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Modelling interactions between cowpea cover crops and residue retention in Australian dryland cropping systems under climate change

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ABSTRACT

Conservation agriculture management practices (e.g., cover crops and residue retention) have been widely promoted to improve soil quality and environmental sustainability. However, little is known about the long-term interactive effects of cover crops and residue retention on yield of the cash crops and environmental outcomes in dryland cropping systems under climate change. We used the pre-validated APSIM model, driven by statistically downscaled daily climate data from 27 Global Climate Models (GCMs) under two Shared Socioeconomic Pathways (SSP245 and SSP585), to assess the combined influences of cowpea cover crops and three residue retention levels on soil water balance, soil organic carbon (SOC), nitrogen (N) dynamics, crop yield and gross margin across six crop rotation systems during the historical period (1985–2020), near future (2021–2056), and far future (2057–2092) in southeast Australia. Our results showed that, on average, cover crops decreased soil moisture on the day of sowing the succeeding cash crop (by 22%), but led to greater SOC stock (21%), reduced N loss through leaching (71%), and enhanced N uptake and yield of cereals, but decreased N uptake and yield of field pea. The effects of cover crops on yield and gross margin became more positive in the far future under both SSPs, which may be attributed to the SOC increase and greater N availability in the long term. These benefits were more evident under residue removal due to the partly compensatory effects from cover crop residues. Furthermore, cover crops were profitable in the wetter parts of the study region (east), but reduced gross margin in the drier west due to depletion of soil water reserves for the next cash crop. We conclude that particularly where residues are removed, the long-term adoption of cowpea cover crops could be a potential practice to sustain crop productivity with environmental co-benefits under climate change in the wetter parts of the dryland cropping region of southeast Australia.

1. Introduction

Meeting projected food demand by a growing population presents an enormous challenge for global agriculture (Godfray et al., 2010). Intensive conventional agriculture (e.g., using high inputs of synthetic fertilizer and pesticide) has been successful in boosting crop yields (Knapp and Heijden, 2018), but has also raised many environmental issues such as water pollution, soil degradation, and nutrient loss (Beyer et al., 2022; Bommarco et al., 2013). A shift to conservation agriculture has been proposed as a feasible solution to enhance food security,

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provide environmental services and improve the resilience of cropping systems to climate change (Lal, 2015; Nouri et al., 2021).

Conservation agriculture encompasses three principles: minimum soil disturbance (i.e. no tillage), permanent soil cover with crop residues or cover crops, and diversified crop rotations (FAO, 2022). In recent years, conservation agriculture has been rapidly adopted, growing from 106 million ha (7.5% of global cropland) in 2008/09 to 205 million ha (14.7% of global cropland) in 2018/19 (CA GLOBAL, https://www.ca-global.net/ca-stat). However, due to the complex interactions between different management practices, local climate conditions and soil characteristics, the effects of conservation agriculture on crop yields are unclear and strongly debated (Brouder and Gomez-Macpherson, 2014; Pittelkow et al., 2015; Su et al., 2021; Sun et al., 2020).

Growing cover crops is a typical conservation agriculture practice that involves planting a non-cash crop during the fallow period (Griffiths et al., 2022). The adoption rate of cover crops in the U.S. has increased from 3.4% of cropland in 2012 to 5.1% in 2017 (Wallander et al., 2021) and in Canada, from 8.2% of farms in 2010 to 13.7% in 2015 (Statistics Canada, 2015). The growing interest in cover crops around the world is due to its potential to provide multiple agroecosystem services, such as soil quality improvement (Qi et al., 2022; Simon et al., 2022), nutrient recycling (Teixeira et al., 2021; White et al., 2017), and pest control (Bowers et al., 2020; Schipanski et al., 2014), which are key factors for more resilient agroecosystems under climate change. However, planting a cover crop is likely to consume soil water, which could reduce subsequent cash crop yields especially in water-limited environments. A meta-analysis has demonstrated that cover crops reduced cash crop yields by 11% and 12% in temperate dryland and dry climates, but increased cash crop yields by 4% and 15% in continental and tropical climates, respectively (Garba et al., 2022). Olin et al. (2015) found that grass cover crops reduced nitrogen leaching by 15% but also decreased cash crop yields by 5%. Thus, several studies have shown a trade-off between environmental benefits of cover crops and cash crop yields. To encourage the adoption of cover crops, it is necessary to identify conditions in which yield penalties could be avoided.

The impacts of planting cover crops may be synergistic with residue retention, for example, residues from both cash crops and cover crops build soil organic matter and release nitrogen for the succeeding crops (Fontaine et al., 2020; Qi et al., 2022). Legume cover crops, that fix N from the atmosphere, can also be ploughed in as ‘green manure’ to release additional mineral N (Jensen et al., 2021). In addition, residues and cover crops can benefit water conservation by increasing infiltration and reducing surface runoff, soil evaporation and drainage (Liu et al., 2017; Wang et al., 2021a). The water retention from crop residue mulching could also offset part of the water consumption of cover crops. Taghizadeh-Toosi et al. (2022) found that straw retention was more important than cover crops for soil C storage, and cover crops played a more important role in suppressing N leaching in a wet temperature climate. Furthermore, Qi et al. (2022) reported that cover crops and residues both increased the soil structural stability, but through aggregation (due to binding agents from roots) and increased soil organic carbon, respectively. These studies focused on the effects of cover crops on soil properties and functions, however, the interactive effects of cover crops and residue management on cash crop yields and farm income are still unclear. In addition, increasing the diversity of crop rotations has been promoted as a conservation agriculture strategy to benefit crop production (Degani et al., 2019; Renwick et al., 2021; Zhao et al., 2022), but few studies have investigated the holistic performance of cover crops and residue retention levels across different rotation systems.

The Australian dryland cropping area expanded by 7.7% from 2010/11 to 2015/16, with the greatest expansion occurring in New South Wales (ABS, 2021). Dryland crop production in Australia is threatened by the highly variable distribution of seasonal rainfall (Anwar et al., 2015; Feng et al., 2018; Wang et al., 2018). Further, increases in rainfall variability and temperature in the future could exacerbate the climate-driven decline in dryland crop yields (Hochman et al., 2017). This challenging production environment has spawned some agricultural research and development funding measures that encouraged farmers to grow crops using conservation agriculture principles (Bellotti and Rochecouste, 2014). Therefore, there is a need to assess the potential of conservation agriculture as an adaptation to future climate change in Australian dryland cropping systems.

Process-based models such as APSIM (Agricultural Production Systems sIMulator) can explicitly simulate the water-carbon-nutrient balance and crop growth in climate-soil-plant systems, thus complementing field trials and controlled environment studies to assess the effects of different conservation agriculture practices on crop productivity under climate change (Bahri et al., 2019; Basche et al., 2016; Liu et al., 2014; Liu et al., 2017; Teixeira et al., 2021). In this study, based on simulated outputs from APSIM, we aimed to: (1) investigate the interactions between cover crops and residue retention on soil water balance, soil organic carbon and nitrogen dynamics under six common rotation systems; (2) assess the influence of cover crops on cash crop yields and gross margins under climate change; and (3) explore the impacts of climate conditions and residue retention levels on cover crop performance. These results are expected to provide insights into the suitability of cover crops to increase resilience to climate change of dryland cropping in southeast Australia.

2. Materials and methods

2.1. Study area and soil data

The 204 sites selected for this study were distributed across the Riverina cropping region in southern NSW, in southeast Australia (Fig. 1). The annual total rainfall is low in the west (~300 mm) and high in the east (~1000 mm), and the annual mean temperatures range from around 12–18 ℃. The main soil types are Chromosols, Dermosols, and Vertosols (Isbell and National Committee on Soil and Terrain, 2021). Dryland cereals (e.g., wheat, barley, and oats), oilseeds (e.g., canola) and pulses (e.g., field pea) are the major crops grown (Department of Primary Industries, 2020).

Soil data from APSoil database (Dalgliesh et al., 2012), a component of APSIM that provides input values for soil parameters of each soil layer, were used within the APSIM framework. Soil sites that were identified to be geographically closest to the study sites were selected, and in total 41 soil sites were used. Using the geographically closest APSoil soil profiles as APSIM input is a common practice that has been used in many crop modelling studies in Australia (Houshmandfar et al., 2019; Innes et al., 2015; Western et al., 2018).

2.2. Climate change scenarios

Daily minimum and maximum temperature, solar radiation and precipitation at the 204 study sites during the historical period of 1920–2020 were downloaded from the Scientific Information for Land Owners patched point (SILO-PPD) dataset, which is available at https://www.longpaddock.qld.gov.au/silo. The SILO-PPD dataset (Jeffrey et al., 2001) has been extensively used for running point-scale models in Australia (Liu et al., 2020). The representative Shared Socio-economic Pathways (SSPs) with intermediate (SSP2–4.5, hereafter SSP245) and very high (SSP5–8.5, hereafter SSP585) emission trajectories were employed to represent future climate scenarios during 2021–2092. These two scenarios have nominal radiative forcing of 4.5 and 8.5 W m^{-2}, and atmospheric CO_2 concentrations of 603 and 1135 ppm for SSP245 and SSP585 by 2100, respectively (Meinshausen et al., 2020).

In order to cover variations in future climate projections, an ensemble of 27 global climate models (GCMs, Table S1.1) was used for downscaled climate projections. Gridded monthly radiation, temperature and precipitation data were extracted from the GCM simulations in the Coupled Model Intercomparison Project Phase 6 (CMIP6, https://

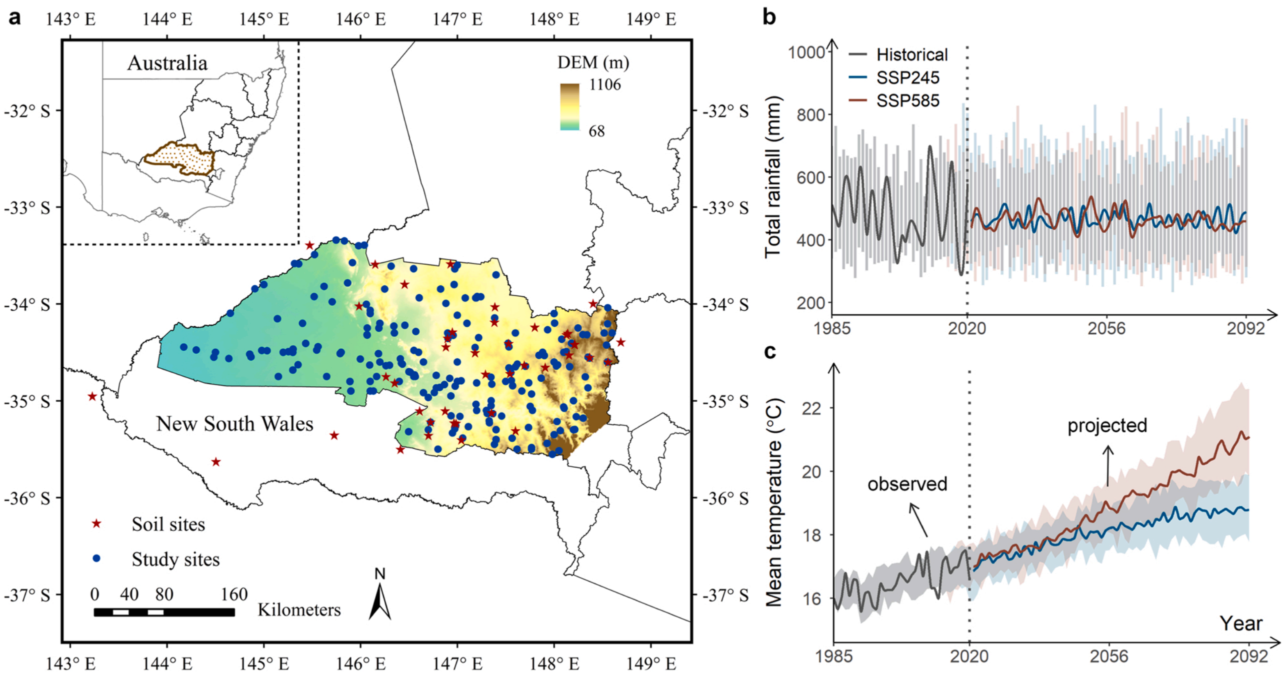

Fig. 1. Locations of the 204 study sites and 41 soil sites in the Riverina cropping region in southeast Australia (a), annual total rainfall (b) and mean temperature (c) under the SSP245 and SSP585 scenarios. The grey line represents the observed historical climate. The red and blue lines represent the median values, and shaded ranges represent the 10th and 90th percentiles based on 27 GCM projections for SSP245 and SSP585, respectively.

pcmdi.llnl.gov/CMIP6). As APSIM requires daily climate data, these GCM-generated monthly gridded data were downscaled to each study site using the method developed by Liu and Zuo (2012). First, inverse distance-weighted interpolation (IDW) was used to spatially downscale the monthly data for each of the 204 sites. Second, a bias correction was applied based on the interpolation relationship between historical observed climate and GCM projected climate data. Finally, a modified WGEN stochastic weather generator (Richardson and Wright, 1984) was used to disaggregate the corrected monthly data into daily values.

In addition, APSIM requires atmospheric CO_2 concentrations to simulate crop growth. The yearly atmospheric [CO_2] was calculated using empirical functions that were obtained by non-linear least-squares regression, based on the concentration pathway given by the Scenario Model Inter-comparison Project for CMIP6 (O'Neill et al., 2016), which can be expressed as (He et al., 2022):

$$[CO_2]_{SSP245} = 62.044 + \frac{34.002 - 3.8702\text{y}}{0.24423 - 1.1542y^{2.4901}} + 0.028057 \times (\text{y} - 1900)^2 + 0.00026827 \times (\text{y} - 1960)^3 - 9.2751 \times 10^{-7} \times (\text{y} - 1910)^4 - 2.2448 \times (\text{y} - 2030) \quad (1)$$

$$[CO_2]_{SSP585} = 757.44 + \frac{84.938 - 1.537\text{y}}{2.2011 - 3.8289y^{-0.45242}} + 2.4712 \times 10^{-4} \times (\text{y} + 15)^2 + 1.9299 \times 10^{-5} \times (\text{y} - 1937)^3 + 5.1137 \times 10^{-7} \times (\text{y} - 1910)^4 \quad (2)$$

where y is the calendar year from 1985 to 2092 (i.e., y = 1985, 1986, …, 2092).

2.3. APSIM modeling

APSIM (https://www.apsim.info) is a daily time-step model that contains a suite of modules with comprehensive physical and biological process representations to simulate the response of farming systems to different management practices and climate change (Holzworth et al., 2014; Keating et al., 2003). In this study, APSIM version 7.10 was used to simulate crop growth, soil water balance, soil carbon and nitrogen dynamics.

2.3.1. Soil water balance

The APSIM *SoilWat* module was used to simulate the soil water balance at a daily scale. The water balance during the growing season (from sowing date to harvesting date) can be expressed as:

$$P - E - T - RO - DD = \Delta SWS \quad (3)$$

where, E, T, RO, DD and P are soil evaporation, actual crop transpiration, runoff, deep drainage, and cumulative precipitation from the day of sowing to harvest, respectively. ΔSWS is soil water change, calculated as the difference in soil water storage between the end and beginning of the crop growing season.

2.3.2. Soil organic carbon

Two APSIM modules, *SoilN* and *SurfaceOM*, control the carbon transformation in the soil and on the soil surface. The *SoilN* module divides total SOC into four conceptual pools, namely fresh organic matter pool (FOM), microbial biomass pool (BIOM), humic organic matter pool (HUM), and inert organic matter pool (IOM). Except for IOM which is indecomposable, the decomposition of the other three pools is calculated as first-order processes with the rates modified by soil water content and temperature. Decomposition of any pool leads to the release of CO_2 and carbon transfer into BIOM and HUM pools. The *SurfaceOM* module deals with decomposition of crop residue based on the C and N ratio of the residue and its degree of contact with soil. Decomposition of surface residue releases CO_2 into the atmosphere and transfers remaining C to the BIOM and HUM pools.

2.3.3. Nitrogen dynamics

The *SoilWat* and *SoilN*, coupled with *SurfaceOM* module, control the N dynamics on a daily time-step, including N mineralization, N immobilization and nitrification, and the N losses from denitrification and leaching. Mineralization or immobilization of mineral N is determined as the balance between the N release from decomposition and N immobilization through microbial synthesis and protection of organic matter. Nitrification in *SoilN* is assumed to follow Michaelis-Menten kinetics with limiting factors of soil moisture, temperature and pH. Denitrification is calculated as a function of NO_3-N multiplied by active carbon, soil moisture and temperature. More details can be found in Thorburn et al. (2010). In this study, we focused on N dynamics (balance between N inputs through fertilizer and biological nitrogen fixation and N losses through leaching and harvest, respectively). The cumulative amount of NO_3-N leaching in APSIM is calculated from daily drainage multiplied by daily NO_3-N concentrations. Grain N, controlled by both soil and crop modules, is translocated from other plant parts until the tissues reach their defined minimum N concentrations. The N demand of grain is also affected by water stress and temperature (Keating et al., 2001).

2.3.4. Crop yield and gross margin

APSIM is comprised of a set of modules for simulating growth, development and yields for different crops. Crop phenology from emergence towards maturity is driven by thermal time of each specific growth stage, which is determined by accumulating growing degree-day (GDD, ℃). Daily biomass production is determined by available water for transpiration and radiant energy for potential photosynthesis, with the minimum of these two variables determining the actual biomass production for the day. Crop response to increasing atmospheric CO_2 concentration is simulated by modifying the radiation use efficiency and crop transpiration efficiency. Grain formation is simulated through assimilate partitioning to different organs. Grain yield is calculated as the product of grain weight and grain number.

For the direct comparison of different rotations, the calculation of gross margin for each crop was coded in the *Manager* module to be incorporated with other APSIM outputs. The gross margin was calculated as the difference between the grain yield income and the variable costs of production, which can be expressed as:

$$GM = (GI - C_S - C_T - C_F - C_H - C_I - C_C) \times (1 - L) \quad (4)$$

where GI is the crop yield (t ha^{-1}) multiplied by price for that crop ($ t^{-1}). C_S, C_T, C_F, C_H and C_I are the costs for sowing, tillage, fertilizer, harvest and pest control, respectively ($ ha^{-1}). C_C is the cost of sowing and terminating the cover crop, and L is the government levy (%). The on-farm costs and prices are given in Table S1.2.

2.4. Simulation scenarios

Similar to Liu et al. (2017) and O'Leary et al. (2016), APSIM was initialized for each location using a 41-year spin-up period to establish

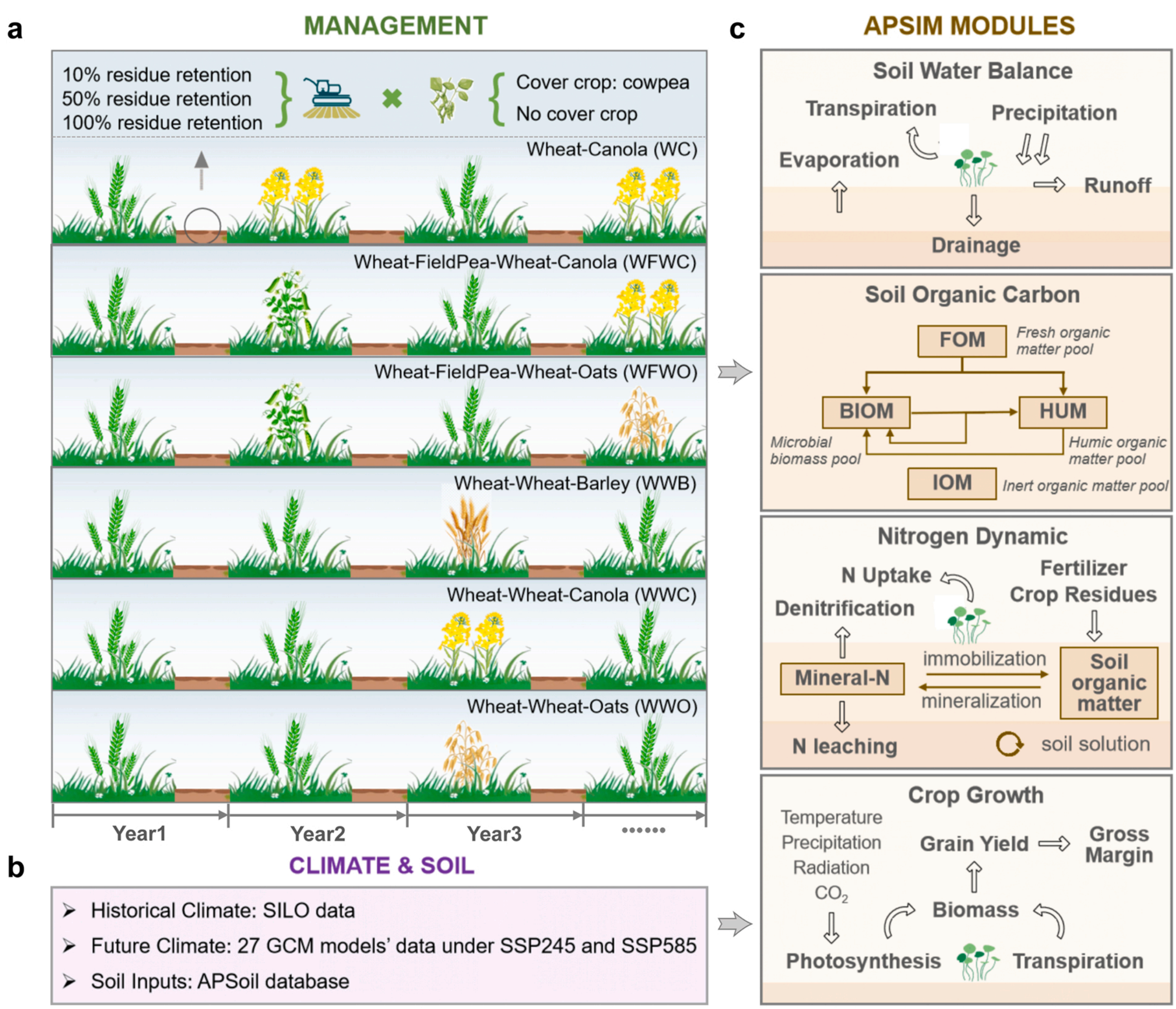

Fig. 2. The framework of the model simulation showing multiple management options (a), climate and soil data inputs (b), and different APSIM modules used to simulate the soil water balance, soil carbon, nitrogen (N) dynamics and crop growth (c). SILO, Scientific Information for Land Owners; GCM, General Circulation Model; SSP, Shared Socioeconomic Pathway. See more detailed description of the climate and crop models in Sections 2.2 and 2.3.

stable SOC fractions before simulating cropping scenarios. This was necessary because SOC recorded in the APSoil database reflected different cropping histories and farming management for each site at the time of sampling. During initialization, the model was run from 1920 to 1960 for a continuous wheat cropping system with 50 kg N ha^{-1} added as fertilizer at sowing and 25% residue retention. After the initialization, six different rotations were simulated from 1961 to 2092, with three levels of residue retention and with or without cowpea sown as a cover crop. The details of model configuration are shown in Fig. 2.

2.4.1. Crop rotation cycle

We simulated five typical crops, including wheat (W), canola (C), field pea (F), barley (B) and oats (O), in six rotations (WC, WFWC, WFWO, WWB, WWC, and WWO), which are common rotation cycles grown across the study region. For comparison of the two-year, three-year and four-year rotations, a 36-year period was used as it gives 18, 12, and 9 complete cropping cycles, respectively. Thus, three 36-year periods (1985–2020, 2021–2056, and 2057–2092) were used to represent the historical period, near future and far future, respectively. The annual mean values using inverse distance weighted interpolation method across the study region were averaged over each of the three periods, to compare results between rotations. The sowing windows were set for each crop following the sowing guidelines of NSW Department of Primary Industries (Matthews et al., 2015). The sowing dates were determined as a function of soil water content, rainfall in preceding one day, the day of year, and plant available water capacity as described in Liu et al. (2019), to avoid failure of crop establishment under the widely varied soil and climate conditions across the region (GRDC, 2013), as described in Supplementary materials S1 and shown in Fig. S1.1. Nitrogen fertilizer for cereals and canola varied between 43 and 121 kg N ha^{-1} based on the rainfall at each site, and was 10 kg N ha^{-1} for field pea. More details of fertilization can be found in He et al. (2022).

2.4.2. Residue retention and cover crop

For each rotation, three residue retention rates (10%: R10, 50%: R50, 100%: R100) were simulated. The three levels represent a typical burning, a moderate rate of residue removal, and retaining all crop residues, respectively. In each rotation system, a cowpea cover crop was sown (CC) or not sown (NC) during the fallow period. The sowing window of cowpea started four days after the harvesting of the cash crop and ended 50 days before sowing the next cash crop. The criteria to determine sowing date were soil moisture ≥ 0.85 PAWC and soil temperature ≥ 18 ℃ at 9:00 am for three consecutive days. The soil temperature at 9:00 am was estimated as (Simmons et al., 2022):

$$T = T_{\min} + (T_{\max} - T_{\min}) \times 0.375 \tag{5}$$

where, $T_{\min}$ and $T_{\max}$ are the minimum and maximum air temperature.

If the requirements of soil moisture and temperature were not met during the sowing window, cowpea was sown on the last day of the sowing window. Cowpea was assumed to be terminated mechanically at the flower initiation stage, but if this stage was not achieved, cowpea was forced to be terminated 20 days before the start of the sowing window of the next cash crop. No fertilizer was applied to cowpea, and cowpea residues were not removed from the field.

2.5. Secondary bias correction

Due to the non-stationary bias in the GCM data and imperfections in the bias correction during the downscaling procedure (Haerter et al., 2011), there are some differences between the GCM climate data and observations. These differences can be corrected, denoted as a secondary bias correction procedure. By reducing residual biases that may remain after the primary bias correction in the downscaling procedure of climate data, a secondary bias correction can strengthen the comparability of outputs from different GCMs, allowing for a more reliable assessment of potential impacts under future climate conditions. We applied this method between the model outputs driven by the downscaled GCM climate and outputs driven by the observed climate data, following the method used by Yang et al. (2016):

$$Y = S_{GCM} - (S_{BL} - S_{OB}) \tag{6}$$

where Y is the output after the secondary bias correction. S_{OB}, S_{GCM} and S_{BL} are the APSIM simulated values derived from observed climate data (1985–2020), GCM projected climate data for future period (2021–2092), and GCM projected climate data for baseline period (1985–2020), respectively.

3. Results

3.1. Soil water change

The inclusion of a cowpea cover crop in rotations significantly decreased runoff and deep drainage during the cash crop growing season compared to no cover crop, with average reductions of − 16.1% and − 47.8% under SSP245 (Fig. S2.1A-B), and − 17.7% and − 48.5% under SSP585 (Fig. S2.2A-B), respectively, across the period 1985–2092. Growing a cash crop after a cover crop rather than fallow also generally reduced soil evaporation and increased cash crop transpiration on average by − 3.0% and + 4.4% under SSP245 (Fig. S2.1 C-D), and − 3.4% and + 5.3% under SSP585 (Fig. S2.2 C-D), respectively. These effects were more obvious under R10 compared to R100, and also more obvious in the far future compared to the historical period (Fig. S2.1-S2.2). After growing cover crops during the traditional fallow period, the simulated soil water contents on the day of sowing the succeeding cash crop were lower than without cover crop for all rotation systems (Fig. 3). The average reductions in soil moisture of the whole soil profile were 33 mm (−21.8%) and 35 mm (−22.8%) under SSP245 and SSP585, respectively. The soil water storage in topsoil 0–50 cm (the main depth of crop water uptake in early growth) on the day of sowing the next cash crop was lower after cover crops by 9 mm (−15.3%) and 2 mm (−2.3%) compared to fallow under SSP245 and SSP585, respectively (Fig. S2.3).

3.2. Soil organic carbon

Without cover crops, the SOC stocks (0–30 cm) decreased steadily over time for both R10 and R50, and increased slightly but then plateaued for R100. With cover crops, however, SOC stocks increased throughout the simulation period for R50 and R100, and remained constant for R10 under all rotations and both SSPs (Fig. 4). For R100, the long-term implementation of cover crops showed a positive effect on SOC stock, with an average sequestration rate of 0.08 t ha^{-1} $year^{-1}$ from 1985 to 2092 compared to no cover crop (0.02 t ha^{-1} $year^{-1}$). Residue retention also contributed to SOC sequestration, and the sequestration rate was maximized when cover crops were combined with full residue retention.

3.3. Nitrogen dynamics

Cover crops reduced annual N leaching by 71.2% on average (median values) under both SSPs (Fig. 5). The reduced N loss through leaching was accompanied by increased soil N availability. Thus, the soil mineral N content on the day of sowing the next cash crop was increased by cover crops, and the effect was more positive in the far future (9.3% for SSP245 and 11.1% for SSP585 on average) than that in the historical period (6.9% on average) (Fig. S2.4).

The inclusion of cover crops increased N uptake in grain for wheat, barley, and oats by 13.6% (from 6.2 to 7.1 g m^{-2}), 14.9% (from 5.4 to 6.2 g m^{-2}), and 40.7% (from 4.7 to 6.5 g m^{-2}) on average (Fig. S2.5). Consistently, the total N uptake of cash crops (including the N in grain

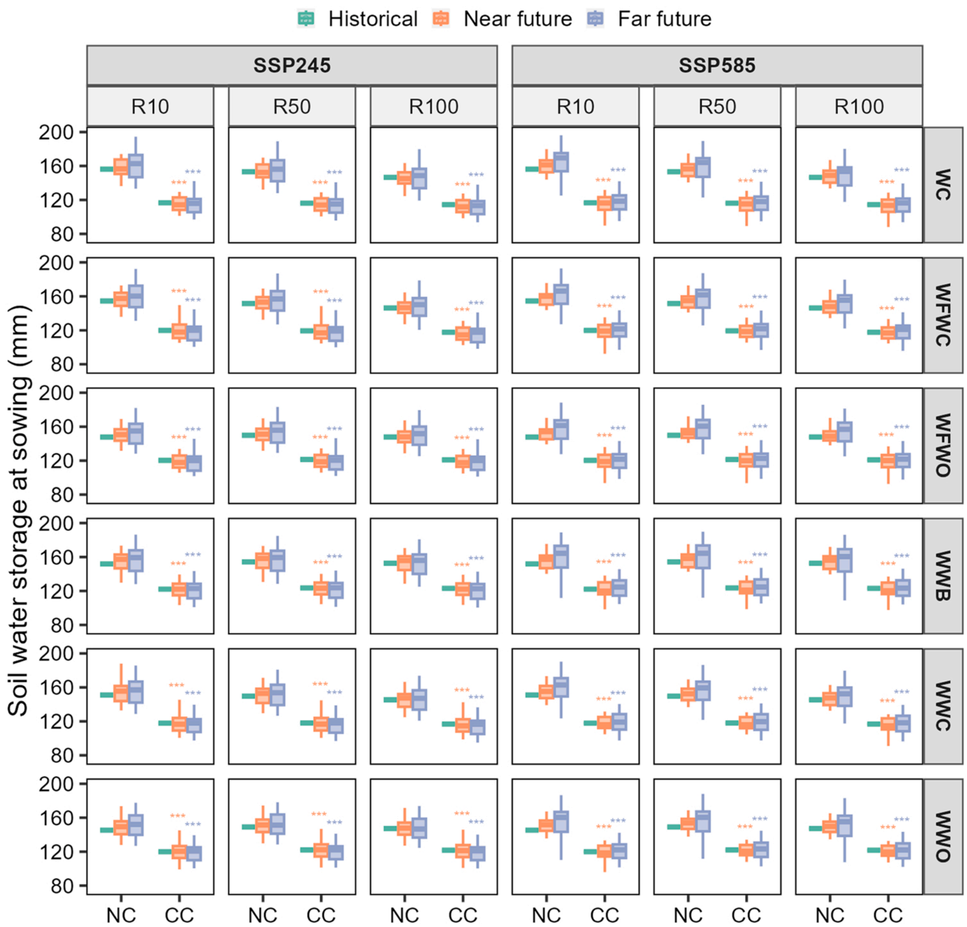

Fig. 3. Simulated soil water storage in the whole profile on the day of sowing the next cash crop with cover crop (CC) and without cover crop (NC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats) during three time periods (historical period: 1985–2020, near future: 2021–2056, and far future: 2057–2092) under SSP245 and SSP585. The boxplots for the historical period and future periods are based on the simulations with observed climate data and 27 GCMs, respectively. Asterisks represent significant differences between CC and NC for each treatment with 27 GCMs using paired t-test (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

and biomass) was also increased by cover crops (9.3–48.3% for wheat, 28.8–61.4% for oats, 15.1–28.5% for barley, and 4.1–34.8% for canola), except for field pea which decreased by 14.7–25.8% across each treatment and scenario (Fig. 6). The positive effects of cover crops on N uptake were greater in the far future compared to historical period, and also were more evident with R10 compared to R100 for most crops.

3.4. Crop yield and gross margin

The inclusion of cover crops increased cereal yields on average by 7.6%, 13.5%, 33.8% (SSP245) and 10.3%, 13.4%, 34.3% (SSP585) for wheat, barley, and oats, respectively across the study region, but had a negative effect on the yields of canola in some rotations and field pea in all rotations (Fig. 7). The positive effects decreased with residue retention for wheat (14.1% to no effect), barley (15.0% to 12.0%), and oats (34.9% to 31.4%) from R10 to R100 on average under SSP245 (Table S2.1). Positive effects of cover crops on cereal yields were more evident in the future compared to the historical period. For example, the average effects of cover crop on wheat, barley and oats increased from 6.8%, 12.0% and 28.4% (historical) to 10.7%, 15.5% and 39.6% (far future) under SSP245, respectively (Table S2.1). Similar trends were found for SSP585. The effects of cover crops on yields varied widely across the region, and were generally negative in the drier western part and positive in the wetter eastern part, as reflected in the gross margins (Fig. S2.9-S2.10). Residue retention also contributed to yield enhancement. Relative to R10, crop yields for R100 increased by 13.3% (SSP245) and 14.1% (SSP585) for without cover crop, and 6.6% (SSP245) and 6.9% (SSP585) with cover crops, respectively (Fig. S2.6).

The inclusion of cover crops decreased the gross margin of most rotations during the historical period, and the negative effect was greater with residue retention but weakened (or became positive) in the future, under climate change (Fig. 8). For example, cover crops reduced the gross margin by − 4.6% (R10) and − 9.1% (R100) on average during the historical period (Table S2.2). In contrast, the effect on gross margin changed from − 4.6% (historical) to + 1.4% (SSP245) and + 7.3% (SSP585) in the far future under R10, and from − 9.1% (historical) to − 8.2% (SSP245) and − 4.5% (SSP585) in the far future under R100 (Table S2.2). Overall, rotations that included canola (e.g., WC, WFWC and WWC) had higher gross margins because of the higher price received for canola relative to cereals, but yields of canola were reduced by sowing cover crops in some rotations (Fig. 7), thus gross margins of these rotations were negatively affected (Fig. 8). In contrast, due to the yield benefits provided by cover crops on cereals, gross margins of WWB and WWO were greater when cover crops were sown (Fig. 8). Importantly, the effects of cover crops on gross margins varied widely across the region, generally increasing with cover crops in the east, especially where residue was removed and rotations were dominated by cereals, but decreasing in the west in all rotations and residue treatments (Fig. S2.9-S2.10).

3.5. Climate effect on cover crop performance

Considering the large variations of rainfall and temperature across the study region, we further investigated the effects of climate variables on cover crop performance. Regression analysis showed that the responses of SOC, N uptake, yield and gross margin to cover crop implementation significantly increased with rainfall, while the reductions of soil water storage at sowing and N leaching from cover crops diminished with increasing rainfall (Fig. 9 and Fig. S2.7). In contrast, the responses of N uptake, yield and gross margin to cover crops were inversely related

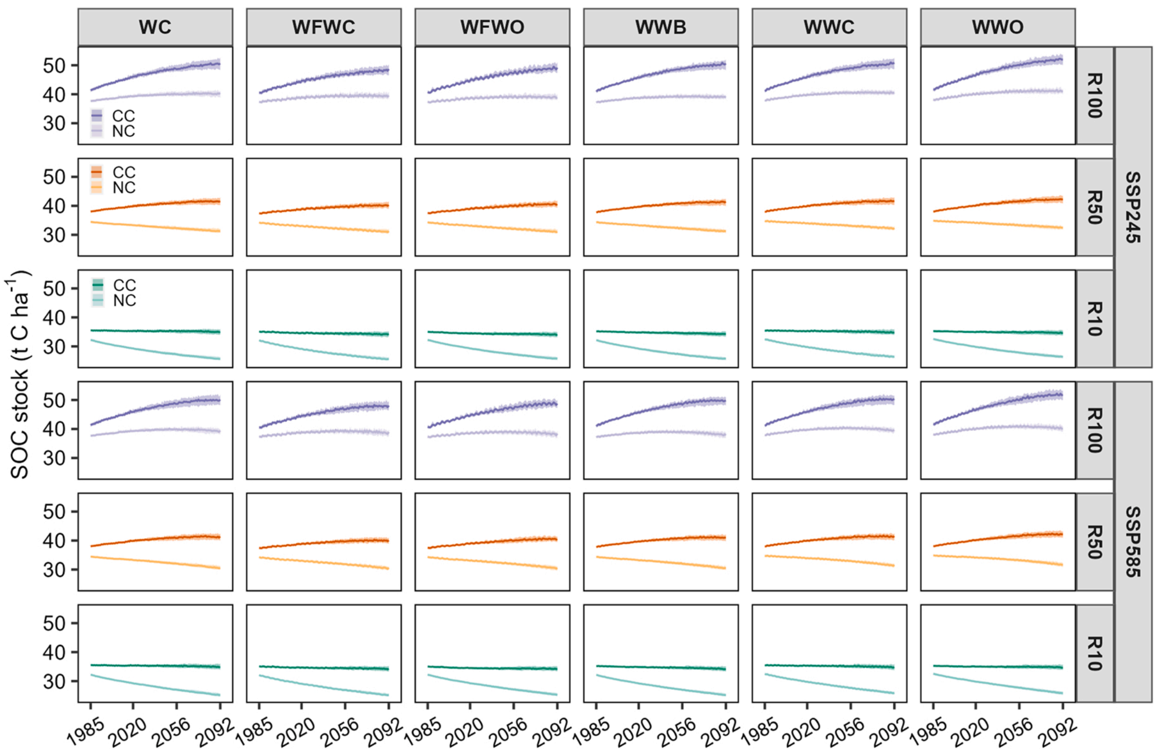

Fig. 4. Simulated annual soil organic carbon (SOC, 0–30 cm) stock from 1985 to 2092 without cover crop (NC) and with cover crop (CC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats) under SSP245 and SSP585. The lines represent the median values, and the shaded areas represent the 10th and 90th percentiles based on APSIM simulations using 27 GCMs.

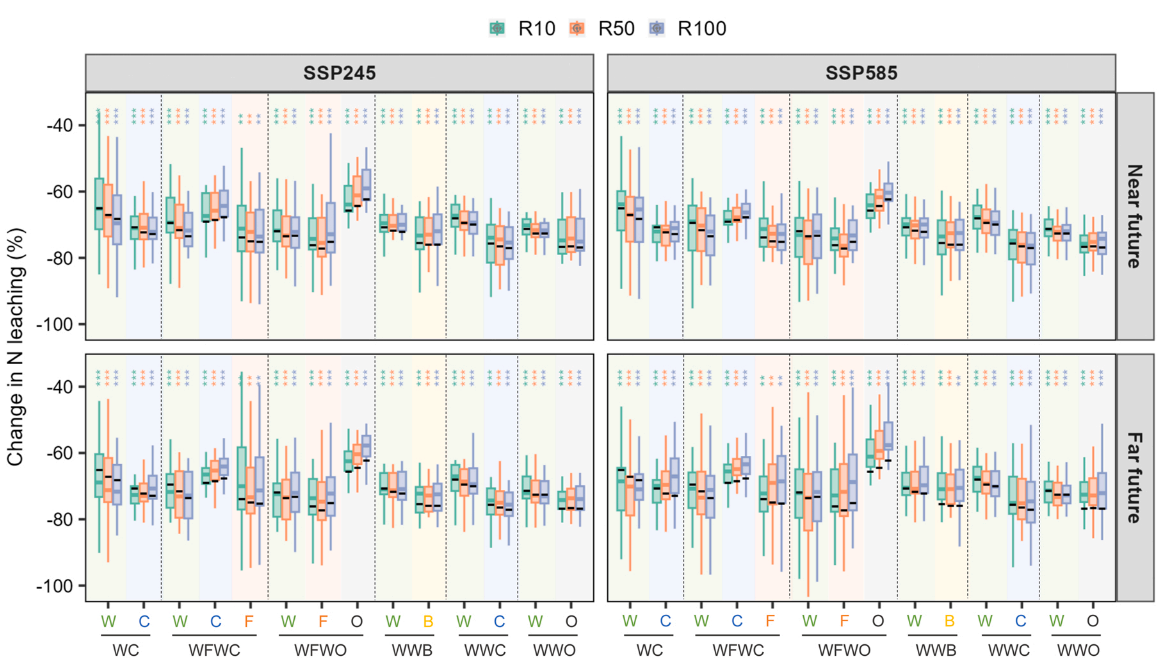

Fig. 5. The change (%) in simulated annual N leaching with cover crop (CC) compared to without cover crop (NC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats). The black dashes represent historical simulations based on observed climate data. The boxplots for two future periods are based on the simulations from 27 GCMs. Asterisks represent significant differences between CC and NC for each treatment with 27 GCMs using paired t-test (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

to temperature, but the reductions in soil water storage at sowing, and N leaching, induced by cover crops were greater with increasing temperature (Fig. 10 and Fig. S2.8).

The changes in gross margin induced by cover crops had closer relationships with both rainfall and temperature, giving the highest R^2 values compared to other variables. The relationships of yield and gross

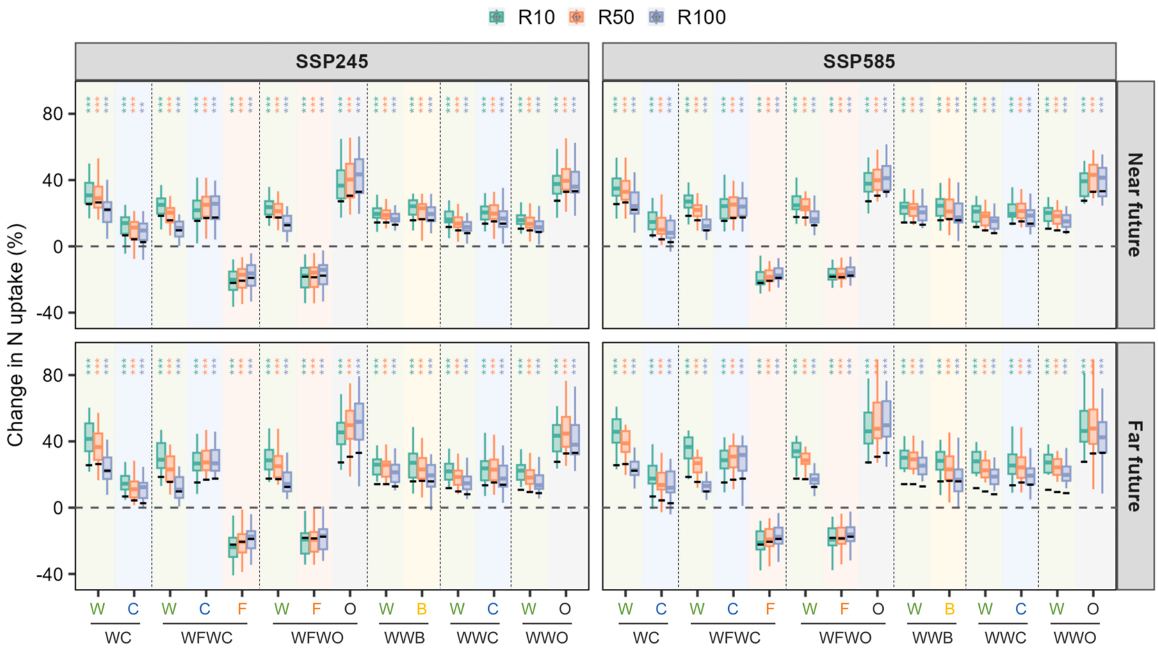

Fig. 6. The change (%) in simulated N uptake by cash crops with cover crop (CC) compared to no cover crop (NC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats). The black dashes represent historical simulations based on observed climate data. The boxplots for two future periods are based on the simulations from 27 GCMs. Asterisks represent significant differences between CC and NC for each treatment with 27 GCMs using paired t-test (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

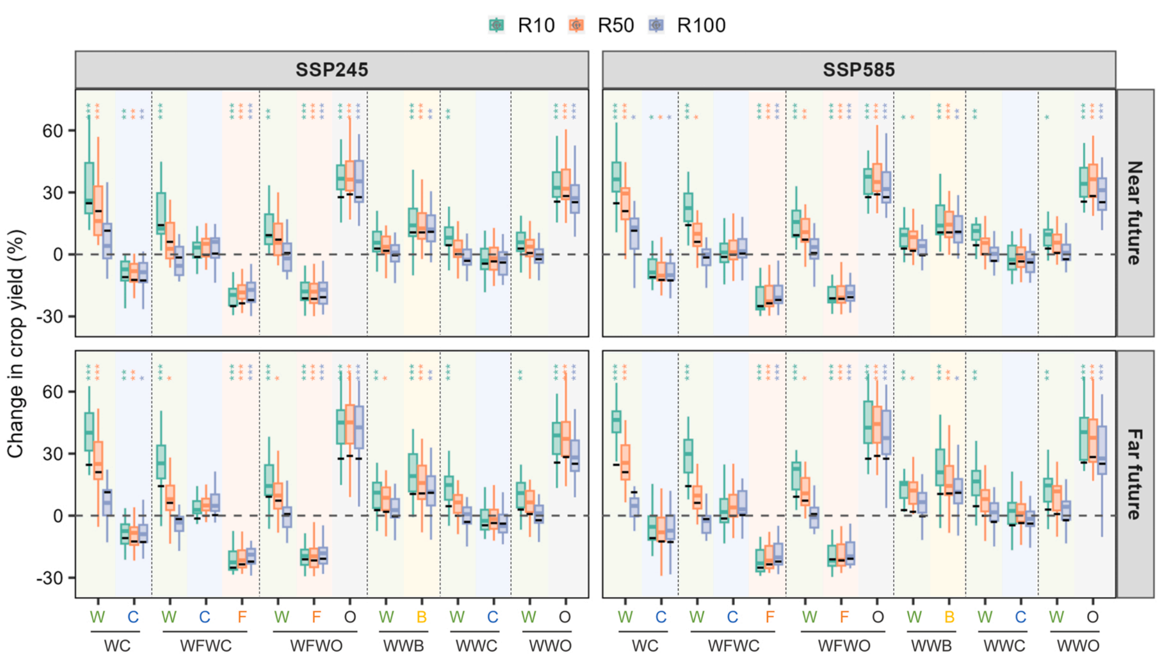

Fig. 7. The change (%) in simulated crop yields with cover crop (CC) compared to without cover crop (NC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats). The black dashes represent historical simulations based on observed climate data. The boxplots for two future periods are based on the simulations from 27 GCMs. Asterisks represent significant differences between CC and NC for each treatment with 27 GCMs using paired t-test (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

margin to rainfall and temperature were stronger under R10 than R100, showing more positive effects of cover crops where there was no residue retained. These responses varied spatially, reflecting the site-specific cover crop effects across the study region. Cover crop effects on gross margin under R10 were negative in the west and positive in the east for all rotations, for example, 47–97% of the interpolating area "dry and warm west" showed negative changes, and 3–53% of "wet and cool east" had positive changes in the far future under SSP245 (Fig. S2.9c). These positive effects were stronger under SSP585 (Fig. S2.10) compared to SSP245 (Fig. S2.9).

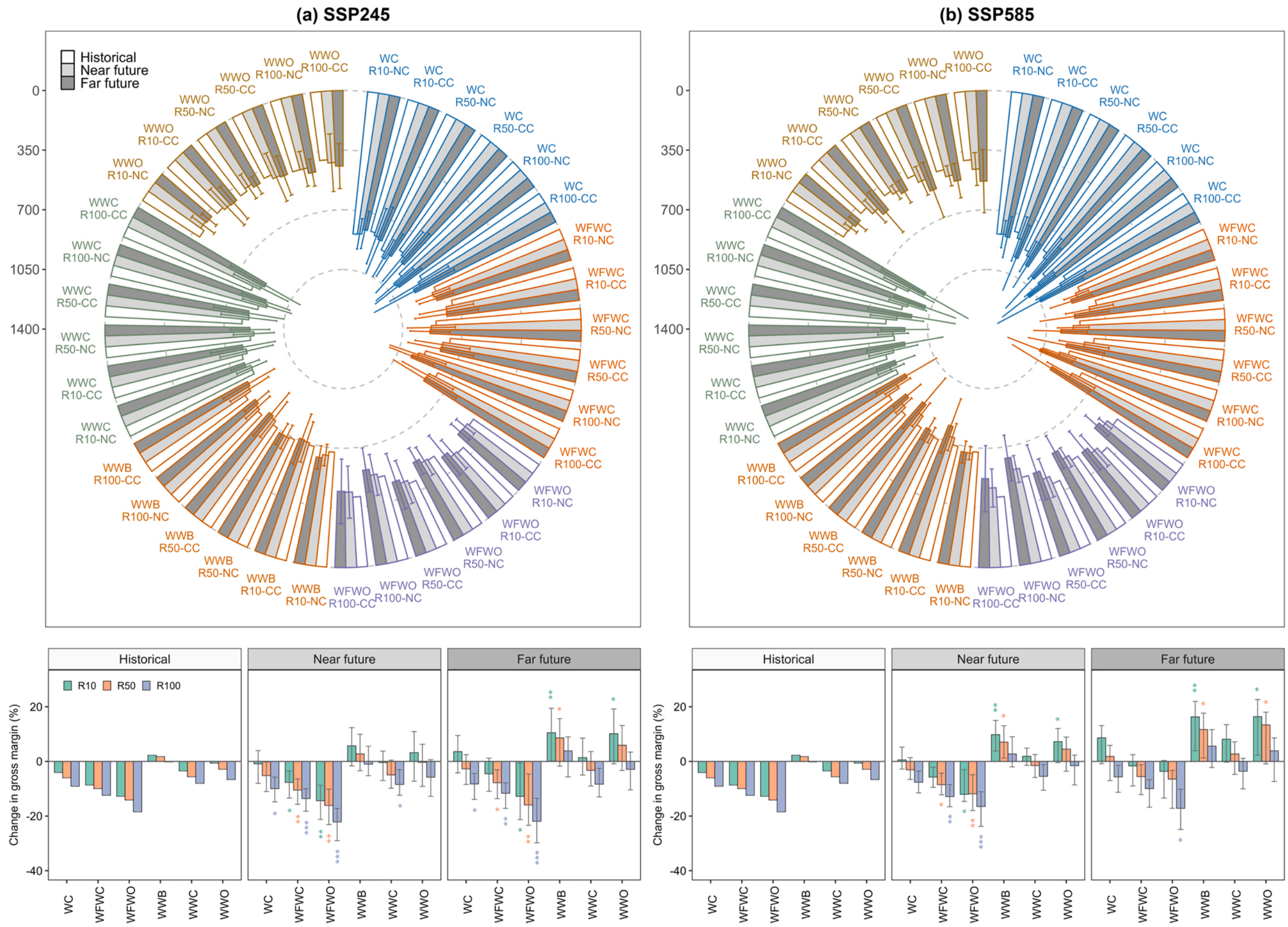

Fig. 8. Median values of gross margin (AUD ha^{-1}) with the 25th and 75th percentiles of simulations based on 27 GCMs under SSP245 (a) and SSP585 (b), and the corresponding change (%) in gross margin with cover crop (CC) compared to without cover crop (NC) for three residue retention (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats). Asterisks represent significant differences between CC and NC for each treatment with 27 GCMs using paired t-test (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

4. Discussion

4.1. *Overview of simulated cover crop effects compared to previous studies*

APSIM has been widely applied to simulate cover crop performance in different cropping systems (Basche et al., 2016; Chatterjee et al., 2020; Martinez-Feria et al., 2016; Teixeira et al., 2021; Wunsch et al., 2017), and is recognized as a useful tool to investigate the long-term effects of management strategies under climate change. In this study, simulated effects of legume cover crops included increased soil organic carbon, increased crop N uptake except for field pea, and reduction in N leaching for the majority of the study region, but also reduced soil water storage at sowing of the subsequent cash crop in all rotation and residue treatments (see Table S3.1 for comparison with literature values). A major concern over the adoption of cover crops is whether the water used by the cover crop reduces subsequent cash crop growth and causes a yield penalty (Garba et al., 2022). Previous studies reported that legume cover crops enhanced yields by 9% across four farming systems in Switzerland (Wittwer et al., 2017), and legume and mixed cover crops were found to increase yields for wheat, barley and oats by 6% in the Nordic countries (Valkama et al., 2015). However, Olin et al. (2015) reported a decline of 5% in simulated yields for wheat and maize after cover crops, while retaining all residues increased yields, at the global scale. Our results showed that the impacts of cover crops on cash crop yields ranged from negative to positive, with large variations across the region, and between residue retention levels as well as crop types (Fig. 7 and Fig. S2.9-S2.10).

4.2. *Effects of long-term implementation of cover crops*

Soil organic carbon is closely linked with soil quality, functionality and health (Lal, 2016). There is a strong consensus that cover crops have significant potential to increase SOC stocks in temperate environments (Blanco-Canqui et al., 2015; Kaye and Quemada, 2017; Poeplau and Don, 2015). For the Australian dryland cropping zone with generally nutrient-depleted soils, SOC sequestration from cover crops is limited by low productivity (McNee et al., 2022). Nevertheless, our simulations revealed small increments but substantial increases in SOC over the long term (Fig. 4), which could be because legume cover crops contributed to both organic matter addition and higher N availability. This is consistent with other reports of improved soil nutrient levels and physical properties over long-term implementation of cover crops (Nouri et al., 2019; Simon et al., 2022). Additionally, due to decreased deep drainage (Fig. S2.1B-S2.2B), cover crops reduced N leaching losses, and consequently increased the N uptake of most cash crops. These positive effects became more obvious over time, especially in the far future (Fig. 6 and Fig. S2.5). The reduction in N leaching and increase in crop N uptake induced by cover crops suggest the potential of cover crops to sustain cash crop growth with lower reliance on synthetic N fertilization (Martinez-Feria et al., 2016; Nouri et al., 2020; Porwollik et al., 2022).

Although soil carbon and nitrogen were increased by cover crops,

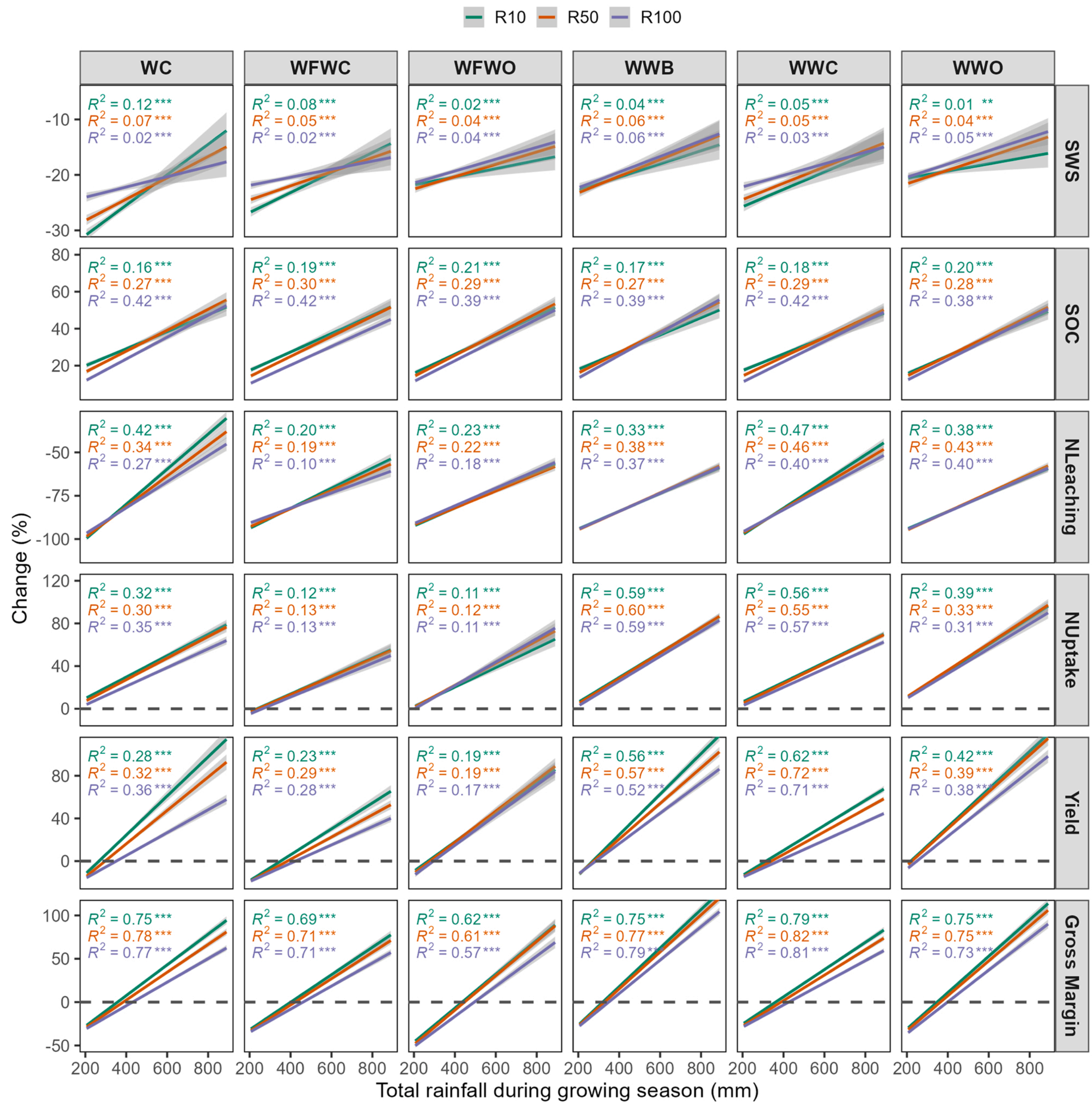

Fig. 9. The relationship between total rainfall during growing season (April to November) and change (%) induced by cover crop (CC) compared to no cover crop (NC) across three residue retention levels (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats) for simulated soil water storage on the day of sowing the next cash crop (SWS), soil organic carbon (SOC), N leaching (NLeaching), crop N uptake (NUptake), crop yield, and gross margin. Median values of changes (as shown in Figs. 3–8) and rainfall projected from 27 GCMs under SSP245 were averaged over three periods (1985–2020, 2021–2056, and 2057–2092). The linear regression with 95% confidence interval used simulations across 204 sites (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

our study found that they also reduced the soil water storage in the whole soil profile at cash crop sowing by 25–51 mm (Fig. 3). However, due to our sowing criterion based on soil moisture (Fig. S1.1), which delayed the sowing date for the cash crops by 14 days on average (Table S3.2), the soil water storage in top 50 cm at sowing was reduced by only 0–14 mm with cover crops (Fig. S2.3). Cash crops mainly use the soil water in topsoil at the early growth stage, so adverse effects of cover crop water use in the whole soil profile can be avoided if autumn rains replenish soil moisture later (Martinez-Feria et al., 2016). Previous studies have found that early termination of cover crops could mitigate yield loss (Krueger et al., 2011; Qin et al., 2021), and 1–2 months duration was suggested for cover cropping in southern Australia (Rose et al., 2022). In our study, the cover crop was terminated 20 days before sowing the succeeding cash crop (as described in Section 2.4) with the aim to minimize adverse effects on cash crop yields, so cover crops were grown for about one month only.

With the short implementation of cover crops, yields of cereals (wheat, barley and oats) were increased in the long run (Fig. 7). Particularly, the larger increase for oats reflects that oats were N-limited in the no-cover crop treatment, due to the low rate of N fertilizer applied in our simulations (based on the local farmer practice). Thus, the legume cover crops boosted the growth of oats (Fig. 7), and led to a large

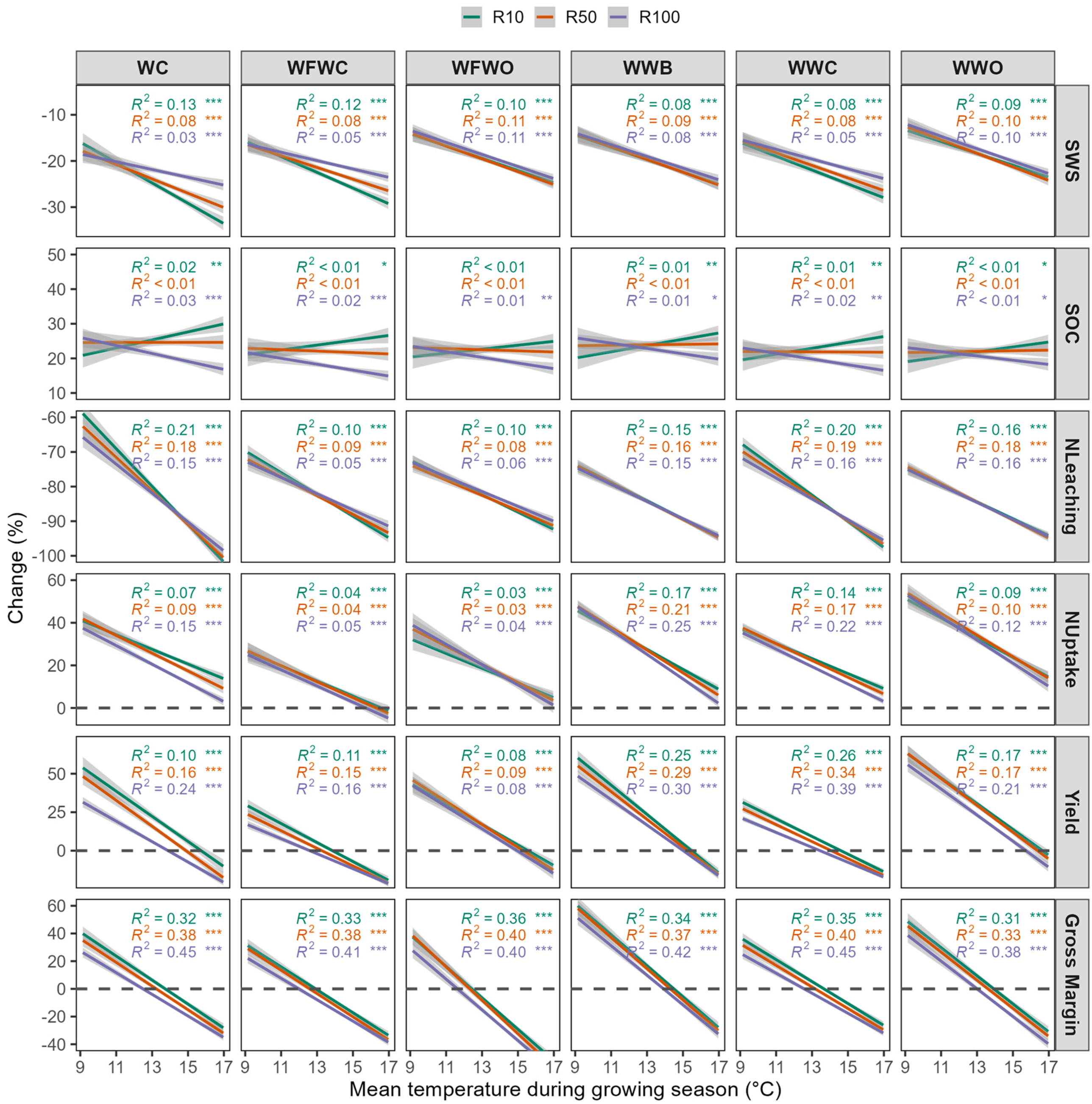

Fig. 10. The relationship between mean temperature during growing season (April to November) and change (%) induced by cover crop (CC) compared to no cover crop (NC) across three residue retention levels (R10: 10%, R50: 50%, and R100: 100%), and six rotations (WC: wheat-canola, WFWC: wheat-field pea-wheat-canola, WFWO: wheat-field pea-wheat-oats, WWB: wheat-wheat-barley, WWC: wheat-wheat-canola, and WWO: wheat-wheat-oats) for simulated soil water storage on the day of sowing the next cash crop (SWS), soil organic carbon (SOC), N leaching (NLeaching), crop N uptake (NUptake), crop yield, and gross margin. Median values of changes (as shown in Figs. 3–8) and temperature projected from 27 GCMs under SSP245 were averaged over three periods (1985–2020, 2021–2056, and 2057–2092). The linear regression with 95% confidence interval used simulations across 204 sites (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$).

increase in N uptake in grains (Fig. S2.5). However, the yields of broadleaf crops (canola and field pea) in most rotations were negatively impacted. A possible reason is that canola is generally more sensitive to water stress than cereals (Dreccer et al., 2018). Canola requires extra energy for oil production compared to the starch production in cereal grains, which is specified by a coefficient for conversion of assimilate to seed mass in APSIM (Robertson et al., 2002). Field pea is able to use biologically fixed N for growth when the N demand cannot be satisfied by mass flow or active uptake from soil, so may be insensitive to the N added by legume cover crops. The nitrogen fixation process requires additional water, and the APSIM model reduces N fixation capacity on the basis of the daily soil water status (Robertson et al., 2002), causing a more likely reduction in growth when water is limited (Alexieva et al., 2001; Couchoud et al., 2020). In addition, broadleaf crops were found to flower earlier than cereals (Liu et al., 2017). APSIM used a constant rate per degree-day to simulate leaf senescence after flowering, so greater soil evaporation caused by earlier leaf senescence occurred for canola and field pea than cereals (Fig. S2.1-S2.2).

Consistently, cover crops increased water use efficiency (WUE) for cereals, with more positive effects in the far future (Fig. S3.1). Increased cereal yield but reduced soil water losses by deep drainage, runoff and evaporation, resulted in the increased WUE for wheat, barley and oats with cover crops compared to no cover crop, as also reported by Wang et al. (2021a). From the perspective of the whole rotation, cover crops decreased gross margins during the historical period but increased gross margins for most rotations in the far future, particularly where residues were removed (Fig. 8). The increased benefit from cover crops probably resulted from the greater N availability for crop growth, and the slow accumulation of soil organic matter which leads to a gradual improvement in soil nutrient and water availability (DeVincentis et al., 2020; Wang et al., 2021b). Note also the large uncertainty in the estimates of gross margin impacts. In many cases, while the average indicates positive effects of cover crop, the large range, from positive to negative values, suggests that there is a substantial risk associated with a choice to adopt cover cropping (Fig. S2.9-S2.10).

4.3. Interaction of cover crop effects with residue retention and climate

Some studies reported that inclusion of cover crops in cropping systems offered an opportunity to counterbalance the negative effects of cash crop residue removal. For example, cover crops can maintain SOC and soil fertility where residues were removed for livestock feed or bioenergy (Klopp and Blanco-Canqui, 2022; Pratt et al., 2014; Ruis et al., 2017). Similarly, we found that positive effects of cover crops on cash crop yields were more evident under residue removal compared to residue retention (Fig. 7), which may be ascribed to the partly compensatory effects of cover crops on residue removal. However, under full residue retention, cover crops had small benefits on yields, which is probably because that legume cover crops produced less biomass than cash crops (during the short growth period of cover crops applied in our modelling), and thus cover crops provided little additional benefit to cash crop yields where residues were retained, as reported in some previous studies (Han et al., 2018; Wang et al., 2019; Xia et al., 2018).

The strong regional variation in cash crop yields in response to growing cover crops indicates that caution is needed in implementing cover crops in low rainfall drylands (Fig. S2.9-S2.10). The impacts of cover crop are climate-driven, and therefore highly variable depending on where the crops are grown (Garba et al., 2022). In this study, cover crops grown during summer were reliant upon stored soil moisture, elevating the risk of depleting soil water reserves for the next cash crops especially in the drier area. Under wetter conditions, water used by cover crops has a greater likelihood of being replenished through rainfall during the growing season, so cash crops were less affected.

The interactions of cover crops with residue retention and climate are complex and dynamic. Our results showed that cover crops were more beneficial to yields and gross margins under future climate change (Figs. 7–8). This may be attributed to the elevated CO_2 concentration in the future which led to greater plant biomass production (Fig. S3.2) and increased organic matter input to soil, as also reported in some previous modeling studies (Banger et al., 2015; Huang et al., 2020; Tian et al., 2015). Moreover, residues of legume crops, with a lower carbon and nitrogen ratio, are decomposed faster than residues of other crops in APSIM, so provide a greater boost to soil nutrient levels. The stimulation of cover crops due to elevated CO_2 synergistically benefited cereal yields, with more positive changes under SSP585 compared to SSP245 (Table S2.1). Therefore, our results imply that inclusion of cover crops during the fallow period could contribute to building a climate-resilient agricultural system under certain climate conditions, but further work is necessary to examine the causes of yield declines in canola and field pea, and to clearly define the rainfall thresholds above which cover crops are likely to be profitable.

4.4. Limitations and implications

Our simulations captured the water, carbon and nitrogen dynamics under cowpea cover crops (or fallow) in rotations and the subsequent wheat, barley, oats, canola and field pea crops. One weakness of the biophysical simulations is that impacts of cover crops on weeds, pests, and diseases are not accounted for in the APSIM model. We also did not consider the option of reducing synthetic N fertilizer inputs after adopting cover crops. Farmers utilizing cover crops could potentially reduce insecticide and fertilizer inputs without yield penalty (Bowers et al., 2020; DeVincentis et al., 2020; Nouri et al., 2020). Thus, gross margins under cover cropping in this study may be underestimated. Furthermore, agricultural prices and management costs are likely to change with market demands in the future, which may shift the relative profitability between systems with or without cover crops. We also found that simulations had greater variation in the far future, because the variability of climate data from 27 different GCMs increased progressively into the future, as shown in Fig. 1b-c. Uncertainties in climate change impact projections, which increase with rising atmospheric CO_2 concentration and associated warming, could be reduced by further improving CO_2 and temperature relationships in models (Asseng et al., 2013).

The expected impacts at the cropping system level due to including cover crops vary depending on cash crop types, residue retention levels, and local climate conditions. In general, our simulations indicated that a reduction in soil water storage at sowing can lead to reduced plant growth and crop yields where water is limiting. For example, most crop yields with R100 were reduced by cover crops where total rainfall during the growing season is lower than around 400 mm (Fig. 9 and Fig. S2.7). The increase in soil organic carbon and N availability induced by cover crops can result in increased crop yields in the longer term, associated with improved soil fertility. However, it is important to note that cover crop management practices can also have a significant impact on the overall outcomes. For example, some studies have shown that effects on cash crop yields varied with cover crop types (Alvarez et al., 2017), planting and terminating time of cover crops (Qin et al., 2021), and soil texture (Wang et al., 2021a). The present study used a summer legume, cowpea, as a cover crop, because it could be adequately established during the dry and hot summers in southern Australia (McNee et al., 2022), and is adapted to a wide range of soils. Other species of cover crops may be more suitable to specific soil types, providing potentially greater benefits than demonstrated here. Thus, further investigation of alternative species and site-specific management may lead to greater advantages from cover crops.

Based on simulated outputs under the different scenarios considered in this study, we found that incorporating cover crops into conventional rotations could enhance sustainability and profitability of cereal-dominated rotations in higher rainfall regions, particularly under climate change. However, cereal dominated rotations are less likely to be grown in higher rainfall areas because rotations that include canola are more profitable in the study region, and growing canola in rotations can reduce disease incidence for cereal crops (Angus et al., 1991). Nevertheless, results of this study suggest that there may be potential for the adoption of cover crops to sustain yields in cereal crops, and to allow partial removal of crop residues for bioenergy or livestock feed. Further studies that consider other combination of practices (e.g., fertilizer optimization, biochar, and intercropping) are needed to identify management that sustain crop yields in dryland cropping systems under climate extremes or climate change (Nouri et al., 2021; Su et al., 2021).

5. Conclusion

This modelling study, that presents temporal and spatial quantification of the impacts of a cowpea cover crop combined with residue management for six rotation systems, has identified important insights for the adoption of cover crops in southeast Australia. First, cover crops decreased soil moisture, but enabled greater SOC sequestration and reduced N loss through leaching. Second, declines in crop N uptake and yield induced by cover crops were found for field pea, but for wheat, barley and oats, the crop N uptake and yield generally increased. Third, benefits from cover crops on yield and gross margin increased with higher rainfall and lower temperature, thus cover crops were profitable in the east but not in the west of the study region. Finally, cover crop effects on yield were more positive under residue removal and future climate change. The long-term implementation of cover crops has the potential to improve current crop rotations and sustain crop productivity with reduced environmental impacts only under wetter conditions in Australian dryland cropping. Further work is required to clearly define the rainfall thresholds above which cover crops are profitable, and to optimize site-specific management for cover crop adoption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108536.

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