Legume-based crop rotation impacts productivity and nitrogen use efficiency in south-eastern Australia

Fekremariam Asargew Mihretie, Julianne M. Lilley, David M. Deery, Di He, John A. Kirkegaard, Roger A. Lawes, Andrew Fletcher, Xiaoxi Li

Agriculture and Food, CSIRO, ACT 2601 Australia, mih012@csiro.au

Abstract
A simulation study using APSIM was conducted to assess the impacts of different crop rotation and nitrogen rate scenarios on crop yields, soil carbon, and nitrogen use efficiency at four contrasting study sites (Boorowa, Cootamundra, Ardlethan, and Condobolin) in southeastern Australia. The study evaluated four crop rotations and five nitrogen rates (0, 50, 100, 150, and 200 kg N/ha) to determine their effects on long-term crop yields, profitability, and resource use efficiency. The crop rotation scenarios were: 1. Canola-wheat-wheat-canola-wheat-wheat/conventional (RS1); 2. Lucerne-lucerne-lucerne canola-wheat-wheat (RS2); 3. Faba bean-barley-oat-canola-lupin-wheat (RS3); 4. Faba bean-canola-wheat-barley-faba bean-wheat (RS4). Results showed that without nitrogen fertilizer, wheat yields ranked as RS2 > RS4 > RS3 > RS1 across all locations. At 50 kg N/ha, yields were ordered as RS4 > RS2 > RS1 > RS3. For nitrogen rates of 100, 150, and 200 kg N/ha, yields ranked as RS4 > RS1 > RS2 > RS3. Regarding soil organic carbon (SOC), without nitrogen fertilizer, the order was RS2 > RS4 > RS3 > RS1 consistently across all study sites. A similar pattern was observed at 50 kg N/ha. However, at nitrogen rates of 100, 150, and 200 kg N/ha, the RS1 rotation became superior in SOC compared to other systems. In comparison to the conventional cropping system (RS1), the RS2, RS3, and RS4 systems reduced nitrogen fertilizer application by 90%, -2%, and 55%, respectively, while achieving optimum wheat yields in the long term.

Keywords
crop model, profitability, climate smart, nitrogen fertiliser, APSIM

Introduction
Monocropping cropping systems require high fertilizer input to attain optimum yields but are highly vulnerable to risks due to high costs, climate variability, and the occurrence of diseases and insects (Rosa-Schleich et al., 2019). Monocropping can lead to soil resource depletion and increased carbon emissions in the long-term. Integrating legumes, an important source of nitrogen, into crop rotation systems, such as in the wheat and canola-dominated systems of southeastern Australia, offers multiple benefits. These benefits include reducing the number of inorganic inputs needed for optimal crop yields and serving as a break crop to decrease the occurrence of diseases and insects (Xing et al., 2017). For instance, in New South Wales, legumes like field pea and lupin have been shown to contribute 60–110 kg N/ha to subsequent crops over two years (Park et al., 2010). Field experiments which integrated legumes into the cropping system attributed the increased yield of following cereal crops to a reduction in the occurrence of leaf and root diseases (Jensen et al., 2020). Despite the short-term benefits of legume- based cropping system is well known, strong evidence into the long-term effects is required for demonstrating their sustained impact on crop yields, soil health, and resource use efficiency. This can enhance grower confidence and decision-making capacity by providing reliable information under varying circumstances.

While existing evidence predominantly focuses on short-term implications, comprehensive data on long-term outcomes remains limited (Watson et al., 2015). Conducting long-term experiments is often impractical due to high costs, time constraints, and resource demands, especially as scenarios and complexities increase. Therefore, computer-based mechanistic growth models such as APSIM are increasingly valuable for predicting how agronomic practices, including crop rotations, affect crop yields and soil nutrient dynamics in the long-term across diverse biophysical conditions in Australia and beyond (Balboa et al., 2019).

The objective of this research is to assess the long-term impacts of various crop rotation systems and nitrogen fertilizer application scenarios within diverse agroecological contexts using APSIM. This study aims to evaluate impacts on crop yields, profitability, soil attributes, and resource use efficiency. The ultimate purpose is to investigate how legume-based crop rotation systems can reduce inputs and risks while enhancing soil health, in comparison to conventional cropping systems

Methods

A simulation study was conducted at four contrasting sites in southeastern Australia. Boorowa and Cootamundra, with annual rainfalls of 589 mm and 575 mm respectively, represent areas with relatively high rainfall. In contrast, Ardlethan and Condobolin, receiving 427 mm and 444 mm annually, are characterized by lower rainfall. We used APSIM (Agricultural Production Systems Simulator) (v. 7.10) for this study. APSIM is a well-calibrated and validated farming system model used globally to simulate crop growth, yield, and soil nutrient dynamics. The impacts of four crop rotation and five nitrogen rate (0, 50, 100, 150, and 200 kg N/ha) scenarios on long-term crop yields, profitability, and resource use efficiency were assessed using APSIM. The crop rotation scenarios were as follows: 1.Canola-wheat-wheat-canola-wheat-wheat (RS1), representing the conventional crop rotation system; 2. Lucerne- lucerne- lucerne-canola-wheat-wheat (RS2), representing crop rotation with pasture; 3. Faba bean-barley-oat-canola-lupin-wheat (RS3), representing a diversified and legume-based crop rotation; 4. Faba bean-canola-wheat-barley-faba bean-wheat (RS4), representing a cereal-legume-based crop rotation.

Long-term (1990-2022) weather data (Daily temperature, humidity, rainfall and solar radiation), soil physical and chemical characteristics, and agronomic practices for each study site were used as inputs for APSIM to run simulations for the scenarios. Simulation outputs, including crop yields, lucerne biomass, mineral nitrogen and organic carbon, were used to determine the long-term impacts of various scenarios on yields (using wheat yield as a benchmark), profitability (using input and output prices), and nitrogen fertilizer use efficiency. This paper will focus primarily on the results related to soil organic carbon and crop yields. However, the long-term impacts of these rotation scenarios, such as water use efficiency, fertilizer use efficiency, and profitability, are not covered in detail in this discussion.

Results

Impacts on crop yields

The results from this study indicated that yield response was highly variable across different crop rotation systems, N rates, and locations, using wheat yield as a benchmark **(Fig.1)**. For the canola-wheat-wheat crop rotation (RS1), wheat yield increased with N rate in Boorowa but plateaued after 50 kg N/ha in Ardlethan and Condobolin, and after 100 kg N/ha in Cootamundra. In the lucerne-lucerne-lucerne-canola-wheat crop rotation (RS2), wheat yield was generally unresponsive to N application, except for slight increases with higher N rates in Boorowa and Cootamundra, where the response plateaued after 150 kg N/ha and 50 kg N/ha, respectively. Similarly, under the faba bean-barley-oat-canola-lupin-wheat crop rotation (RS3), wheat yield did not increase beyond 50 kg N/ha in Ardlethan, Condobolin, and Cootamundra, and showed no response beyond 100 kg N/ha in Boorowa. However, yield increased with N rates in Boorowa and Cootamundra but was unresponsive beyond 50 kg N/ha in Ardlethan and Condobolin under the faba bean-canola-wheat-barley-faba bean-wheat crop rotation system (RS4). Generally, variability in wheat yield across seasons were high for high N rates regardless of the locations and crop rotation systems. With no nitrogen fertiliser, yield performance of crop rotation systems were in order of RS2 > RS4 > Rs3 > RS1 regardless of the locations. For low N input (50 kg N/ha), yield performance was in order of RS4 > R2 > CRS1> RS3. Under higher N inputs (100, 150 and 200 kg N/ha), yield performance was in order of RS4 > RS1 > RS2 > RS3. Comparing locations, despite some inconsistencies, in most of the cases wheat yield was in order of Cootamundra > Boorowa > Condobolin > Ardlethan.

Differences in crop yields are highly attributed to changes in crop growth conditions due to variations in soil carbon status for each crop rotation system and the rate of nitrogen fertilizer application. Variations in study sites are attributed to seasonal differences in rainfall and initial soil characteristics.

Impacts on soil organic carbon

Changes in soil organic carbon (SOC) at the topsoil layer (0-20 cm) were varied across study sites and nitrogen (N) rates over the years (Fig. 2). Initially, in 1990, the SOC status of the study sites was in the order of Cootamundra > Ardelthean > Boorowa > Condobolin. However, by the end of the simulation in 2022, the order had slightly changed to Boorowa > Cootamundra > Ardelthean > Condobolin. The differences in soil organic carbon among the crop rotation systems were more pronounced at lower nitrogen application rates (0 and 50 kg N/ha). The rate of increase in soil organic carbon improved with higher nitrogen rates, irrespective of the study sites. The difference among the crop rotation systems was least at an application rate of 100 kg N/ha but slightly increased again at higher rates (150 and 200 kg N/ha).Under low nitrogen input (0 kg N/ha), soil organic carbon showed either a slow increase or no change for the RS2, RS4, and RS3 rotations, while it sharply declined over time for the RS1 rotation. Under 0 kg N/ha, soil organic carbon was substantially higher for RS2 and lower for RS1. Generally, the order of soil organic carbon was RS2 > RS4 > RS3 > RS1 consistently across study sites and years at 0 kg N/ha. A similar pattern was observed at 50 kg N/ha, although the differences between crop rotation systems diminished. At 100, 150, and 200 kg N/ha, despite some inconsistencies and the narrowing of differences among rotation systems, C-W-W became superior compared to the other crop rotation systems.

Differences in soil organic carbon among various crop rotation systems are primarily attributed to variations in biomass contributions, influenced by nitrogen fertilizer application and nitrogen fixation by legumes within each rotation system. Variations in soil organic carbon between locations are largely due to differences in soil and weather characteristics specific to the study sites.

Resource use efficiency

Based on the regression analysis, achieving a target wheat yield of 4000 kg/ha required approximately 112 kg N/ha for the RS1 cropping system, 13 kg N/ha for RS2, 125 kg N/ha for RS3, and 55 kg N/ha for RS4. Compared to the conventional cropping system (RS1), the RS2, RS3, and RS4 systems reduced nitrogen fertilizer application by 90%, -2%, and 55%, respectively, in the long term.

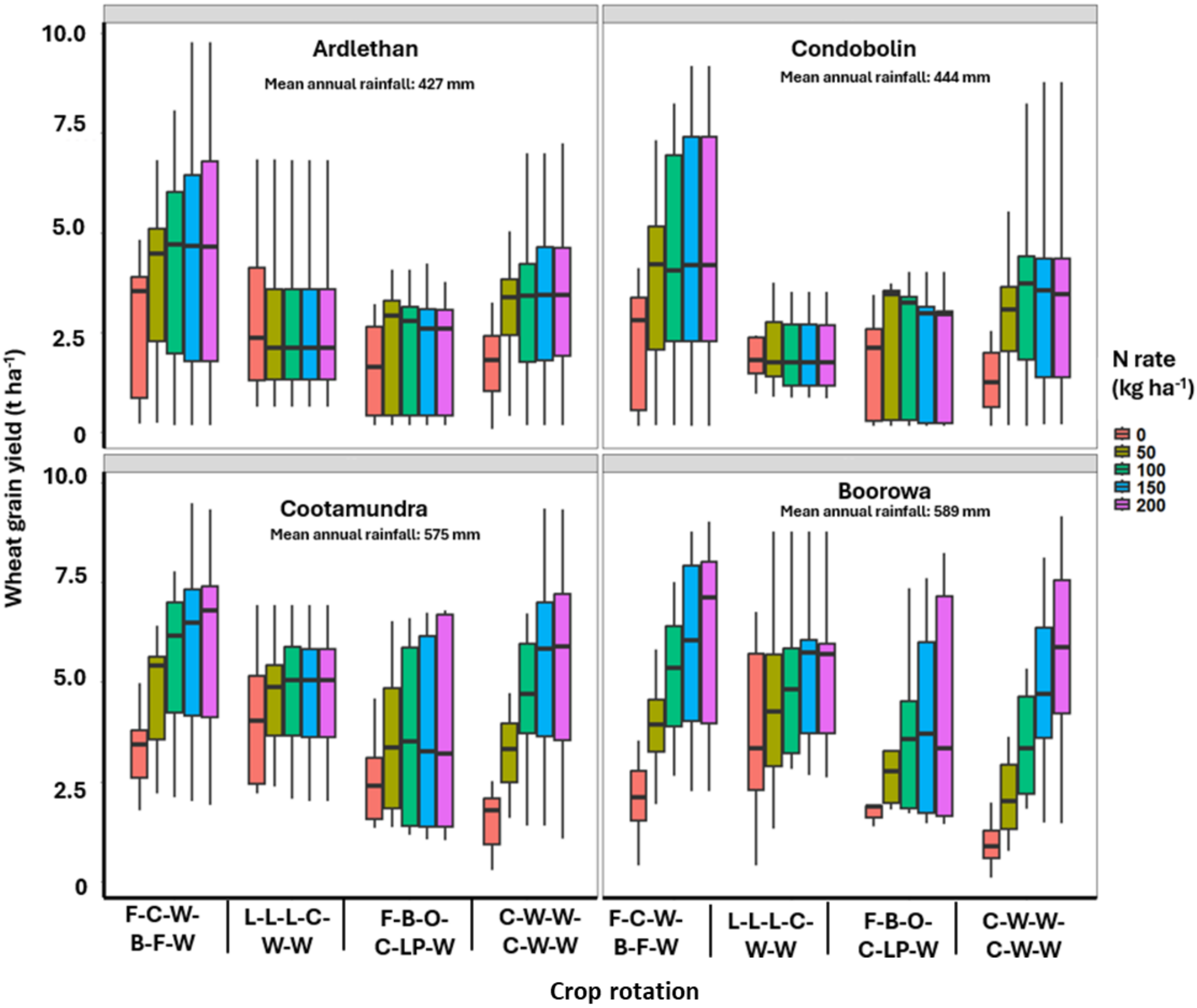

Fig.1. Wheat grain yield response to different crop rotation systems and N rates (kg ha^{-1}) at Ardlethan, Boorowa, Condobolin and Cootamundra of southern-eastern Australia. Condobolin the annual rainfall is lower.
C, canola; W, wheat; L, lucerne; F, faba bean; B, barley; LP, lupin; O, oats.

Conclusion

The response of wheat yield varied across different crop rotation systems, nitrogen (N) application rates, and study sites, demonstrating an overall increase with higher N application rates. At lower levels of inorganic N input, crop rotation systems integrating Lucerne and more faba beans were particularly effective in maintaining wheat yields due to nitrogen fixation capabilities. This underscores the potential of integrating legumes into crop rotations to sustain yields with reduced reliance on inorganic fertilizers over the long term.

Compared to conventional wheat-canola systems, legume-based crop rotations can significantly reduce N inputs by 55-90% while achieving optimal wheat yields. Moreover, integrating legumes such as lucerne and faba beans into cropping systems leads to enhanced organic carbon accumulation without compromising wheat yield compared to monoculture systems.

This study underscores the importance of legume-based crop rotations in enhancing productivity, resource-use efficiency, and resilience in agricultural systems. The findings provide insights which expand on field-based research investigating sustainable agricultural practices in southeastern Australia.

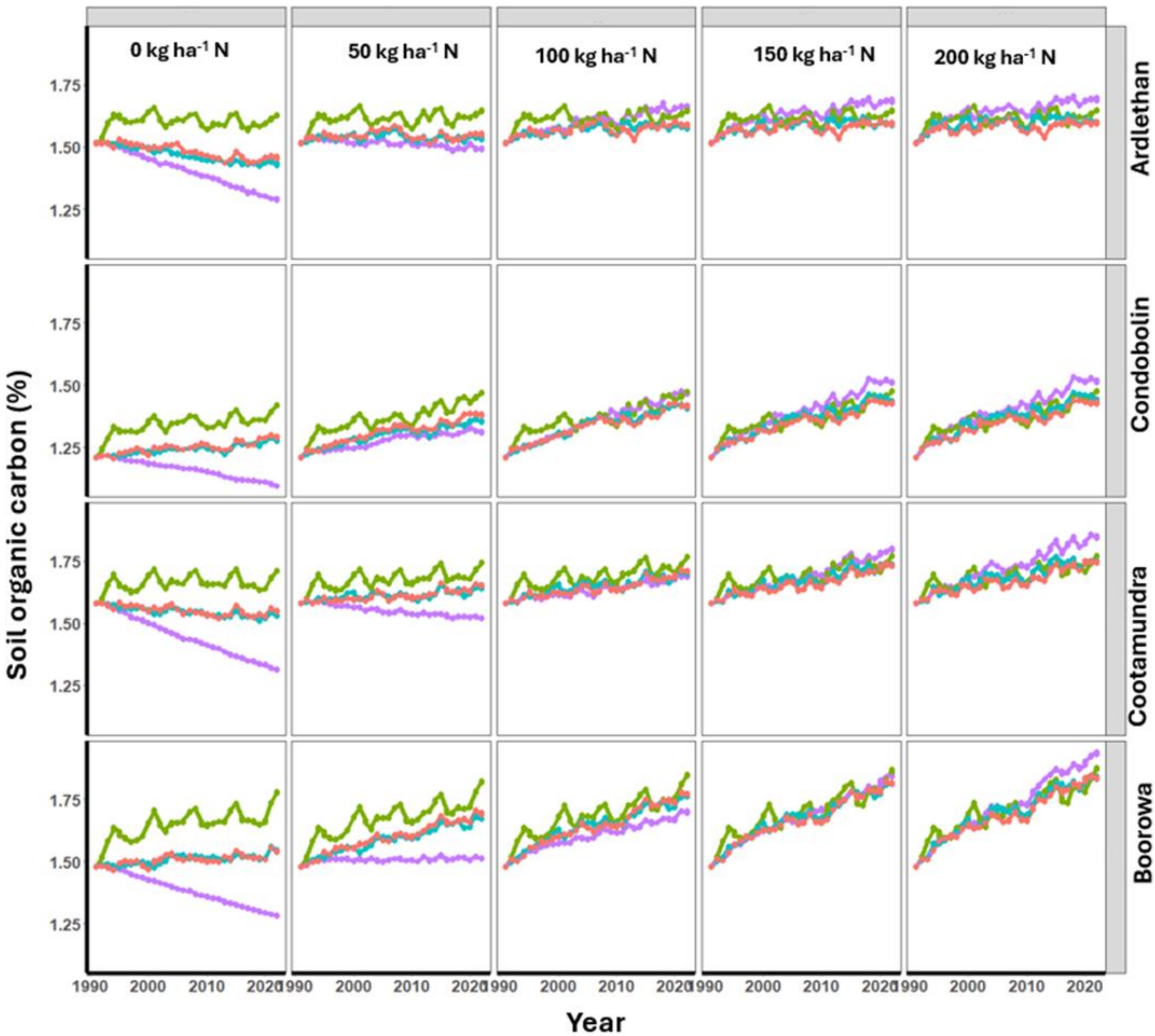

Fig.2. Soil organic carbon (%) response to different crop rotation systems and N rates (kg ha^{-1}) at Ardlethan, Boorowa, Condobolin and Cootamundra of southern-eastern Australia. Condobolin the annual rainfall is lower.
C, canola; W, wheat; L, lucerne; F, faba bean; B, barley; LP, lupin; O, oats.

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