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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-