Improving farming systems efficiency in southern NSW
GRDC Project Number CSP2110-004RMX

Milestone 115 Part 3: - GHG Emission Report

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GHG emissions of the Southern Farming Systems - a life cycle assessment

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Take home messages

1. The greenhouse gas (GHG) emissions and emission intensity of the baseline and alternative farming systems were assessed using a **static** Life Cycle Assessment (LCA) approach. Additionally, a **dynamic** approach with APSIM was used to simulate soil organic carbon (SOC) change and nitrous oxide (N_2O) emissions by taking account of complex local information. Across sites, the baseline system emitted 130-245 kg CO_2-equivelent/t grain yield (static approach), which was lower than the previous national benchmark at about 300 kg CO_2-equivelent/t yield (GRDC northern region). The Baseline systems were intermediate in their emission intensity.
2. Because a considerable amount of **soil C sequestration was predicted by APSIM** for most of the systems, the net emissions estimated using the dynamic approach were generally lower than that using the static approach which assumed no SOC change. There was good agreement between the two methods only for systems where small changes in SOC were predicted, which demonstrates the importance of SOC change in determining the net GHG emissions. The scheduled SOC measurement six years after the start of the trial will provide valuable data to verify the APSIM predictions.
3. Two of the legume-based diversified systems, **DivHV2_T_2** and **DivMix_T_2**, had among the lowest emissions across sites. Higher rates of N fertiliser resulted in higher emissions, as did extending the growth period by sowing early, presumably due to the larger N fertiliser requirement to maintain the same decile yield targets and the larger amount of residues remaining. Consequently, the **Intense Baseline (canola-wheat) sequence was among the highest emission systems**, especially when applied with a higher dose of N and sown early (static).
4. Emissions associated with fertiliser use (scope 1 and 3 combined) were a big contributor to the total emissions of the systems (static). Although the net emissions were elevated at higher N rates, APSIM simulated higher SOC sequestration in some systems (e.g., intense baseline at Condobolin and Wagga), consistent with previous findings. The underlying mechanisms are worth further exploration.
5. A trade-off analysis between profit and GHG emissions indicated that two legume-based diversified systems, **DivHV2_T_2** and **DivLV_T_2**, were among the most efficient in achieving optimal trade-off between profit and emissions. All early-sown systems, regardless of a legume (or fallow) phase, were generally below the trade-off efficient frontier, but this was presumably driven by the inappropriate choice of cultivars for sowing early in Phase 1 (winter types).

Introduction

The impetus of improved sustainability in agriculture requires reduction of greenhouse gas (GHG) emissions and/or optimising GHG intensity (i.e., the amount of GHG emitted per unit of grain yield produced) while increasing the productivity through agricultural innovations. The Australian grain industry is largely export-oriented and has been increasingly focused on improving its sustainability credentials. It is therefore important to quantify the GHG emissions of the grain-based production systems.

The GHG emission baseline for the Australian grain production sector has been establish with successful application of the life cycle assessment (LCA) approach in a recent GRDC funded project (Sevenster et al., 2022). It used production data of a variety of grain crops compiled nationwide and found that the Australian grain production sector generally showed lower emissions than other major grain-exporting countries with some regional differences (Sevenster et al., 2022). However, it is also important to quantify and compare the impact of different management practices on GHG emissions and emission intensities at the local cropping system level. Characteristics of local pedo-climatic conditions and their interaction with management practices are expected to exert influences on GHG emissions and emission intensities not only at the individual crop level, but at the rotation level over a longer period. The latter may be more relevant to the reality of agricultural practices, as there could be either synergistic, antagonistic, or no apparent effect on GHG emissions when multiple crops are grown in a sequence at a larger time scale (> one season) that are subject to a combination of different management practices. Such information will inform future mitigation and adaptation strategies by designing cropping systems with optimal choices of crops and management practices that are locally relevant.

The ongoing GRDC funded farming systems project in southern NSW has provided a unique and valuable opportunity to compare GHG emissions influenced by different farming practices at the cropping system level across a wide range of environments. Here we report on some preliminary findings of GHG emissions, emission intensities and contributions of different sources to the total emissions of different farming systems tested in the four Southern Farming Systems experiments. The same LCA approach that was applied earlier to the Australian grain production sector was used in this report.

Methods

Detailed description of the LCA approach can be found in the previous reports submitted to GRDC (Sevenster et al., 2022) and can also be found in a similar GHG report prepared for the Northern Farming Systems Project.

In the southern project, systems included in this report were all non-grazed, which differed either in the (i) cropping sequences, i.e., baseline without legumes (**Base**), diversified sequences with grain legumes (**DivHV1, DivHV2, DivLV**) or a legume mixture for hay (**DivMix**), continuous wheat (**ContWheat**), intense sequences with a higher frequency of canola (**IntBase**) and those including a fallow phase (**Fallow**); (ii) time of sowing (early vs. timely) and (iii) nitrogen fertilising strategies applied to non-legumes (decile 2 vs. 7) (Table 1).

Table 1. Cropping systems included in this report. In the system name, T and E indicate timely and early sowing; the number 2 and 7 indicate decile 2 and 7 N strategy. The total number of systems is shown in the brackets below each site name.

System	Crop sequence	Site			
		Greenethorpe (10)	Wagga (16)	Condobolin (10)	Urana (10)
Base_T_2	Canola X Wheat X Wheat	✓	✓*	✓*	✓*
Base_T_7		✓	✓*		
IntBase_T_2	Canola X Wheat	✓	✓	✓	✓
IntBase_T_7		✓	✓	✓	✓
IntBase_E_2					✓
IntBase_E_7					✓
DivHV1_T_2	Lentil X Canola X Wheat **		✓	✓	✓
DivHV1_T_7			✓		✓
DivHV1_E_2		✓	✓	✓	
DivHV1_E_7		✓	✓		
DivHV2_T_2	Chickpea X Wheat	✓	✓		
DivLV_T_2	Faba bean X Canola X Wheat	✓	✓***	✓***	✓
DivMix_T_2	Legume mix X Canola X Wheat	✓	✓	✓	✓
DivMix_T_7			✓	✓	✓
Fallow_T_7	Fallow X Canola X Wheat		✓	✓	
Fallow_E_7			✓	✓	
ContWheat_T_2	Wheat	✓	✓		
ContWheat_T_7			✓		

* The baseline crop sequence was Canola X Wheat X Barley

** Lentil in all DivHV1 was replaced with chickpea from 2020

*** The DivLV crop sequence was Lupin X Canola X Wheat

Input and output, on-farm activity, soil and meteorological data at each of the four southern experimental sites during 2018-2022 were used in the assessments. To be consistent with the northern project, the data included were from the start of the first crop season (2018) up until April 2022 (i.e., four crop seasons). This included the time and rate of application of fertilisers, chemicals, lime, operations of sowing, fertilising, spraying and spreading, harvesting and related fuel use, yield of grains, biomass and hay, total costs, gross income and gross margin.

Scope 1 and 3 emissions, but not scope 2 emissions were calculated and reported in this report. Scope 1 emissions are emissions associated with inputs and activities occurred on-farm. Scope 3 emissions represent the embedded emissions of production and transport of the inputs used on farm. Scope 2 emissions associated with the electricity consumption on-farm were not calculated due to unavailable data and negligible emissions based on the results from the previous grain-sector assessment (i.e., 0.1% of total GHG emissions, Sevenster et al., 2022).

Two approaches were compared to estimate GHG emissions of different farming systems, i.e., a static approach by applying a set of emission factors (EFs) from the national inventory report (NIR) and a dynamic approach combining the dynamic APSIM simulation and the NIR. Figure 1 shows the main difference between the two approaches used in this report. Nitrous oxide (N_2O) is a potent GHG and a key component of GHG emissions in farming systems. Simulations using APSIM can provide dynamic estimation on direct emissions of nitrous oxide (N_2O) from microbial activities in the soil and nitrate leached out of the soil profile which contributes indirectly to N_2O emissions. In this way, the seasonal variability in N_2O fluxes can be captured at a higher resolution and accuracy compared with the static approach. Similarly, APSIM simulation can provide dynamic estimates of soil organic C (SOC) change, which affects the net GHG emission. Emissions from other sources were calculated the same as the static approach (Figure 1). This dynamic approach may be more suitable for system comparisons at the local level than the static approach when detailed measurements of N_2O emissions and SOC change are not available. With the static approach, changes in soil organic matter (SOM) are currently assumed to be zero during the study period. As the second soil carbon measurement is due by the end of this year (2023) in the Southern Farming Systems experiments, there is no data on direct measurement of SOC change at the time of writing of this report.

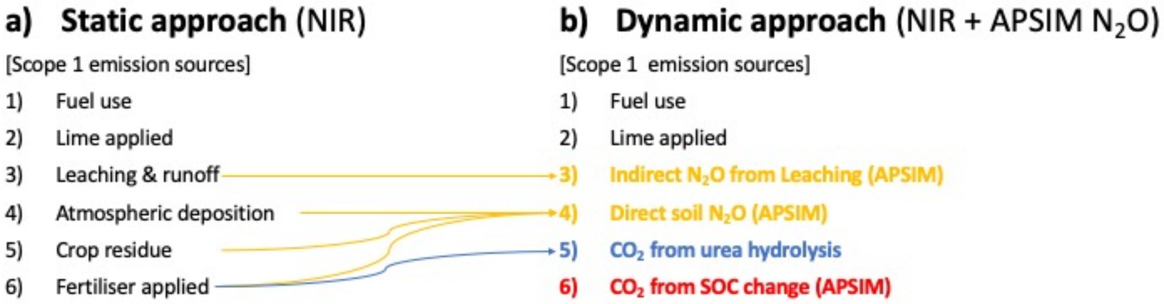

Figure 1. Diagram showing the main difference between the static and dynamic approach. APSIM has output of N_2O emissions from all N sources including those considered in the static approach (orange arrows). The dynamic approach only estimate the CO_2 emissions resulted from C change because the N_2O emission from mineralisation of SOM has already been accounted for in the simulated N_2O; on the other hand, the static approach assumes no significant soil C change during the study period, and hence no GHG emissions from SOC change were calculated.

Simulations with APSIM were set up for individual plots at each site during 2018-2022 using the actual crop sequences and management, basic soil properties determined before the start of the experiments in 2017 and early 2018, and daily weather data. The simulated total N_2O emissions (direct and indirect) were computed for the entire study period during April 2018-April 2022. The changes in simulated SOC in the top 30 cm soil layer was also calculated for the entire study period, which was then multiplied by a factor (i.e., 44/12) to convert it to CO_2e. The total CO_2e was then computed as the sum of the CO_2e from the APSIM simulated N_2O, CO_2 from SOC change and hydrolysis of applied urea, and CO_2e from all other sources were calculated the same as the static approach. The N_2O derived from urea application, residue decomposition and SOC change has been accounted for in the model simulated N_2O and thus no EF was applied in the calculation using the dynamic approach. The model was not set up to simulate crop mixtures at this stage and thus the DivMix systems were not included in the dynamic estimates. For annual GHG emissions of each system, the total emission was divided by the total number of days (April 2018-April 2022) and multiplied by 365.

As the experiments were phased with three replicates (blocks), the annual GHG emissions for individual cropping systems were reported as the average across phase (n = 1-3) × block (n = 3) × seasons (n = 4).

Results and Discussion

Static approach - Annual greenhouse gas emissions of farming systems

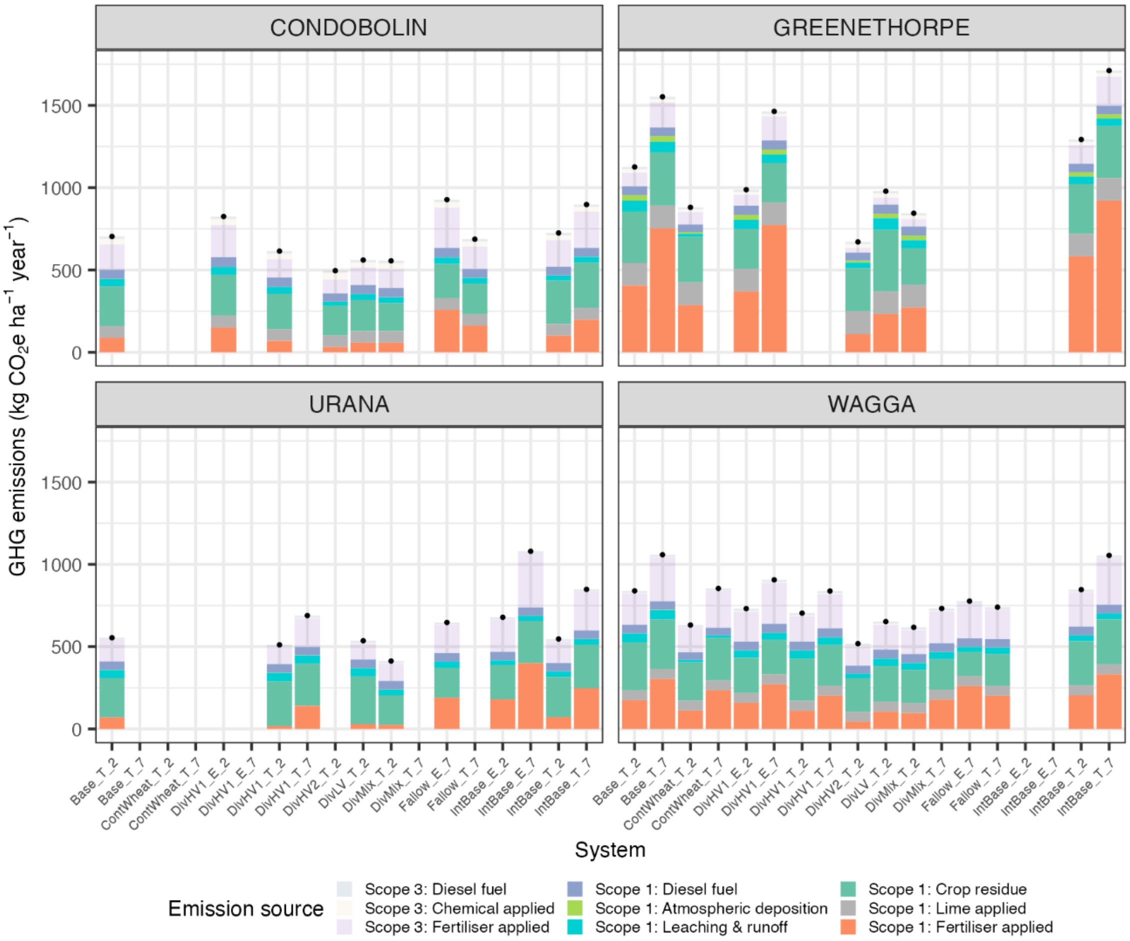

Figure 2. Stacked bar chart showing the annual total GHG emissions (kg CO_2-equivelent/ha/year) for individual farming systems tested at the four experimental sites in Southern NSW during April 2018 - April 2022, which was calculated using the static national inventory approach. The contributions of different sources to the total emissions are represented by different colours. Scope 1 means emissions occurred on-farm from inputs, changes and microbial activities in the soil and on-farm activities, and scope 3 indicates the pre-farm emissions embedded in the production of the inputs of fertilisers, chemicals and fuels. The black dot on top of each bar indicates the overall net emissions. The same applies to other similar figures in this report. Emissions associated with SOC changes were not included as on-farm measurement of SOC was unavailable.

Using the static approach, the estimated annual GHG emissions of systems showed clear differences between systems, N fertilising rates, time of sowing and sites (Figure 2 and Appendix Figure A1). It was in the range of 500-1100 kg CO_2e/ha/yr at the three low-rainfall sites, and 670-1700 kg CO_2e/ha/yr at Greenethorpe where the average annual rainfall is higher. The baseline system (i.e., Base_T_2) showed annual emissions ranging from 552 (at Urana) to 1126 kg CO_2e/ha/yr (at Greenethorpe), all intermediate among systems. Across sites, the non-legume-based systems (canola – wheat – wheat or canola – wheat) that were applied with higher doses of N fertiliser (i.e., Base_T_7, IntBase_T_7 or IntBase_E_7) were among the top emitters (850-1700 kg CO_2e/ha/yr) except that at Condobolin, the fallow - canola – wheat (Fallow_E_7) showed the highest emission. By contrast, the diversified systems with a legume phase (with timely sown and decile 2 N strategy) tended to have lower emissions (at 500-1000 kg CO_2e/ha/yr). The system with the lowest fertiliser-associated emission and thus lowest total emission (500-670 kg CO_2e/ha/yr) was DivHV2_T_2 where a high-value legume (chickpea) was sown every other year (at Condobolin, Greenethorpe and Wagga) or DivMix_T_2 where a legume mixture was sown and cut for hay every third year at Urana. This was due to no N fertiliser application to the legume phase, resulting in lower average annual N fertiliser inputs across the phases within each rotation sequence.

There is a clear difference in annual GHG emissions between the two N strategies (decile 2 and 7), and between the early and timely sowing systems. Higher total emissions in systems with decile 7 N than decile 2 N strategy is apparently driven by larger emissions associated with greater N fertiliser inputs (Figure 2). Emissions associated with fertiliser application (scope 1 and scope 3 combined) generally accounted for the largest proportion of the total emission in all systems across the four sites, especially in systems without legumes. It is in line with the previous Australian Grains Baseline report (Sevenster et al., 2022). The early sowing systems (E)showed generally higher annual emissions than the corresponding timely sowing systems (T), e.g., the systems of DivHV1 and Fallow at Condobolin and Wagga, and the IntBase system at Urana (Figure 2). This may be explained by higher N fertiliser requirement and generally larger residue loads left due to prolonged growth season.

The higher GHG emission at Greenethorpe than the other sites was partly driven by the definition of the high rainfall zone (i.e., long-term average annual rainfall exceeding 600 mm) adopted in the national inventory report (NIR). Thus, a much higher inorganic fertiliser EF of 0.0085 was used at Greenethorpe, compared to 0.0005 used at the other three sites. This is a methodological issue that needs to be resolved in the future, for example, by using site-specific EF mediated by the rainfall. The dynamic approach with APSIM simulation is able to overcome the problem as it simulates N_2O from all N sources at a daily time step using site-specific soil and weather data instead of using a simplified EF (see further discussion regarding the dynamic results).

Following fertiliser use, crop residue was another large contributor to the total GHG emissions, especially in systems with a legume phase (Figure 2). Lime was applied a couple of times across the experimental fields except for Urana. It also accounted for a significant portion of the total emissions even if that the lime-induced emission was assumed to be evenly spread over a 6-year period.

Static approach - Emission intensity of farming systems

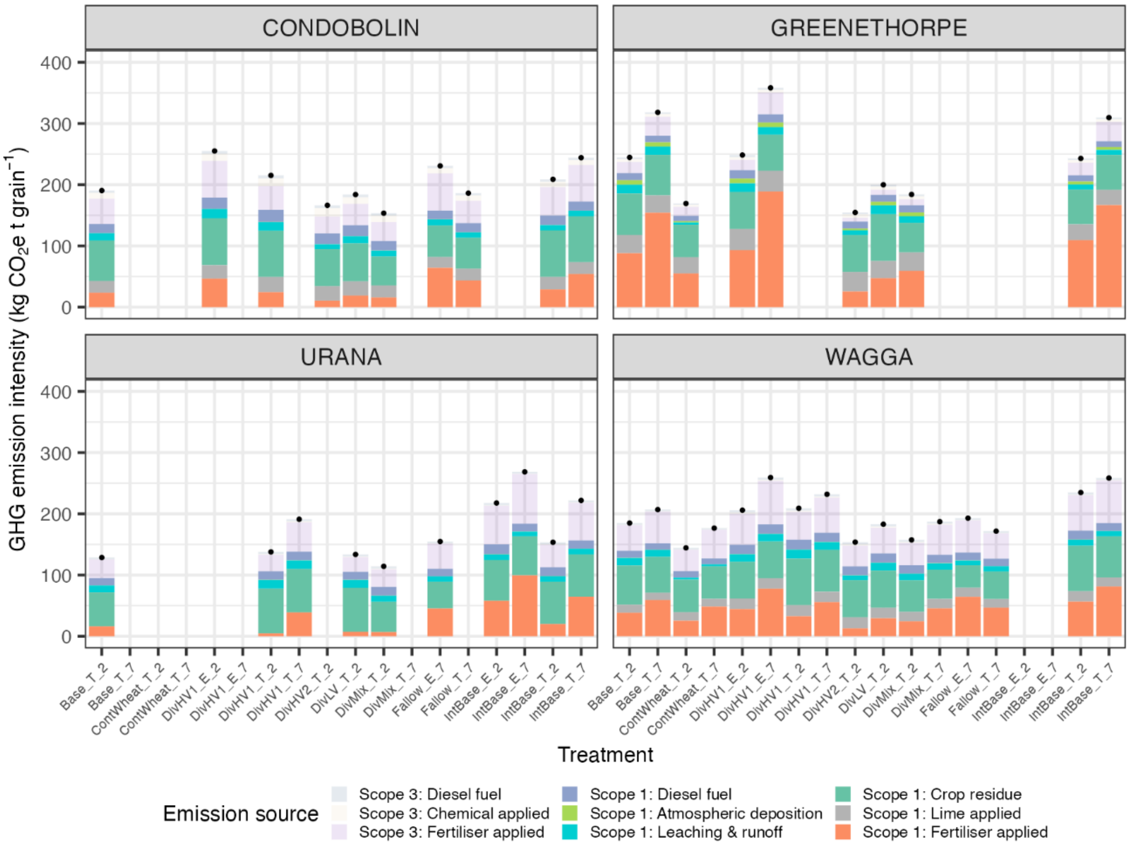

Figure 3. Stacked bar chart showing the GHG emission intensity in terms of the amount of CO_2-equivelent per unit of grain production for individual farming systems tested at the four experimental sites in Southern NSW during April 2018 - April 2022. The emissions were calculated using the static national inventory approach.

Emission intensity, i.e., the amount of GHG emitted per unit yield produced, is a measure of sustainability that considers the trade-off between grain production and GHG emission. The emission intensity of the baseline system (Base_T_2) was 245, 185, 190 and 129 kg CO_2e/t grain yield at Greenethorpe, Wagga, Condobolin and Urana, respectively (Figure 3). All values were lower than 315 kg CO_2e/t grain yield, the average emission intensity reported earlier for the baseline year (2005) of the GRDC northern region of grains production (Sevenster et al., 2022). In fact, except for three systems at Greenethorpe, the emission intensity of all systems across the four sites were in the range of 130-270 kg CO_2e/t grain yield. The legume-based diversified systems, DivHV2 (chickpea – wheat), DivLV system (with a low value pulse crop faba bean or lupin) and DivMix (legume mixture – canola – wheat) showed emission intensity lower than or similar to the respective baseline due to lower fertiliser associated emissions. The diversified system with a high-value pulse, DivHV1 with lentil (or chickpea) in a 3-year cropping sequence, tended to have a higher emission intensity than the baseline, especially the early-sowing and/or higher N strategy systems (e.g., DivHV1_E_7). This may be related to the lower yields of lentil and chickpea.

Among the non-legume-based systems, the intensified rotations (IntBase) with a higher frequency of canola (1/2 vs. 1/3 in the baseline) tended to have a higher emission intensity than the respective Baseline at Urana and Wagga. It was even worse if the growth season was extended by early sowing (IntBase_E vs. IntBase_T). The emission intensity of the continuous wheat (ContWheat_T_2) was much lower than the baseline at Greenethorpe and Wagga, and thus in the group of lowest-emission systems. This was related to the relatively higher yield of the wheat crop than other crops included in the rotations. It is worth noting that the yield was averaged simply across the crop type during the study period (April 2018-April 2022) to obtain the annual grain yield for each system. It would be better to standardise the yield considering crop type, for example, by converting the yield of individual crop types to calorific yield, protein yield, economic return and so on, for better comparison. The difficulty is that cereals are normally valued for its calorific production, oilseeds for its oil production, pulses for its protein production, and hay for other considerations. The higher emission intensity from systems with decile 7 than 2 N strategy was largely related to the difference in N inputs, which is similar to that of the annual total system emissions.

Static approach – Trade-off between system profit and GHG emissions

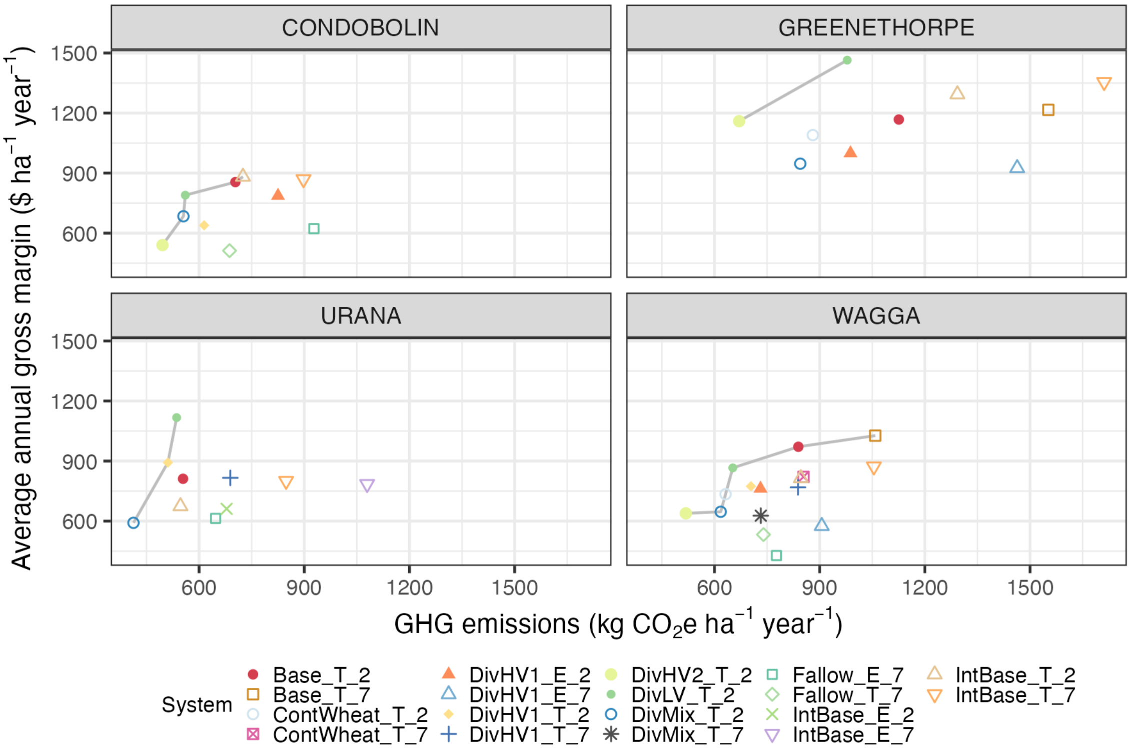

Figure 4. Scatter plot showing the annual gross margin against the annual total GHG emissions for the farming systems tested at the four experimental sites in Southern NSW during April 2018 - April 2022. The emissions were calculated using the static national inventory approach. Systems joined by lines form the efficient frontier for trade-off between the system profit and GHG emissions.

Figure 4 shows the trade-off between the profit and the emissions at the cropping system level. The “ideal” system would be expected to appear on the top left corner with maximised gross margin and minimised emissions. If we draw a line from the highest point (e.g., most profitable systems) to the next highest point to its left (e.g., less GHG emissions) and repeat until the leftmost point is connected on each panel, it forms a frontier to approximate the Pareto front (Hockman et al., 2021). Systems on this efficient frontier are considered most efficient in terms of achieving the optimal trade-off between the profit and emissions compared to those falling below and to the right of this front. It appears DivHV2_T_2 and DivLV_T_2 systems were always on the front across all sites. Additionally, the baseline and intense baseline at Condobolin, DivHV1_T_2 and DivMix_T_2 at Urana, and the baseline with both high and low N strategy at Wagga were also on the front. For the diversified cropping sequence with a legume phase (DivHV1 and DivMix), the systems with higher N strategy tended to be further away from the efficient frontier than the respective lower N strategy, and thus sub-optimal in maximising profit and minimising emissions simultaneously. All early-sown systems, regardless of containing a legume (or fallow) phase or not, were away from the efficient frontier for the optimal trade-off between the economic return and GHG emissions. It is worth noting that the judgement was made based on the tested systems under the current management practice, environmental, cost and price conditions. Future analysis could include more simulated systems of different scenarios to better determine the frontier for efficient trade-off between competing criteria at the system level as we demonstrated here with the system profit and emissions.

Dynamic approach - Annual emissions

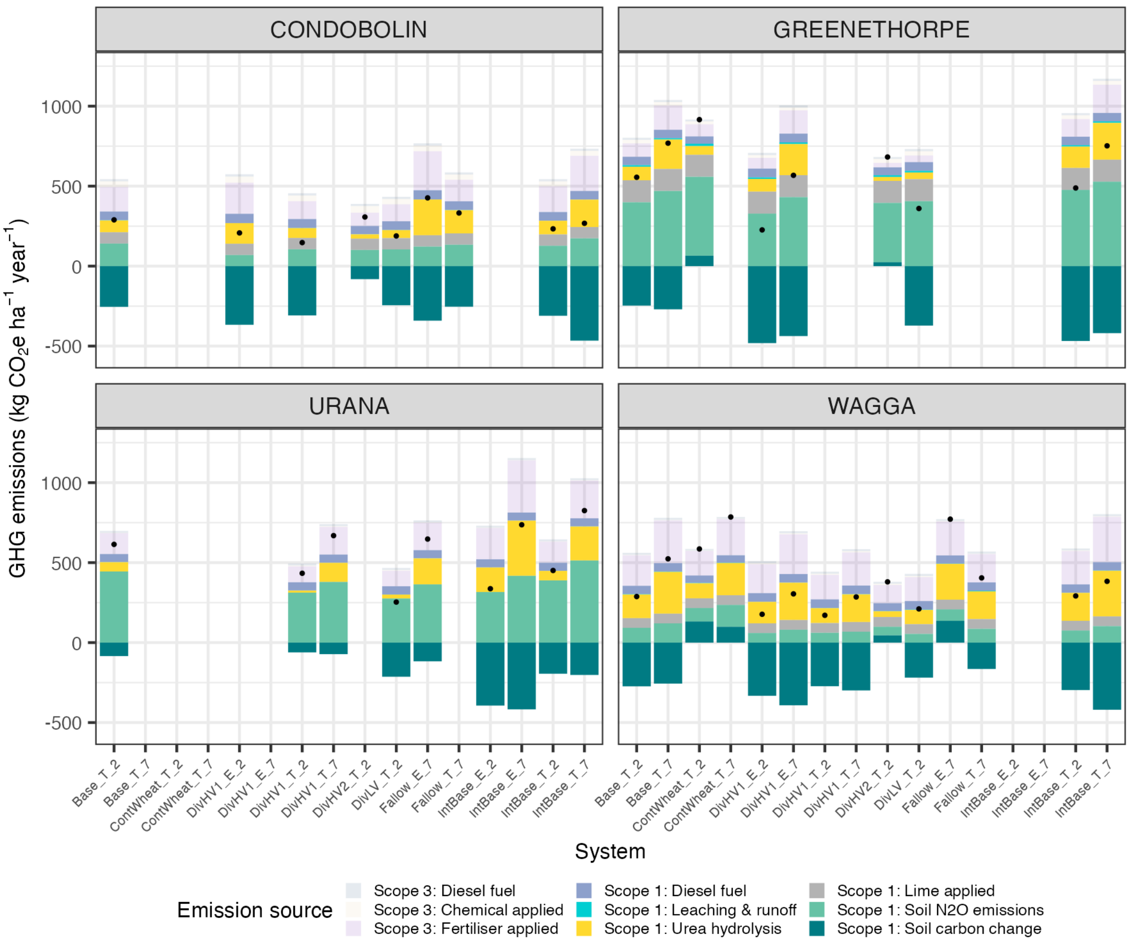

Figure 5. Stacked bar chart showing the annual total GHG emissions (kg CO_2-equivelent/ha/year) for individual farming systems tested at the four experimental sites in Southern NSW during April 2018 - April 2022. The emissions were calculated using the dynamic approach that incorporated APSIM simulated N_2O emissions and SOC change.

Compared with the static estimate, the dynamic estimate with APSIM simulation showed considerable amounts of soil carbon sequestration (i.e., negative CO_2 emissions associated with SOC change) in most of the systems across sites and large contributions of N_2O to the total emissions at Greenethorpe, the wettest site, and at Urana, a heavy soil (Figure 5 and 2). The following GHG components were calculated the same for both static and dynamic approaches, all scope 3 emissions, scope 1 diesel fuel and lime applied. Thus, the difference in annual emission (and emission intensity) between the two approaches were driven by how different they were calculated between the collective emissions from leaching, urea hydrolysis, soil N_2O and SOC change using the dynamic approach and that of leaching, crop residues, and fertiliser applied using the static approach (Figure 1). With the dynamic approach, APSIM can simulate and export N_2O fluxes and SOC content at daily time step in a process-based manner, while with the static approach, relevant EFs were assigned to different N sources for estimation of N_2O emissions and no changes assumed for SOC due to no direct measurement. It also needs to be noted that the DivMix system was not assessed using the dynamic approach for complexity in simulation of crop mixtures.

Comparing systems with high and low N strategies (e.g., IntBase, DivHV1), there tended to be more soil carbon sequestration at higher N rates especially at the drier sites of Condobolin and Wagga (Figure 5), which is consistent with findings from our earlier projects. However, it was not the case at Greenethorpe with higher average rainfall. It also needs to be noted that the net GHG emissions increased with higher N rates (Figure 5). The underlying mechanisms worth further exploration to help achieve low-emission farming systems via increased soil carbon sequestration.

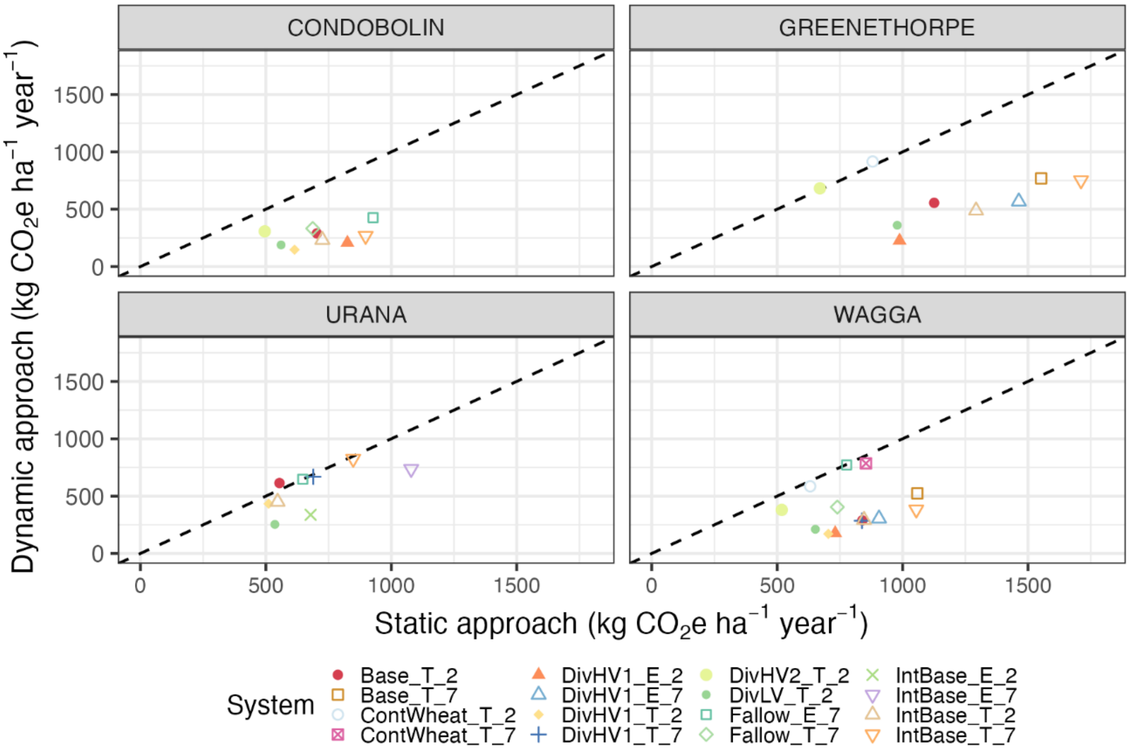

Figure 6. Scatter plot showing the annual total GHG emissions (kg CO_2-equivelent/ha/year) for individual farming systems using the dynamic approach vs. that using the static approach. The dashed line is the 1:1 line.

The two approaches estimated similar annual emissions only for systems where APSIM estimated a net SOC loss (i.e., continuous wheat, chickpea-wheat (DivHV2) and fallow systems at Greenethorpe and Wagga) or small SOC increase (e.g., six of nine systems at Urana, Figures 5-6), but it estimated much lower emissions using the dynamic approach than the static approach for all other systems with a large APSIM-simulated SOC gain (Figures 1, 5, 6). It shows the importance of determining SOC change and N_2O emissions in the estimation of overall GHG emissions, and the advantage of process-based simulation models over universal EFs in this area. The scheduled SOC measurement after the current crop season in the southern farming systems project will provide valuable information to verify the APSIM-simulated SOC data.

Dynamic approach - Emission intensity

The net emission intensity estimated by the dynamic approach was smaller than that by the static approach because a net soil carbon gain was estimated by APSIM in most systems resulting in reduction in the total emission. The emission intensity of the baseline system was ranging 63-142 kg CO_2e/t grain yield using the dynamic approach (Figure 7 and A4), which is much lower than previous national benchmark of 315 kg CO_2e/t grain yield for the northern region (Sevenster et al., 2022). The highest emission intensity of all systems, 216 kg CO_2e/t grain yield, was from the intense baseline system with a high N fertilising rate (IntBase_T_7) at Urana. Cropping systems including a legume phase with decile 2 N strategy tended to show similar or lower emission intensities than the baseline. There was an exception of elevated emissions per tonne of grain production in the DivHV2 system with chickpea-wheat rotation where a small soil carbon loss was estimated at Greenethorpe and Wagga, and the smallest amount of soil carbon gain at Condobolin. However, lower emission intensities were estimated for this system than the baseline using the static approach assuming no SOC change (Figure 3). It highlighted again the importance of SOC change in GHG accounting for cropping systems.

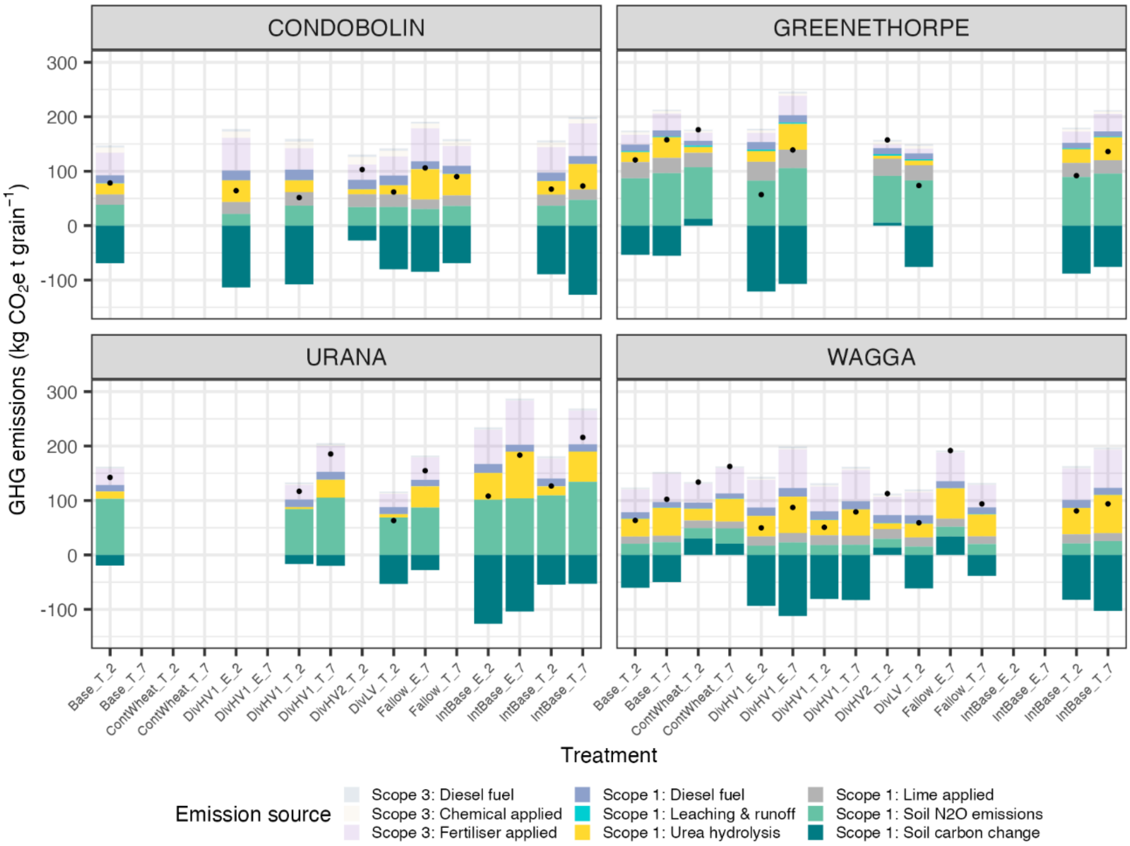

Figure 7. Stacked bar chart showing the GHG emission intensity. The emissions were calculated using the dynamic approach that incorporated APSIM simulated N_2O emissions and SOC change.

Dynamic approach - Trade-off between system profit and GHG emissions

Differences were identified in the trade-off analysis between profit and emissions of farming systems using the two approaches (Figures 4 and 8). This is mainly related to the reduction in GHG emissions resulted from large soil carbon sequestration estimated using the dynamic approach compared to that using the static approach where no SOC change was assumed (Figure 5). Notably, compared to the static approach (Figure 4), the system with a low-value pulse crop (DivLV) at all sites and the baseline system (at either low or high N rates) at Wagga remained on the efficient frontier; additionally, the lentil (chickpea)-canola-wheat systems (DivHV1, either sown early or timely) receiving low N rates moved on to the efficient frontier; the system with a pulse crop every second year (DivHV2, chickpea-wheat) moved away from the efficient frontier to the right-hand side (Figure 8).

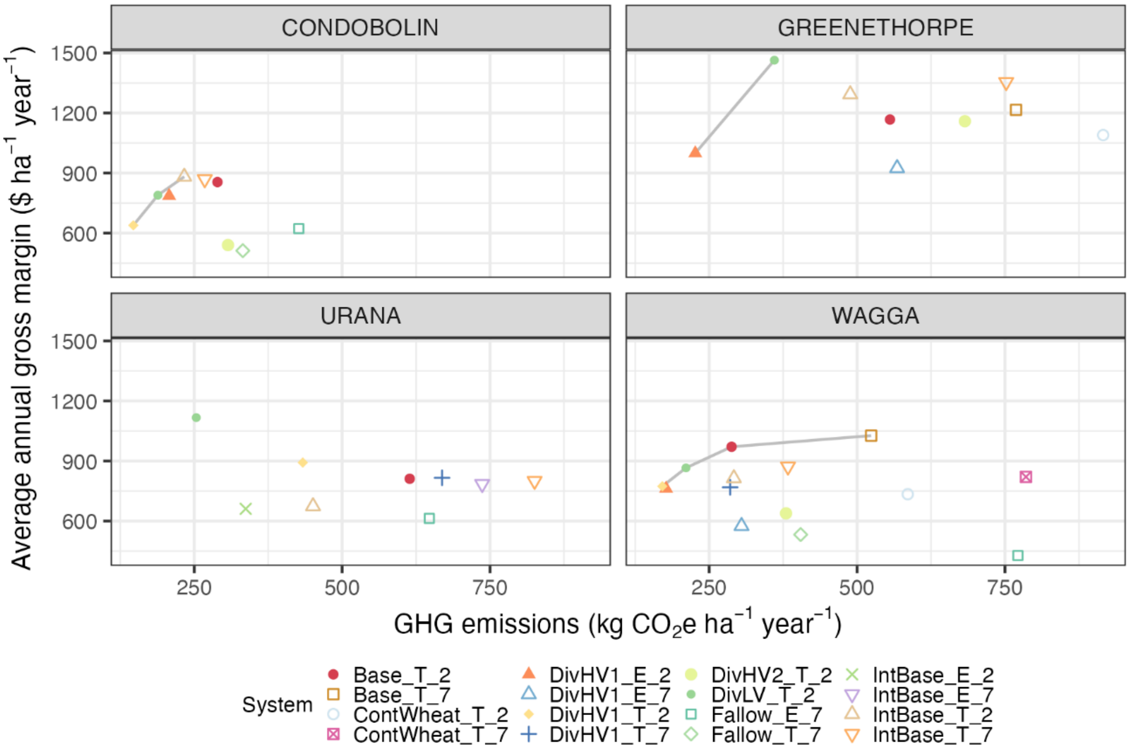

Figure 8. Scatter plot showing the annual gross margin against the annual net GHG emissions for the farming systems. The emissions were calculated using the dynamic approach that incorporated APSIM simulated N_2O emissions and SOC change. Systems joined by lines form the efficient frontier for trade-off between the system profit and GHG emissions.

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Appendix

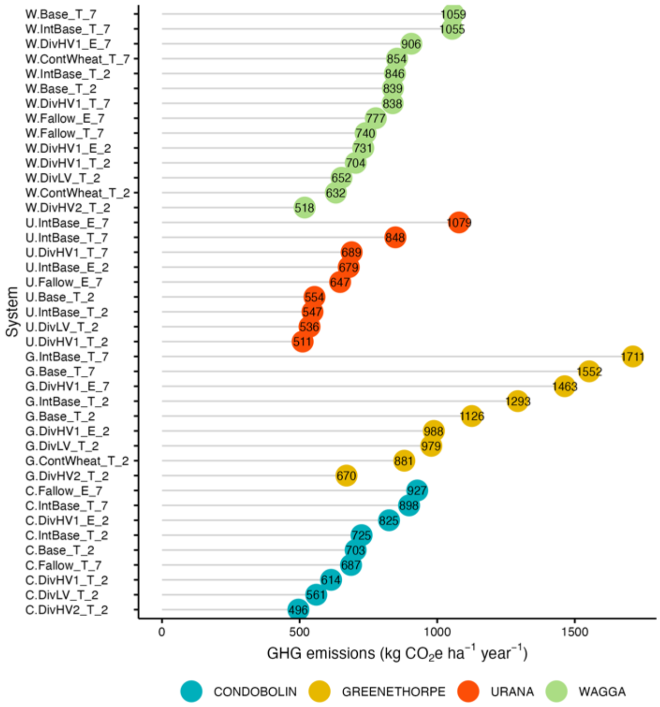

Figure A1. Ranking of the annual total GHG emissions of systems at each of the four sites (indicated by four colours). Emissions were calculated using the **static** approach and presented as numbers in circles on the graph.

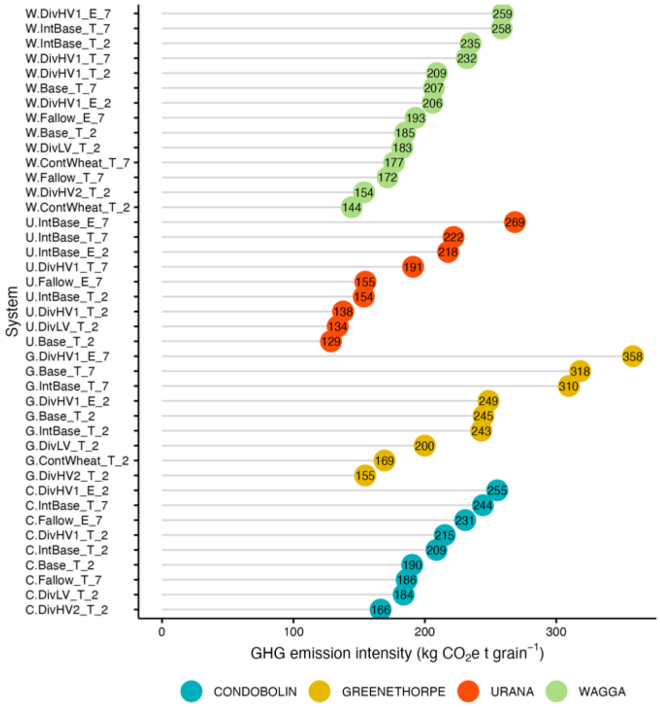

Figure A2. Ranking of the GHG emission intensity of systems at each of the four sites (indicated by four colours). Emissions were calculated using the **static** approach and presented as numbers in circles on the graph.

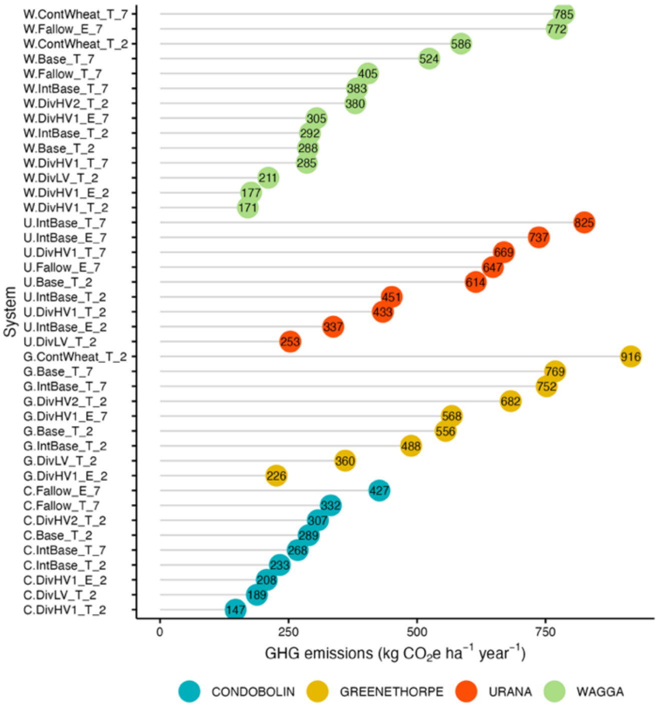

Figure A3. Ranking of the annual total GHG emissions of systems at each of the four sites (indicated by four colours). Emissions were calculated using the **dynamic** approach and presented as numbers in circles on the graph.

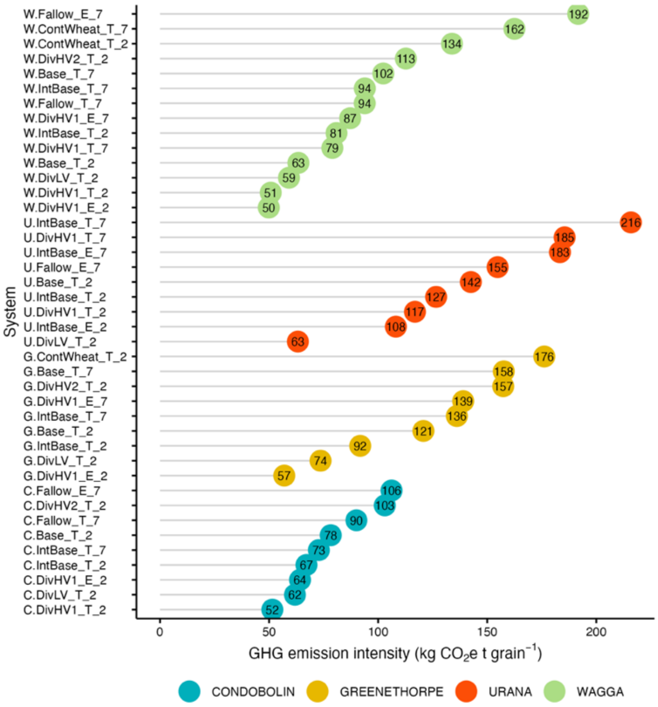

Figure A4. Ranking of the GHG emission intensity of systems at each of the four sites (indicated by four colours). Emissions were calculated using the **dynamic** approach and presented as numbers in circles on the graph.