The impact of future climate change on the contribution of legume fixed N to the subsequent crop in the rainfed cropping systems in Southern Australia

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Abstract
Legume crops are one of key rotation components in agricultural systems, supplying nitrogen (N) to following crops and potentially increasing farm profitability. However, with the increasing atmospheric greenhouse gas concentrations, Australia will become warmer and dryer in the future. This greatly threatens Australian crop production and brings uncertain impacts on the profitability of adding legumes into non-legume crop sequences. In this study, we optimised the crop model, APSIM, using 4-year experimental data, collected in Wagga Wagga, New South Wales, Australia. The optimised model was then used to predict lupin biological N_2 fixation (BNF) and the contribution of fixed N to the subsequent canola under historical and future climatic conditions in the rainfed cropping systems. The simulation results showed that, when there was no N fertilizer applied to canola in lupin-canola rotations, BNF increased about 3% by 2071-2100 under the higher greenhouse gas emission scenario, comparing to 1961-2000. This results in about 20% of increase in the contribution of lupin fixed N to the subsequent canola seasons (NC). However, these benefits will be reduced to zero when N fertilizer applied in canola seasons is over 40 kg N/ha for BNF and 60 kg N/ha for NC, respectively, by 2071-2100 for RCP8.5. This indicates that future climate change would enhance the N contribution of legume fixed N to subsequent crops only when the non-legume crops received lower N fertilizer in the legume added rotation cropping systems.
Key Words: Climate change, legume, canola, N benefit

Introduction

Nitrogen (N) is the element most often limiting to net primary production in many terrestrial ecosystems. Biological N_2 fixation provides an important N input to the legume-included rotation systems, potentially increasing the productivity of the subsequent crops (Peoples *et al.*, 2009).

In the recent IPCC assessment (IPCC, 2014), the atmospheric CO_2 concentration will increase to 540 ppm and 940 ppm in RCP4.5 and RCP8.5 by 2100, respectively. Correspondingly, Australian annual air temperature would increase about 1.4 - 2.7°C and 2.8 - 5.1°C by the end of this century for RCP4.5 and RCP8.5 future scenarios, respectively, with a possible decrease in spring and winter rainfall (CSIRO and Bureau of Meteorology, 2015). Changes in these three linked variables (CO_2, temperature, and rainfall) will alter plant growth, biomass, and plant community composition, as well as contribution of legume fixed N to the subsequent crops and agro-systems at local, regional, and global scales (Vadez *et al.*, 2012; Thomas *et al.*, 2015).

In this study, we optimised the Agricultural Production Systems sIMulator (APSIM) in modelling yields and above-ground biomass of lupin and canola, and BNF of lupin. The optimised model was run in historical (1961-2000) and future climates (2031-2050 (2040s) and 2071-2100 (2080s) for RCP 4.5 and RCP8.5 future scenarios). The aim is to investigate effects of future climate changes on the N benefits of adding narrowleaf lupin (*Lupinus angustifolius*) into a rainfed canola cropping systems in southern New South Wales (NSW), Australia.

Methods

Site description

Experiments were conducted in 2013-2016 at Wagga Wagga, NSW (35°01’45” S, 147°20’36” E; 210 m a.s.l) in a Red Kandosol (Isbell, 1996). The soil was slightly acidic with a pH of 5.1 in $CaCl_2$ and soil organic carbon content was 1.64% at the soil surface (0-0.1 m). Details of the soil properties are given in Li *et al.* (2016) and Xing *et al.* (2017). Narrowleaf lupin (cv. Jenabillup) and canola (*Brassica napus* cv. Hyola 575) were sown in April each year. Canola received 25 kg N ha^{-1} at sowing and 50 kg N ha^{-1} in the branching stage. Wagga Wagga has a semi-arid continental climate with an annual average minimum/maximum temperature of 9.1/22.4°C and a mean annual rainfall of 558 mm.

Brief description of APSIM-Canola and APSIM-Legume modules

The APSIM-Canola and APSIM-Legume modules are the modified version of the generic crop model template in the APSIM framework. It has been used for simulating crop development and growth, above-ground biomass and yields for a wide range species (Farre *et al.*, 2002; Robertson *et al.*, 2002; He *et al.*, 2017). Its performance in simulations of legume biological N_2 fixation and N contributions to next crops is generally acceptable (Chen *et al.*, 2016; Xing *et al.*, 2017).

In this study, the observed data collected in 2013-2016 were used to optimise APSIM-Legume and Canola for simulating the above-ground biomass and yield of canola and lupin, and lupin BNF. The reverse approach for estimating N contribution to the subsequent crop was adopted. The details of this approach were given by Xing *et al.* (2017).

Daily weather variables, including maximum and minimum air temperature, solar radiation, and rainfall from 1961 to 2016 for Wagga Wagga were obtained from the SILO Patched Point Dataset. RCP4.5 and RCP8.5 simulations of the 28 GCMs were downscaled using the statistical downscaling and bias-correction method of Liu and Zuo (2012).

Results and discussion

Projected future climate change

Most of the GCMs projected future rainfall in crop growing season (April-November) in Wagga Wagga, NSW, would decrease (Fig. 1a), comparing to 1961-2000. Between 1961–2000 and 2071–2100 (2080s), the projected mean growing season rainfall would decrease about 7.0% for RCP4.5 and 5.3% for RCP8.5, which is close to the regional rainfall changes estimated by Wang *et al.* (2018). All GCMs agreed on a future temperature rise and, RCP8.5 had higher temperature increases than RCP4.5 (Fig.1b), which is consistent with greater greenhouse forcing of the climate system.

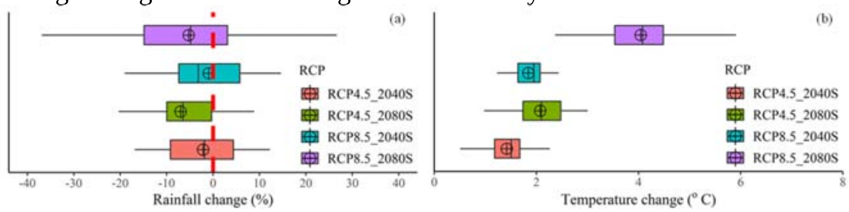

Figure. 1. Projected changes in crop growing season (April-November) (a) rainfall and (b) mean temperature from 28 CMIP5 GCMs in Wagga Wagga for RCP4.5 and RCP8.5 by 2040s (2031–2060) and 2080s (2071–2100) compared to 1961–2000, respectively. Box boundaries indicate the 25th and 75th percentiles across GCMs, whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the multi-model median and mean, respectively.

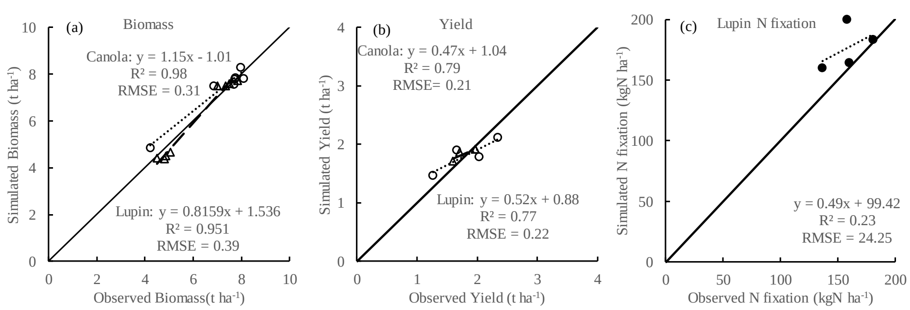

Figure. 2. Comparisons of observed and simulated above-ground biomass and yield of canola and lupin, and biological N_2 fixation of lupin in rainfed cropping systems at Wagga Wagga, NSW, Australia.

APSIM performance for simulating the growth of canola and lupin

The above-ground biomass of canola and lupin, measured in flowering and maturity stages, were simulated by APSIM-Canola and APSIM-Legume with a root mean square error (RMSE) of 0.31 and 0.39 t ha^{-1}, respectively (Fig. 2a). APSIM-Canola and APSIM-Legume could explain 79% and 77% of the variations in grain-yield of canola and lupin, respectively, across environment and N fertilizer treatments (Fig. 2b). APSIM-Legume predicted the biological N_2 fixation with a R^2 of 0.23 and RMSE of 24.25 kg ha^{-1}(Fig. 2c). The agreement between the simulated and observed values indicates that APSIM was able to capture the changes of above-ground biomass and yield of these two crops and BNF of lupin in response to climatic variations and N fertilizer applications in the study region.

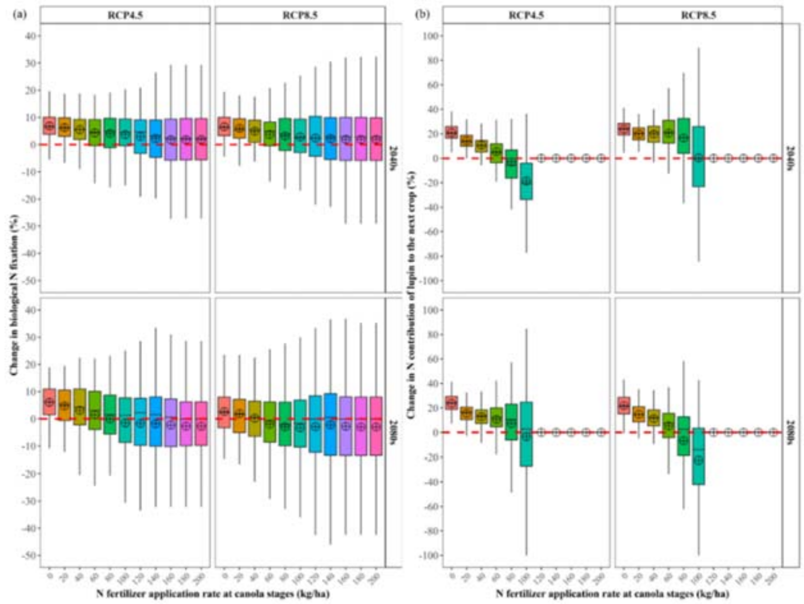

Figure. 3. Projected changes in the impacts of N fertilization application in canola season on (a) biological N_2 fixation (BNF) of lupin and (b) N contribution to the following canola season in a rainfed cropping system. Changes are for RCP4.5 and RCP8.5 for 2040s (2031–2060) and 2080s (2071–2100) compared to 1961–2000. Box boundaries indicate the 25th and 75th percentiles across GCMs, whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and black crosshairs within each box indicate the multi-model median and mean, respectively.

Projected changes lupin biological N_2 fixation and contribution of fixed N to the next crop

Figure 3 shows that the impacts of future climate changes on the response of BNF and the contribution of lupin fixed N to the subsequent canola (NC) under N fertilizer application rates in canola seasons. Comparing to 1961-2000, in the non-N fertilizer scenarios, annual average BNF in 2040s (2031-2060) increases about 6.9% and 6.6% for RCP4.5 and RCP8.5, respectively, and about 6.1% and 2.7% in 2080s (2071-2100) for RCP4.5 and RCP 8.5, respectively. By 2040s, as the N fertilizer applied in canola seasons increase to 200 kg N/ha, the benefit in BNF because of future climate change declines to 1.8% and 1.9% for RCP4.5 and RCP8.5, respectively. By 2080s, the benefit in BNF decline to 0.0, when N fertilizer is 60 and 40 kg N/ha for RCP4.5 and RCP8.5, and the future climate change lead to further decrease in BNF as the N fertilizer application is above 60 and 40 kg N/ha for RCP4.5 and RCP8.5 (Fig. 3a). Correspondingly, comparing to 1961- 2000, when the system does not receive any N fertilizer, the contribution of fixed N to the following canola season increases about 21% and 24% by 2040s for RCP4.5 and RCP8.5, respectively, and 24% and 22% by 2080s for RCP4.5 and RCP8.5, respectively. When N fertilizer application rate in canola seasons is 100 kg N/ha, the changes in N contribution declines to -15% and 2% by 2040s for RCP4.5 and RCP8.5, respectively, and declines to -1.5% and -22.5% by 2080s for RCP4.5 and RCP8.5, respectively. This indicates the future climate would enhance the N benefit of adding legume crop into crop sequence only when N fertilizer application in non-legume crops is relative low. Our simulation might have some uncertainties in estimating the N benefit of adding legume crops into crop sequences in the future climate conditions. This is because we don't consider the response of BNF to atmospheric CO_2 concentration in this study, which was reported that the increase of atmospheric CO_2 concentration would stimulates photosynthesis and biomass production of N_2-fixing plants, and correspondingly nitrogenase activity (Vadez *et al.*, 2012; Thomas *et al.*, 2015; Parvin *et al.*, 2018). Furthermore, the functions for depicting the response of lupin production to the elevated CO_2 are borrowed from APSIM-Wheat module as there are not enough data to quantify this response for lupin or legume crops. This leads to an uncertainty for estimating the N benefit in the future climatic conditions with the elevated CO_2 concentrations. Therefore, future research in these areas would decrease the uncertainty in estimating the benefit of adding legume into non-legume crop sequences, and better assisting in making strategies for adapting the future climate changes for Australian grain industry.

Conclusion

Our simulation study confirmed that APSIM is a reliable tool to estimate the N contribution of grain legumes to subsequent crops after careful validation against observed data relating to growth, above-ground biomass,

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yield and biological N_2 fixation. Future climate would enhance the N benefit of adding legume crop into crop sequences when N fertilizer applied non-legume crop is low.

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