# Pathways to Net Zero Farm in Australia Broadacre Farming: A Comparative Study Using a whole farm model

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**Abstract**
Markets and society increasingly demand food production systems that balance output, profitability, and environmental impact. Here we quantify the likely efficacy of alternative farming strategies in terms of their ability to mitigate greenhouse gas (GHG) emissions, enhance farmer profitability, and mitigate risks. We used the APSFarm NextGen model, to simulate crop production and emissions of six contrasting farming strategies: (i) intensive energy use (Fuel Burner), (ii) Opportunistic crop rotations, (iii) Rigid crop rotations, (iv) Agroecology, (v) Conservation Agriculture, and (vi) NetZero. We simulated 50 years of climatology (1970-2019) and a range of future climate scenarios (2021-2070), across three case study farms of Queensland. Benefits and trade-offs associated to each strategy are discussed in terms of gross margins (GM, AU$ $ha^{-1}$ $year^{-1}$), downside risks (likelihood of a negative return), and GHG emissions (kg $CO_2$-eq $ha^{-1}$ $yr^{-1}$). This study highlights the potential for achieving NetZero emissions in Queensland's agricultural sector, providing guidance for farmers and policymakers to develop adaptive strategies that align with government goals. Additionally, the whole farm modelling framework for NetZero research used in this study is also applicable to agricultural emission reduction plans in other countries and regions across the world.

## Keywords
Farm profits and risks; Greenhouse gas emissions; Whole farm modelling; APSFarm; APSIM.

## Introduction
Achieving NetZero without affecting productivity, farm profits, or risk exposure, represents a challenge for agriculture anywhere in the world. The Australian government aims for a 43% reduction in emissions by 2030 and net zero by 2050, in alignment with the Paris Agreement (Agreement, 2015). In Australia, agriculture accounts for 14% of total GHG emissions (Verge, et al 2007). Numerous studies demonstrate that agricultural management strategies—including strategic crop rotation, organic fertilizers and pesticides, nitrogen-fixing and cover crops, no-till farming, and legume cultivation—significantly reduce emissions in agricultural systems (Donner and Kucharik, 2003; Halvorson et al. 2010; Halvorson et al. 2008; Jiang et al. 2018; Muhammad et al. 2019; Parkin and Kaspar, 2006). However, there are natural limitations in reducing GHG emissions from agricultural system due to the cycling of soil organic carbon and soil organic nitrogen (Chen et al. 2010; Luo et al. 2011). Achieving NetZero emissions in agriculture only be feasible through compensatory measures such as carbon sequestration (González-Ramírez et al. 2012). Whole farm models can help quantify emissions and guide sustainable and economically viable farming strategies. The aim of this in-silico study was to (i) incorporate GHG emission capabilities in APSFarm NextGen, to simulate emissions and return from cropping systems, and (ii) calculate benefits and trade-offs across economic and environmental indicators for alternative pathways towards achieving NetZero.

## Methods
*Climate and Soil Data Collection*
Case study farm from three regions, Georgetown (142.85°E, 18.15°S) in Queensland's semi-arid tropics, Capella (148.02°E, 23.09°S) in Central Queensland, and Dalby (151.27°E, 27.17°S) in the Darling Downs, of Australia, were selected for this study. Previously published case study farms were used for this study (Adhikari et al. 2023; Rodriguez et al. 2014; Rodriguez et al. 2011). The historical climate data (1970-2019) was downloaded from the Scientific Information for Landowners (Jeffrey et al. 2001). The future climate data were obtained from ISMIP (Inter-Sectoral Impact Model Intercomparison Project) (Lange S and Matthias B 2021). Future climates include three SSP (Shared Socioeconomic Pathways), each SSP was an ensemble of five GCMs. Soil data was obtained from the APSoil database (Dalgliesh et al. 2012).

*Simulated strategies*
To compare the NetZero potential of different agricultural management models, six farm strategies were parameterized based on published case study farms (Adhikari et al. 2023; Rodriguez et al. 2011). Carbon offsets, in the NetZero strategy, are achieved by planting eucalyptus trees on the lest fertile soils.

 

Opportunistic crop rotation (OR): "Opportunistic crop rotation" refers to a flexible management strategy in this experiment. Under this strategy, farmers adjust the types of crops and planting schedules based on indicators such as soil moisture, rainfall, and planting area. This strategy employs chemical fertilizers, pesticides, and herbicides. The strategy uses no-till after harvesting the crops. The crops planted include sorghum, wheat, and chickpea (Rodriguez et al. 2011).
Rigid crop rotation (RR): “Rigid crop rotation” refers to a more fixed management strategy. In this strategy, farmers adhere to a pre-established planting plan, planting specific crops at fixed times regardless of other conditions. The strategy uses no-till after harvesting the crops. The crops planted include sorghum, wheat, maize, and chickpea (Rodriguez et al. 2011).
High energy use or fuel burner (FB): This strategy focuses on yield optimization through a rigid crop rotation system and the heavy use of chemical fertilizers. In FB strategy, tillage is commonly performed post-harvest to incorporate crop residues into the soil. Chemical pesticides and herbicides are utilized to control pests and weeds. This approach aims to achieve high yields through substantial inputs and may exert considerable stress on the soil and the environment. The main crops include wheat, sorghum, and chickpea.
Conservation agriculture (CA): Conservation agriculture focuses on enhancing production efficiency while protecting soil health. This strategy employs Opportunistic crop rotation and no-till management aimed at improving resilience, reducing soil erosion, and improving soil health. Regarding pest and weed control, CA uses chemical pesticides and herbicides. It uses chemical fertilizers for crop nutrition management. The primary crops grown include sorghum, wheat, maize, mungbean, soybean, and chickpea. By minimizing soil disturbance and maintaining soil cover, CA strives to enhance soil health without decreasing yield (Pittelkow et al. 2015).
Agroecology (AE): Agroecology strategy emphasizes the integration of ecological principles into agricultural management to support sustainable agriculture.in terms of crop nutrition management, AE uses organic manure instead of chemical fertilizer. Regarding pest and weed control, CA selects organic herbicides and natural pesticides, focusing on ecological balance and environmental protection. The variety of crops includes sorghum, wheat, maize, mungbean, soybean, and chickpea. This approach aims to achieve sustainable agricultural development while protecting the ecosystem (Gliessman S 2018).
NetZero (NZ): The management of NetZero strategy is the same as that of AE. However, in the NetZero strategy, we use afforestation to offset farm residue greenhouse gas emissions by incrementally increasing the afforested area on the farm. Specific percentages of farm area (2%, 4%, 6%, 8%, 10% until achieving zero emissions) are designated for afforestation to systematically evaluate the impact on achieving NetZero objectives.

*Greenhouse gas emissions, gross margins, and downside risk*
To assess the impacts of management strategies on whole farm GHG emissions (kg CO2-eq ha$^{-1}$ yr$^{-1}$) and gross margin (GM, AU$ ha$^{-1}$ year$^{-1}$), APSFarm was run from 1970 to 2019 for each strategy. Each simulation quantified the GHG emissions in $CO_2$ equivalents, which was calculated as the sum of soil $CO_2$ and $N_2O$ fluxes, emissions from fuel burning, and emissions from agrochemicals (fungicides and herbicides).
The APSFarm economic module monitors input costs and sales revenue to compute the gross margin for each crop type. The data on seed costs and agricultural product prices were sourced from AgMargins. To minimize uncertainty, we applied a five-year average.
In this study, downside risk (%) is defined as the probability of annual gross margins falling below zero. Using the APSFarm model, we calculated annual GM for various strategies across different sites. We then computed the cumulative distribution probabilities of annual returns using R (4.3) to determine the downside risk.

## Results
*Trade-offs GHG emissions, GM, and downside risk*
Annual gross margin (GM, AU$ ha$^{-1}$ yr$^{-1}$), annual GHG emissions (kg CO2-eq ha$^{-1}$ yr$^{-1}$), and downside risk (%) using climatology (1970-2019) for three experimental sites are presented in Figure 1.
At the three sites, the CA strategy always had the highest mean gross margins (Figure 1). The NZ strategy always had the lowest mean GHG emissions. The mean gross margin of NZ strategies (NZ4, NZ6, NZ14) was similar to baseline strategies (opportunistic and rigid). Across all the strategies, only the NZ strategy could achieve NetZero emissions. As shown in Figure 1, NetZero mean emission farms were achieved with NZ14, NZ6, and NZ4 strategies at all three experimental sites. At Georgetown, NZ14 resulted in GHG emissions of -21 kg CO2-eq ha$^{-1}$ yr$^{-1}$ and a GM of 608 AU$ ha$^{-1}$ yr$^{-1}$. At Capella, NZ6 showed GHG emissions of -184 kg CO2-eq ha$^{-1}$ yr$^{-1}$ and a GM of 903 AU$ ha$^{-1}$ yr$^{-1}$. At Dalby, NZ4 produced GHG emissions of -42 kg CO2-eq ha$^{-1}$ yr$^{-1}$ and a GM of 1193 AU$ ha$^{-1}$ yr$^{-1}$. Compared to the baseline strategies, the NZ strategies reduced

downside risk. For example, the downside risk of NZ4, opportunistic, and rigid strategy at Dalby were 10%, 12%, and 16%, respectively (Figure 1).

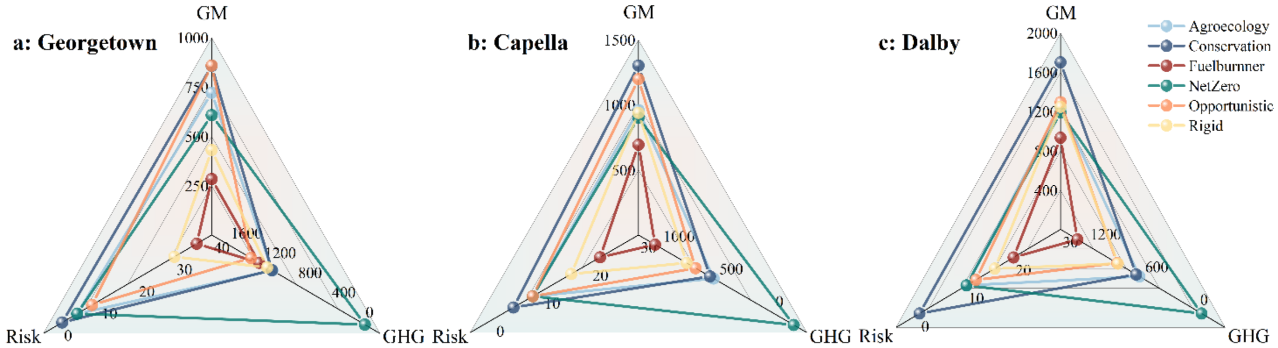


**Figure 1. Trade-offs GM (AU$ ha-1 yr-1), GHG (kg CO2-eq ha-1 yr-1), and downside risk (%) under historical climate scenarios (1970-2019) at three experimental sites. Every point summarised the mean value of one strategy for 50 years. In each radar chart, the performance of each strategy is represented by lines connecting the vertices. The NetZero strategy for each site was selected as the minimum afforestation area (Georgetown: 14%, Capella: 6%, Dalby: 4%) that could achieve NetZero mean emission**

*Optimizing Farmland Allocation for Afforestation to achieve NetZero farm*

NZ series strategy can achieve net zero emissions under historical climate in Dalby, Capella, and Georgetown by dedicating 4%, 6%, and 14%, respectively, of the farm area to afforestation. This results, except for the Georgetown region, were similar to those produced by GRDC (Sevenster et al 2022). GRDC believed in that 5.5% of the current area used for grain cultivation would need to be set aside for environmental plantings to offset the GHG emissions. A key difference is that the annual mean temperature in Georgetown is higher (26.68℃) than that in the other regions (19.36℃ and 22.67℃). Compared with the agroecology strategy, the NZ series strategies had lower gross margin but equal downside risk (Figure 1). For the NZ series strategies, with the area of afforestation increase, the gross margin and GHG emissions both decreases but the downside risk keeps stable (Figure 1).

## Conclusion

In this study, we used the whole farm model APSFarm Next Gen to explore potential pathways to NetZero on Queensland cropping farm. We quantified the interactions between agricultural management strategies and climate change on GHG emissions, GM, and downside risks. Our simulations showed that using organic fertilizers, no-tillage farming, planting cover crops and legumes, and opportunistic crop rotation could mitigate GHG emissions but not enough to achieve NetZero farm. Therefore, measures to offset farm GHG emissions are necessary. NZ series strategy can achieve net zero emissions under historical climate in Dalby, Capella, and Georgetown by dedicating 4%, 6%, and 14%, respectively, of the farm area to afforestation. Under future climate scenarios, as temperatures rise, more agricultural land will be needed for afforestation to offset GHG emissions to achieve NetZero farm. Further investigation will assess more how future climate factors influence farms' potential to achieve NetZero emissions. The case study demonstrated the potential of NetZero emissions for QLD agricultural farms, which can guide farmers and policymakers in developing adaptive strategies to achieve the NetZero emissions goals of the QLD government. Additionally, the whole farm modelling framework for NetZero research used in this study is also applicable to agricultural emission reduction plans in other countries and regions across the world.

## References


Adhikari L, et al. (2023). A framework for the assessment of farm diversification options in broadacre agriculture. Agricultural Systems, 210, 103724. (Doi: 10.1016/j.agsy.2023.103724)

Agreement P. (2015). Paris agreement. report of the conference of the parties to the United Nations framework convention on climate change (21st session, 2015: Paris). Retrived December. Vol. 4. No. 2017. Getzville, NY, USA: HeinOnline. (https://heinonline.org/)

Chen C, et al. (2010). Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Climatic Change, 100(3-4), 559-578. (Doi: 10.1007/s10584-009-9690-3)

Dalgliesh N et al. (2012). APSoil-providing soils information to consultants, farmers and researchers. 16th Australian Agronomy Conference 2012: Armidale, NSW

Donner S D, and Kucharik C J. (2003). Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. Global Biogeochemical Cycles, 17(3). (Doi: 10.1029/2001GB001808)

Gliessman S. (2018). Defining agroecology. Agroecology and Sustainable Food Systems, 42(6), 599-600. (Doi: 10.1080/21683565.2018.1432329)

González-Ramírez et al. (2012). An overview of carbon offsets from agriculture. Annu. Rev. Resour. Econ., 4(1), 145-160. (Doi: 10.1146/annurev-resource-083110-120016)

Halvorson A D, et al. (2010). Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Science Society of America Journal, 74(2), 436-445. (Doi: 10.2136/sssaj2009.0072)

Halvorson A D et al. (2008). Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. Journal of Environmental Quality, 37(4), 1337-1344. (Doi: 10.2134/jeq2007.0268)

Jeffrey S J et al. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software, 16(4), 309-330. (Doi: 10.1016/S1364-8152(01)00008-1)

Jiang G, et al. (2018). Manure and mineral fertilizer effects on crop yield and soil carbon sequestration: a meta‐analysis and modeling across China. Global Biogeochemical Cycles, 32(11), 1659-1672. (Doi: 10.1029/2018GB005960)

Lange S, and Büchner M. (2021). ISIMIP3b bias-adjusted atmospheric climate input data (v1. 1). (Doi: 10.48364/ISIMIP.842396.1 )

Luo Z, et al. (2011). Modeling long-term soil carbon dynamics and sequestration potential in semi-arid agro-ecosystems. Agricultural and Forest Meteorology, 151(12), 1529-1544. (Doi: 10.1016/j.agrformet.2011.06.011 )

Muhammad I, et al. (2019). Regulation of soil CO2 and N2O emissions by cover crops: A meta-analysis. Soil and Tillage Research, 192, 103-112. (Doi: 10.1016/j.still.2019.04.020)

Parkin T B, and Kaspar T C. (2006). Nitrous oxide emissions from corn–soybean systems in the Midwest. Journal of Environmental Quality, 35(4), 1496-1506. (Doi: 10.2134/jeq2005.0183)

Pittelkow, et al. Productivity limits and potentials of the principles of conservation agriculture. Nature 517.7534 (2015): 365-368. (Doi: 10.1038/nature13809)

Rodriguez D, et al. (2011). The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. Field Crops Research, 124(2), 157-170. (Doi:10.1016/j.fcr.2011.02.012)

Sevenster M et al. (2022). Australian grains baseline and mitigation assessment. GRAINS RESEARCH UPDATE, 16. (https://grdc.com.au/)

Verge, et al. (2007). Agricultural production, greenhouse gas emissions and mitigation potential. Agricultural and forest meteorology, 142(2-4), 255-269. (Doi: 10.1016/j.agrformet.2006.06.011)