



Nitrogen management is the key for low-emission wheat production in Australia: A life cycle perspective



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ABSTRACT

Farm management affects the global greenhouse gas (GHG) budget by changing not only soil organic carbon (SOC) stocks and nitrous oxide (N₂O) emissions but also other pre-farm, on-farm and off-site emissions. The life cycle assessment (LCA) approach has been widely adopted to assess the “carbon footprint” of agricultural products, but rarely used as a tool to identify effective mitigation strategies. In this study, the global warming impacts of no-till (NT) vs. conventional till (CT), stubble retention (SR) vs. stubble burning (SB), and N fertilization (NF) vs. no N fertilization (N0) in an Australian wheat cropping system were assessed using *in situ* measurements of N₂O fluxes over three years, SOC changes over forty years and including other supply chain GHG sources and sinks. The results demonstrated the importance of full GHG accounting compared to considering SOC changes or N₂O emissions alone for assessing the global warming impacts of different management practices, and highlighted the significance of accurately accounting for SOC changes and N₂O emissions in LCAs. The GHG footprints of wheat production were on averaged 475 kg carbon dioxide equivalent (CO₂-e) ha⁻¹ (or 186 kg CO₂-e t⁻¹ grain) higher under NF than N0. Where fertilizer N was applied (70 kg N ha⁻¹), the life cycle emissions were 200 kg CO₂-e ha⁻¹ (or 87 t⁻¹ grain) lower under NT than CT and 364 kg CO₂-e ha⁻¹ (or 155 t⁻¹ grain) lower under SR than SB. Classification of the emission sources/sinks and re-calculation of published data indicated that under the common practices of SR combined with NT, N-related GHG emissions contributed 60–95% of the life cycle emissions in the predominantly rain-fed wheat production systems in Australia. Therefore, future mitigation efforts should aim to improve N use efficiency, explore non-synthetic N sources, and most importantly avoid excessive N fertilizer use whilst practising NT and SR.

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1. Introduction

Wheat (*Triticum* spp.) is one of the most important arable crops, with a total growing area of approximately 13.7 million hectares in Australia (ABARES, 2013) and 217 million hectares in the world (FAO, 2012). Identification and development of low-emission management strategies in wheat farming systems would significantly contribute to the world-wide efforts to reduce greenhouse gas (GHG) emissions from the agricultural sector. To achieve this, knowledge of GHG sources, sinks and magnitudes in relation to different management practices is required.

There have been many studies on GHG emissions and uptakes under different management practices in arable cropping systems

(Smith et al., 2008; Rees et al., 2013; Lam et al., 2013). However, most studies typically focused on either N₂O emissions, CH₄ fluxes or soil organic carbon changes. From a whole-system's perspective, recommendation of emission mitigation strategies based on studies focusing only on a limited number of emission sources/sinks may not necessarily reduce the overall global warming impacts due to the accompaniment of undesirable trade-off effects (Robertson et al., 2000; Smith et al., 2001). For example, application of N fertilizer and manure may enhance soil organic C sequestration (Lam et al., 2013), but can also increase N₂O emissions (Smith et al., 1998; Wang et al., 2011). Thus, the positive and negative effects of a farming practice on greenhouse gas emission/uptake could counterbalance each other.

Besides the above-mentioned GHG exchanges between soil and the atmosphere, other emission sources in wheat production include: CH₄ and N₂O releases from crop residue burning (CO₂ release is considered as greenhouse neutral); CO₂ from fossil fuel combustion during farm machinery operations; and CO₂ from urea

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hydrolysis and lime breakdown (if applied). In addition to these on-farm sources, GHG emissions occur during manufacture and transport of farm equipment and materials (Lal, 2004a), which altogether can be referred to as pre-farm emissions. Furthermore, N compounds other than N_2O such as NH_3 , NO_x (NO and NO_2) and NO_3^- can leak from a farming system by pathways such as volatilization, biomass burning and leaching. These N compounds will eventually re-deposit off the site and result in further N_2O emissions. The consumption of farming materials and the pathways and magnitudes of N losses differ considerably under different management regimes. For comprehensive and reliable assessment of the overall greenhouse impacts of different farming practices, a holistic analysis including all related GHG fluxes would provide more meaningful information for identification of the mitigation strategies that lead to the lowest GHG footprint whilst maintaining crop yield.

Life cycle assessment (LCA) provides a useful tool for the above purpose. A number of LCAs on GHG footprints for wheat production in Australia have been conducted (Biswas et al., 2008, 2010; Maraseni and Cockfield, 2011; Brock et al., 2012) and in the world (Robertson et al., 2000; Hillier et al., 2009; Cheng et al., 2014). However, most analyzes undertaken so far focused on the GHG footprint of a product without detailed distinction between different management regimes. In this context, the LCAs often relied on the international or national default emission factors in the analysis (Maraseni and Cockfield, 2011; Cheng et al., 2014). While these generic emission factors are appropriate to use for emission sources that are minor or less variable, region-specific values should be used for the emissions such as N_2O from fertilizer N that may account for large parts in the life cycle inventory and differ substantially in different regions (Stehfest and Bouwman, 2006; Biswas et al., 2008). Furthermore, most carbon footprint analyzes did not take into account soil organic carbon (SOC) changes based on an assumption that SOC changes should be negligible compared to other emission sources/sinks (e.g., Biswas et al., 2008; Brock et al., 2012).

In this paper, we report an LCA on GHG emissions for a wheat cropping system in southern Queensland (QLD), Australia. In extension to a previous carbon-only analysis (Wang and Dalal, 2006), we included *in-situ* measurements of N_2O emissions over a 3-year period, N_2O emissions from stubble burning, indirect off-site N_2O emissions and SOC changes over 40 years in a long-term experiment. The objectives of this study were to: (i) assess the global warming impacts of no-till (NT) vs. conventional till (CT), stubble retention (SR) vs. stubble burning (SB), and N fertilizer application (NF) vs. no N fertilization (NO); (ii) identify the major emission sources/sinks from a life cycle perspective; and (iii) revisit previous studies and suggest the most effective mitigation strategies for effectively reducing the GHG emissions from wheat production in Australia.

2. Materials and methods

2.1. Site description

The experimental site is located at the Hermitage Research Station ($28^\circ 12'S$, $152^\circ 06'E$), southern Queensland (QLD), Australia. The soil is a Vertosol (IUSS Working Group WRB, 2014) or cracking clay, which is the major soil type for wheat cropping in Queensland, Australia. The soil contains 65% clay, 24% silt and 11% sand in the top 10 cm depth, with minor changes with depth. The soil bulk densities were low, 1.00 t m^{-3} in the 0–10 cm layer and 1.12 t m^{-3} in the 10–20 cm layer, with no significant differences between treatments (e.g., CT vs. NT) probably due to the high clay contents and the shrink–swell properties of this soil. The soil pH (1:5 soil to water

ratio) in the 0–20 cm layer was 6.3–7.0 for the NF treatments and 7.4–7.8 for the NO treatments. The long-term (1965–1999) annual mean temperature in this area is 17.1°C (Bureau of Meteorology, 2014). The mean annual rainfall (1970–2000) is 728 mm, about 60% of which is received during the summer/early autumn months from December to March. The mean annual areal actual evapotranspiration (1961–1990) is c.a. 700 mm with a mean annual potential evapotranspiration of 1400 mm (Bureau of Meteorology, 2014).

A long-term field trial was established in December 1968. Wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.; 1975–77 and 1988–89) was grown generally from June/July to November/December each year. Like most wheat farms in Australia, the crops were completely rainfed without irrigation. As a result, no crop was grown in 1982, 1991, 1994 and 2004, when there was insufficient rainfall for sowing. These four years without cropping and N fertilizer application were not included in the LCA and their effects on the long-term SOC changes were assumed to be minor. This study included eight treatments consisting of a factorial combination of tillage (CT or NT), stubble management (SR or SB) and N fertilization (NO or NF). The treatments under CT received on average three tillage operations with a chisel plough to about 10 cm depth during the fallow period each year, while the plots under NT were sprayed with herbicides to control weeds. Crop residues with the SB practice were burnt shortly after harvest. The treatments with NF received urea at $70\text{ kg N ha}^{-1}\text{ year}^{-1}$ on average during the 36 years with cropping. The N fertilizer was applied at ~5 cm depth at sowing ($40\text{ kg seed ha}^{-1}$). Based on the soil physiochemical properties, lime and P/K fertilizers were not required. Insecticides and fungicides were rarely used.

2.2. Measurement of N_2O and CH_4 fluxes from soil

Nitrous oxide and CH_4 fluxes were measured using both manual and automatic gas sampling chambers from July 2006 to June 2009 over three cropping–fallow cycles (Wang et al., 2011). The manual chamber consisted of a square stainless steel base ($50\text{ cm W} \times 50\text{ cm L} \times 15\text{ cm H}$) and a cover box ($50\text{ cm L} \times 50\text{ cm W} \times 55\text{ cm H}$). One chamber was installed in each plot, giving four replicates per treatment (32 chambers in total). Gas samples were taken about 2–3 times per week during the high emission periods (e.g., following fertilization and substantial precipitation) and less frequently when the soil was dry. Automatic gas sampling chambers, which could make 10 samplings per chamber per day, were also deployed for the SR treatments, with two replications for the CT-SR-NO, NT-SR-NO and NT-SR-NF treatments and three for the CT-SR-NF treatment. The automatic chamber consisted of a stainless steel base that was identical to the manual chamber base, an extension (0.3 m deep) and a cover box (0.3 m deep) with stainless steel frames and two lids on the top panel that can be opened and closed automatically at pre-set intervals. Detailed descriptions of the measurement and data processing methods were given by Wang et al. (2011).

2.3. Determination of soil organic carbon (SOC) changes

The treatment effects on SOC concentration at this site were detectable only in the top 10 cm soil (Wang et al., 2004; Dalal et al., 2011). Therefore, only SOC changes in the 0–20 cm layer were taken into account in the present study because inclusion of deeper soil tends to obscure the treatment effects due to spatial variability. In May 2008 at the late stage of a fallow period, soil samples were collected randomly from five points in each plot with a 50-mm diameter tube (Dalal et al., 2011). The soil from the same depth at 0–10 cm, 10–20 cm and 20–30 cm was bulked and mixed. After removal of large plant pieces, the samples were air-dried, ground to <2 mm, and then sub-sampled and fine-ground to

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