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# Opportunities for enhancing yield and soil carbon sequestration while reducing $N_2O$ emissions in rainfed cropping systems

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ABSTRACT

Producing the food required to feed the growing global population will inevitably put pressure on the environment and requires sustainable management of agroecosystems. The management strategies should be context-specific, and will require consideration of different stakeholders' interests, and of the local soil and climatic conditions. We developed a framework to analyse nitrogen (N) management options with the objective of increasing crop production while reducing $CO_2$ and nitrous oxide ($N_2O$) emissions from soil, and applied this framework to Australian rainfed wheat systems using a systems modelling approach. The results indicated that modified N management strategies in Australian rainfed wheat systems could increase average grain yield by up to 76% (from 1.7 to 3.0 Mg ha$^{-1}$) while substantially reducing net soil and $N_2O$ emissions (expressed in $CO_2$ equivalents, $CO_2$-eq), compared with current farming practice. Meta-modelling of the simulation results from 613 sites across the Australian wheat-growing regions indicated that site-specific best N management aimed at increasing yield and reducing net soil $CO_2$-eq emissions significantly correlated with water availability, temperature, and antecedent soil carbon content. The results emphasise the opportunity for well-managed intensification to simultaneously increase yield and reduce soil $CO_2$ and $N_2O$ emissions in Australian rainfed cropping regions. The 'win-win' N management recommendations should, and can be specified according to local climate and soil conditions.



## 1. Introduction

Based on the average world agricultural production from 2005 to 2007, a 60% increase in agricultural production by 2050 is required to meet the increasing global demand for food, feed, fibre and fuel (Alexandratos and Bruinsma, 2012). However, agricultural development to date has affected the environment, as evidenced by degradation in water quality, greenhouse gas (GHG) emissions, soil acidification and soil structural degradation (Robertson et al., 2000; Moss, 2008). Sustainable agricultural intensification of existing cultivated lands is a central element of the global response to food security and environmental protection (Tilman et al., 2011; Chen et al., 2014; Gan et al., 2014; Lipper et al., 2014). Both agricultural production and the environmental consequences are affected by management inputs, and soil and climatic conditions (Mueller et al., 2012; Gan et al., 2014; Lipper et al., 2014). It is crucial to quantify the effects of different agronomic management strategies on both crop productivity and environmental externalities, accounting for different soil and climatic conditions, to enable astute evaluation of intensification options.

In most countries, especially developing countries, there remains unrealised potential to increase crop yields through suitable nitrogen (N) management (Neumann et al., 2010; Mueller et al., 2012). In 80 (mostly developing countries) of the 127 countries producing wheat, yields are below the world average of 2.97 Mg ha$^{-1}$ (FAO, 2015; Fig. 1). The corresponding area harvested accounts for 69% of global wheat area ($\sim 2.4 \times 10^8$ ha). In those regions where yield is below average, nitrogen (N) fertilizer use (39 kg N ha$^{-1}$ on average) is much lower than other regions (111 kg N ha$^{-1}$ yr$^{-1}$ on average) where yield is above the average (FAO, 2015; Fig. 1). Based on the positive correlation between cereal yields and N uses (Fig. 1), it is reasonable to assume that increasing N inputs in those countries has the potential to increase the global yield.

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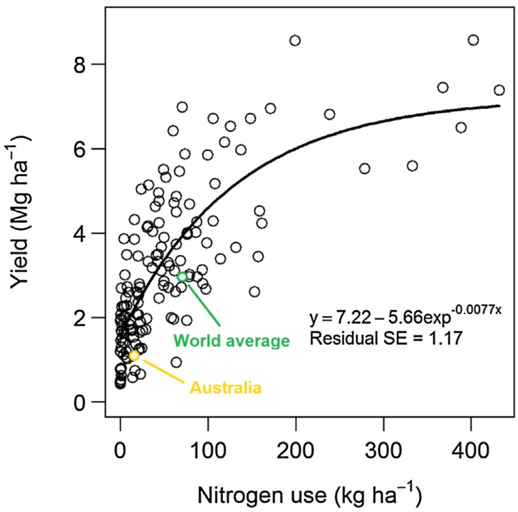


**Fig. 1.** The effect of nitrogen use on cereal crop yield at the country level. Yield and nitrogen use data show the average yield of all cereal crops and average nitrogen use on areas cropped at the country level. Data was extracted from FAOSTAT (http://faostat3.fao.org/home/E).

Along with the potential increase of yield with higher N inputs, the amount of crop residues also increases. If all the crop residues were retained, they should enhance soil organic carbon (SOC) sequestration or lessen SOC losses (Luo et al., 2010, 2011; Wang et al., 2016; Zhao et al., 2013). Carbon (C) inputs (mainly crop residues in croplands) are one of the two dominant factors controlling SOC balance in croplands (the other one is C outputs caused by microbial decomposition). Wang et al. (2016) have estimated that on average 2.0 Mg C ha$^{-1}$ yr$^{-1}$ (equivalent to 5 Mg ha$^{-1}$ yr$^{-1}$ of residue, assuming it has 40% C) is required to maintain current SOC stocks in world wheat systems. Increased crop yield results in greater amounts of crop residue with a subsequent positive effect on SOC sequestration. However, increasing N fertilizer application may result in increased nitrous oxide ($N_2O$) emissions from soil. $N_2O$ is a much more powerful greenhouse gas than $CO_2$, so increased $N_2O$ emissions have the potential to off-set the mitigation benefits generated through SOC sequestration (Liu and Greaver 2009; Powlson et al., 2011; Zaehle et al., 2011; Zhou et al., 2014; Plaza-Bonilla et al., 2015). The responses of crop yield, SOC sequestration and $N_2O$ emissions to changed fertilizer management need to be systematically quantified to identify management options that can increase crop yield and help mitigate climate change by enhancing soil C sequestration while limiting $N_2O$ emissions (Gan et al., 2011).

In Australia, both N use (20.4 kg N ha$^{-1}$ yr$^{-1}$) and wheat yield (1.5 Mg ha$^{-1}$) are lower than the world average (FAO, 2015; Fig. 1). This is mainly due to that Australian farmers pursue maximum economic return and have a history of relying on N derived from soil organic matter and legume residues. Additionally, most framers are conscious of the risks to crop production (e.g., frost, flooding, low seasonal rainfall) and usually invest less in N fertilisers than the economic optimum. It is generally accepted that a major contributing factor to crop yields being below the water limited potential in Australia is the lack of available N (Angus, 2001; Carberry et al., 2013; Hochman et al., 2009a,b). To close such yield gaps through increasing N applications, we need to consider the subsequent environmental consequences, particularly $CO_2$ and $N_2O$ emissions from soil.

Here we developed a framework (Fig. 2) to assess the relationships between N rates, crop yield and soil $CO_2$ and $N_2O$ emissions in Australian cropping systems using a systems modelling approach. A representative continuous wheat system was modelled and N rates, yield and soil $CO_2$ and $N_2O$ emissions were determined for three targets (Fig. 2): (i) 90% of the maximum crop yield (Fig. 2a), (ii) minimum $CO_2$ and $N_2O$ emissions (Fig. 2b), and (iii) minimum $CO_2$ and $N_2O$ emissions per unit production (Fig. 2c). We selected 90% of the maximum simulated yield because yields above this figure are associated with significantly diminished economic return (Carberry et al., 2013). N demands, soil $CO_2$ and $N_2O$ emissions were also predicted for the target of maintaining current yield – the baseline condition, and the results were compared with other three targets. The aims of this study were to: (i) identify N management that could enable simultaneous enhancement of yield and reduction of $CO_2$ and $N_2O$ emissions, and (ii) assess whether and how the N management and yield, $CO_2$ and $N_2O$ emissions correlate to soil and climate conditions. This information will guide the development of "win-win" N management strategies to increase crop yield and reduce GHG emissions.

## 2. Materials and methods

### 2.1. Study region, soil and climate data

This study used soil profile data collated by the Agricultural Production Systems Research Unit (http://www.asris.csiro.au/themes/model.html#) from 613 sites covering different regions and a broad range of soil conditions (e.g., plant available water in the soil profile ranging from <100 to >400 mm, and SOC stocks in the top 0.3 m of soil ranging from 9 to 140 Mg ha$^{-1}$, Fig. 3). These sites are all located on arable land within cereal-growing regions of Australia. Most of the soil data were collected in the last decade, and all include detailed information on soil C and N, and soil hydrological parameters within the soil profile. Daily weather data (including rainfall, maximum and minimum temperature, radiation) from 1889 to 2013 at the nearest climate station to each of the 613 sites were obtained from the SILO Database (http://www.longpaddock.qld.gov.au/silo/). Annual average temperature ranges from 11 to 23 °C, and annual average rainfall varies from 257 to 827 mm across the 613 sites, representing a wide range of climatic conditions. The 613 sites are subject to different agronomic management but when used with local climate data, they provide a realistic and representative set of sites and conditions for the APSIM simulations and make it possible to assess how crop yield, SOC dynamics and soil $N_2O$ emissions correlate with different soil and climatic conditions.

### 2.2. The APSIM model

The Agricultural Production Systems sIMulator APSIM (Holzworth et al., 2014) was used in this study. APSIM is a process-based biophysical model, and has been comprehensively verified and used to study productivity, nutrient cycling and environmental impacts of farming systems as influenced by climate variability and management interventions from plot to regional scales (Wang et al., 2009; Chen et al., 2010; Luo et al., 2011, 2013; Zhao et al., 2013). APSIM simulates crop growth and soil processes on a daily time-step in response to climate (i.e., temperature, rainfall, and radiation), soil water availability, and soil nutrient status.

APSIM simulates the dynamics of C and N in each soil layer using a framework similar to that used in other C dynamic models (e.g., RothC and Century; Smith et al., 1997). In general, soil organic matter is divided into four conceptual pools [fresh organic matter (which is further divided into three sub-pools including carbohydrate, cellulose, and lignin), humic organic matter, microbial biomass and inert organic matter] and the decomposition of each pool (except inert organic matter which does not decompose) is treated as a first-order decay process modified by temperature,