) regions. The capacity to simulate soil nitrogen dynamics, which are mechanistically linked to SOC dynamics, and its interactions with crop management, is an important and often used feature of the model (Holzworth et al., 2014). Over recent years, increasing attention has been paid to testing the model's capability for simulating processes relevant to GHG abatement in soils. Specifically, this testing has included prediction of SOC (Luo et al., 2011; Basche et al., 2016; O'Leary et al., 2016) and N_2O emissions (Mielenz et al., 2015, 2016; Giltrap et al., 2015), in a range of soil and cropping systems. However, the Australian studies (Luo et al., 2011; O'Leary et al., 2016; Mielenz et al., 2015, 2016) have examined soils and cropping systems in eastern Australia. As well, treatments affecting SOC in these studies have focused on stubble management and, in one case, intensity of pasture grazing. Thus the model's performance for simulating processes relevant to GHG abatement in soils is less well established for the coarse soils of Western Australia and for large organic matter inputs (such as manure additions, S7). Therefore, we tested this aspect of the model against results from two field experiments located in Buntine and

Table 3
Scenarios modelled at the Dalwallinu and Wimmera case study farms. Scenario S1 was selected to represent the baseline practice for the case study farms. Scenarios S2–S10 describe variations to the baseline practice.

Scenario no.	Name	Management practice description	Average increase or decrease in costs from baseline values	
			Dalwallinu ($AUD ha^{-1} yr^{-1})	Wimmera ($AUD ha^{-1} yr^{-1})
S1	Baseline	Usual practice (stubble burnt, bare summer fallow, unimproved pasture)		
S2	No burn	Stubble retained	− 4	− 5
S3	Burn + N	Stubble burnt + 25% extra N fertiliser	18	9
S4	Burn − N	Stubble burnt − 25% less fertiliser	− 20	− 9
S5	No burn + N	Stubble retained + 25% extra N fertiliser	12	4
S6	No burn − N	Stubble retained − 25% less fertiliser	− 26	− 14
S7	Manure[a]	Stubble retained + manure application	31	30
S8	Summer crop	Stubble retained + summer crop	37	34
S9	Improved pasture[b]	Stubble retained + improved pasture	− 5	− 2
S10	Combination[b]	Stubble retained + summer crop + improved pasture	37	36

[a] Manure (water content 20%; carbon fraction 0.4; C:N ratio 20:1) applied at 5 Mg ha^{-1} each five years.
[b] Applied only to pasture in the 'pasture' rotation at Dalwallinu and the uncropped fallow at Wimmera.

Wongan Hills in Western Australia (Liebe Group, 2015; Barton et al., 2013).

2.4.1. The Buntine experiment

The Buntine experiment was established to test the effect of organic matter addition on SOC and yield (Liebe Group, 2015). The soil properties and climate at the site were similar to those of the Dalwallinu sand (Table 1) so simulations used these soil parameters and climate data. Canola, wheat, barley, lupin and oat crops were grown during the experiment and managed according to the farmer's usual practice. Some crops were sprayed out and the biomass retained on-site for green manure (lupins, 2003 and 2006) or because of crop failure (wheat, 2007). The treatments in the experiment most relevant to this study were the control (minimum till, stubble retained), a burnt residues treatment (crop residues burnt in March each year), and an organic matter addition treatment (20 Mg ha^{-1} of canola, barley or oat crop residues were applied at 3-yearly intervals and incorporated into the top 0.1 m of soil). The crop rotations and other management practices in these treatments were represented in the model.

2.4.2. The Wongan Hills experiment

In the Wongan Hills experiment, soil N_2O emissions were measured in 2009–2010 from different crop rotations and under different lime application rates (Table 4; Barton et al., 2013). The site had similar climate to the Buntine experiment and nitrogen inputs were similar in both experiments (Table 4; Unkovich et al., 2010; Barton et al., 2013). The soil, a freely-drained sand with pH ($CaCl_2$) of ~5 and initial SOC of ~10 g kg^{-1} (0–0.2 m), was also similar to the Buntine soil, so simulations used these soil parameters and climate data. N_2O emissions simulated in APSIM were compared with emissions from the treatment with a minimum-till lupin-wheat crop rotation without lime applied, which was similar to the Buntine control treatment and so most relevant to this study.

2.5. Calculations for global warming potential

The GHGs included in the calculation of global warming potential (GWP) were limited to on-farm changes in (a) CO_2 associated with SOC stocks (0.0–0.3 m), and (b) emissions of N_2O from the soil. Changes in SOC stocks and emissions of N_2O from the soil were converted to CO_2e by multiplying with factors of 3.67 and 298, respectively (IPCC, 2013). Net GWP was reported as the sum of CO_2e values derived from each practice compared to those derived from the baseline scenario (S1). Emissions from off-farm activities (e.g. manufacture and transport of fertilisers and manure, or transport of grain to port) were excluded from the analysis.

Table 4
Emissions of N_2O-N measured from the lupin-wheat rotation without lime treatment in the Wongan Hills experiment (Barton et al., 2013) and those simulated from the minimum-till control treatment of the Buntine experiment (Liebe Group, 2015) that had similar soils and management to the Wongan Hills experiment; in model testing for the Dalwallinu case study farm.

	N_2O emissions			
	Wongan Hills		Buntine	
	2009 Lupin	2010 Wheat	2009 Lupin	2010 Wheat
Duration	2/6/2009–8/6/2010	9/6/2010–8/6/2011	14/5/2009–27/5/2010	28/5/2010–31/5/2011
Days	371	364	378	368
N inputs (fertiliser + fixation; kg N ha^{-1})	99	20	122	23
Measured N_2O emissions (kg N_2O-N ha^{-1} yr^{-1})	0.037	0.059	–	–
Predicted N_2O emissions (kg N_2O-N ha^{-1} yr^{-1})	–	–	0.041	0.053

GWPs were presented at 25 and 100 yr after the simulation commenced, consistent with the time horizons identified by the Intergovernmental Panel on Climate Change (Solomon and Srinivasan, 1995) and Australian GHG emissions reduction policy (Clean Energy Regulator, 2015).

2.6. Gross margins analysis

The economic feasibility of GHG abatement was estimated using gross margins (Australian dollars, $AUD). These were calculated as the crop price multiplied by simulated crop yield to give gross revenue, less the variable costs associated with growing the crop. Farm gate prices for grains varied between locations and over time according to supply and demand (e.g. iGrain, 2017). Therefore, crop prices and variable cost data were obtained from published prices (DAFWA, 2012; Rural Solutions SA, 2015; Wylie, 2007) and the collaborating farmers (Supplementary Information). The main variable costs at both case study farms were fertiliser (29–47% of total variable costs), chemicals for pest and weed control (23–29%) and seed (6–11%). Other substantial costs were contract labour at the Wimmera farm (13%) and lime application at the Dalwallinu farm (8%). Fixed costs such as farm owner-manager wages, overheads (e.g. insurance and administration costs, machinery and capital expenditure) were not included in the gross margin analysis.

2.7. Statistics

Model performance for parameterisation of the model to simulate SOC and yield (Section 3.1) was assessed with the root mean square error (RMSE) and Nash and Sutcliffe (1970) statistics. For RMSE, better model performance is indicated by smaller calculated values. For the Nash-Sutcliffe statistic, greater accuracy in model performance is indicated by values approaching unity; negative values indicate a model performance that is worse than using the mean of measured values. Tukey's Honestly Significant Difference test (Yandell, 1997) was used to identify significant differences ($p < 0.05$) between the scenarios (S2–S10) and baseline means (Section 3.2) using simulation start years as replicates in the RStudio statistical package (v0.99.465).

3. Results

3.1. Model testing

3.1.1. Yield, SOC and N_2O emissions in dryland grain systems in response to large organic matter inputs

The overall trend in crop yields from the Buntine experiment was well captured by the model with RMSE and Nash-Sutcliffe values of 0.58 and 0.61, respectively (Fig. 1a), indicating that APSIM was capable of predicting dryland grain yield in response to large inputs of organic matter in this environment. While the root mean squared error (RMSE) between predicted and average measured yields appeared large (0.58 Mg ha^{-1}), it was less than or comparable to the variability in measured yields. Changes in SOC (0.0–0.1 m) in the Buntine experiment were also well captured by APSIM (RMSE = 0.09 and Nash-Sutcliffe = 0.88; Fig. 1b).

Cumulative N_2O emissions simulated for the minimum-till lupin-wheat treatment in Wongan Hills experiment were comparable with measured values (Table 4). The range of daily emissions predicted (0.0 to 7.0 g N_2O-N ha^{-1} d^{-1}) during these two years was within the range of the measured values (-1.4 to 9.2 g N_2O-N ha^{-1} d^{-1}; Barton et al., 2013). The data reported by Barton et al. did not permit model performance statistics to be calculated; but due to the close alignment between measured and simulated values we conclude that the model can be relied upon to capture N_2O emissions for these environmental conditions.

3.1.2. Case study farm yield

Collaborating farmers provided estimates for yields that had been achieved over recent years for the case study farms (Fig. 2). In addition, the average farm yields for crops grown during the period 2001–2010 had been measured at the Wimmera case study farm (van Rees et al., 2014). Both the farmer's estimated and actual yields fell within the standard deviation of 100-year simulated yield values. In particular, the average yield of crops on the Dalwallinu texture contrast soil was less than on the Dalwallinu sand, consistent with the lower plant available water of this soil (Table 1). The average simulated yields for the Wimmera clay also occurred between the farmer's estimated and actual yield values. Thus we conclude that the model set up was reliable for simulating realistic crop yields at the case study farms.

3.2. GHG abatement and profitability

GHG abatement was predicted to occur consistently across site-soil combinations only from scenarios with increased cropping intensity (S8–S10; Fig. 3). This abatement was significant for both 25 and 100-year time slices and all soils, and greater for the Wimmera clay than from the Dalwallinu soils. Average abatement relative to the baseline ranged from 0.2–0.5 Mg CO_2e ha^{-1} yr^{-1} (depending on the farm/soil and time) for the summer crop and improved pasture scenarios (S8, S9), to 1.0–2.0 Mg CO_2e ha^{-1} yr^{-1} for the combination scenario (S10). However, the only scenario predicted to deliver a 'win-win' outcome relative to baseline values of both GHG abatement with increased or unchanged gross margins across all locations, soils and time slices was the improved pasture scenario (S9), which decreased GWP by 0.3–0.4 Mg CO_2e ha^{-1} yr^{-1} and increased gross margins by $AUD0–67 ha^{-1} yr^{-1}.

3.3. Changes in SOC stocks and N_2O emissions

3.3.1. SOC stocks

For all location-soil combinations, SOC stocks increased relative to the baseline when stubbles were retained (S2, S5–S10; Fig. 4a–c). The rate of change in SOC stocks declined over the 100-year period (data not presented), so greater average GHG abatement (lower GWP) was achieved in the first 25 yr than when averaged over 100 yr (Fig. 3). SOC concentrations in scenarios S2–S7 approached constant values toward the end of this period so had little potential to provide further abatement from increasing SOC stocks.

Absolute values of SOC (0.0–0.3 m) for all locations increased only in scenarios S8–S10 (data not shown), by amounts up to 7 to 16 Mg C ha^{-1} under S10 for the different soils. For these scenarios, SOC stocks were predicted to increase throughout the 100-year simulation period and so had potential to provide abatement beyond this period.

Change in the amount of SOC stored in response to management practices in the scenarios was linked to differences in the amount of organic matter added to the soils in the scenarios. In the stubble retention scenarios

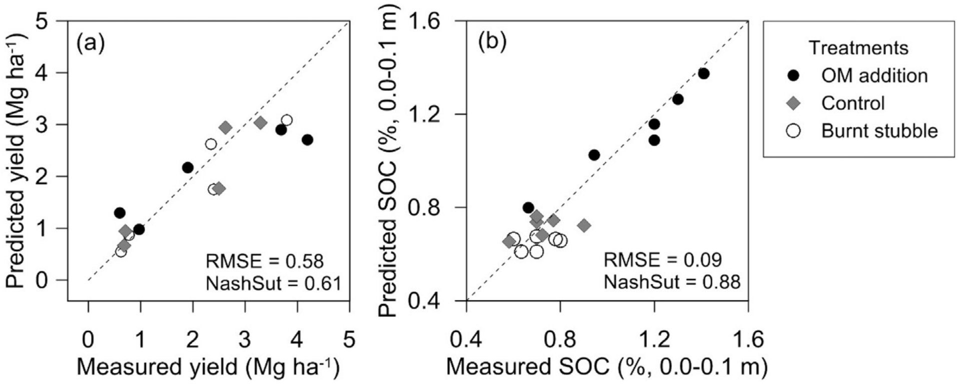

Fig. 1. Prediction of (a) wheat, barley, oat and canola yields for 2010–2014, and (b) SOC (0.0–0.1 m) for 2003–2014, for the minimum-till control, burnt and organic matter (OM) addition treatments in the Buntine experiment, in model testing for the Dalwallinu case study farm. Root mean square error (RMSE) and Nash-Sutcliffe (NashSut) statistics are provided for predicted yields and SOC.

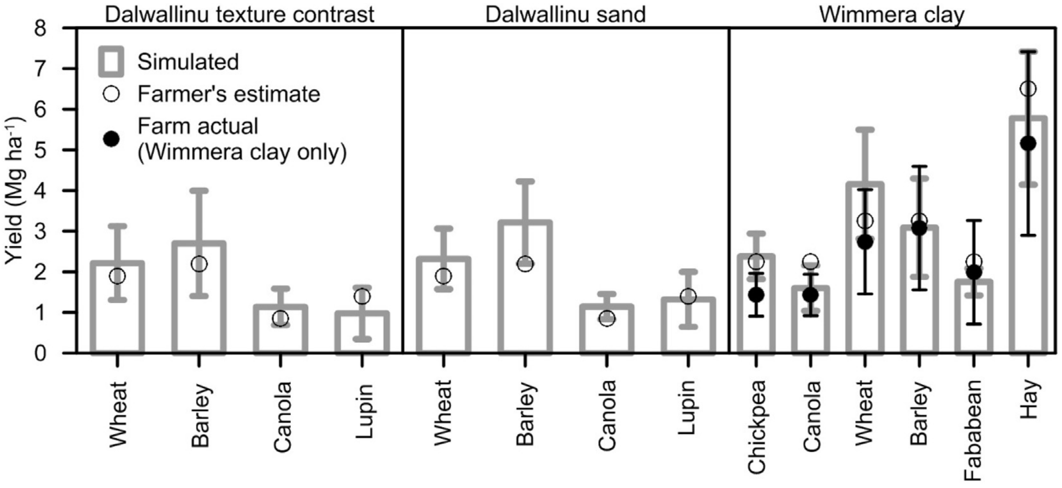

Fig. 2. Yields for the case study farms sourced from farmer's estimates, farm records and average values simulated over a 100-year period. Error bars for simulated and actual farm values represent the standard deviation of yield values.

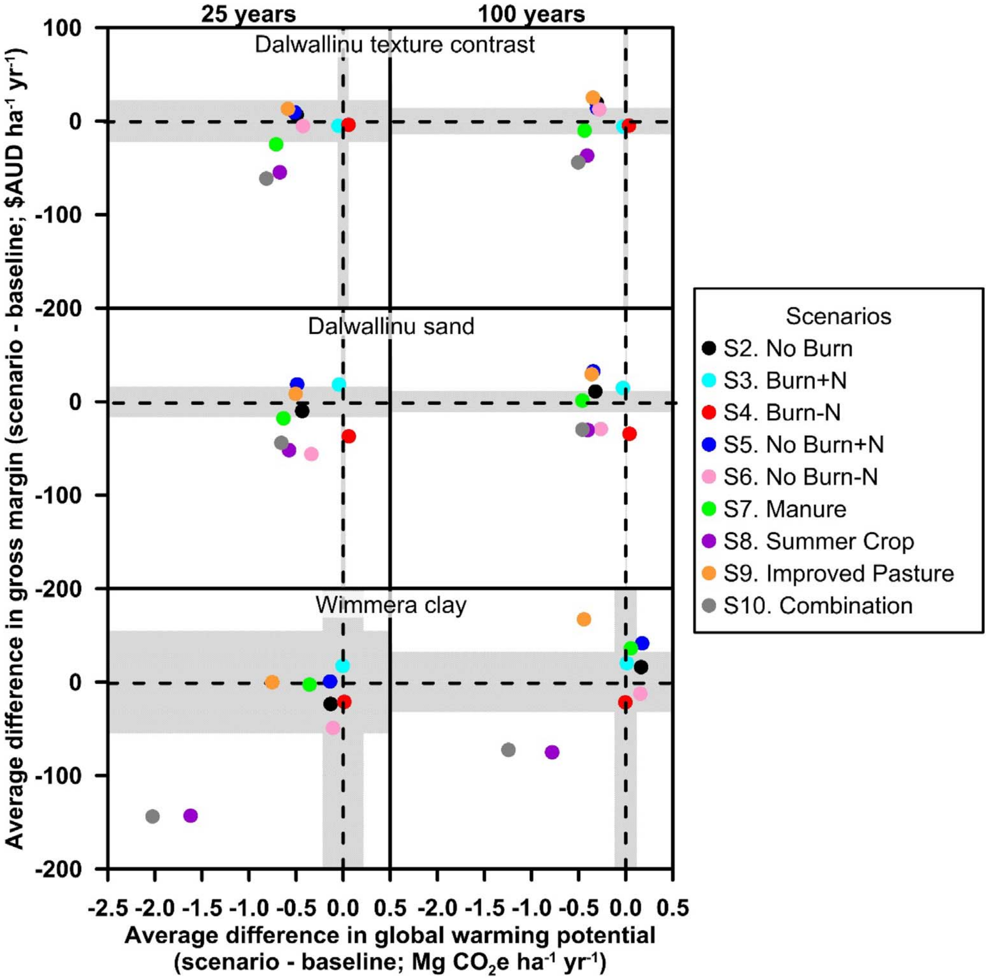

Fig. 3. Difference between alternative scenarios and baseline values for net GWP and gross margins on the Dalwallinu texture contrast and sand soils, and the Wimmera clay. Data points represent the average of simulated values at 25 and 100 yr into the simulation period and positive values represent an increase in gross margins or GWP relative to the baseline scenario. Scenarios that are significantly different ($p < 0.05$) from the baseline plot outside the shaded bands. Scenarios are described in Table 3.

(S2, S5–S10), 2–4 Mg ha^{-1} yr^{-1} of dry matter (DM) was retained on the soil surface instead of removing it by burning. The amount of SOC stored increased further for all location-soil combinations in response to additional inputs of organic matter from manure (equivalent to 0.8 Mg DM ha^{-1} yr^{-1}; S7) and from additional crops when cropping intensity was increased (S8–S10). The amount of SOC stored in S8–S10 was higher at Wimmera (~12 Mg DM ha^{-1} yr^{-1}) than at Dalwallinu (3.5–5.0 Mg DM ha^{-1} yr^{-1}) due to higher rainfall (Table 1), greater soil plant available water (Table 1) and better crop growth resulting in larger DM inputs.

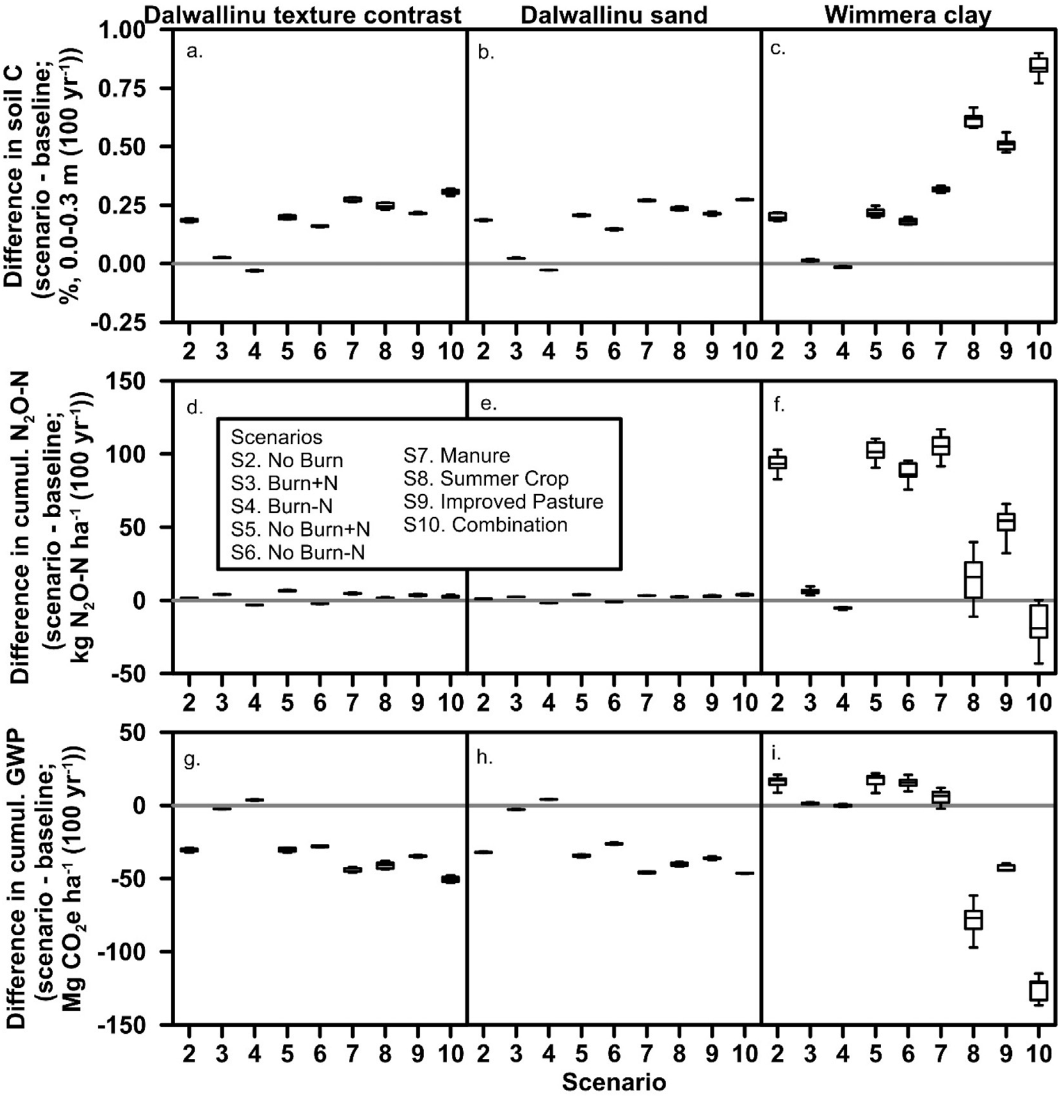

Fig. 4. Difference in (a–c) soil carbon and (d–f) cumulative N_2O-N emissions from soil in the scenarios relative to the baseline practice over 100 yr. Changes in soil carbon and N_2O emissions are converted to CO_2e and summed to calculate the net GWP of the scenarios (g–i). Scenarios with a decrease in GWP provided GHG abatement relative to the baseline practice. Variability in the values represented in box plots occur because 10 different start years were used to replicate simulations. Scenarios are described in Table 3.

3.3.2. Soil N_2O emissions

The maximum increase in N_2O-N emissions from the Dalwallinu soils in any scenario was ≤ 0.064 kg N_2O-N ha^{-1} yr^{-1} above baseline values (Fig. 4d, e). These changes were small compared to Wimmera due to the lower SOC, better drainage on coarser-textured soils and lower rainfall (and, consequently, low average soil water contents) in that environment (Barton et al., 2008, 2013).

For the Wimmera clay, emissions were greater than from the baseline scenario when stubble was retained (S2, S5–S9; Fig. 4f) regardless of changes in N fertiliser rate or when manure was applied. However, when stubble was retained in the combination scenario (S10), N_2O-N emissions were decreased by an average of 0.19 kg N ha^{-1} yr^{-1} below baseline values. This reduction was due to a large decrease in N_2O emissions during the summer compared with the baseline (data not shown).

3.3.3. Net abatement

Net abatement was determined by the combined emissions or abatement from changes in SOC and N_2O emissions in scenarios relative to the baseline practice (Fig. 4g–i). Abatement at Dalwallinu (Fig. 4g, h) followed a similar pattern to changes in SOC storage (Fig. 4a, b) and was therefore possible in all scenarios where more SOC was retained than in the baseline scenario (i.e. all scenarios except those with burnt stubble; S2, S5–S10). At Wimmera, abatement was determined by both changes in SOC stocks and N_2O emissions relative to the baseline (Fig. 4c, f, i).

The trade-off between SOC storage and N_2O emissions in determining net GWP differed between locations (Fig. 5). Because N_2O emissions have a large conversion factor of 298, these emissions have the potential to dominate net GWP. Despite this, the net abatement at Dalwallinu was insensitive to changes in N_2O because emissions were consistently low (−0.01–0.03 Mg CO_2e ha^{-1} yr^{-1} across scenarios) and so changes in SOC were the main determinant of net GWP (Fig. 5a, b). At Wimmera, both SOC storage (−0.02–1.2 Mg CO_2e ha^{-1} yr^{-1}) and N_2O emissions (−0.08–0.5 Mg CO_2e ha^{-1} yr^{-1}) had potential to increase under the scenarios (Fig. 5c). However, net abatement was only available from cropping intensity scenarios (S8–S10) because large increases in SOC in these scenarios more than offset the GWP of N_2O emissions, and because of decreased N_2O emissions in the combination scenario (S10).

3.4. Yield response to scenarios

Crop yields increased under scenarios which provided greater inputs of N than the baseline scenario (e.g. for wheat crops, Fig. 6). There was

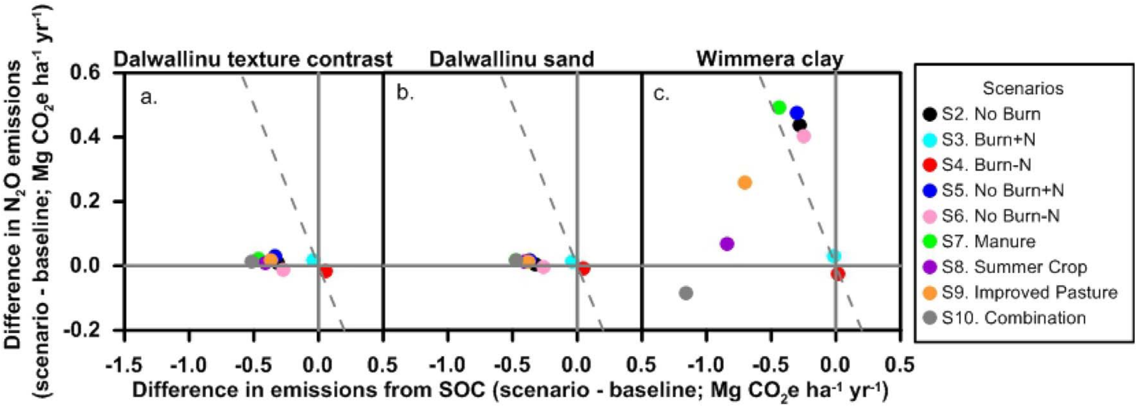

Fig. 5. Trade-off in CO_2e from average changes in soil organic carbon (SOC) and soil N_2O emissions relative to the Baseline (S1) practice over 100 yr. The dotted line is where the change in CO_2e from carbon sequestration equals change in CO_2e from N_2O emissions and therefore where there is no change in net GWP compared to baseline (S1) values. Points below the dotted line provide abatement relative to baseline values. Scenarios are described in Table 3.

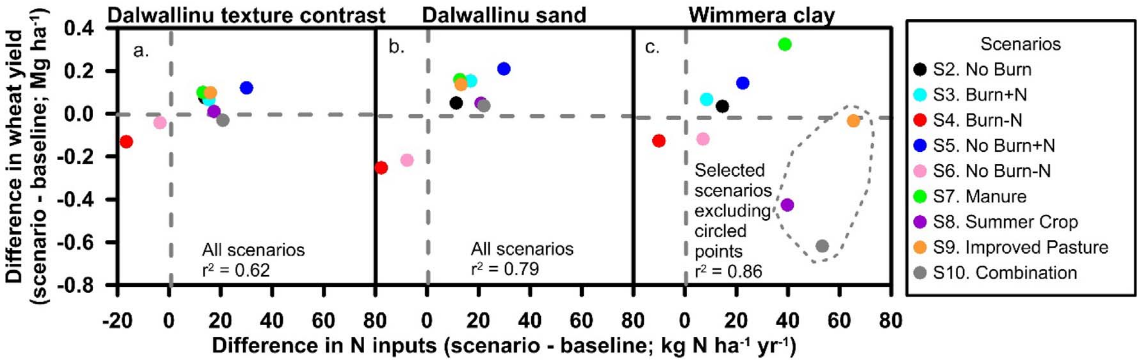

Fig. 6. Average yield of wheat crops in the scenarios in response to N inputs from fertiliser, retained stubble, legumes and manure. Data represents the difference between values in the scenarios and values from the baseline scenario. Scenarios are described in Table 3. Coefficients of determination (r^2) are for linear regressions of all scenarios (Dalwallinu texture contrast and sand soils) or for selected scenarios which excluded the summer crop, improved pasture and combination scenarios (Wimmera clay).

a close relationship between N inputs and yield for all soils (r^2 values between 0.62 and 0.86; Fig. 6), indicating that yields in the baseline simulations were limited by N availability. An exception occurred at Wimmera in S8–S10 where yields declined relative to baseline values despite the substantial additional N inputs of 40 to 65 kg ha^{-1} yr^{-1} (Fig. 6c). This occurred because the additional green manure legume crops grown in fallow periods in these scenarios used soil water which then decreased water available for wheat and other crops in the rotation (data not shown). This response did not occur at Dalwallinu because there was little summer rainfall to support summer crops and limited water storage in these sandy soils, and so the soil water available to the following wheat crop was little affected by the additional crops.

3.5. Gross margins analysis

Differences in gross margins between scenarios were driven by differences in yield, N inputs and soil water (Section 3.4). Scenarios with gross margins that were greater than the baseline were therefore those where (1) greater revenue (from increased yield) was generated relative to increases in variable costs (e.g. for increased N-inputs), or (2) where a decrease in revenue (due to lower yields) was less than the reduction in variable costs (Fig. 7).

Gross margins improved for all locations and soils when N inputs could be increased without increasing net costs, as in the no burn (S2) and improved pasture (S9) scenarios (Fig. 7). For the Dalwallinu sand and Wimmera clay soils, where yields responded to N inputs, gross margins increased in response to increasing N fertiliser applications (S3, S5) and were decreased by decreasing N fertiliser applications (S4, S6; Fig. 7b, c). Crop yields also increased when manure (S7) was applied, but the high cost of this input could only be recovered at the Wimmera site (Fig. 7c). For all locations and soils, the high cost of sowing summer crops (S8, S10) corresponded with unchanged or decreased yield (Fig. 4; Section 3.4) and hence decreased income (Fig. 7).

4. Discussion

In this study we identified cropping practices that provided net GHG abatement from the trade-off between increasing SOC stocks and/or reducing N_2O emissions from the soil (Fig. 4). The extent of abatement that was predicted from scenarios was determined by characteristics of the sites, especially the magnitude of soil N_2O emissions (Fig. 4d–f). For the well-drained Dalwallinu soils with low N_2O emissions, there was an increase in abatement from essentially any management practice scenario that increased SOC inputs to the soil (Table 5). By comparison, the net abatement available from scenarios on the Wimmera soil was determined by a trade-off between SOC storage and N_2O emissions under the scenarios. Despite these differences, there was consistent abatement from increased cropping scenarios S8–S10 across all site-soil combinations (Table 5).

Financial benefit has been shown to be an important factor in farmers' decisions to adopt new practices (Cary and Wilkinson, 1997; Frost, 2000; Maybery et al., 2005; Pannell et al., 2006), including GHG abatement practices (Morgan et al., 2015). Both GHG abatement and increased gross margins were achieved for improved pasture (S9) (Fig. 3) whereas other scenarios provided profitable abatement in specific location-soil combinations. However, the scenarios that provided the greatest abatement (i.e. by including summer crops, S8 and S10) decreased gross margins by the greatest amount (Fig. 3). For these practices, incentives or compensation payments that cover the costs of

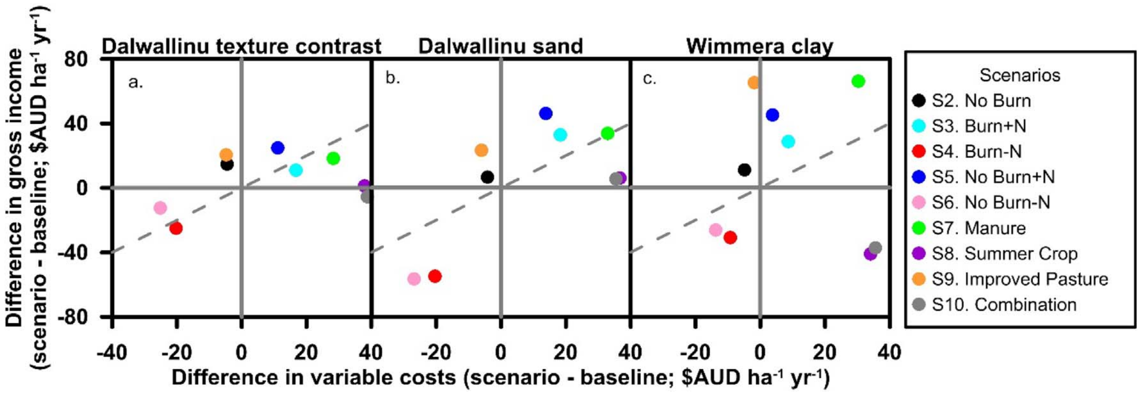

Fig. 7. Difference in annual variable costs and revenue from baseline values averaged over 100 yr for each scenario on the Dalwallinu texture contrast and sand soils, and on the Wimmera clay. The dotted line represents changes in variable costs and revenue that are equal and therefore result in the same gross margin as the baseline scenario. Points that plot above the dotted line have a greater gross margin than the baseline scenario (S1). Scenarios are described in Table 3.

adopting mitigation practices could assist adoption. However, the current incentive prices in Australia are substantially lower than the predicted decrease in gross margins for some scenarios included in this study. The main incentive program in Australia is the Emissions Reduction Fund, which offers businesses, including farms, payments for emissions reductions through a reverse auction scheme. The average payments received at auction for emissions reductions was ~ $AUD10–14 (Clean Energy Regulator, 2016b), which are lower than some of the predicted reduction in gross margins in this and other studies (e.g. $AUD87 per Mg CO_2e, Kragt et al., 2012; $AUD93 per Mg CO_2e, Barton et al., 2014). Given the low payments offered under the Emissions Reduction Fund, efforts to increase GHG abatement in the broadacre cropping sector may be best directed toward increasing the adoption of the profitable practices, i.e. the use of improved pastures in cropping rotations.

An additional consideration for the incentivisation of practices that provide GHG abatement is the underlying effect of the practices on productivity. In this study, the scenarios that provided greatest abatement (S8, S10) were unprofitable because they decreased average yield (particularly on the Wimmera farm) and thereby crop income (Figs. 4, 5). Incentivisation of the agricultural sector for practices such as these could conflict with the sector's task of feeding a growing global population (FAO, 2009). A consideration in attaining both GHG abatement and food production may be to consider the land suitability for the different tasks (e.g. Grundy et al., 2016). For example, dedicating highly-productive land to food production and less productive land to other activities including GHG abatement may contribute to a decrease in overall emissions intensity per unit of food production.

The net abatement identified from scenarios was small (~0.5–2.0 Mg CO_2e ha^{-1} yr^{-1}; Fig. 3) but had potential to be applied over large areas (several million hectares; see Section 2.1). Practices described in scenarios also fit within existing farming systems and use existing technology. Therefore these scenarios may be more readily adopted compared to practices which are complex, unfamiliar or require a large upfront investment (Bryan et al., 2014; Connor et al., 2015). While agroforestry is a key strategic practice proposed for delivering substantial abatement from agricultural land (IPCC, 2014b; CSIRO, 2015), high productivity carbon plantings are not suited to the Dalwallinu environment and substantial resistance toward adopting new land uses such as agroforestry has been observed (Bryan et al., 2014; Connor et al., 2015). The abatement practices identified in this study therefore represent achievable abatement within the existing land use and the environmental limitations of the existing land use.

Abatement was provided from a subset of scenarios when simulated for both 25 and 100 yr, but the annual abatement provided from the scenarios was lower when averaged over the longer time period (Fig. 3). This was linked to the declining contribution of SOC to net GHG abatement over time (Section 3.3). Where SOC concentrations attain equilibrium concentrations (at a time $>$ 100 yrs), the contribution of scenarios to net GHG abatement will be determined by the effect of the scenario on N_2O emissions alone. The effect of any scenario on N_2O emissions was very small at Dalwallinu (Fig. 4d, e), and so future ($>$ 100 yr) GHG emissions from scenarios at this location could approach baseline (S1) values. At Wimmera, the combination scenario (S10) decreased N_2O emissions relative to baseline (S1) values (Fig. 4f), and so could provide ongoing abatement after gains in SOC storage have ceased. However, the abatement provided from the summer crop (S8) and improved pasture (S9) scenarios at this site resulted from a trade-off between SOC storage and N_2O emissions (Fig. 4c, f, i). Thus there could be an increase in net GWP relative to baseline values once the difference in GWP from soil N_2O emissions exceed those from increases in SOC stocks.

The field-scale approach adopted in this study for identifying GHG abatement practices was useful for identifying site-specific, soil-based GHG trade-offs and abatement that were broadly consistent with the farm-based emissions approach funded through the Australian Emissions Reduction Fund. However, it was limited by not including the off-site implications of practices. Assessment of the overall impact

Table 5
Summary of effect of scenarios on GHG abatement and gross margins for location-soil combinations.

Description	Dalwallinu	Wimmera
Key site factors	Well-drained soils leading to low N_2O emissions	Slowly drained soils leading to high N_2O emissions
Abatement tactic	Increase carbon	Both increase carbon and decrease N_2O emissions by avoiding conditions where high soil water promotes N_2O emissions
Abatement practices	Stubble retention (S2, S5, S6), manure application (S7), increased cropping intensity (S8–S10)	Increased cropping intensity (S8–S10)
'Win-win' scenarios with both consistent abatement over 100 yr and increased gross margins	No burn (S2), no burn + N (S5), improved pasture (S9)	Improved pasture (S9)
Scenarios with consistent abatement over 100 yr and reduced gross margins	Summer crops (S8), combination (S10)	Summer crops (S8), combination (S10)

of practices on abatement is important in order to ensure that field-scale abatement is not achieved at the expense of increasing absolute emissions. For example, while manure application (S7) at Wimmera increased SOC (Fig. 4), it greatly increased soil N_2O emissions and resulted in a net increase in GWP at this site. However, this outcome does not represent the real impact of manure application because (1) N_2O emissions from feedlot manure may occur regardless of how the manure is used (Powlson et al., 2011), and (2) emissions from fuel incurred from transporting and spreading the manure are not included in the calculation of net GWP. There is potential for mitigation strategies to change depending on the system boundary (e.g. O'Brien et al., 2012). None the less, the additional emissions that could be included in a broader life cycle analysis (e.g. distance and hence fuel emissions required to transport feedlot manure) are heavily dependent upon assumptions that vary from farm to farm. A sensitivity analysis describing how various off-farm GHGs contribute to the net GWP of scenarios is beyond the scope of this study.

5. Conclusion

Scenarios with increased cropping intensity (S8–S10) represented additional practices that could be adopted within cropping systems to provide on-farm GHG abatement. Emissions reductions (averaged over 100 yr) from these practices were 0.3–1.2 Mg CO_2e ha^{-1} yr^{-1} relative to baseline values; for S10 absolute rather than relative abatement of 0.02–0.5 Mg CO_2e ha^{-1} yr^{-1} were simulated. For these three scenarios, the greatest emissions reductions relative to baseline values was available from S8 and S10 (0.4–1.2 Mg CO_2e ha^{-1} yr^{-1}) but this reduced gross margins by 30–75 $AUD ha^{-1} yr^{-1} relative to baseline values. This would not be compensated by current Emissions Reduction Fund payments, so promotion of abatement practices for the grains industry should therefore focus on those that are also profitable. The improved pasture scenario (S9) was the only abatement practice that could be adopted profitably to reduce on-farm emissions (0.3–0.4 Mg CO_2e ha^{-1} yr^{-1}) and increase gross margins (25–67 $AUD ha^{-1} yr^{-1}) relative to the baseline practice. The potential for the practices with increased cropping intensity to deliver abatement more generally over a greater range of Australian environments requires further research.

Identifying the relative contribution of different GHGs to net GWP was essential for determining abatement tactics that could be adopted at different locations. Thus, additional abatement practices (stubble retention, manure application) could provide abatement at well-drained, low rainfall locations such as Dalwallinu. Abatement from such practices in the low rainfall environments of this study are likely to provide small, incremental outcomes over the long term, but have potential to be implemented over large areas.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.04.012.

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