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Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate?

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ABSTRACT

Agriculture production contributes to global warming directly via the release of carbon dioxide (CO_2), methane and nitrous oxide emissions, and indirectly through the consumption of inputs such as fertilizer, fuel and herbicides. We investigated if including a grain legume (*Lupinus angustifolius*) in a cropping rotation, and/or applying agricultural lime to increase the pH of an acidic soil, decreased greenhouse gas (GHG) emissions from wheat production in a semi-arid environment by conducting a streamlined life cycle assessment analysis that utilized *in situ* GHG emission measurements, rather than international default values. We also assessed the economic viability of each GHG mitigation strategy. Incorporating a grain legume in a two year cropping rotation decreased GHG emissions from wheat production by 56% on a per hectare basis, and 35% on a per tonne of wheat basis, primarily by lowering nitrogen fertilizer inputs. However, a large incentive ($93 per tonne of carbon dioxide equivalents reduced) was required for the inclusion of grain legumes to be financially attractive. Applying lime was profitable but increased GHG emissions by varying amounts depending upon whether the lime was assumed to dissolve over one, five or 10 years. We recommend further investigating the impact of liming on both CO_2 and non-CO_2 emissions to accurately account for its effect on GHG emissions from agricultural production.

1. Introduction

Semi-arid and arid regions represent one third of the global land area and are widely used for grain production (Harrison and Pearce, 2000). Developing strategies for minimizing greenhouse gas (GHG) emissions from these regions is therefore important if global emissions from agriculture are to be lowered. Agriculture production contributes to global warming directly via the release of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from soil, and indirectly through its demand for inputs such as fuel and fertilizer (Robertson and Grace, 2004; Smith et al., 2012, 2008). Furthermore, GHG emissions from agriculture are predicted to increase as the world's population continues to grow and the demand for meat and grain increases (Smith et al., 2007). Development and deployment of economically viable mitigation practices that decrease GHG emissions from agriculture is therefore essential. The development of strategies for decreasing GHG emissions from agricultural soils in semi-arid regions has received limited attention, with the limited analysis that has occurred, relying on hypothetical rather than regionally-specific field data (Engelbrecht et al., 2013).

Nitrogen (N) fertilizer production and its application to land contributes significantly to agricultural GHG emissions (Biswas et al., 2008; Gascol et al., 2007; Robertson et al., 2000). The Haber–Bosch process for producing synthetic N fertilizer results in 0.375 mol of CO_2 per mole of N produced (Schlesinger, 1999); while its subsequent application to crops and pastures enhances soil N_2O emissions via microbial activity (Firestone and Davidson, 1989) and

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Abbreviations: $AUD, Australian dollar; CO_2, carbon dioxide; CO_2-eq, carbon dioxide equivalents; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LCI, life cycle inventory; $CaCO_3$, lime; CH_4, methane; LW, Lupin-wheat rotation; LW lime, lupin-wheat rotation with lime; N, nitrogen; N_2O, nitrous oxide; SLCA, streamline life cycle assessment; WW, wheat–wheat rotation; WW lime, wheat–wheat rotation with lime.

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CO_2 emissions from hydrolysis when N fertilizer is applied as urea (Eggleston et al., 2006). Increased use of synthetic N fertilizer since the industrial revolution has increased atmospheric N_2O concentrations from 271 ppbv to in excess of 320 ppbv (Solomon et al., 2007). Decreasing GHG emissions from the production and use of synthetic N fertilizer therefore has the potential to significantly lower the contribution of agriculture to global warming.

Incorporating grain legumes into cropping rotations can lower synthetic N requirements and may decrease GHG emissions from agriculture. Conservative estimates indicate 50 to 70 Tg N per year is fixed biologically in agricultural systems, despite the progressive replacement of legume rotations with synthetic N fertilizers over the past four decades (Crews and Peoples, 2004; Herridge et al., 2008; Smil, 2001). Whilst it has been suggested that including grain legumes in crop rotation may increase the risk of soil N_2O emissions, this is typically not the case (Jensen et al., 2012). Rather global and regional analyzes indicate replacing a portion of cereal crops with legumes is likely to lower GHG emissions from crop production, although these calculations largely utilize international default values for estimating soil GHG emissions derived from temperate climates (e.g., Eady et al., 2012; Engelbrecht et al., 2013; Jensen et al., 2012; Lemke et al., 2007; Nemecek et al., 2008). Indeed, the discussion of the effects of crop rotation on GHG emissions, and the use of site-specific emission data, is inadequate (Kendall and Chang, 2009). A streamlined life cycle assessment (SLCA) of GHG emissions, which accounts for emissions across production stages and utilizes site specific, field-based measurements for a range of climates and soil types, is needed to fully assess the role of grain legumes in mitigating agricultural GHG emissions.

In addition to decreasing the use of synthetic N fertilizers, mitigating soil N_2O emissions resulting from the use of synthetic N fertilizers is also recommended as an approach to lowering GHG emissions from agricultural soils (Smith et al., 2008). Soil N_2O can be emitted in direct response to the N fertilizer application, via biological processes such as nitrification or denitrification, or indirectly via N leaching and runoff, as well as from ammonia (NH_3) volatilization (Eggleston et al., 2006). Most strategies for decreasing N_2O emissions from cropped soils focus on improving N fertilizer use efficiency by fine-tuning plant growth-limiting factors and improving the synchrony between plant N uptake and N supply from all sources (Cassman et al., 2002; Ladha et al., 2005). These approaches, however, are unlikely to be effective at mitigating N_2O emissions that do not occur in direct response to N fertilizer applications. For example, a significant proportion of N_2O emissions from semi-arid agricultural soils can occur post-harvest, when the soil is fallow, and in response to summer-autumn rainfall (Barton et al., 2008; Galbally et al., 2008). Increasing soil pH, by applying agricultural lime ($CaCO_{3,}$ herein referred to as ‘lime’), may be one approach to decreasing N_2O emitted in semi-arid environments in response to summer rainfall events (Barton et al., 2013a, 2013b; Page et al., 2009). However, liming will only decrease total GHG emissions from these agricultural production systems if mitigated N_2O emissions are greater than the CO_2 emissions resulting from the dissolution and transport of the lime. For example, the Intergovernmental Panel on Climate Change (IPCC) assumes that all of the carbonate contained in lime ($CaCO_3$) will be released as CO_2 within the first year of application (Eggleston et al., 2006).

The overall objective of this study was to investigate strategies for decreasing GHG emissions resulting from the use of N fertilizers in rain-fed cropping systems in a semi-arid region. Specifically we investigated if including lupin (a grain legume commonly grown the region) in the cropping rotation, or applying lime to increase soil pH, decreased the life cycle global warming potential of wheat produced in a semi-arid climate. This was achieved by incorporating locally derived field-based measurements of GHG emissions derived from a companion study (Barton et al., 2013b) into a life cycle assessment (LCA) analysis. The economic viability of each rotation was also assessed, and where necessary, the financial incentive required to lower emissions calculated.

2. Materials and methods

2.1. Study site and experimental design

The effect of incorporating a grain legume in a cropping rotation, and applying lime, on GHG emissions from the wheat production was investigated in south-western Australia. The field site was located at Wongan Hills (30° 89′ S, 116° 72′ E) on a free-draining sand (Typic Quartzipsamment; USDA, 1992), which has an average annual rainfall of 374 mm that mainly falls in winter (Commonwealth Bureau of Meteorology, http://www.bom.gov.au/climate/averages). The field study consisted of a randomized-block design: two cropping rotations (lupin-wheat, wheat–wheat) by two liming treatments (0, 3.5 t ha^{-1}) by three field plot replicates (Barton et al., 2013b). Lime sand was surface applied to the soil approximately 2.5 months (18 March 2009) before planting in Year 1 with the aim of achieving a soil pH > 6.0 so as to influence the biological processes responsible for N_2O emissions. In Year 1 (June 2009), plots were either seeded to lupin (for the lupin-wheat rotation) or to wheat (*Triticum aestivum* cv Carnamah; for the wheat–wheat rotation), with N fertilizer only applied to the wheat (75 kg N ha^{-1} as urea). The following year (Year 2; June 2010) all plots were planted to wheat with the amount of urea applied to the lupin-wheat rotation taking into account the residual N from the 2009 lupin crop (Barton et al., 2013b). Consequently in 2010, the lupin-wheat plots received 20 kg N ha^{-1} as urea, while the wheat–wheat plots received 50 kg N ha^{-1}. Additional chemical inputs were recorded, and were typical of local farming practices. Each year the crops were harvested in November and the yield recorded for each plot. Soil GHG emissions (N_2O and CH_4) were measured continuously (subdaily) from each plot throughout the two year study using an automated chamber system connected to a gas chromatograph located at the field site, providing very high resolution (temporal) data. For further details of the study site, including the measurement of *in situ* N_2O and CH_4 emissions see Barton et al. (2013b).

2.2. Streamlined LCA assessment of GHG emissions from each cropping rotation

2.2.1. Goal and scope

The goal of the LCA was to compare GHG emissions from a lupin-wheat rotation with that emitted from a wheat–wheat rotation; both with or without lime. This was achieved after establishing the functional unit, selecting system boundaries, determining data requirements for the life cycle inventory (LCI), and finally calculating the GHG emissions for each cropping rotation. The functional unit was: 1) one hectare of cropped land; or 2) the production and transportation of one tonne of wheat to the port. We adopted a streamlined LCA (SLCA) approach that considered cradle-to-port GHG emissions, but ignored activities after the port (Engelbrecht et al., 2013; Todd and Curran, 1999). Consequently, our research considered GHG emissions in terms of an LCA, but with a focus on one impact category only, i.e. climate change (Finkbeiner et al., 2011).

2.2.2. Life cycle inventory

A LCI was completed prior to conducting the SLCA and consisted of the inputs (e.g., fertilizers, herbicides) and outputs (e.g., CO_2, CH_4, and N_2O) from three life cycle stages: pre-farm, on-farm and post-farm. *Pre-farm* activities included farm machinery manufacture and the production, plus transport of chemicals and fertilizers to the study site at Wongan Hills, and were calculated on a per hectare basis for each year (see Supporting Information Table 1). Most of the pre-farm emissions were calculated using emission factors available from the Australian LCA database (RMIT, 2007), and emission factors not available in the Australian database were developed by gathering basic information from the local industries (e.g. CSBP, a local fertilizer company, provided energy consumption information for determining the GHG emission factor for super phosphate production). The GHG emissions from the manufacture of farm machinery were estimated using the USA input/output database (Suh, 2004), based on the value of the machinery, with allowances for exchange rates and inflation. The USA input/output database contains environmental emission data for the production of US$ 1 equivalent farm machinery. The current price of farm machinery was deflated to the 1998 price (in AUD) at 2.98% per year. Following this, the 1998 price of machinery in AUD/hectare was converted to1998 US$ by multiplying by 0.6. Once the machinery cost for one tonne of wheat production was determined in terms of 1998 US$, this value was then multiplied by the GHG emission factor of machinery production (kg CO_2e-/US$). Greenhouse gas emissions from the transport of inputs to the study site were calculated using the Australian LCA database (RMIT, 2007). Various modes of transportation were used including shipping, rail and articulated trucks (30 tonne), with the tonnage of input transported from manufacturer to the farm recorded (tkm). Where sea transportation was used to transport inputs, a single sea journey on a tanker to the port closest to the manufacturer was assumed. The GHG emissions from the production of chemicals was calculated using the Australian LCA database (RMIT, 2007). Herbicides not included in this Australian LCA database were converted to glyphosate equivalents before calculating GHG emissions, while GHG emissions associated with fertilizers not included in the Australian LCA database (e.g., super phosphate, Macro Pro, Big Phos Mn) were calculated using information collected from local fertilizer manufacturers (CSBP). The emission factor for urea production includes CO_2 associated with energy used to produce urea, plus the fossil fuel derived CO_2 used to manufacture the urea (i.e., $2NH_3 + CO_2 \rightarrow H_2N - COONH_4$). The amount of CO_2 that is used to manufacture the urea is subsequently released when the fertilizer is applied to land it is therefore included in the on-farm GHG contribution (see below). Only the CO_2 associated with the energy used to produce urea is considered in the pre-farm data.

On-farm data included information associated with the planting, maintaining and harvesting the crop, plus soil GHG emissions (see Supporting Information Table 1). The GHG emissions from fuel consumed during farm machinery operation were calculated using the Australian LCA database (RMIT, 2007). Machinery usage was expressed in terms of the amount of liters of fuel per hectare of land utilizing machinery typical for the region (L hr^{-1} ha^{-1}; See Supporting Information Table 1). Fuel consumption was dependent on land area, machinery width and the number of times the machinery passed across the land. Only direct N_2O emissions and CH_4 emissions from soil were quantified at the experimental site (Barton et al., 2013b), with indirect N_2O emissions, and CO_2 emission from urea hydrolysis, estimated using the Intergovernmental Panel on Climate Change (IPCC) default values (Eggleston et al., 2006). Indirect emissions include the N_2O emissions from N leaching and runoff, as well as those from NH_3 volatilization. The N_2O emissions from N leaching were assumed to be zero as the ratio of mean annual evapotranspiration (Et) to annual precipitation (P) was >1 for the experimental site, and the IPCC methodology predicts leaching only occurs when Et/P is between 0.8 and 1. For NH_3 volatilization, the IPCC methodology assumes that 10% of N fertilizer applied will be emitted as NH_3 via volatilization thereafter a portion of NH_3 will be converted to N_2O following its deposition to land (Eggleston et al., 2006). A conversion factor of 0.08% was used to calculate the proportion of deposited NH_3 released as N_2O in this study, as this value is consistent with the value used by Australia to estimate direct N_2O emissions from the application of N fertilizer to non-irrigated land. Carbon dioxide emissions from lime dissolution were calculated using three scenarios based on different dissolution periods:

> Scenario I: Lime dissolved within one year of application. This scenario is consistent with the IPCC's recommended approach to calculating CO_2 emissions from lime dissolution (Eggleston et al., 2006).
> Scenario II: Lime assumed to dissolve in five years. Consequently this scenario equates to two-fifths of the CO_2 emissions from Scenario I, as it only includes the first two years (current LCA timeframe) of the five year dissolution period in the LCA; and
> Scenario III: Lime assumed to dissolve in 10 years, equating to one-fifth of the CO_2 emissions from Scenario I, as it only includes the first two years (current LCA timeframe) of the 10 year dissolution period in the LCA. This scenario was chosen as it is represents the regularity that growers would apply 3.5 t ha^{-1} of lime in the study region.

Post-farm emissions included grain storage (5.6 kg CO_2 per tonne of wheat) and also 19.2 kg CO_2 per tonne of wheat transported to port (Kwinana, Western Australia) with a 30 tonne truck (Biswas et al., 2008; see Supporting Information Table 1).

2.2.3. Calculating GHG emissions from each cropping rotation

Individual greenhouse gas (CO_2, N_2O, CH_4) emissions from each production stage were converted to CO_2-eq using established conversion factors (Eggleston et al., 2006). Greenhouse gas emissions (as CO_2-eq) were then calculated on either a *per hectare* basis or a *per tonne of wheat* basis for each cropping rotation (with or without lime). The annual CO_2-eq per hectare (kg CO_2-eq ha^{-1} yr^{-1}) was calculated by summing CO_2-eq from each year and then dividing by the number of study years (two).

Total GHG emissions per tonne of wheat (CO_2-eq per tonne wheat) were calculated differently for each cropping rotation. For the wheat–wheat rotation, CO_2-eq per tonne wheat was calculated by summing the CO_2-eq ha^{-1} for each year and then dividing by the total wheat yield (t ha^{-1}) for the two years. Calculating the CO_2-eq per tonne wheat for the lupin-wheat rotation was more complicated, requiring the allocation of emissions from lupin production to the wheat production. The approach adopted for this allocation (described in the subsequent paragraph) is broadly consistent with the approaches proposed for allocating the environment impact of applying N derived from animal and green manure to crop rotations (Knudsen et al., 2014; van Zeijts et al., 1999).

The lupin was included in the cropping rotation to decrease the synthetic N fertilizer applied to the subsequent wheat crop. However, as only a proportion of the N from the lupin is used by the subsequent wheat crop, only a proportion of the emissions from the lupin crop were allocated to the following wheat crop. This proportion or 'allocation factor' was calculated by dividing the total amount of fertilizer avoided (i.e., saved) by the amount of N contained in the lupin crop (above- and below-ground):

$$\text{Allocation factor} = \frac{\text{Nfert saved}}{\text{Lupin } N_{AG} + \text{Lupin } N_{BG}}$$

Where, Nfert saved is the amount of N fertilizer saved by growing the lupin (30 kg N ha^{-1}), Lupin N_{AG} is the amount of N contained in the above-ground biomass of the lupin crop (kg N ha^{-1}), and Lupin N_{BG} amount of N contained in the below-ground biomass (kg N ha^{-1}). The total of Lupin N_{AG} plus Lupin N_{BG} varied from 199 to 241 kg N ha^{-1} depending on liming treatment (Barton et al., 2013b; Unkovich et al., 2010), meaning the allocation factor ranged from 12 to 15%. Therefore the CO_2-eq per tonne wheat for the lupin-wheat rotation was calculated by summing 12–15% of the GHG emitted from the lupin crop production (2009–2010) with the GHG emissions from wheat production in the second year of crop rotation (2010–2011), and then dividing this summed value with the wheat yield from the second year of the rotation (i.e., 2010–2011).

2.3. Economic analysis of each cropping rotation

A budgeting analysis was conducted to determine the economic viability of each rotation on a per hectare basis ($ ha^{-1} yr^{-1}), and if necessary, the incentive required to make a lower emitting rotation financially attractive for grain producers. To assess the economic viability of each rotation, the costs of inputs from the LCI was calculated, and the financial return from the grain yield determined. With the exception of grain prices (which were based on the average real farm-gate prices between 2007 and 2011), all prices were sourced from local suppliers. Machinery costs included an allowance for depreciation, labor, repairs and maintenance. Indirect, fixed production costs like land taxes were omitted as these would be identical for all rotations. Grain growers typically apply lime intermittently, consequently the net present value of the costs and benefits of lime and its application were annualized assuming a realistic commercial discount rate of 7%, and reapplication every 10 years; this timeframe is considered to be conservative as research in the study region has found applying lime at 2.5 t ha^{-1} continued to increase wheat yield by 25% up to 15 years later (Tang et al., 2003). The cropping rotations were treated as discrete options for two specific years with the (undiscounted) net returns of the rotations averaged across the two years. All monetary values are presented in Australian dollars ($AUD). Where a rotation caused fewer emissions, but had lower profitability, the minimum amount of money farmers would have to receive for it to be financially attractive to change to the lower emitting rotation (expressed in terms of $ per tonne of reduction in CO_2-eq emissions) was determined. These incentive payments were only calculated using per hectare emissions because the financial attractiveness of a rotation depends on the net profit from the entire cropping sequence.

2.4. Statistical analysis

A statistical analysis was conducted to assess if CO_2-eq emitted for each stage of wheat production was significantly affected by either cropping rotation or the application of lime. All data were statistically analyzed using a general linear model (completely randomized design) (Genstat, 2009). Post-hoc pair-wise comparisons of means were made using least significant difference (LSD; 5% level). It was not possible to conduct the statistical analysis of CO_2-eq on a per hectare basis (except for on-farm N_2O and CH_4 emissions) as inputs did not vary between field replicates.

3. Results

Including a grain legume in the cropping rotation generally decreased GHG emissions on both a per hectare and per tonne of wheat basis, irrespective of the application of lime ($P < 0.05$; Figs. 1 and 2). However on a per tonne of wheat basis, GHG emissions did not differ between the two cropping rotations when lime was assumed to dissolve in five years ($P < 0.05$; Fig. 2b). Including a grain legume in the cropping rotation did not compromise wheat yield in the second year of the cropping rotation (see Supporting Information Table 2).

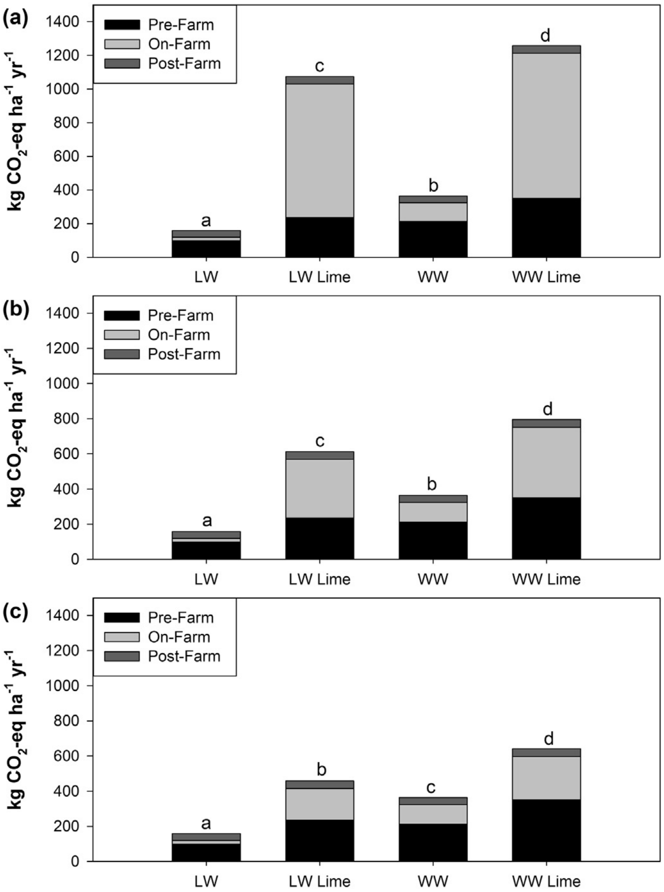

Fig. 1. Life cycle assessment of greenhouse gas emissions produced per hectare of cropped land per year without lime, and when lime dissolves in (a) one year, (b) five years, and 10 years (c). Input data based on a lupin-wheat (LW) and wheat–wheat (WW) rotation at Wongan Hills, Australia (2009–2011). Columns in the same pane containing the same letter above them are not significantly differently at the 5% level.

3.1. Effect of grain legume on cropping rotation GHG emissions in the absence of lime

On a per hectare basis, including a grain legume in the rotation decreased GHG emissions from 364 to 159 kg CO_2-eq ha^{-1} yr^{-1} when lime was not applied. The pre-farm stage contributed approximately 60% to total GHG emissions from both rotations (no lime; Fig. 1); herbicide and fertilizer production was the greatest source of pre-farm emissions for the lupin-wheat and wheat–wheat rotation, respectively (Table 1). The on-farm stage represented 10% of the total GHG emissions from the lupin-wheat rotation, and 30% of the total emissions from the wheat–wheat rotation (no lime; Fig. 1). Carbon dioxide emissions from urea dissolution was the greatest source of on-farm emissions for the wheat–wheat rotation (no lime), and were 9-times greater than from the lupin-wheat rotation (no lime; Table 2).

On a per tonne of wheat basis, including a grain legume in the cropping rotation, decreased total GHG emissions from 227 to 148 kg CO_2-eq per tonne of wheat when lime was not applied ($P < 0.05$; Fig. 2). The pre-farm stage represented 58% (wheat–wheat, no lime) to 66% (lupin-wheat, no lime) of total GHG emissions, whereas the on-farm stage contributed 17% (lupin-wheat, no lime) to 30% (wheat–wheat, no lime; Fig. 2). Herbicide or

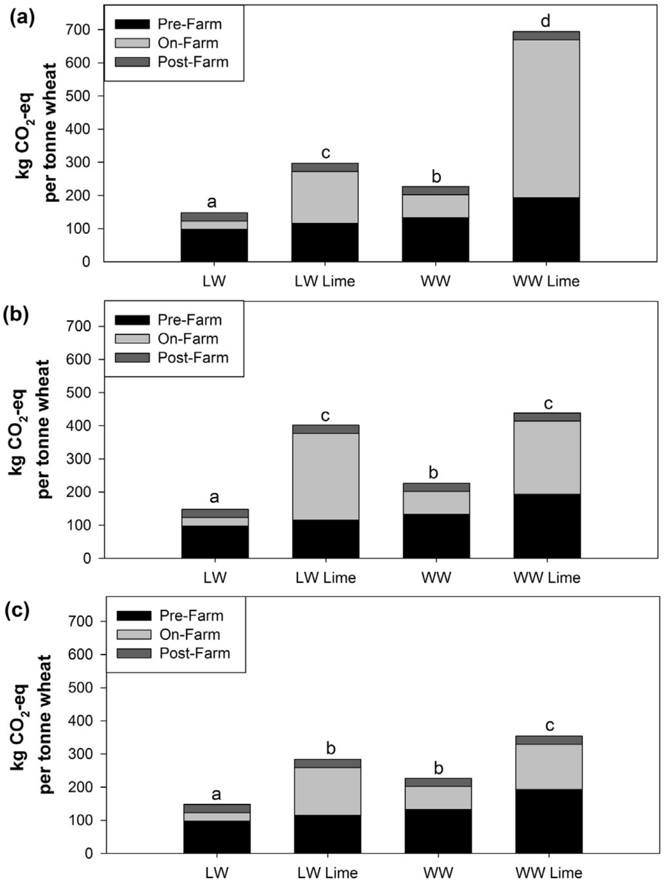

Fig. 2. Life cycle assessment of greenhouse gas emissions produced per tonne of wheat without lime and when lime dissolves in (a) one year, (b) five years, and 10 years (c). Input data based on a lupin-wheat (LW) and wheat–wheat (WW) rotation at Wongan Hills, Australia (2009–2011). Columns in the same pane containing the same letter above them are not significantly different at the 5% level.

fertilizer production mostly contributed to pre-farm emissions (Table 3), while soil N_2O and CO_2 emissions from the application of urea to land were the main sources of on-farm emissions (Table 4).

3.2. *Effect of liming on GHG emissions*

On a per hectare basis, applying lime at least doubled GHG emissions from both rotations ($P < 0.05$; Fig. 1). Although the dissolution time of the lime did not alter pre-farm GHG emissions in absolute terms, it did alter the proportion of total emissions attributed to the pre-farm stage. For example, pre-farm emissions contributed up to 28% to total GHG emissions when lime was assumed to dissolve in one year, but increased to 55% when lime dissolved in 10 years (Fig. 1); lime transport, fertilizer production (wheat–wheat only), and herbicide production were all major sources of pre-farm emissions (Table 1). The on-farm stage produced 70% of the total GHG emissions from both rotations when lime dissolved in one year, decreasing to approximately 40% when lime dissolved in 10 years (Fig. 1). Irrespective of the dissolution rate, CO_2 emissions from lime dissolution were the greatest source of on-farm emissions for both rotations (Table 2). For example, under the assumption that lime dissolved in one year, CO_2 emissions from liming were almost 9-times greater than CO_2 emissions from urea hydrolysis (Table 2). Applying lime also decreased direct soil N_2O emissions from the wheat–wheat rotation ($P < 0.05$; Table 2).

On a per tonne of wheat basis, applying lime at least doubled emissions from both rotations ($P < 0.05$; Fig. 2). Again while liming did not alter absolute pre-farm GHG emission, the proportion of total emissions attributed to this stage increased from approximately 40%, when lime was assumed to dissolve in one year, to up to 55% when lime dissolved in 10 years (Fig. 2), due to lower CO_2 emissions from lime dissolution in the on-farm stage. Lime transport, fertilizer (wheat–wheat only) and herbicide production were the main source of pre-farm emissions (Table 3). Up to 70% of the total GHG emissions from both rotations were attributed to the on-farm stage when lime dissolved in one year, which decreased to approximately 50% when lime dissolved in 10 years (Fig. 2). Lime dissolution was the greatest source of on-farm emissions for both rotations, even when it dissolved in 10 years (Table 4). Storage and transport of grain to port (i.e., post-farm emissions) contributed relatively little (<10%) to GHG emissions from the production of one tonne of wheat when lime was applied to both rotations.

3.3. *Economic viability of cropping rotations*

Initial analysis indicated that the lupin-wheat rotation was \$37 ha^{-1} yr^{-1} more profitable than the wheat–wheat rotation with lime, and \$58 ha^{-1} yr^{-1} without lime (see Supporting Information Table 3). However, wheat yield was unusually low relative to the lupin grain yield in Year 1 (2009 harvest) of the present study. Historical data for the region shows wheat yield to be 166% of lupin yield (by mass), and in 2009 averaged 143% on commercial farms in the present study district (Planfarm, 2010). At the present study site, wheat yield was 111% of the lupin yield in 2009; perhaps because wheat was also grown at the site for two consecutive years prior to the current study, limiting rotational benefits from sowing different crops (Seymour et al., 2012). Consequently, we reassessed

Table 1
Contribution of pre-farm inputs and outputs to greenhouse gas emissions (kg CO_2-eq per year) from one hectare of cropped land. Values are identical for all liming scenarios.

	Lupin-wheat	Lupin-wheat (lime)	Wheat–wheat	Wheat–wheat (lime)
N-fertilizer				
Production[a]	11.3	11.3	100.1	100.1
Transport	1.7	1.7	13.9	13.9
Lime				
Production	0.0	29.6	0.0	29.6
Transport	0.0	108.3	0.0	108.3
Herbicide production	61.0	61.0	73.5	73.5
Farm machinery production	17.6	17.7	17.7	17.9
Other inputs[b]				
Production	3.3	3.3	3.9	2.9
Transport	3.1	3.1	3.6	3.6

[a] Excludes CO_2 emissions from urea hydrolysis.
[b] Fungicides, oil, non N-fertilizers, pesticides, and rhizobium.

Table 2
Contribution of on-farm inputs and outputs to greenhouse gas emissions (kg CO_2-eq per year) from one hectare of cropped land for all liming scenarios[a]. Values in the same row containing the same letter are not significantly different at the 5% level.

	Lime scenario	Lupin-wheat	Lupin-wheat (lime)	Wheat–wheat	Wheat–wheat (lime)	$LSD_{0.05}$[b]
CO_2 from urea		9.4	9.4	86.4	86.4	NA[c]
CO_2 from lime	I	0.0	770.0	0.0	770.0	NA
	II	0.0	308.0	0.0	308.0	
	III	0.0	154.0	0.0	154.0	
Soil N_2O emissions		22.2^{ab}	24.1^{b}	28.2^{b}	16.4^{a}	6.5
Indirect N_2O emissions		0.2	0.2	2.0	2.0	NA
Soil CH_4 emissions		-16.5^{ab}	-15.7^{ab}	-11.8^{ab}	-18.6^{a}	5.6
Farm machinery use		5.7	6.4	6.0	6.7	NA

[a] Scenario I, lime dissolves in one year; Scenario II, lime dissolves in five years; Scenario III, lime dissolves in 10 years.
[b] LSD, least significant difference.
[c] NA, not applicable.

Table 3
Contribution of pre-farm inputs and outputs to greenhouse gas emissions (kg CO_2-eq) from the production and transport of one tonne of wheat to port. Values are identical for all liming scenarios. Values in the same row containing the same letter are not significantly different at the 5% level.

	Lupin-wheat	Lupin-wheat (lime)	Wheat–wheat	Wheat–wheat (lime)	$LSD_{0.05}$[d]
N-fertilizer					
Production[e]	16.1^{a}	15.3^{a}	62.5^{b}	55.2^{b}	9.3
Transport	2.4^{a}	2.3^{a}	8.7^{b}	7.7^{b}	1.3
Lime					
Production	0.0^{a}	5.0^{b}	0.0^{a}	16.3^{c}	0.7
Transport	0.0^{a}	18.4^{b}	0.0^{a}	59.8^{c}	2.7
Herbicide production	59.3^{c}	55.8^{bc}	45.9^{ab}	40.5^{a}	10.4
Farm machinery production	14.5^{c}	13.5^{bc}	11.1^{ab}	9.9^{a}	2.5
Other inputs[f]					
Production	2.5^{b}	2.3^{b}	2.4^{b}	1.6^{a}	0.5
Transport	2.8^{c}	2.6^{bc}	2.2^{ab}	2.0^{a}	0.5

[d] LSD, least significant difference.
[e] Excludes CO_2 emissions from urea hydrolysis.
[f] Fungicides, oil, non N-fertilizers, pesticides, and rhizobium.

the economic viability of each cropping rotation after scaling the 2009 wheat yields reported in this study so that they were 143% of lupin yield. Inputs and environmental conditions were unchanged from the original economic analysis, and it was assumed that GHG emissions from the soil would not differ as a result of the scaling. However, the higher yield increased grain handling and thus emissions per hectare (see Supporting Information Table 3).

After scaling the wheat yield, the wheat–wheat rotations were more profitable than the lupin-wheat rotation. For example, without lime, wheat–wheat was \$20 ha^{-1} yr^{-1} more profitable than the lupin-wheat rotation (see Supporting Information Table 3). At the same time the wheat–wheat rotation would also emit 371 kg of CO_2-eq ha^{-1} yr^{-1}, which is 2.3 times more than lupin-wheat (see Supporting Information Table 3). Therefore grain producers would require some form of pecuniary incentive to change rotations and realize emissions savings. An incentive equivalent to \$93 per every tonne of CO_2-eq decreased would be required to change from a wheat–wheat rotation to lupin-wheat rotation if lime was not applied (Table 5). If lime was applied, then the incentive would need to be \$256 t^{-1} CO_2-eq^{-1} (the time it takes lime to dissolve does not alter this incentive as the changes in emissions when lime dissolves over longer time frames affect both the lupin-wheat and wheat–wheat rotations identically).

4. Discussion

4.1. Grain legumes and GHG emissions from wheat production

Including a grain legume in a cropping rotation decreased total GHG emissions produced from rain-fed wheat grown in a semi-arid environment on both a per hectare and per tonne of wheat basis. Utilizing legume-fixed N in a two year cropping rotation decreased

Table 4
Contribution of on-farm inputs and outputs to greenhouse gas emissions (kg CO_2-eq) from the production and transport of one tonne of wheat to port for all liming scenarios[d]. Values in the same row containing the same letter are not significantly different at the 5% level.

	Lime scenario	Lupin-wheat	Lupin-wheat (lime)	Wheat–wheat	Wheat–wheat (lime)	$LSD_{0.05}$[e]
CO_2 from urea		13.4^{a}	12.8^{a}	53.9^{b}	47.7^{b}	8.0
CO_2 from lime	I	0.0^{a}	130.4^{b}	0^{a}	424.8^{c}	19.2
	II	0.0^{a}	235.4^{c}	0^{a}	169.9^{b}	29.1
	III	0.0^{a}	117.7^{c}	0^{a}	85.0^{b}	14.5
Soil N_2O emissions		21.4^{b}	20.9^{b}	17.6^{b}	9.0^{a}	6.7
Indirect N_2O emissions		0.3^{a}	0.3^{a}	1.3^{b}	1.1^{b}	0.2
Soil CH_4 emissions		-14.6^{a}	-12.2^{ab}	-7.3^{c}	-10.3^{bc}	3.4
Farm machinery use		4.9^{b}	4.7^{b}	3.8^{a}	3.7^{a}	0.9

[d] Scenario I, lime dissolves in one year; Scenario II, lime dissolves in five years; Scenario III, lime dissolves in 10 years.
[e] LSD, least significant difference.

Table 5
The minimum incentive required to make the lupin-wheat rotation more viable than the wheat–wheat rotation (after scaling 2009 wheat yields) as affected by input and output prices.

Scenario	Without lime	With lime
	$ t^{-1} CO_2-eq	
Standard input & output prices	93	256
Fertilizer & pesticide prices 10% higher	59	219
Fertilizer & pesticide prices 10% lower	127	294
Wheat prices 10% higher	246	456
Lupin prices 10% higher	−8[a]	129

[a] Negative value indicates no incentive required.

emissions from wheat production by 56% per hectare (e.g., 364 to 159 kg CO_2-eq ha^{-1} yr^{-1} when lime not applied), and by 35% per tonne of wheat (e.g., 227 to 148 kg CO_2-eq per tonne of wheat when lime not applied). This occurred as less N fertilizer was applied to the lupin-wheat than the wheat–wheat rotation, which subsequently decreased CO_2 emissions from fertilizer production and urea hydrolysis, and without additional soil N_2O emissions. Decreasing N fertilizer inputs to wheat production also decreased emissions from fertilizer transportation (pre-farm), and indirect soil N_2O emissions (on-farm). In the present study 227 kg CO_2-eq were produced per tonne of wheat when N was sourced from fertilizer and lime was not applied, which is comparable to a previous estimate (304 kg CO_2-eq per tonne of wheat) for the region (Biswas et al., 2008).

Our observations are also consistent with the general expectation that replacing a cereal crop with a legume crop, or substituting fertilizer N with, legume-fixed N will lower GHG emissions from crop production (Eady et al., 2012; Engelbrecht et al., 2013; Jensen et al., 2012; Lemke et al., 2007; Nemecek et al., 2008). However previous research has utilized IPCC default values rather than site or regional specific emission data, and has been largely conducted in more temperate climates that the present study. To our knowledge, this is the first GHG emission analysis that utilizes field-based emission data to quantify the effect of incorporating grain legumes in a cropping rotation on GHG emissions from cereal grain production in a semi-arid environment. This is important because in semi-arid environments such as the study region, IPCC emission factors have been found to significantly over estimate emissions of N_2O from agricultural soil (Barton et al., 2008, 2010), and agricultural production is widespread in semi-arid regions.

Production, transport and application of N fertilizer, is the greatest source of GHG emission in wheat production in the present semi-arid region. For example in the current study, it contributed 231 kg CO_2-eq per ha, or 144 kg CO_2-eq per tonne of wheat (63% of total GHG emissions when a grain legume was not included in the rotation). This is comparable to a previous study in the same region where N fertilizer supply and use produced almost 190 kg CO_2-eq per tonne of wheat (62% of total GHG emissions; Biswas et al., 2008). Including a grain legume in the present study decreased the contribution from N fertilizer use from 231 to 45 kg CO_2-eq ha^{-1} yr^{-1}, or from 144 to 54 kg CO_2-eq per tonne of wheat. Others have also shown including perennial and annual grain legumes in cropping rotations lowered energy inputs, via decreased N fertilizer inputs, by up to 27% (Hoeppner et al., 2005; Rathke et al., 2007; Zentner et al., 2001). The extent to which incorporating a grain legume into a cropping rotation decreases energy inputs and GHG emissions from crop production will depend on how much N fertilizer is saved, which will in turn be determined by grain legume yield, the type of grain legume grown, and the regularity grain legumes are included in the rotation (Lemke et al., 2007; Peoples et al., 2009).

Including a grain legume in a two year cropping rotation for the purpose of decreasing GHG emissions would require a large incentive (per tonne of emission saved) to be financially attractive to grain producers in the study region. Despite requiring less expenditure on N fertilizer, the lupin-wheat rotation was still less profitable than wheat–wheat because both the yield of grain per ha, and the price per tonne of this grain, was lower when lupin grain was produced instead of wheat grain. Therefore an opportunity cost would be incurred by growing the lupin-wheat rotation. And so although the difference in emissions between the lupin-wheat and wheat–wheat rotations appears impressive, the absolute size of these emissions saving was small compared to this opportunity cost. For instance changing from wheat–wheat to a lupin-wheat rotation without lime would cause per hectare emissions to fall by 57% (mainly because of reduced emissions from N fertilizer production and use). However in absolute terms, this was a decrease of only 0.21 t CO_2-equ ha^{-1} yr^{-1} for a reduction in profit (i.e., opportunity cost) of $20 ha^{-1} yr^{-1}, suggesting a financial incentive equivalent to $93 t^{-1} CO_2-equ would be required to change from a wheat–wheat rotation to lupin-wheat. This is much larger than contemporary global carbon prices. However it should be noted that the financial incentive is sensitive to input costs (e.g., fertilizer and pesticides) and, in particular grain prices (Table 5); both of which do vary temporally. Had seasonal conditions in Year 2 (2010) of the study been more favorable, then it is possible that wheat yield would have responded more positively to inclusions of the grain legume in the rotation, lowering the incentive required to make the lupin-wheat rotation financially attractive.

The present study presents a simplified crop rotation so that field-based data (Barton et al., 2013b) could be incorporated in the analyses. Typically grain legumes are included in cropping rotations in the study region, but not every second year. Decreasing the frequency that grain legumes are grown (in comparison to the present study) would decrease the financial incentive required per tonne of emissions reduction to include a grain legume in the cropping rotation, although not necessarily by a large amount, as less frequent legumes would mean less tonnes of emissions reductions. Also, we have considered the financial performance of the rotations in isolation rather than as part of the entire farms operation (Pannell, 1995). The adoption of agricultural practices often depends on a broader range of technical, social, cultural, economic and personal factors, and not just financial attractiveness (Pannell et al., 2006). These limitations aside, the results of the economic analysis still provide a guide to the likely cost-effectiveness (and thus desirability) of pursuing the rotation change in question to decreasing GHG emissions on the study region.

4.2. Soil liming and the GHG emissions from grain production

Applying lime increased the profitability of grain production, but at the same time increased total GHG emissions on both a per hectare and per tonne of wheat basis in the present study. Similarly, soil liming increased GHG emissions from grains production from 304 to 466 kg CO_2-eq per tonne of wheat in a previous assessment in the same region as the present study (Biswas et al., 2008). However, the extent to which liming contributes to GHG emissions in the present study varied depending on the rate of lime dissolution (Figs. 1 and 2). Calculating the contribution of soil liming to CO_2 emissions, and specifically the validity of the IPCC default values, has been widely debated (Biasi et al., 2008; Hamilton et al., 2007; West and McBride, 2005). As previously mentioned, the IPCC guidelines for preparing national GHG inventories assumes that, in the absence of country-specific data, all of the carbonate contained in calcic limestone will be released as CO_2 within a year of application (Eggleston et al., 2006). However a review of the contribution of agricultural lime use to CO_2 emissions in the United States estimated only 49% of the applied carbonate was emitted as CO_2 (West and McBride, 2005). Further research clarifying the amount (and timing) of CO_2 emitted by lime dissolution is required. Given our SLCA results were very sensitive to the inclusion of soil liming, such research could have implications for calculating the carbon foot print of agricultural production, and national GHG inventories more generally, where the SLCA is sensitive to CO_2 emissions from liming.

The influence of liming on GHG emissions from agricultural production is often considered low in comparison to other emission sources (e.g., Brock et al., 2012; Kendall and Chang, 2009; Raucci et al., 2014), which is in direct contrast to findings in the present study. For example, Brock et al. (2012) reported a much lower contribution of liming to GHG emissions from wheat produced in south-eastern Australia than found in the current study. We attribute this to differences in lime application rates [i.e., 3500 kg ha^{-1} in present study versus 31.5 kg ha^{-1} in Brock et al. (2012)] and grain yield between the two studies, as both studies used the IPCC methodology (Eggleston et al., 2006) to estimate the CO_2 emissions from lime dissolution. We would argue that the contribution of liming to GHG emissions from agricultural systems will be influenced by amount of lime applied, the assumed dissolution rate, grain yield, and its contribution relative to other GHG emitting inputs (e.g., N fertilizers) and should therefore not be overlooked when conducting agricultural LCAs. In low grain-yielding environments, where N fertilizer inputs and N_2O emissions are minimized, and where large amounts of lime may be required to remediate soil acidity, the influence of liming on GHG emissions from grain production may be greater than temperate environments.

Emissions associated with the use of lime also need to be viewed in the context of total GHG emissions and soil carbon sequestration. For example, soil liming may partly offset other on-farm GHG emissions in rain-fed, agricultural soils in semi-arid region. In the companion study that provided the *in situ* soil N_2O and CH_4 emission data utilized in the present study, increasing soil pH (via liming) decreased cumulative N_2O emissions from the wheat–wheat rotation by 30% by lowering N_2O emissions following summer-autumn rainfall events, and increasing CH_4 uptake (Barton et al., 2013b). This observed phenomenon decreased the GHG emissions of wheat production in the present study by up to 19 kg CO_2-eq ha^{-1} yr^{-1} or 11 kg CO_2-eq per tonne of wheat, but was insufficient to offset the CO_2 emissions resulting from the transport and dissolution of lime (e.g., 292–910 kg CO_2-eq ha^{-1} yr^{-1}, or 141–501 kg CO_2-eq per tonne of wheat; Tables 2 and 4). The dissolution of lime can also be a net sink for CO_2 in soil with relatively high pH, but a net source of CO_2 in acidic soils (West and McBride, 2005). However, avoiding liming to decrease GHG emissions risks other adverse environmental impacts like soil acidification.

4.3. Contribution of soil N_2O emissions

Several studies have demonstrated that indirect and direct N_2O emissions substantially increase the GHG emissions of agricultural production (Biswas et al., 2010; Crutzen et al., 2008; Popp et al., 2011). In contrast N_2O emissions were negligible in our study, generally contributing less than 10% to total emissions depending on the cropping rotation. This reflects the current understanding that soil N_2O emissions from rain-fed crops in semi-arid regions are very low in comparison to other soils and climates, and significantly less than that predicted using the IPCC emission factors (Barton et al., 2011, 2008). Although soil and agricultural scientists recognize that the proportion of N fertilizer converted to N_2O emissions varies significantly with soil type, climate and land management practices (Stehfest and Bouwman, 2006), this is not as widely recognized by LCA practitioners (Kendall and Chang, 2009). We therefore support recommendations to use regionally specific data when calculating GHG emissions and performing any associated economic analyses for agricultural production systems (Hörtenhuber et al., 2013; Kendall and Chang, 2009; Thamo et al., 2013), rather than IPCC default values (e.g., 1.0%) across all geographic and climatic regions. Furthermore in soils and climates conducive to N_2O emissions (or if IPCC default emission factors had been used in the present study), it should be recognized that the economic incentive required to induce emission-saving practice change may be smaller than in the present study.

Including grain legumes in cropping rotations is unlikely to increase GHG emissions of semi-arid agricultural systems as a result of increased soil N_2O emissions (Tables 2 and 4). Our field-based research demonstrated that a growing a grain legume did not enhance soil N_2O emissions during either the growth of the grain legume, or during the subsequent wheat crop, when N fertilizer inputs were adjusted to account for residual N from the grain legume crop (Barton et al., 2011). Indeed, total N_2O losses were approximately 0.1 kg N_2O–N ha^{-1} after two years for both the lupin-wheat and wheat–wheat rotations (when averaged across liming treatment). Our observations is consistent with recent reviews of N_2O fluxes from various agro-eco-systems that have also concluded that there is a tendency for legume crops to emit similar, if not less, N_2O than fertilized non-legume crops (Dick et al., 2008; Helgason et al., 2005; MacKenzie et al., 1998; Parkin and Kaspar, 2006; Rochette et al., 2004; Rochette and Janzen, 2005).

4.4. Impact of functional unit

Expressing GHG emissions on both a per hectare or product (tonne of wheat) basis showed similar trends across treatments. This contrasts with some other agricultural systems (O'Brien et al., 2012). On one hand, expressing GHG emissions on an area basis directly reflects the total emissions likely to enter the atmosphere; on the other, expressing emissions on a product basis reflects the production efficiency (but only for that product, not the agricultural system as a whole). The latter is particularly relevant when considered in the context of increasing global production and associated demand for food. Expressing GHG emissions on a product basis, however can lead to perverse outcomes as a result of choices made when allocating emissions. For example, when we assumed that lime dissolved in five years rather than one, the GHG emissions per tonne of wheat actually increased for the lupin-wheat rotation due to the allocation process used to allocate emissions from the lupin crop to the following wheat crop. Consequently for the five year scenario, the GHG emitted per tonne of grain was the same for the lupin-wheat plus lime rotation as the wheat–wheat plus lime rotation; whereas GHG emitted per hectare were lower from the lupin-wheat plus lime than wheat–wheat plus lime. Furthermore, in low grain-yielding environments expressing GHG emissions per tonne can be misleading by indicating these environments are less efficient than higher yielding environments (Hörtenhuber et al., 2013). We recommend expressing GHG emissions on both per hectare and product (tonne of wheat) basis when using SLCA to assess the global warming potential of agricultural production.

5. Conclusions

Including a grain legume in a two-year cropping rotation lowered the GHG emissions of wheat production by lowering the need for synthetic N fertilizer without comprising grain yield, but required a large incentive (per tonne of emission saved) to be financially attractive. By contrast, applying lime to raise soil pH was profitable but increased total GHG emissions from wheat production by varying amounts depending on the time that lime was assumed to dissolve. Analysis of GHG emissions from agricultural production systems is sensitive to the inclusion of soil liming and further research is needed to fully understand the interaction between soil liming and GHG emissions if this common management practice is to be accurately accounted for by SLCA. We recommend expressing GHG emissions on both per hectare and per product (tonne wheat) basis when using SLCA to assess the global warming potential of agricultural production. Our findings demonstrate that while there are land management strategies available to lower GHG emissions from grain production in semi-arid climates, economic incentives may be required to encourage adoption.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.07.020.

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