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A food-energy-water-carbon nexus framework informs region-specific optimal strategies for agricultural sustainability

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ABSTRACT

Agricultural sustainability is threatened by pressures from water scarcity, energy crises, escalating greenhouse gas (GHG) emissions, and diminishing farm profitability. Practices that diversify crop rotations, retain crop residues, and incorporate cover crops have been widely studied for their impacts on soil organic carbon and crop production. However, their associated usage of natural resources and economic returns have been overlooked. Here, we employed a food-energy-water-carbon (FEWC) nexus framework to assess the sustainability of crop rotations plus various management strategies across three sub-regions of New South Wales (NSW) in Australia. We found that compared with residue burning and fallowing, residue retention and cover cropping contributed to GHG abatement, but the latter consumed more energy and water per hectare. The composite sustainability scores, calculated with the FEWC framework, suggested that legume-inclusive rotations were generally more sustainable. Furthermore, in northern NSW (with existing sorghum/wheat/chickpea/wheat rotation), residue retention with cover cropping was most suitable combination, while the use of residue retention with fallow yielded greater benefits in southern NSW (with existing wheat/field pea/wheat/canola rotation). Regional disparities in climate, soil, cropping systems, and on-farm costs prompted region-specific strategies to address the unbalanced distribution among FEWC domains. Our study provides assessments for identifying feasible management practices to advance agricultural sustainability.

1. Introduction

1.1. Background

Meeting the mounting demands for nutritious food, amidst a growing population, degrading soil, and changing climate, poses an unprecedented challenge for global food systems (Xie et al., 2023). Yet the promotion of input-intensive agriculture to boost crop growth has led to serious compromises for natural resources and environment (Gu et al., 2023; Pellegrini and Fernández, 2018). Major threats, such as water

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scarcity, energy crisis, global warming, and their likely linked social, economic and political consequences, underscore the need to shift towards more sustainable agriculture (Chaudhary et al., 2018; Gustafson et al., 2021). The United Nations, therefore, explicitly included sustainable agriculture as one of the Sustainable Development Goals (SDGs) in 2015, especially as SDG 2.4.1: "*Proportion of agricultural area under productive and sustainable agriculture practices*". Moving forward, although the SDGs are globally applicable, their achievement requires specific measures customized to local conditions (Chaudhary et al., 2018).

Notwithstanding the fact that effects of climate cannot be influenced by landholders, long-term sustainability can be shaped by management and land stewardship (Muleke et al., 2022). Sustainable intensification (SI) has been proposed as a framework focusing on increasing yields with fewer inputs and without cropland expansion (Muleke et al., 2023; Pretty, 2008); climate-smart agriculture (CSA) is often put forward as an integrated approach for securing productivity under climate change and curbing greenhouse gas (GHG) emissions (Lipper et al., 2014). Both concepts are closely linked, and are aligned with conservation agriculture (CA) – an operational strategy that aims to sustain crop production while also building the health of the agroecosystem (Hobbs, 2007; Prestele et al., 2018). Practices applied under CA include zero or reduced tillage (Nouri et al., 2021), crop rotation (Gao et al., 2022; Hochman et al., 2021), residue return (Liu et al., 2023), cover crops (Quemada et al., 2020), biochar application (Huang et al., 2023), and nitrogen management (Parihar et al., 2022). Adoption of CA to improve sustainability of crop production has implications for water (SDG 6), energy (SDG 7) and climate change (SDG 13), due to the deep interconnections between these domains. Specifically, water is essential for plant growth and must be supplied through rainfall or irrigation; energy is required in the whole process of crop production including mechanical operations, fertilization and irrigation (Pellegrini and Fernández, 2018); and crop products can be converted into energy resources (Xing et al., 2022). Meanwhile, all these processes are associated with GHG emissions (Sándor et al., 2020; Zou et al., 2022). Few studies, however, have undertaken holistic assessment of the impacts of CA practices on food, energy, water and GHG emissions on a regional scale to provide comprehensive solutions to inform landscape-scale resource management. Indeed, transdisciplinary work focusing on systems has shown that prospective adaptations differ much when multiple objectives are factored in (Bilotto et al., 2023).

The nexus approach has been developed to address cross-sectoral integration for simultaneously achieving multiple SDGs (Liu et al., 2018). Recent applications in the natural resource realm have explored the food-energy-water nexus with the addition of issues like GHG emissions in the context of carbon neutrality (He et al., 2022a; Saray et al., 2022; Yadav et al., 2021; Yoon et al., 2022; Zhu et al., 2023). The focus of these studies is on simple cropping systems. Comparatively, nexus research on multiple rotational systems with various management practices lags behind. Moreover, heterogeneity in environmental conditions and economic considerations have seldom been taken into account, despite calls to tailor management strategies based on region-specific context (Amelung et al., 2020; Prestele and Verburg, 2020).

1.2. Goal and scope

Australia holds a prominent position on the global stage as a major exporter of agricultural products, but its production systems are associated with high levels of GHG emissions, water extractions and habitat loss (Hatfield-Dodds et al., 2015). There is an increasing interest in CA practices due to industry and government policies aimed at motivating Australia's farmers to improve sustainability (ABARES, 2023a). Australia is one of the world leaders in the adoption of zero/reduced tillage (ABARES, 2023b), and efforts are being made to promote residue return, diversifying crop rotations, and incorporating cover crops for soil carbon sequestration to support the national net-zero GHG emissions target for 2050 (Feron et al., 2022). Furthermore, adoption of CA practices will support climate change adaptation, which is particularly crucial as Australian agriculture is uniquely vulnerable to climate change (Phelan et al., 2015; Wood et al., 2021). Reaping the win-win between sustained crop yields and emission abatement where and when possible using CA practices is laudable (He et al., 2022b). However, water and energy consumption are also influenced by these practices, but often tend to be overlooked (Li et al., 2019; Zhang et al., 2022). Here, our aim is to fill gaps in the research linking economics (i.e., crop production and farm income), environment (i.e., GHG emissions), and resource use (i.e., energy and water) in Australian cropping systems.

In this study, we defined sustainable farming systems from a food-energy-water-carbon nexus perspective as a system that allows for minimal resource consumption and environmental costs while maintaining food production and ensuring adequate income. We seek to investigate the following three questions: (1) How do food production and profitability, energy, water and carbon footprints change under different management practices? (2) How sustainable are these farming systems based on a composite food-energy-water-carbon index? (3) What are the differences in sustainability performance across different sub-regions? To answer the above questions, a footprint method based on a set of data from relevant literature was developed to evaluate the energy footprint (EF), water footprint (WF) and carbon footprint (CF) from the production of crops in different rotations under multiple scenarios. To accurately reflect the footprint dynamics, a biophysical process-based model called APSIM, was used to provide data related to crop growth and soil processes. We aimed to examine farming practices based on local realities and provide a preliminary evaluation to support decision-makers to manage cropland in a more sustainable way.

2. Materials and methods

2.1. Study area

The study area is located in the state of New South Wales (NSW) in south-eastern Australia, covering three adjacent Local Land Services (LLS) regions: North West, Central West, and Riverina (Fig. 1). LLS is a regional-focused NSW Government agency, which aims to deliver quality customer services for agricultural production and natural resource management relevant to local needs (https://www.lls.nsw.gov.au/). These three LLS regions were selected as they are main NSW cropping zones, and provide a profile of diverse agricultural operations (Wang et al., 2022a). The pattern of rainfall shifts from summer-dominant rainfall in the north to more even rainfall distribution in the south, and transitions from high rainfall in the east to low rainfall in the west (Table B.1). Agriculture is an important enterprise in these three LLS regions, with cropping systems occupying 26 %, 23 %, and 50 % of the land area for North West, Central West, and Riverina, respectively (NSW, 2018). These LLS regions accounted for about half of NSW total gross value of agricultural production (DPI, 2020), making it an important area for the study of suitable crop management options in the context of sustainable agriculture.

2.2. Scenarios

From discussions with farmer groups and research staff, several crop rotations reflecting local farming practices were selected for the three regions, in which winter cereals (wheat, barley, and oats) were rotated with summer cereal (sorghum), and/or oilseed crop (canola), and/or pulse crops (chickpea and field pea) (Table 1). These rotations are representative of the cropping sequences used in each region. For each rotation, the following four scenarios were modelled to investigate the effects of residue retention and cover cropping on farming systems:

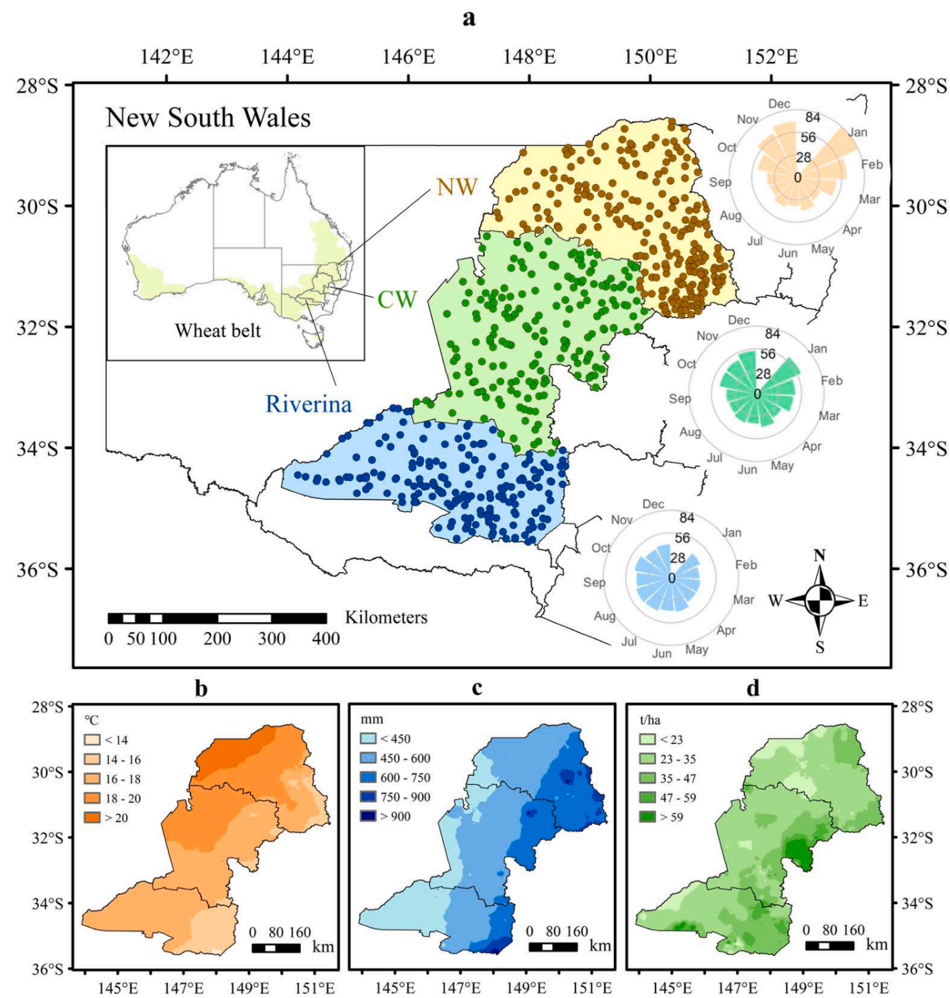

Fig. 1. **(a)** Locations of three regions and the study sites of each region; **(b-c)** annual mean temperature and rainfall during 1961–2020; **(d)** initial soil organic carbon stock in topsoil 0–30 cm before scenario set in the APSIM model. The monthly average rainfall of each region is shown as radial charts in **(a)**.

Table 1
Crop rotations selected for each region.

Region	Rotation	Year1	Year2	Year3	Year4	Year5
North West	WWB	Wheat	Wheat	Barley	…[a]	…
	SWW	Sorghum	#[b]	Wheat	Wheat	…
	SWKW	Sorghum	#	Wheat	Chickpea	Wheat
Central West	WWB	Wheat	Wheat	Barley	…	…
	WWO	Wheat	Wheat	Oats	…	…
	WC	Wheat	Canola	Wheat	Canola	…
	WWC	Wheat	Wheat	Canola	…	…
	WFWC	Wheat	Field pea	Wheat	Canola	…
	WKWC	Wheat	Chickpea	Wheat	Canola	…
Riverina	WWB	Wheat	Wheat	Barley	…	…
	WWO	Wheat	Wheat	Oats	…	…
	WC	Wheat	Canola	Wheat	Canola	…
	WWC	Wheat	Wheat	Canola	…	…
	WFWC	Wheat	Field pea	Wheat	Canola	…
	WFWO	Wheat	Field pea	Wheat	Oats	…

[a] Start of subsequent rotation cycle same as the first.
[b] In the North West, no crop is sown in the first year after sorghum because soil moisture is depleted, and growing season rainfall may be insufficient to sustain winter crops (Serafin et al., 2019).

1. ResBurnFallow – cash crop residues were burnt after harvest, followed by a fallow period before the sowing of cash crop in the next year.
2. ResBurnCowpea – cash crop residues were burnt after harvest, followed by a cowpea cover crop before the sowing of cash crop in the next year.
3. ResRetainFallow – cash crop residues were fully retained in field, followed by a fallow period before the sowing of cash crop in the next year.
4. ResRetainCowpea – cash crop residues were fully retained in field, followed by a cowpea cover crop before the sowing of cash crop in the next year.

Therefore, a total of 245 (sites) × 3 (rotations) × 4 (scenarios) = 2940 cases for North West, 199 × 6 × 4 = 4776 cases for Central West, and 204 × 6 × 4 = 4896 cases for Riverina, were investigated from 1961 to 2020 using annual climate data at each site in this study.

2.3. Evaluation indicators

The evaluation framework is shown in Fig. 2. Site-level carbon footprint, energy footprint, water footprint, and economic value of each scenario were calculated. Considering the uneven spatial distribution of sites, all average values of each region were calculated by inverse distance weighted average method. Specific APSIM modeling processes are presented in Supplemental Appendix A.

2.3.1. Carbon footprint

The GHG emissions associated with tractor use for on-farm opera-

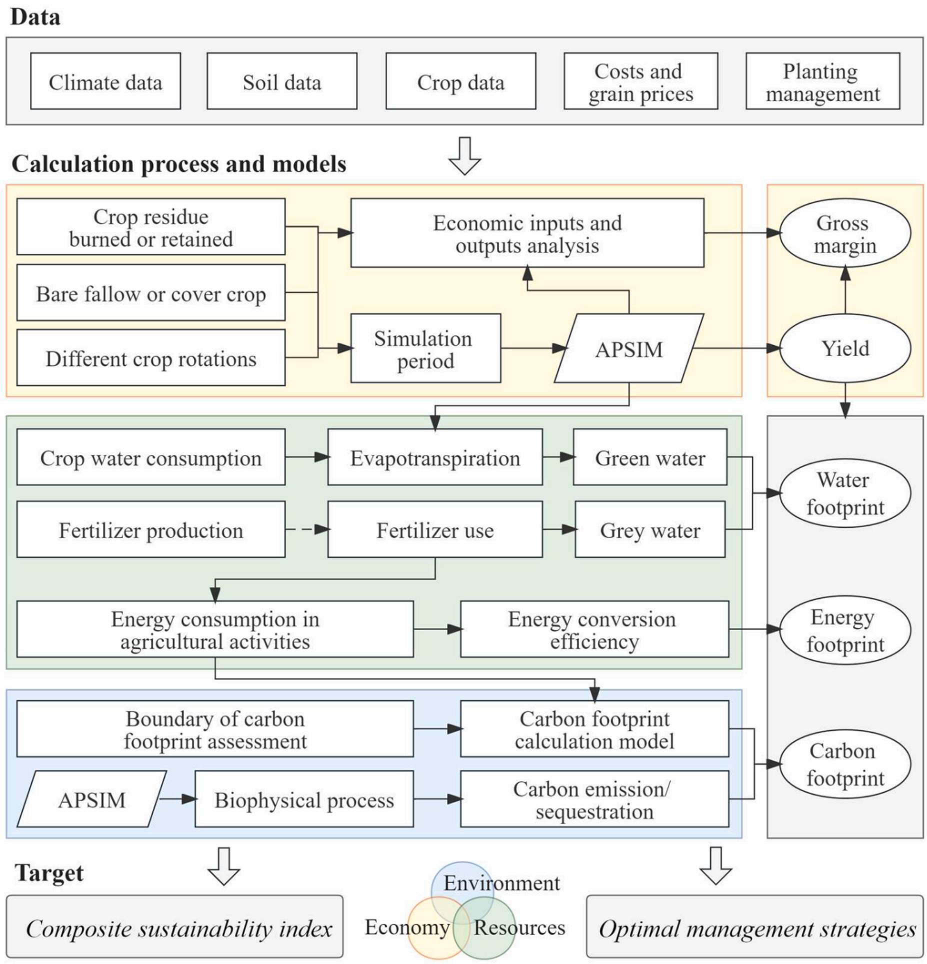

Fig. 2. Framework for sustainability evaluation based on resource consumption, environmental impact, and food economic benefit.

tions were calculated using data and assumptions from (Simmons et al., 2020; 2019). Emissions from diesel used for sowing, spraying, spreading, tilling, harvesting and grain collection were calculated by multiplying fuels use by the relevant emission factors. Lime was applied once every 10 years, so its emission was averaged over a 10-year period. Where GHG emissions were dependent on dynamic biophysical processes, the outputs from APSIM were used. For example, we used the amount of N leaching simulated by APSIM multiplied with the emission factor from NIR (2020) to estimate N_2O emission from N leaching, as described in our earlier work (He et al., 2022b). In addition, the annual SOC changes simulated from APSIM can be positive or negative, which indicate that the soil is a net sink or source of atmospheric CO_2, respectively. The details of emission calculations are shown in Fig. B.1. Finally, total GHG emissions were estimated by converting specific emissions of CO_2, N_2O, and CH_4 to CO_2-eq by multiplying the estimated values with their respective 100-year global warming potential (GWP) factors (IPCC, 2014):

$$GHG = 265\ \times \left[N_2O\right] + 28\ \times [CH_4] + 1\ \times\ [CO_2] - \frac{44}{12} \times\ \Delta SOC_{d30} \tag{1}$$

where $[N_2O]$, $[CH_4]$ and $[CO_2]$ represent the amounts of flux in kg mass ha^{-1} yr^{-1}; ΔSOC_{d30} is SOC change in 30 cm topsoil (kg C ha^{-1} yr^{-1}); -44/12 is the factor to convert the ΔSOC_{d30} to CO_2 emissions (kg CO_2-eq ha^{-1} yr^{-1}). The GWP conversion factors for CO_2, N_2O and CH_4 are 1, 265 and 28, respectively.

The carbon footprint (CF) was estimated based on the boundary established at the field level. Upstream emissions such as emissions from fertilizer manufacture, are excluded as the focus of the study was on-farm emissions. Calculations of the CF for various rotation systems were made based on the annual emissions and corresponding crop yields, which were used to evaluate the GHG emitted per unit of grain produced (Yadav et al., 2021):

$$CF_j = \frac{\sum_{i=1}^{n} GHG_{i,j}}{Yield_j} \tag{2}$$

where $GHG_{i,j}$ $(i = 1,\ 2, \ldots,\ 10)$ represent the total GHG emissions (kg CO_2-eq ha^{-1} yr^{-1}) from different agricultural activities and biophysical processes of the year j (Table B.2); $Yield_j$ $(j = 1,\ 2,\ \ldots,\ 60)$ is the crop yield in t ha^{-1} from 1961 to 2020.

2.3.2. Energy footprint

The material input in the above-mentioned crop production process is not only accompanied by GHG emissions, but also energy inputs (He et al., 2022a). These energy inputs were computed by multiplying the quantity of inputs with their respective energy equivalent coefficients, as reported in several studies (Table B.2-B.3). Then, the energy footprint (EF) was calculated as follows (Jiang et al., 2022):

$$EF_j = \frac{\sum_{i=1}^{n} EI_{i,j}}{Yield_j} \tag{3}$$

where $EI_{i,j}$ $(i = 1,\ 2, \ldots,\ 9)$ are the energy inputs (MJ ha^{-1} yr^{-1}) for crop seeds, nitrogen fertilizer and lime application, and diesel used for sowing, spraying, spreading, tilling, harvesting and grain collection of the year j.

2.3.3. Water footprint

The water footprint (WF) introduced by Hoekstra et al. (2011) is expressed as the water consumption (green and blue water) and the degree of pollution (grey water) per unit of product. In the case of rain-fed crops, blue water use is zero, and green water use is calculated by summing the daily values of actual evapotranspiration (ET) over the length of the growing period (Mekonnen and Hoekstra, 2011). Because the cover crop consumed water during the fallow period, the ET of cover crop and soil evaporation (E) of fallow were also considered for the comparison between scenarios. Therefore, the water consumption of the whole year was taken into the WF calculation:

$$WF_j = WF_{Green,j} + WF_{Grey,j} \tag{4}$$

$$WF_{Green,j} = \frac{10 \times \sum_{i=1}^{n} ET_{i,j}}{Yield_j} \tag{5}$$

$$WF_{Grey,j} = \frac{(\alpha \times AR_j)/(C_{max} - C_{nat})}{Yield_j} \tag{6}$$

where $ET_{i,j}$ $(i = 1, 2, 3)$ are the water used by cash crop, cover crop, and fallow (mm, modelled by APSIM), 10 is the factor that converts water depth (mm) into water volume per unit area (m^3 ha^{-1}); α is the percentage of nitrogen fertilizer lost through leaching, and AR_j is the application rate of nitrogen fertilizer of the year j. We used the nitrogen leaching modelled by APSIM instead of a constant ratio to represent the dynamic nitrogen loss in this study. C_{max} is the allowable maximum level of nitrogen in fresh water, following the standard of 10 mg L^{-1} of nitrate-nitrogen in Australia (https://www.dcceew.gov.au/environment/); C_{nat} is the natural level of nitrogen in water bodies, which was assumed to be zero in Australia (Hossain et al., 2021).

2.3.4. Gross margin

The economic analysis was performed by multiplying the crop price by its yield, less the variable costs associated with growing the crop, to give a gross margin (GM), which can be used to represent the profitability of food production. Input costs and grain prices were obtained from NSW Department of Primary Industries across the three regions (Table B.4). The calculation was similar to He et al. (2023):

$$GM_j = \left(GI_j - \sum_{i=1}^{n} CO_{i,j}\right) \times (1 - L) \tag{7}$$

where GI_j is the grain income (AU$ t^{-1}) of the year j; $CO_{i,j}$ $(i = 1, 2, \ldots, 6)$ are the costs for cultivation, sowing, pest control, harvest, tilling, and fertilizer; additional cowpea costs are also considered under cover cropping scenarios; and L is the government levy that funds research and development, assumed to be 1.02%.

2.4. Agricultural sustainability assessment framework

To assess the four domains – food production profitability (that is gross margin in this study), energy footprint, water footprint, and carbon footprint – hereafter referred as food-energy-water-carbon (FEWC), we computed a composite sustainability index based on the FEWC nexus framework as developed in recent studies (Hua et al., 2020; Jiang et al., 2022; Nhamo et al., 2020; Simpson et al., 2022), following steps below:

(1) Normalization. For the comparison between these indicators measured in different units, their values were first normalized to transform them into a uniform scale from 0 to 100. Because a lower value of footprint is better, but a higher value of gross margin is more favorable, two min-max methods were utilized for the normalization of footprint and profitability indicators, respectively:

$$S_{EWC} = \frac{S_{max} - S_i}{S_{max} - S_{min}} \tag{8}$$

$$S_F = \frac{S_i - S_{min}}{S_{max} - S_{min}} \tag{9}$$

where S_{EWC} and S_F are the normalized values of energy, water, carbon, and food, respectively. S_{max} and S_{min} are the maximum and minimum values of each indicator. Thus, the higher values of S represent higher sustainability.

(1) Aggregation. The sustainability score was then calculated using the arithmetic average of the four normalized indicators. Equal weighting was used such that each domains has equal importance:

$$S_{FEWC} = (S_F + S_E + S_W + S_C)/4 \tag{10}$$

where S_{FEWC} is the composite sustainability index ranged from 0 to 100.

(1) Evenness. Given that uneven FEWC indicators may lead to the same composite sustainability value, an improved radar chart method (from polygon to sector radar) was used to assess the evenness score from the four normalized indicators (Eqs. 8 and 9) following Liu et al. (2020):

$$ES = \frac{A_i}{\pi \times (L_i/2\pi)^2} \times 100 \tag{11}$$

$$A_i = \sum_{i=1}^{n} \pi w_i r_i^2 \tag{12}$$

$$L_i = 2(r_{i,max} - r_{i,min}) + \sum_{i=1}^{n} 2\pi w_i r_i \tag{13}$$

where ES is the evenness score, which refers to the ratio between the total area A_i $(i = 1, 2, 3, 4)$ of the radar chart formed by four indicators and the area of a circle with the same perimeter L_i (the evenest distribution of the four indicators). ES ranges from 0 to 100, and decreases as unevenness among four indicators increases. w_i represents the weight, and is 1/4 for each indicator in this study. r_i represents the value of each indicator which was used as the radius. The doubled value of the difference between r_{max} and r_{min} represents the part of the perimeter other than the total length of all arcs formed by $2\pi w_i r_i$, as detailed described in Wang et al. (2022b).

3. Results

3.1. GHG emissions and energy & water consumption per unit area

For all three regions, only ResRetainCowpea achieved negative emissions of 199–487 kg CO_2-eq ha^{-1} yr^{-1} (North West), 232–367 kg CO_2-eq ha^{-1} yr^{-1} (Central West), and 180–296 kg CO_2-eq ha^{-1} yr^{-1} (Riverina) across various rotations, in which the increases in SOC offset the emissions mainly from N_2O and liming (Fig. 3a, d, g). This contrasted with the scenario of ResBurnFallow where residues were burnt, emitting a large amount of non-CO_2 GHG (N_2O and CH_4), and SOC decreased substantially, leading to total emissions of 836–966 CO_2-eq ha^{-1} yr^{-1} (North West), 905–982 CO_2-eq ha^{-1} yr^{-1} (Central West), and 848–919 CO_2-eq ha^{-1} yr^{-1} (Riverina) across various rotations. Additionally,

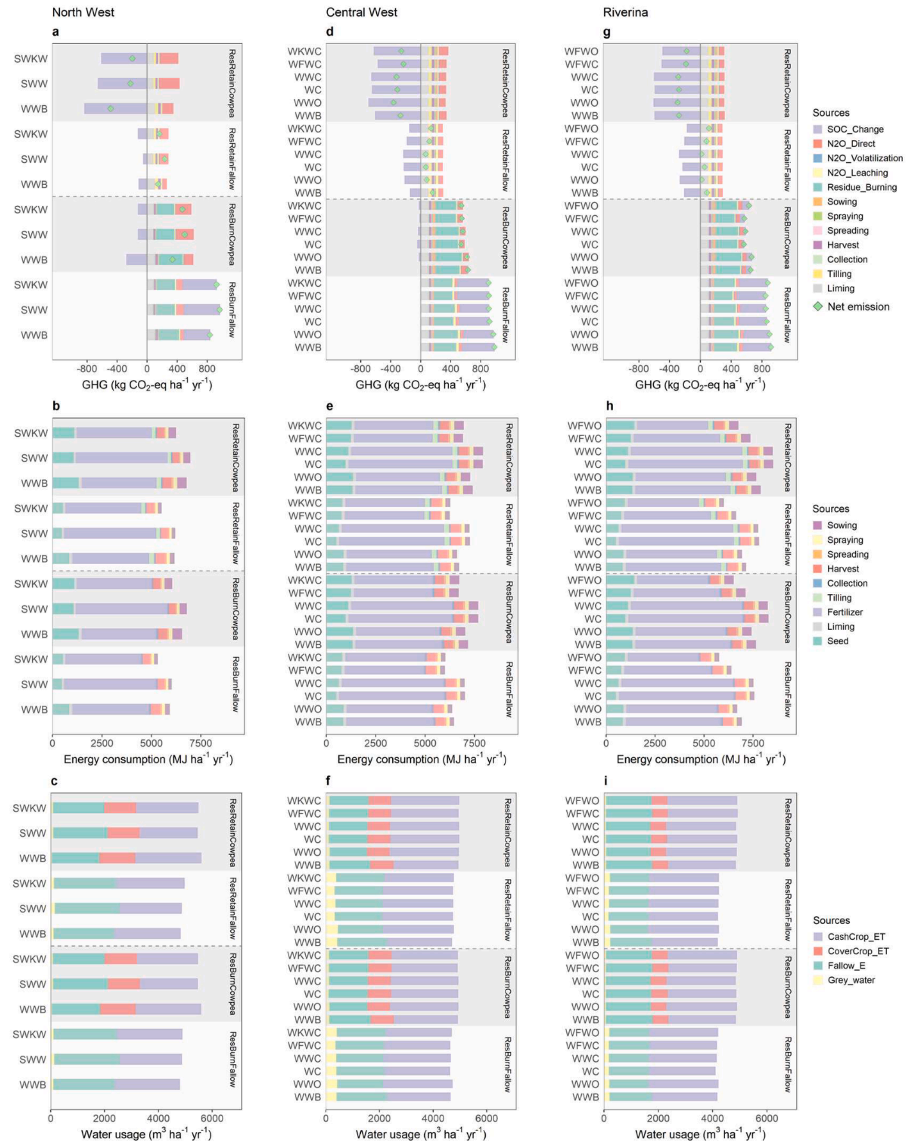

Fig. 3. Average values of GHG emission, energy input, and water consumption for North West **(a-c)**, Central West **(d-f)**, and Riverina **(g-i)** from 1961 to 2020. Negative GHG emissions sourced from SOC change mean increased SOC, and negative net emissions (green diamond) mean net carbon sequestration. The meanings of rotation abbreviations are shown in Table 1.

residue retained with no cover crop (ResRetainFallow) produced low or zero GHG emissions, but cover cropping with residue burned (ResBurnCowpea) still generated high GHG emissions almost without SOC change.

The total energy inputs were mainly contributed by nitrogen fertilizer, contributing 56–78 % (North West), 58–76 % (Central West), and 54–78 % (Riverina) across all rotations and scenarios (Fig. 3b, e, h). The second contributor was the seed, with 7–20 % (North West), 7–19 % (Central West), and 6–22 % (Riverina), in which seed inputs of cover cropping scenarios (ResRetainCowpea and ResBurnCowpea) were higher than others. Notably, although seed inputs of legume-included rotations, such as WKWC and WFWC (Central West), and WFWO and WFWC (Riverina), were relatively higher than those of WC and WWC, their fertilizer inputs were lower, leading to the lowest total energy inputs. This was similar for North West, where SWKW showed the lowest energy inputs.

Compared with fallow scenarios (ResRetainFallow and ResBurnFallow), additional water used by cover crops in ResRetainCowpea and ResBurnCowpea caused a larger total water consumption (Fig. 3c, f, i). The evapotranspiration during cover cropping ranged between 1188 and 1327 m^3 ha^{-1} (North West), 836–876 m^3 ha^{-1} (Central West), and 561–607 m^3 ha^{-1} (Riverina). Meanwhile, soil evaporation during fallow was reduced by two cover cropping periods in North West, but not obviously affected by the single cover cropping in Riverina. The amounts of grey water were negligible, and always close to zero under ResRetainCowpea and ResBurnCowpea. There was little difference in the cash crop evapotranspiration between rotations and scenarios.

3.2. FEWC footprints and productivity

With respect to the carbon footprint, the WWB showed the highest GHG emission under ResBurnFallow (311 CO_2-eq t^{-1}), and moderate carbon sequestration under ResRetainCowpea (-118 CO_2-eq t^{-1}) in North West (Fig. 4a). The WWO had both the highest carbon footprint under ResBurnFallow (407 CO_2-eq t^{-1} and 366 CO_2-eq t^{-1}) and the lowest carbon footprint under ResRetainCowpea (-183 CO_2-eq t^{-1} and −185 CO_2-eq t^{-1}) for Central West and Riverina, respectively (Fig. 4d, g). However, the energy footprint of ResRetainFallow was always lower than those of other scenarios in Central West and Riverina, but was comparable with others in North West (Fig. 4b, e, h). Within

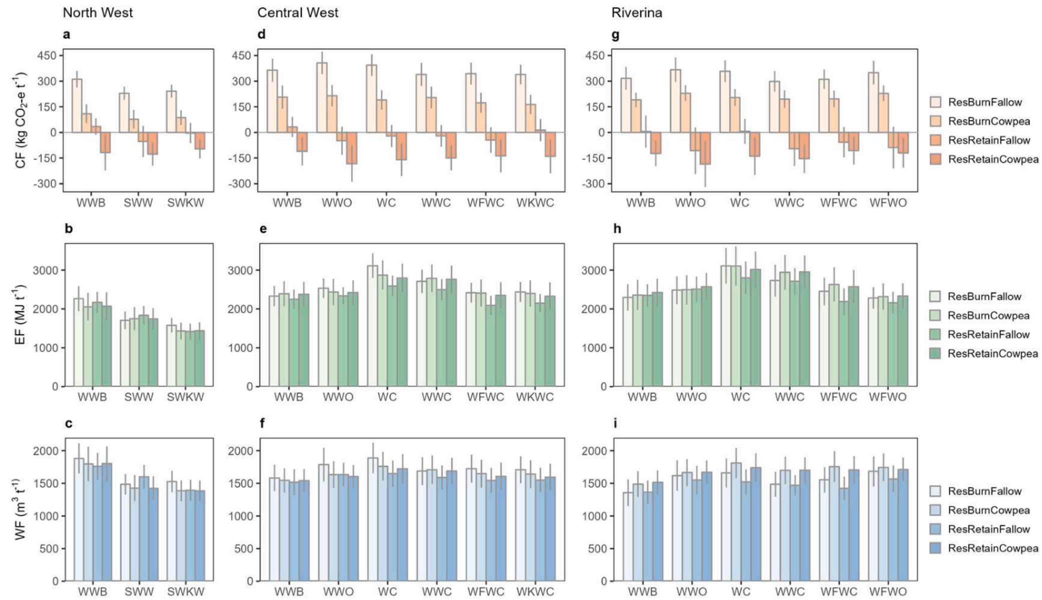

Fig. 4. Average values of carbon footprint (CF), energy footprint (EF), and water footprint (WF) for North West **(a-c)**, Central West **(d-f)**, and Riverina **(g-i)** from 1961 to 2020. The error bars represent the standard deviation across different study sites. The meanings of rotation abbreviations are shown in Table 1.

ResRetainFallow, the legume-included rotations consistently had the lowest energy footprint across all regions, with values of 1416 MJ t^{-1} for SWKW (North West), 2096 MJ t^{-1} for WFWC (Central West), and 2160 MJ t^{-1} for WFWO (Riverina). Similarly, ResRetainFallow had a lower water footprint especially in Riverina, and those of sorghum-included rotations were notably lower than others (Fig. 4c, f, i).

The average yields increased slightly or remained unchanged in residue retained scenarios (ResRetainFallow and ResRetainCowpea) compared to residue burning scenarios (ResBurnFallow and ResBurnCowpea). However, cover cropping (ResRetainCowpea and ResBurnCowpea) increased most cereal yields but reduced the yields of canola and legume relative to fallow (ResRetainFallow and ResBurnFallow), and the benefits were more evident in North West than in Central West and Riverina (Fig. B.2). Accordingly, gross margins were enhanced by ResRetainCowpea and ResBurnCowpea for cereal rotations in North West, but in Central West and Riverina, the ResRetainFallow exhibited the highest gross margins across most rotations (Fig. 5). Given that the different grain prices and on-farm costs of various crops, our results showed that SWKW (509–556 AUD ha^{-1} yr^{-1}), WKWC (599–724 AUD ha^{-1} yr^{-1}), and WC (565–658 AUD ha^{-1} yr^{-1}) were the highest-return rotations in North West, Central West and Riverina, respectively (Fig. 5).

3.3. FEWC composite sustainability and evenness

Based on the FEWC index, the sustainability score exhibited different patterns in the three regions. For North West, it is evident that ResRetainCowpea had the highest score and SWKW was the optimal rotation (Fig. 6a). In contrast, ResRetainFallow had the highest score across most rotations in Central West and all rotations in Riverina, and the canola and legume included rotations (WFWC and WKWC) performed better than others (Fig. 6b-c). Moreover, although composite sustainability scores of these scenarios were moderately high (scores over 50), most rotations cannot reach a balanced improvement regarding the four sustainability domains. For example, ResRetainFallow was more beneficial with respect to water and energy, but weaker in carbon compared to ResRetainCowpea. Considering both sustainability and evenness,

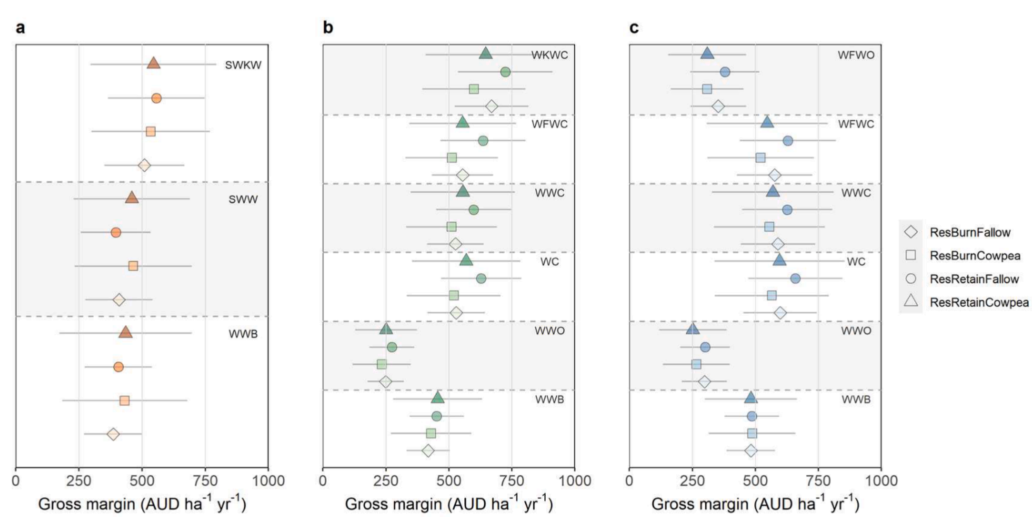

Fig. 5. Average values of gross margin for North West **(a)**, Central West **(b)**, and Riverina **(c)** from 1961 to 2020. The error bars represent the standard deviation across different study sites. The meanings of rotation abbreviations are shown in Table 1.

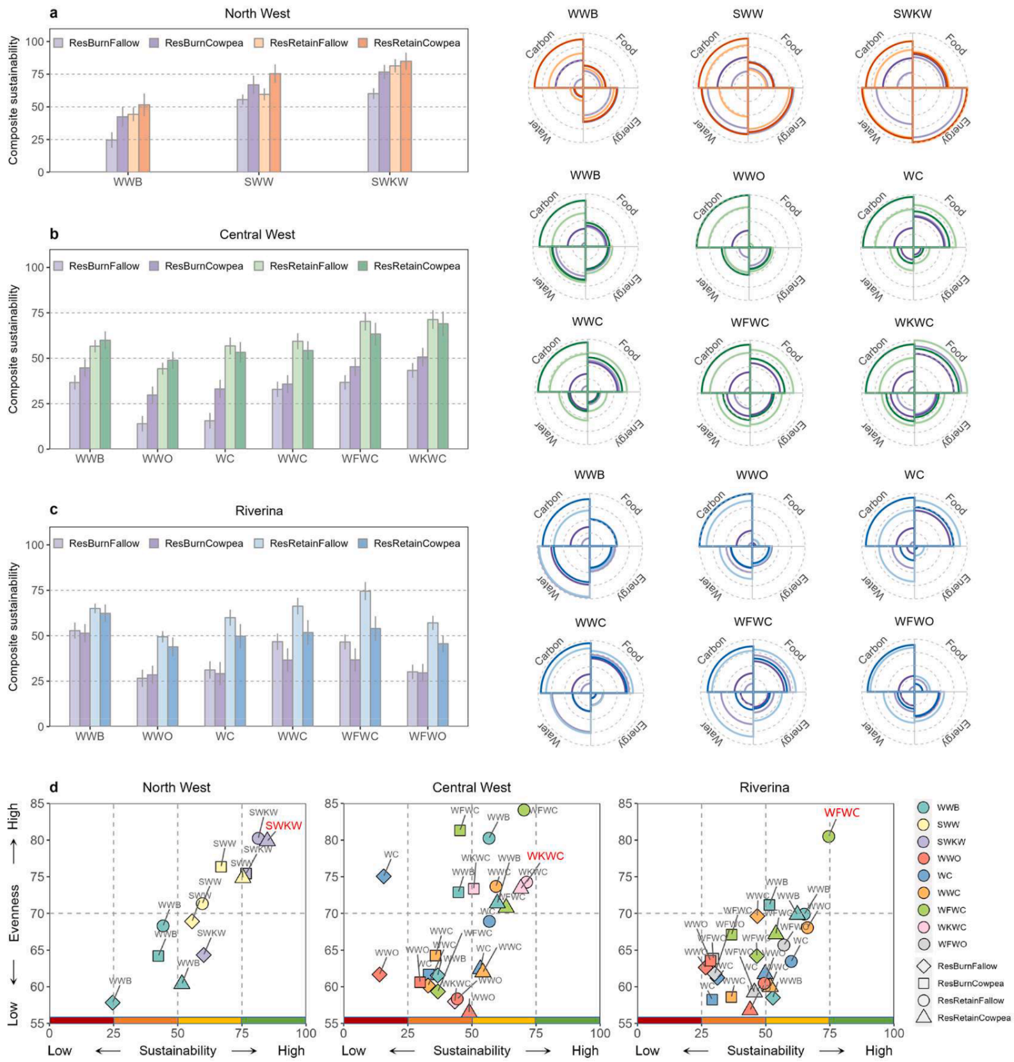

Fig. 6. The composite sustainability with error bars (the standard deviation across different study sites), and performance for each sustainability domain (the inner-to-outer rings represent scores of 0, 25, 50, 75, and 100, respectively) for each rotation in North West **(a)**, Central West **(b)**, Riverina **(c)**, and the distribution of both sustainability and evenness for all rotations in each region **(d)**. The meanings of rotation abbreviations are shown in Table 1.

aforementioned rotations and scenarios with high sustainability in each region also had relatively high evenness (Fig. 6d). Note that, the score only denotes relative sustainability, and a score closer to 100 does not mean that the farming system is definitely sustainable.

3.4. Optimization across sub-regions

Based on the above comparison of rotations over each sub-region, we selected the optimal rotation which had the highest sustainability and high evenness score for North West (SWKW), Central West (WKWC), and Riverina (WFWC) to further investigate the spatial pattern. The map of the best scenario for each location demonstrated that ResRetainCowpea was the optimal strategy at most sites in North West (76 %), while ResRetainFallow was dominant in Riverina (95 %) (Fig. 7a). The advantage of ResRetainCowpea in North West was mainly from the improvement in the carbon domain, but ResRetainFallow in Riverina was generally superior in energy and water domains (Fig. 7b). In addition, the best performance of ResRetainCowpea was concentrated in the east of North West, and sustainability scores were always higher in the east over all regions (Fig. 7a). Considering the climate differences from east to west (Fig. 1b-c), four quantiles of sustainability score of the selected rotations within each optimal scenario were displayed. The results showed that higher sustainability interval (Q4, above 75th percentile) occurred at sites with higher rainfall and lower temperature, and this pattern was the most evident in North West (Fig. 7c).

4. Discussion

4.1. A nexus perspective to optimize management strategy

The FEWC analysis provides quantitative assessment of agricultural sustainability for different management strategies. Results reveal that the overall sustainability was improved by residue retention and cover cropping especially in terms of carbon domain (Fig. 6a-c). Both residues from cash crops and cover crops contributed to soil carbon sequestration, but direct N_2O emissions were doubled with the inclusion of cover crops (Fig. 3a, d, g). The input of organic carbon from crop residues is the key contributor to the increased stock of SOC (Paustian et al., 2016; Yang et al., 2018). N_2O production in soils – which is modelled by nitrification and denitrification processes in APSIM (Thorburn et al., 2010) – occurs readily when stimulated by the amendment of N-rich crop residues. This is more evident in North West where rainfall is higher and sorghum harvesting is followed by a gap year with two cover cropping periods (Fig. 3a). Enhanced N_2O emissions by legume residues have also been reported in previous meta-analysis (Basche et al., 2014; Muhammad et al., 2019) and modeling studies (Lugato et al., 2018;

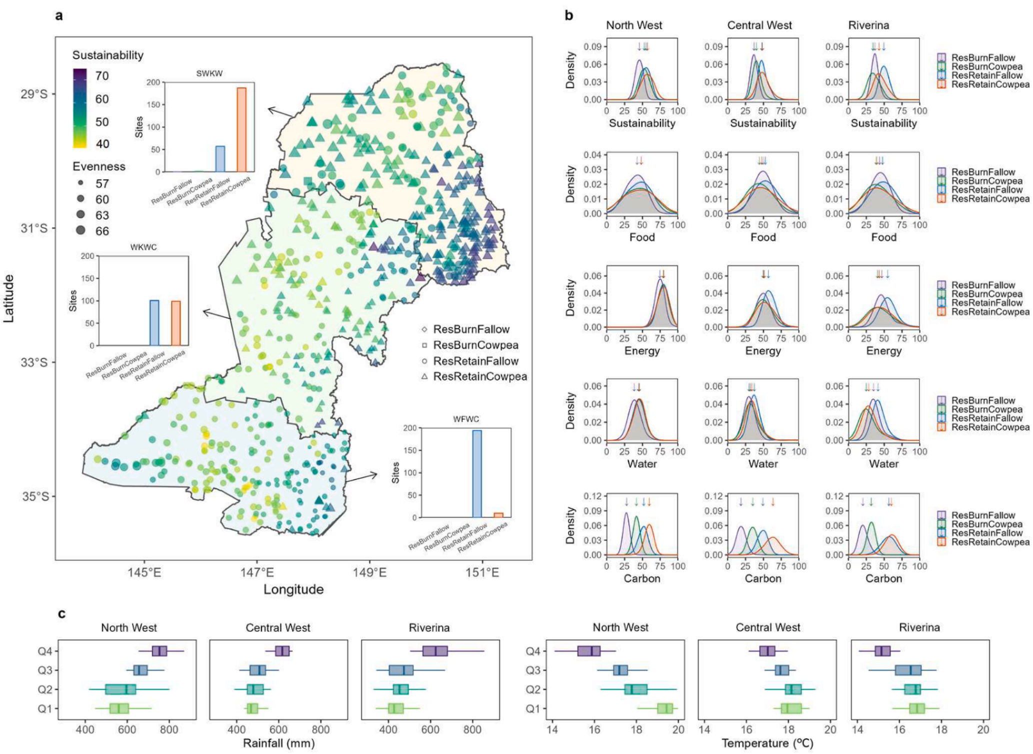

Fig. 7. **(a)** Map of the highest sustainability score within four scenarios for the selected optimal rotations in North West (SWKW), Central West (WKWC), and Riverina (WFWC) at each study site; **(b)** kernel density distributions of scores for sustainability and four contributing domains for the optimal rotations across all sites of each region under four scenarios; **(c-d)** distribution of annual mean rainfall and temperature (from 1961 to 2020) among different sustainability quantiles (Q1: <25th, Q2: 25–50th, Q3: 50–75th, and Q4: >75th) based on the optimal combinations generated from **(a-b)** in North West (SWKW with ResRetainCowpea), Central West (WKWC with ResRetainFallow), and Riverina (WFWC with ResRetainFallow). The meanings of rotation abbreviations are shown in Table 1.

Quemada et al., 2020). The decomposition of legume residues with a low C/N ratio probably resulted in less immobilization of N in soils, leading to more N available for nitrification and denitrification and therefore the production of N_2O (Xia et al., 2018).

Although the inclusion of cover cropping increased soil carbon sequestration, it consumed more energy and water resources. Additional seed input and diesel use for sowing cover crops were the main reasons for the greater energy consumption compared to the fallow scenarios (Fig. 3b, e, h). Nitrogen fertilizer always contributed the most to energy consumption (Farine et al., 2010; Yadav et al., 2020), and was lower in legume-included rotations due to the lower nitrogen requirement of leguminous crops. Interestingly, the grey water induced by nitrogen fertilizer was close to zero under all cover cropping scenarios but not negligible when there was no cover crop, especially in Central West, suggesting a larger amount of nitrogen leaching in this region (Fig. 3c, f, i). Cover cropping has been well recognized as an option to reduce nitrogen leaching through N uptake of excess N remaining in soils after the cash crop harvesting (Abdalla et al., 2019; Nouri et al., 2022; Porwollik et al., 2022; Teixeira et al., 2021). However, the reduced grey water was small and unable to balance the water usage from cover crops, and soil evaporation showed little difference from fallow because one cover crop only lasted for about one month, resulting in larger amounts of water consumption under cover cropping scenarios, as reported by some studies (Garba et al., 2022a; Qin et al., 2021; Shackelford et al., 2019).

Combined with the crop yield and profitability, large inequalities appear to exist among the four domains regarding food, energy, water and carbon (Fig. 6a-c). All rotation systems achieved negative carbon footprints when using both residue retention and cover cropping, but nexus trade-offs occurred and influenced the goals of improving resource use efficiencies and economic benefits. That is, most rotations in Central West and Riverina had higher water and energy footprints but lower gross margin under ResRetainCowpea compared to ResRetainFallow (Figs. 4, 5). This result can be complementary to the findings of He et al. (2022a), in which classical optimal planting patterns were found to be beneficial to water use and profitability, but not to the carbon neutrality. Xu et al. (2020) also reported that supply-oriented management may boost food production at the expense of environmental burdens and resource consumption. Collectively, although conflicts within the FEWC cannot be completely resolved by the implementation of residues or cover crops in this study, we have demonstrated the benefits of applying the nexus perspective to inform identification of optimal management strategies.

4.2. Comparison of sustainability across different regions

Based on the integrated FEWC framework, an optimal rotation system exhibiting a relatively high sustainability across all domains was selected for each region to investigate the spatial performance (Fig. 6d). The scenario with the highest sustainability score at each site was presented on a map which revealed divergent optimal solutions among the three regions (Fig. 7a). ResRetainCowpea was optimal in North West, but ResRetainFallow performed the best in Riverina. The Central West, situated between North West and Riverina, had approximately half each of the sites scoring the highest under ResRetainFallow or ResRetainCowpea. This could be due to that the sorghum within SWKW rotation in North West was followed by a gap year, during which two cover cropping periods benefited both SOC and gross margin, without incurring additional energy consumption (Fig. 7b). The stored soil water from the gap year could also be used by the following cash crops (Chen et al., 2023; Oliver et al., 2010). In addition, the yields of sorghum were double those of wheat, consistent with Stephens et al. (2012). Consequently, when considering the annual average yields of sorghum within the two-year period, they were comparable to wheat yields but had lower energy and water consumption per unit of yield. However, in water-limited conditions, cover crops may compete for soil water resources (Deines et al., 2023; Garba et al., 2022b; Rose et al., 2022). It is evident that ResRetainCowpea scored a little higher in carbon but much lower in energy, water and gross margin domains than ResRetainFallow across most sites in Riverina, leading to a lower composite sustainability score (Fig. 7b). Therefore, adopting cover cropping in the generally wetter North West region is feasible, but not suitable in the intensive rotation systems of Riverina.

Residue retention was beneficial for all regions, as it provided a positive feedback loop that enhanced both SOC and yield, as has been widely reported in Australia (Page et al., 2020), and globally, including in China (Berhane et al., 2020; Han et al., 2018), and Europe (Haas et al., 2022; Sándor et al., 2020). Our study complemented these findings by indicating that residue retention also resulted in lower energy and water footprints compared to residue burning (Fig. 4). Residue retention may therefore play a key role for enhancing sustainability of agriculture (Xiao et al., 2021). Furthermore, the composite sustainability score displayed a clear decreasing trend from east to west across all regions (Fig. 7a). The four quantiles of sustainability scores in relation to rainfall and temperature revealed that the wetter and cooler sites always had higher sustainability scores in this study (Fig. 7d). The site-specific performance highlighted the importance of climate conditions in determining the final outcomes of optimal management strategies (Sun et al., 2020).

4.3. Policy implications and limitations of this study

Integrated thinking and analysis, as simply exemplified in this study, highlighted relationships among different but interconnected FEWC domains. This nexus approach can help to optimize agricultural management strategies in alignment with the SDGs, revealing synergies and trade-offs for potential implications to decision makers.

First, reducing the dependency on nitrogen fertilizer should be a priority for both research and government policy. Nitrogen fertilizer was the most energy intensive input, and also affected the GHG emissions and water usage (Rawnsley et al., 2019). Legume-included rotations were found to use less nitrogen per hectare farmed each year. Rotations with nitrogen-fixing crops can reduce the fertilizer requirement of the subsequent crops, thus alleviating environmental burdens and improving profitability (Li et al., 2021; Xing et al., 2017; Zhao et al., 2022). Reducing N inputs after legumes, in combination with nitrogen adjustment, specifically precision fertilization, should be further considered to better contribute to the various goals of sustainable agriculture.

Second, well-targeted incentives are needed to promote the adoption of cover crops in NSW in areas where they are beneficial. Cover cropping is widely promoted as a management practice for supporting the goal of net zero GHG emissions by sequestering SOC (Abdalla et al., 2019; Muhammad et al., 2019; Tribouillois et al., 2018), but was found to increase water and energy footprints, and decrease profitability in drier regions of this study. This means that cover cropping is not a sustainable option for regions with less rainfall. Our study did not assess different cover cropping scenarios (e.g., crop species, planting and terminating time), which may lead to different water and energy footprints. Furthermore, the possible yield penalties would discourage growers (Deines et al., 2023), and current financial incentives (e.g., carbon credits) for cover crops may not be sufficient to cover the economic costs (Qin et al., 2023). Cover cropping should be adapted to local conditions, and its adoption necessitates increased economic incentives and technical assistance.

Finally, holistic sustainability assessment, in conjunction with emerging technologies (e.g., satellite observation), should be integrated to provide a decision support tool to optimize agricultural management strategies. Our study only focused on the FEWC components of cropping systems, more environmental impacts, such as land footprint and biodiversity footprint, could be included in this nexus framework (Liu et al., 2015). Some statistical indicators, like employment and population, could also be incorporated to better represent the social sustainability dimension (Ren et al., 2023). To guide policymaking effectively, context-specific management strategies should be formulated for different regions. We hope that our agricultural-centered FEWC nexus approach can inform optimal strategies to support the sustainable development.

CRediT authorship contribution statement

Qinsi He: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **De Li Liu:** . **Bin Wang:** Writing – review & editing, Methodology, Conceptualization. **Zikui Wang:** Writing – review & editing, Methodology. **Annette Cowie:** Writing – review & editing, Methodology, Investigation. **Aaron Simmons:** Writing – review & editing, Methodology. **Zhenci Xu:** Writing – review & editing. **Linchao Li:** Writing – review & editing. **Yu Shi:** Writing – review & editing. **Ke Liu:** Writing – review & editing. **Matthew Tom Harrison:** Writing – review & editing. **Cathy Waters:** Resources. **Alfredo Huete:** Writing – review & editing, Supervision. **Qiang Yu:** Writing – review & editing, Supervision.

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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Supplementary materials

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