Greenhouse gas footprint of different farming systems in the northern grains region

Lindsay Bell[1], Dean Schrieke[1], Brook Burrett[1], Maartje Sevenster[1], Nazmul Islam[1], Andrew Erbacher[2], Darren Aisthorpe[2], Jon Baird[3], Branco Duric[3]

[1] CSIRO Agriculture and Food
[2] Department of Agriculture and Food, Queensland
[3] NSW Department of Primary Industries

GRDC code

DAQ2007-004RMX

Keywords

emissions intensity, crop rotation, nitrogen, emissions reductions, greenhouse gas

Take home messages

- Modelled greenhouse gas (GHG) emissions were dominated by soil nitrous oxide (N_2O) losses (>50% of total); Scope 3 (pre-farm gate) emissions were typically <20% of total emissions
- Accounting for changes in soil carbon significantly altered GHG footprint across sites and systems, contributing to, or mitigating, their GHG footprint
- There was up to a twofold difference in total GHG emissions between the highest and lowest emitting cropping systems at each site
- Despite higher inputs, *Higher intensity* cropping systems generated lower total emissions; drier soils and reduced time in fallow limited N_2O losses, and increased biomass inputs improved the soil C balance compared to other systems. In contrast, *Low intensity* systems showed higher total emissions
- *Higher nutrient* input strategies led to higher emissions due to increased N_2O losses, as well as higher emissions associated with fertiliser production and use
- Changing the mix of crops by employing *Higher legume* frequencies or *Higher diversity* systems did not show a consistent effect on total emissions (ranging from 700 kg CO_2-eq/ha/yr lower to 450 kg CO_2-eq/ha/yr higher); differences were site specific.

Introduction

Reducing greenhouse gas (GHG) emissions is crucial for the environmental standing and global market access of Australia's agricultural sector. Identifying and implementing practices that reduce emissions or optimise GHG intensity (maximise productivity per unit of GHG emitted) is a key priority of the Australian grain industry. While national studies have been conducted to assess GHG footprints and mitigation options (see Grains Research and Development Corporation (GRDC)'s Emissions Factsheet), the implications of local practices remains unclear. A localised approach is necessary to provide detailed insights and verify assumptions from broader assessments.

Farming systems experiments funded by GRDC offer a comprehensive dataset for evaluating the GHG impacts of different farming methods across the northern grain regions of New South Wales and Queensland. This dataset spans several years and includes multiple system variations, such as: increasing crop diversity (including legume frequency and alternative crops); altering cropping intensity (balance between fallow and active growth phases); strategies that influence fertiliser and chemical inputs; and the incorporation of regenerative practices such as ley pastures or cover crops. Each of these factors influence soil carbon (C) and nitrogen (N) balances, as well as input requirements. Consequently, this study aims to assess the potential of a diverse range of farming systems to mitigate or lower GHG emissions and intensity.

What we did

Farming systems experiments

Farming systems experiments have been underway at seven locations in central and southeast Queensland and northern New South Wales since 2015. These experiments capture data crucial for estimating GHG emissions and intensity (i.e. GHG per tonne of grain/product), including variables like crop biomass and grain yield, fertiliser and chemical inputs, and operations such as sowing, harvesting, and spraying. Due to intricacies and ambiguities in attributing emissions from livestock grazing, systems that incorporate rotations with ley pastures have been omitted from this analysis (but are likely to be done in the future). As a result, this report focusses on grain-exclusive production systems.

The dataset comprises over 80 combinations of farming system treatments across 7 sites spanning eight years (March 2015 – April 2022). Each site features a *Baseline* system, embodying the prevailing understanding of a best-practice crop sequencing and management of the respective cropping region. Alternative systems modify the *Baseline* sequence in several ways: *Higher/lower crop intensity* – widening sowing windows and altering the soil water threshold to trigger sowing a crop and thus increasing/decreasing the proportion of time when crops are growing; *Higher legume* – incorporating at least 50% grain legume crops; *Higher diversity* – increasing the range of crops available for use (e.g. canola, cotton) and forcing a two-break crop requirement before the same crop can be grown again; and *Higher nutrient* supply systems, which increase the annual nitrogen and phosphorus budget from a median crop yield (Decile 5) to a higher yield expectation (Decile 9). At most sites, individual treatments are applied, whereas combinations of these strategies are evaluated in the core experiment at Pampas on the Eastern Darling Downs.

Calculating GHG emissions

Drawing from farming systems experimental data, we employed a Tier 3 (i.e. locally specified calculations or modelling) approach to estimate GHG emissions over the experimental period (2015–2022). This differs from Tier 2 or Tier 1 approaches that use national or international emissions factors to estimate emissions using regional activity data. Emissions are separated into Scope 1 (on-farm), Scope 2 (associated with electricity use on farm) and Scope 3 (pre-farm gate emissions embedded in farm inputs like fertilisers and pesticides). Scope 2 emissions were negligible (<1% of total) and thus not included in this analysis. Scope 1 emissions occurring on-farm include sources such as N_2O emissions from the soil (including from decomposition of crop residues), and CO_2 emissions from diesel used by on-farm machinery and hydrolysis of urea fertilisers. Using activity data for each site and system we simulated experimental management in APSIM to predict direct N_2O emissions (i.e. from the soil), indirect N_2O emissions (i.e. from N lost in runoff or leaching) and changes in soil C over the experimental period (Figure 1). Other emissions sources were estimated using emissions factors defined in the National Greenhouse Gas Inventory (NGGI) 2021 (National Inventory Report, 2023).

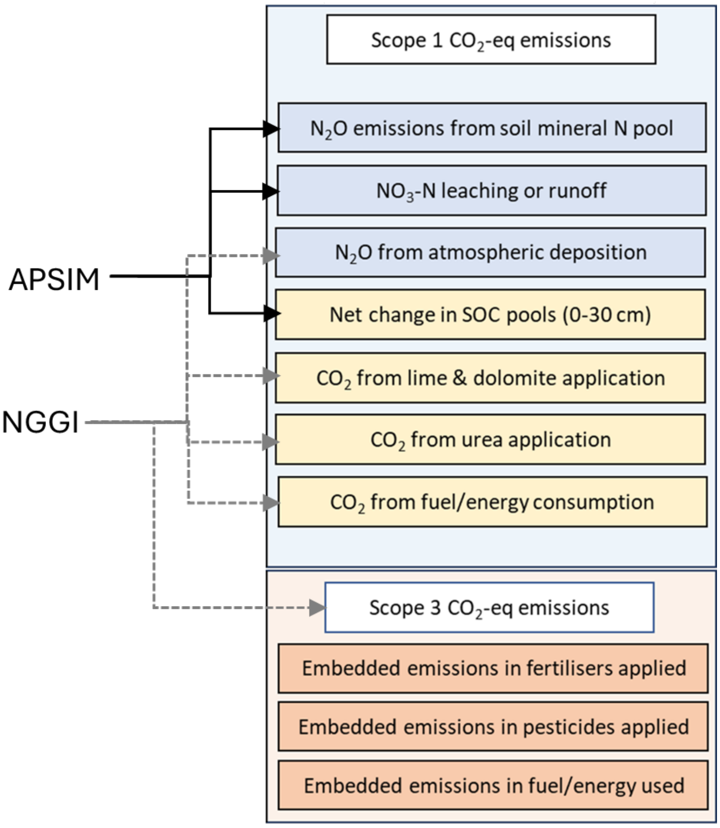

Figure 1. Various GHG sources calculated using activity data from farming systems experiments and those that were estimated from simulations using APSIM and those that used the National Inventory Report (2021) values.

After compiling total GHG emissions from the various sources, we calculated the emissions intensity for each system, defined as the gross margin per kilogram of CO_2 emitted. While other analyses might measure emissions intensity per tonne of grain, this approach does not provide a fair comparison among systems due to variations in yield and values of different crop types that make up these systems. This metric also aids in estimating potential abatement costs, that is, cost to implement a system that reduces net emissions. However, our calculations are based on assumptions about crop prices and inputs, making these figures specific to certain seasons and conditions and not universally applicable.

Emissions sources from farming systems

Without considering soil C change, other emissions sources were estimated to average 830 kg CO_2-eq/ha/yr and vary amongst sites between 650 to 1400 kg CO_2-eq/ha/yr for the *Baseline* systems, except Mungindi which has a drier climate and hence was significantly lower (330 kg CO_2-eq/ha/yr).

Across all sites, emissions associated with direct N_2O losses from the soil were the largest contributor to the GHG footprint of the farming system (Figure 2). While N_2O losses are small, they have a large relative global warming potential, with each kg of N_2O has an impact equivalent to 298 kg of CO_2. It is worth noting that this estimated N_2O emission includes emissions coming from both fertilisers applied as well as from N mineralised from soil organic matter (discussed below). Scope 3 emissions associated with inputs of fuel, fertiliser and pesticides were typically less than 20% of the total emissions at all sites, but the relative contribution of each varied across sites depending on the relative use of these inputs (Figure 2).

There was large variability in the estimated change in soil C between sites, but on average the soil C decline was estimated to contribute 25% of the total emissions.

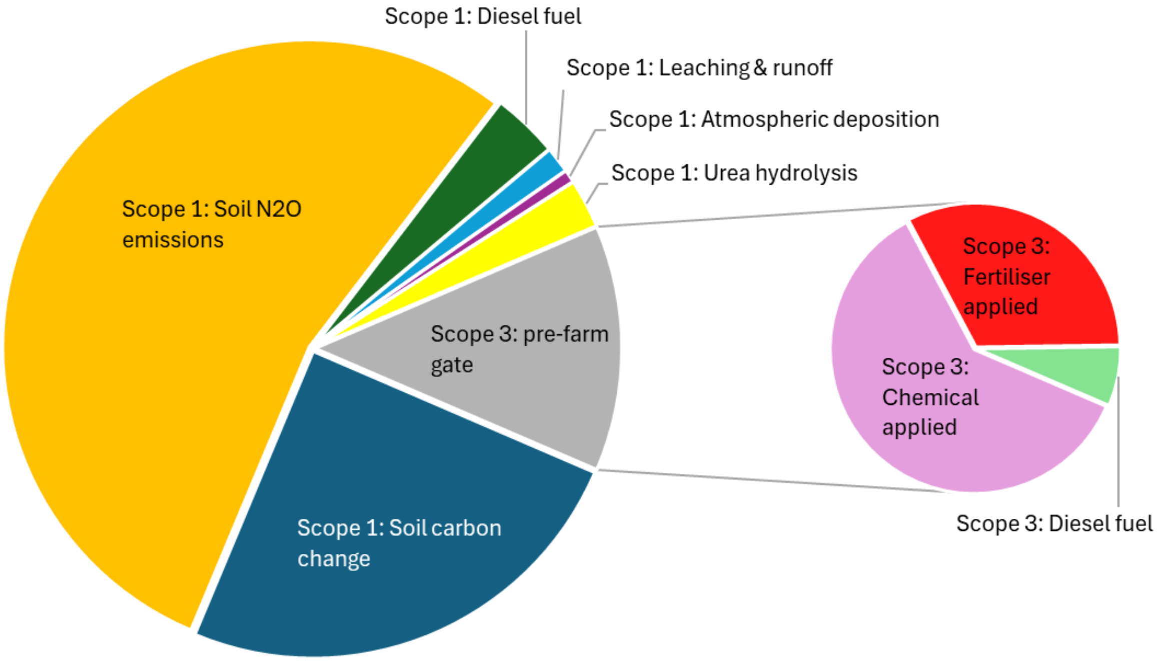

Figure 2. Contribution of different sources of GHG emissions to the net emissions from *Baseline* farming systems (kg CO_2-eq. per ha per year) averaged across all sites over the period 2015–2022.

Farming system impacts on GHG footprint

Emissions before including soil carbon change

There were some consistent trends in terms of relative emissions amongst systems across sites. The *Higher nutrient* strategies, where crops were fertilised to target a maximum grain yield potential, generated higher emissions than the *Baseline*, largely due to elevated N_2O emissions, but also due to slightly higher Scope 3 emissions from fertiliser production and from urea hydrolysis. On average these systems increased emissions by 300 kg CO_2-eq/ha/yr.

The *Higher intensity* farming systems, characterised by more frequent cropping had lower N_2O emissions than other systems, due to the system having less time in fallow and having drier soils that reduced the frequency and size of soil N loss events (e.g. denitrification). On average they had emissions 120 kg CO_2-eq/ha/yr lower than the *Baseline*. Conversely, *Lower intensity* systems, where crops are only grown when the soil profile is full, had longer fallow periods and consequently wetter soils, which led to increased net N_2O emissions compared to their higher-intensity counterparts. On average, these systems had emissions 140 kg CO_2-eq/ha/yr higher than the *Baseline*.

There was large between site variability in response to changing the crop mix via increasing crop diversity or legume frequency. Compared to the *Baseline,* the N_2O emissions from the *Higher legume* system were similar or marginally higher at three sites, lower at one site (Emerald) and significantly higher at two sites; on average emissions were 200 kg CO_2-eq/ha/yr higher than the *Baseline*. This variation appeared to be driven by circumstances when legumes left higher mineral soil N over the subsequent fallow which was then prone to losses (e.g. denitrification). The N_2O emissions from the *Higher crop diversity* systems were reduced at two sites, increased at two sites and were similar at one site; with an overall neutral effect on GHG emissions compared to the *Baseline*. This variation appears to be related to the types of crops implemented to diversify the farming system across the experiments; some sites involved cereals like sorghum, while at others this was replaced by crops like canola or cotton.

Soil carbon change influences system GHG footprint

Incorporating simulated changes in soil C (0-30 cm depth) into the GHG emissions calculations significantly influences the estimated net emissions across sites and between systems. At the Billa Billa and Emerald sites, where simulations were initiated with high measured levels of labile organic C, reductions in soil C contributed to 50–70% of the farming systems' GHG footprint (Figure 3). This corresponds to an annual decrease in soil C ranging from 250 to 450 kg/ha over the experimental period. Measured soil C at both sites has also trended down over the experimental phase. Other experimental sites had relatively stable or minor changes in soil C (150 kg of soil C/ha/year), and in several instances, there was a predicted net C sequestration, which could offset other emissions by up to 550 kg CO_2-equivalent/ha/yr. Notably, some of the higher intensity cropping systems at Pampas were predicted to result in a net C gain over the experimental period, making them GHG positive.

Consistent trends were observed across sites regarding the impact of farming systems on soil C change, which in turn effected the net GHG emissions. Across all sites, the *Higher intensity* farming systems demonstrated a more favourable soil C balance compared to the *Baseline*. This improvement is attributed to the higher biomass (and therefore C) inputs in these systems, resulting from more frequent cropping and reduced time in fallow over the same period. This increase in biomass, combined with lower N_2O emissions, meant that these systems consistently recorded the lowest net GHG emissions. In contrast, the *Lower intensity* systems were predicted to have a negative soil C balance at all sites, performing significantly worse than other farming systems. This adverse outcome is linked to the lower crop frequency, reducing biomass (and C) inputs to counterbalance soil organic matter decomposition over time.

The *Higher legume* systems were estimated to have a more favourable soil C balance than the *Baseline* at most sites. The reasons for this are not entirely clear, but are thought to relate to the lower carbon-to-nitrogen (C:N) ratio of legume residues, which contribute positively to the soil C pools. Although the beneficial effect on soil C was somewhat offset by higher N_2O emissions, the *Higher legume* systems were generally predicted to have lower GHG emissions than the *Baseline* system.

The *High diversity* systems exhibited large site variability in their relative impact on soil C, with some sites showing a positive effect and others neutral or negative. Finally, the *Higher nutrient* strategies were simulated to have a neutral effect on soil C at three sites, and a positive effect at the other three; only at Mungindi was this positive effect large enough to offset the higher N_2O emissions associated with these systems.

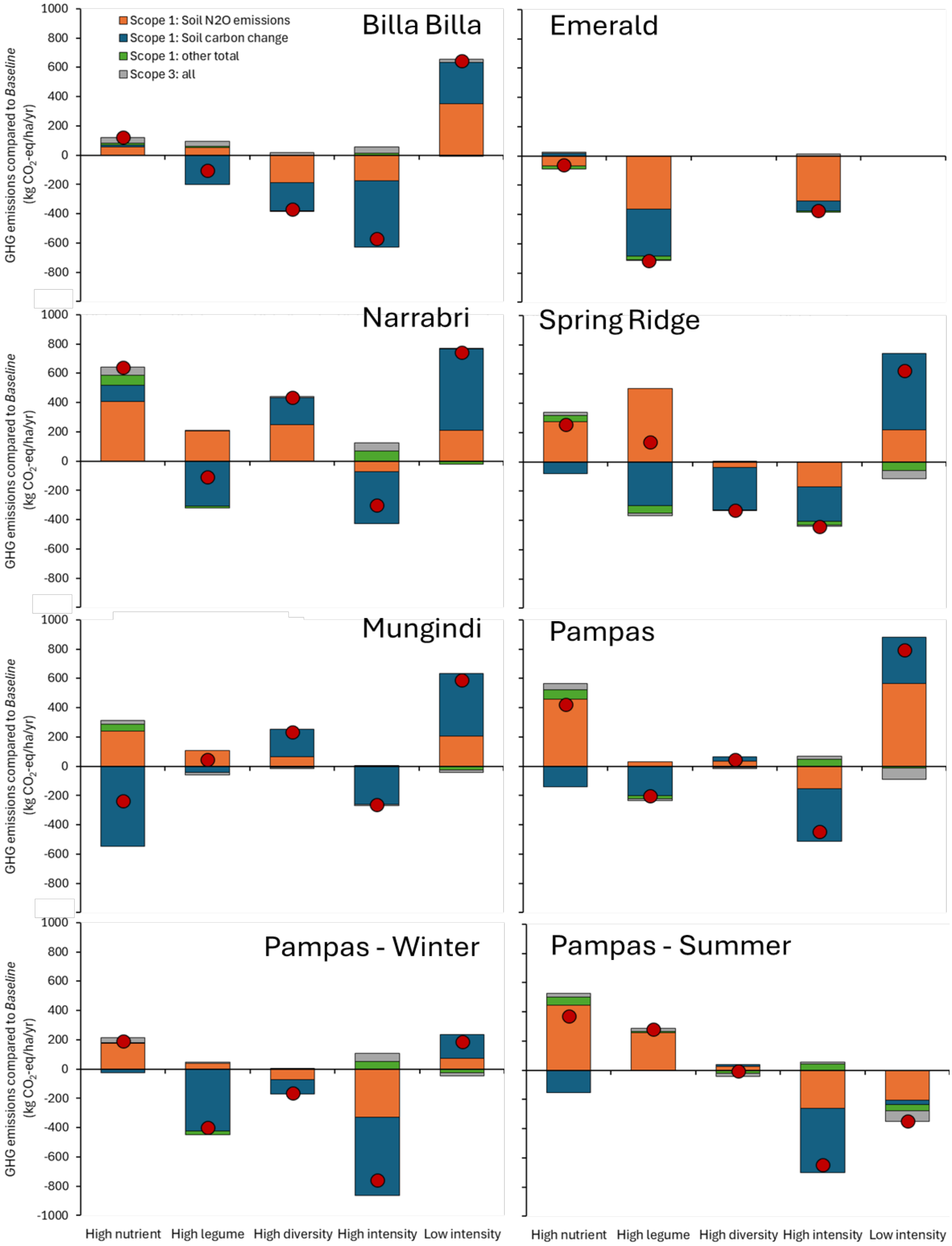

Figure 3. Estimated GHG emissions (kg CO_{2}-eq/ha/yr) and their sources amongst different farming systems compared to the *Baseline* system at each experimental location over 8-years. Bars indicate the magnitude of change (either positive – increasing emissions, or negative – decreasing emissions) and the red dot is the total change accounting for all computed sources. Sources estimated include on-farm (Scope 1) emissions from N2O coming from the soil and crop residue decomposition, simulated increases or decreases in soil carbon over the life of the experiment, other Scope 1 emissions from fuel use, urea hydrolysis or leaching/runoff losses of N and pre-farm gate (Scope 3) emissions embedded in inputs of fertilisers, crop protection products and fuel.

System interactions

Within the core experiment at Pampas, which evaluated a combination of different farming systems strategies, it was evident that increasing the intensity of the farming system consistently reduced net emissions compared to the lower intensity counterparts (Table 1). Amongst these combinations a system combining *Higher intensity* cropping in combination with *Higher diversity* and *Higher legume* frequency achieved a net C positive outcome over the experimental period of about 800 kg CO_2-eq/ha/yr. However, when *Higher nutrient* input strategies were combined with *Higher diversity* cropping, GHG emissions increased relative to the *Baseline*, and were higher than when these strategies were applied independently.

Table 1. Estimates of net change in annual GHG emissions (including soil C change) across the factorial of farming systems changes compared to the *Baseline* system implemented at the core experiment (Pampas) between 2015 and 2022.

	GHG emissions (kg CO_2-e/ha/yr)	
System	***Moderate intensity***	***High intensity***
Baseline	0	-481
Higher nutrient	+386	+55
Higher legume	-208	-333
Higher diversity	+49	-294
Higher diversity + Higher nutrient	+606	+146
Higher diversity + Higher legume	+87	-797

Emissions intensity

Using the total emissions data, which include simulated N_2O losses and accounted for differences in soil C changes among systems, led to distinct rankings in terms of emissions intensity (i.e. $/$CO_2$-eq). The estimated GHG intensities varied significantly across the different farming systems, with values ranging from $190 to $1900 per tonne of CO2-eq/ha. No single system consistently emerged as the 'best' in terms of emissions intensity, and rankings varied across sites when comparing gross margin per emissions. However, the systems with the lowest projected total emissions nearly always displayed the highest productivity, both in terms of gross margin returns (Figure 4). This indicates the existence of numerous 'win-win' scenarios, indicating that optimising for system profitability could also lead to optimised GHG emissions intensity.

The *Higher intensity* farming system generated the most favourable emissions intensity at four of the sites but was the least favourable system at Emerald, where the higher intensity system has shown to have much lower returns over the experimental period. On average, these systems produced $1900 of gross margin return per tonne of CO_2-eq/ha. The *Higher legume* and *Higher diversity* farming systems generated the most favourable GHG intensity at Emerald and Billa Billa sites, respectively. Conversely, the *Lower intensity* systems consistently underperformed across all locations. These systems generated lower annual gross margins and had the highest GHG emissions. In comparison, they generated an average of $300 in gross margin per tonne of CO_2-eq/ha.

At the core experimental site, where factorial combinations of farming systems were evaluated, the *Higher intensity* systems demonstrated higher returns per kg CO_2 compared to their *Lower* *intensity* counterparts. The ranking amongst the systems was consistent with their total emissions, indicating that differences in accumulated gross margin did not significantly alter their relative GHG intensity rankings. This consistency suggests that the efficiency gains in terms of GHG emissions are directly correlated with the intensity of farming practices, independent of the economic performance measured by gross margin.

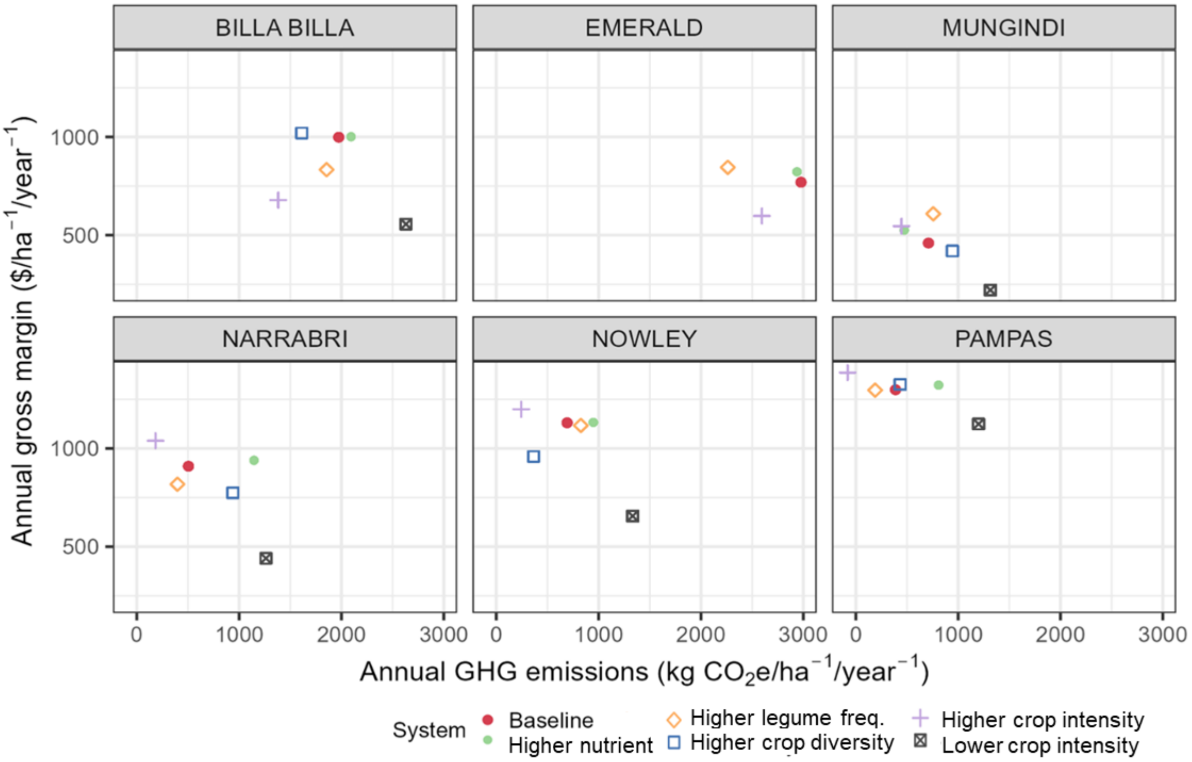

Figure 4. GHG emissions intensity, that is the relationship between estimated annual GHG emissions (Scope 1 & 3) and estimated gross margin of different farming systems over 8-years at the six experimental locations in Australia's northern grain-growing region.

Conclusions

These findings highlight that the GHG footprints of farming systems can vary significantly, with up to a two-fold difference in the main sources of emissions and more than a four-fold difference in emissions per tonne of grain yield or revenue generated. This disparity expands further when changes in soil C are factored into the GHG balance. Typically, farming systems that are more intensive and have fewer idle periods are associated with lower emissions. This is particularly true when accounting for changes in soil C and the reduction of N_2O emissions. In contrast, systems with longer fallows and less time in-crop tend to have the highest emissions. The impact of cropping intensity on emissions proved to be more significant than the choice of crops, which resulted in variable effects on overall GHG emissions across different locations.

This analysis underscores the importance of simulating N and C dynamics to accurately compare different farming systems, rather than relying on static emissions factors that primarily calculate emissions based on activity data, with a particular emphasis on fertiliser inputs. Utilising these more simplistic, yet less comprehensive approaches would have led to vastly different predictions, as they fail to account for impacts on soil moisture states and changes in soil C. The analysis further illustrates that even relatively minor annual changes in soil C can significantly influence the GHG footprint of the production system, acting either as contributors or mitigators. The scale of these predicted changes in soil C are modest enough to pose substantial challenges for measurement, even over decadal time periods. Therefore, alternative approaches are likely to be needed to evaluate the relative impact of different farming systems on soil C, capturing both positive and negative influences.

As farmers face the growing challenge of balancing the environmental footprint of production with the need to produce food, adopting a holistic approach to evaluating different production systems becomes increasingly important. The calculations presented here are one of a few multi-year studies, both nationally and internationally, that directly compare GHG emissions across a variety of farming systems. This research serves as a benchmark for grain production in eastern Australia and offers a detailed insight into how altering agronomic practices, such as crop rotation, nutrient inputs, and cultural methods, can impact GHG emissions and intensities. This analysis not only contributes to our understanding of the environmental aspects of agricultural production but also informs strategies aimed at reducing emissions while maintaining or increasing food production.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the authors would like to thank them for their continued support.

We acknowledge the various collaborators involved with collecting the experimental data and farmer collaborators for hosting the farming systems experiments across the region.

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Contact details

Lindsay Bell
CSIRO
Toowoomba, QLD
Mb: 0409 881 988
Email: lindsay.bell@csiro.au

Date published

July 2024