



# Improving the sustainability of cropping systems via diversified planting in arid irrigation areas

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## Abstract

The development of productively viable cropping systems with lower environmental footprints to maintain sustainable agriculture in arid areas is urgently needed. Increasing crop diversity usually improves system productivity; however, the effects of crop diversification on the carbon footprint and the sustainability of a cropping system remain unclear. A 3-year field experiment (2018–2020) was conducted in northwestern China to determine the carbon footprint and productivity of five cropping systems, including spring wheat-common vetch/maize double relay cropping (three crops a year), wheat-maize intercropping (two crops a year) wheat-common vetch multiple cropping (two crops a year), monoculture maize (one crop a year), and monoculture wheat (one crop a year). The grain yield for wheat-common vetch/maize double relay cropping (the former) was higher by 8.7% in 2020 as compared to wheat-maize intercropping (the latter). For the same two cropping systems, the energy yield of the former was higher by 9.5–25.1% over 3 years. The carbon footprints of the former system were respectively 5.3%, 14.3%, 16.4%, and 7.4% lower than that of the latter in terms of unit area, kg grain yield, unit energy yield, and unit of economic output. Four carbon footprints of the former system were lower by 12.2%, 27.9%, 37.6%, and 29.6% compared with monoculture maize. The highest sustainability index was observed for a three crops per year system (0.94), due to higher productivity and a lower carbon footprint. This is the first demonstration that increased diversity via double relay cropping on the same plot annually maintained productivity without increasing the carbon footprint in arid irrigation areas. The results partly confirm the positive effect of diversified cropping systems by integrating multiple cropping green manure into an intercropping system. Adopting a diversified strategy exemplified by spring wheat-common vetch/maize double relay cropping contributes to improvements in sustainable crop production in arid, irrigated areas.

**Keywords** Crop diversification · Wheat-maize intercropping · Greenhouse gas emissions · Carbon footprint · Sustainability

## 1 Introduction

Global warming and its impact on human-related activities is a major worldwide challenge in the 21st century (Cuello et al. 2015; Viguier et al. 2021), primarily because of an increase in greenhouse gas (GHG) emissions (Huang et al. 2019; Raji and Drsch 2020). The agricultural production sector contributes approximately 15% of the total emissions, and farming

operations and related agriculture practices resulted in considerable GHG emissions (Hu et al. 2013; Wang et al. 2021). A primary source of farmland GHG emissions is inputs of chemical fertilizer, manure, crop residues, and various biochemical processes in soil (Akhtar et al. 2020). The term “carbon footprint” was introduced into agricultural research as an estimate of the total amount of CO<sub>2</sub> emissions directly and indirectly caused by agricultural production (Gan et al. 2011; Liu et al.

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2016). Reducing the carbon footprint and improving the resource use efficiency of agriculture would contribute to the development of sustainable agriculture (Benbi 2018; Taki et al. 2018). However, global food and energy security must be based on the input of chemical fertilizers and other agricultural materials to feed a growing population in the future (Sun et al. 2021; Wang et al. 2018). A great conflict exists between guaranteed food security and decreased environmental costs of agriculture. Finding new and alternative ways to sustain or boost crop yield with a lower carbon footprint is becoming an increasingly urgent need for agriculture production and mitigating climate change.

Lowering the carbon footprint of agriculture can be achieved through adopting best management practices for cropping systems (Benbi 2018; Yang et al. 2014), such as efficiently applying fertilizer (Hu et al. 2013), planting green manure (Lee et al. 2010; Yao et al. 2017), optimizing tillage (Zotarelli et al. 2012), and adopting diversified cropping systems (Rodriguez et al. 2021; Yang et al. 2014). Diversified cropping systems such as intercropping or crop rotation have recently been receiving increased attention regarding the reduction of agricultural carbon emissions (King and Hofmockel 2017; Viguier et al. 2021; Wang et al. 2018). Crop diversification has the distinct advantage of niche differentiation in time and space (Agegnehu et al. 2008; Li et al. 2001), which can effectively promote complementary utilization and realize the highly efficient utilization of resources (King and Hofmockel 2017; Wang et al. 2018; Zhang and Li 2003). Diversified crop combinations could affect which factors determine the soil GHG flux. For instance, previous studies have shown that intercropping systems enhance soil aggregates, soil organic carbon, and soil total nitrogen, which can effectively reduce the loss of nutrients from fields (Gan et al. 2014; Sun et al. 2021). In addition, greater crop diversity stimulates above-ground interactions, increasing the community diversity of soil microbial, and improving nutrient uptake and soil water utilization (Zhang et al. 2021). Therefore, diversified cropping systems provide important and valuable ecological and economic benefits. And the practice has been used for crop production to narrow the gap between actual and potential yields and to mitigate GHG emissions (Fan et al. 2021). In general, diversified cropping systems implemented by combining different crops safeguarded crop yield and mitigated environmental risk (Liu et al. 2016; Qin et al. 2013), optimized nitrogen fertilizer, tillage, and straw management (Gan et al. 2012; Yin et al. 2017). All these studies have demonstrated that using diversified cropping systems provides a powerful tool for developing sustainable agriculture. However, in many studies of

diversified cropping systems, crop diversity was increased via a single diversification strategy such as intercropping, multiple cropping, or a crop rotation system (Rodriguez et al. 2021; Viguier et al. 2021). Few studies investigated the relationship between the carbon footprint or sustainability and the crop diversity of a cropping system on the same plot annually, which contributed to the lack of a scientific basis for establishing more efficient diversified cropping systems. Accordingly, the implementation of a more diversified system based on a combination of several crop diversification schemes for crop production is needed.

In arid irrigation areas, a shortage of heat resources contributes to the difficulty of developing a more diversified cropping system via the integration of conventional crops (Chai et al. 2013; King and Hofmockel 2017). Green manure crops have become a valuable tool for increasing crop diversity in cropping systems as they have a flexible growing season and lower heat requirements (Gentsch et al. 2020; Rodriguez et al. 2021). Leguminous green manure crops are generally employed as additional crops after the spring wheat harvest in arid irrigation areas (Fig. 1a). Multiple cropping with green manure crops plays a vital role in improving crop diversification and increasing the primary crop yield (Fan et al. 2021; Rodriguez et al. 2021). In addition to increasing crop diversity, green manure crops also have the benefits of alleviating some negative environmental impacts of agriculture; e.g., the application of leguminous green manure sustained rice productivity without increasing methane emissions (Haque et al. 2013), and also decreased nitrate leaching by inhibiting soil nitrification (Gao et al. 2020; Lee et al. 2010). Leguminous green manure coupled with cereal-based cropping systems added extra nitrogen to crops (Fan et al. 2021; Plaza-Bonilla et al. 2016), simultaneously replacing some of the chemical fertilizer and potentially reducing the carbon footprint (Lee et al. 2010; Zotarelli et al. 2012). However, other studies have indicated that the application of leguminous green manure contributed to an increase in GHG emissions and the total global warming potential in paddy fields because of the decomposition of green manure by methanogenic archaea (Kim et al. 2013). Previous results have indicated that green manure application increased the yield of primary crops, but its ability to reduce GHG emissions in crop production is questionable. In addition, green manure application was implemented via rotation or intercropping with primary crops in these studies (Fan et al. 2021; Miyazawa et al. 2009). It has not yet been integrated into a diversified cropping system to further enhance the productivity and sustainability of a combined system.

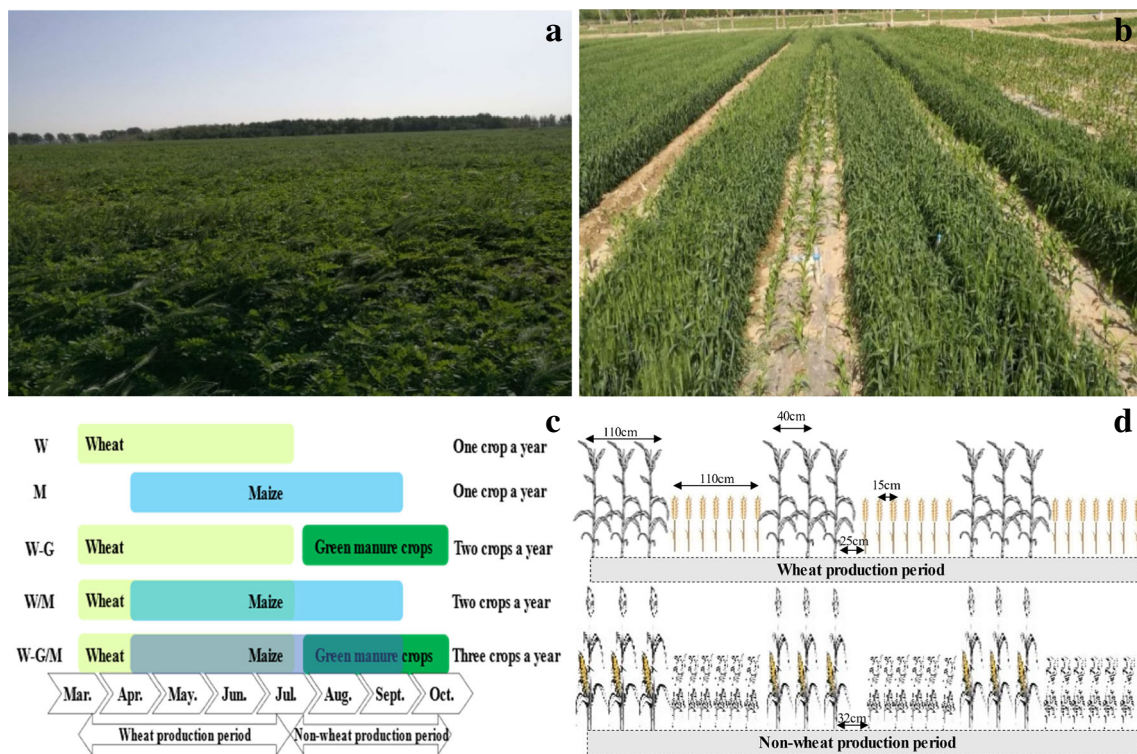
The establishment of more diversified cropping systems to achieve the multiple goals of cleaner agriculture, sustainability, and improved economic benefit in arid irrigation areas is urgent. Spring wheat and maize are the two main food crops grown in arid irrigation areas, and the two crops are usually intercropped in an intensive cropping system (Fig. 1b). This practice has been proven as a high-yield diversified cropping system, but at the cost of higher GHG emissions (Hu et al. 2017; Yin et al. 2017). Therefore, we introduced spring wheat and maize as primary crops and common vetch as a green manure crop to determine how increasing crop diversity via several crop diversification measures on the same plot annually affects crop productivity, the carbon footprint, and sustainability of a cropping system. Based on a carbon footprint calculation by life cycle assessment (LCA) (Yao et al. 2017; Sun et al. 2020), our overall objective was to achieve environmentally friendly agriculture by decoupling a higher yield from a higher carbon footprint in a diversified cropping system. We aimed to determine (i) the response of crop productivity and soil GHG emissions to different crop diversity levels, (ii) the carbon footprint of different cropping systems per unit area, per grain yield, per energy yield, and per economic output, and (iii) sustainable cropping systems using

productivity- and carbon footprint-related variables to support agriculture production in arid irrigation areas. We hypothesized that increased crop diversity on the same plot annually could safeguard or even boost crop productivity without increasing the environmental risk.

## 2 Materials and methods

### 2.1 Study sites

This study was carried out from 2018 to 2020 at Huangyang Town (37°34' N, 102°94' E) in Wuwei City in northwestern China. The mean annual precipitation is approximately 200 mm (1960–2015), and rainfall mainly occurs in late July through October (Fig. S1). The long-term annual average air temperature is 7.3 °C, and the accumulated air temperature greater than 10 °C is 2975 °C. The frost-free period is 156 days. Thus, this area is suitable for developing multiple cropping systems, and wheat-maize intercropping is commonly employed there to increase crop diversity (Hu et al. 2017; Yin et al. 2017). The soil type is an Aridisol whose total nitrogen content, available phosphorous content, available potassium content, and organic matter content in the top 40 cm



**Fig. 1** Multiple cropping with leguminous green manure crops after spring wheat harvest (a) and spring wheat-maize intercropping systems in arid irrigation areas (b). All photographs by the authors. Growth

periods of different cropping systems (c) and the field layout of the intercropping systems (d).

soil are 0.78, 29.2, 152.6, and 14.3 g kg<sup>-1</sup>, respectively. This experimental site is representative of the agricultural land in this region.

## 2.2 Experimental design and management

In 2018 to 2020, a field experiment was conducted on land used for conventional cropping with spring wheat (*cv. Ningchun 4*) and maize (*cv. Xian-yu 335*). Common vetch (*cv. Sujian 3*) is a green manure crop that can be used for multiple cropping after the wheat harvest. Employing these three crops, cropping systems to implement three different crop diversity levels were established: (i) monoculture spring wheat and monoculture maize (the W and M treatments, one crop a year), (ii) spring wheat–common vetch multiple cropping and spring wheat–maize intercropping (the W-G and W/M treatments, two crops a year), and (iii) spring wheat–common vetch/maize double relay cropping (the W-G/M treatment, three crops a year), for a total of five cropping systems. The growth periods and the types of crops in the five cropping systems are shown in Fig. 1c. The width of both the wheat and maize strips was 110 cm in the intercropping system. Three rows of maize were alternated with seven rows of spring wheat with three pairs of intercrop strips inserted in each intercropped plot. Six rows of common vetch were planted after the wheat harvest in the wheat–maize intercropping system (Fig. 1d). The maize strips were deep-plowed in late fall each year. The maize croplands were mulched with plastic film the following spring, which is a common tactic for conserving soil water and temperature in arid areas. The land was ploughed immediately after the wheat harvest, followed by the planting of common vetch. Common vetch as a green manure crop was returned to the field by crushing and pressing it during the flowering stage. The experimental plots were arranged in a completely randomized design 7 m long × 7 m wide, with each treatment replicated three times. Each treatment was conducted on its assigned plot each year.

Each species of the crop was sown and harvested on the same date whether in monoculture or intercropped. Maize and wheat were planted at the same density in each cropping system: maize at 82,500 plants per hectare and wheat at 6,750,000 plants per hectare. The same area-based rate of fertilizer was applied to a given crop in monoculture or in an intercropping system. Nitrogen and phosphorus fertilizers were applied as urea and diammonium phosphate. All fertilizer N and P in wheat and all fertilizer P in maize were top-dressed before sowing. For maize, fertilizer N was applied three times; 30, 50, and 20% of the total top-dressing prior to sowing, at the jointing maize phenological stage, and at the kernel blister maize phenological stage, respectively. Green manure crops were not fertilized. All plots received 120 mm irrigation in late fall. Supplemental irrigation of all maize plots was applied at 75, 90, 75, 90, 75, and 75 mm at the seedling,

jointing, preheading, silking, flowering, and filling stages, respectively. Supplemental irrigation of all spring wheat plots was applied at 75, 90, and 75 mm at the seedling, booting, and grain-filling stages. Supplemental irrigation of all common vetch plots was applied at 70 and 90 mm at the seedling and budding stages, respectively. A drip irrigation system was used for irrigation.

## 2.3 Measurements and calculations

### 2.3.1 System boundaries

Greenhouse gas emissions (GHG) in our study were based on the LCA approach and considered all direct and indirect soil GHG emissions (Yao et al. 2017). Direct GHG emissions (GHG<sub>d</sub>) were the soil GHG emissions from complex reactions. Indirect GHG emissions (GHG<sub>i</sub>) were due to different farm management practices and agrochemical inputs, including (i) every stage of the production of all crops, e.g., manufacture, storage, and transportation of agricultural inputs; (ii) the GHG emissions due to the electricity used for irrigation; (iii) and labor for planting, harvesting, and tilling. Changes in the soil organic carbon storage for the 0–40-cm soil layer were also included in the system boundary, which is shown schematically in Fig. S2.

### 2.3.2 Soil direct greenhouse gas emissions

In this study, we considered soil CO<sub>2</sub> and N<sub>2</sub>O emissions and CH<sub>4</sub> emissions as negligible since northwestern China is a dryland area (Ceschia et al. 2010). For all cropping systems, the soil GHG emission fluxes were measured at 15-day intervals after wheat emergence. To ensure the data consistency, we continued to monitor soil GHG emissions of monoculture spring wheat after harvest until the green manure crop was returned to the soil.

- i. Soil carbon dioxide (CO<sub>2</sub>): Soil CO<sub>2</sub> emission fluxes (F<sub>C</sub>) were measured in each plot every 2 h each day from 8:00 to 20:00 using an LI-8100A system (LI-COR, 4647 Superior Street Lincoln, Nebraska USA). At 24 h before measurement, the respiratory base was pushed 2–3 cm into the soil, and the plastic film was removed from the location of the respiratory base in maize. For intercropping, measurements were taken for both crops by placing the respiratory base in the wheat strips and the maize strips. The soil CO<sub>2</sub> flux of the intercropping system was calculated as the average of the wheat, green manure, and the maize crop strip.

The soil CO<sub>2</sub> emission (CE) was calculated based on F<sub>C</sub>. CE was calculated using the following formula from Zhang et al. (2018):

$$CE = \sum \left[ \frac{F_{C(i+1)} + F_{C_i}}{2} (t_{i+1} - t_i) \times 0.1584 \right] \times 0.2727 \times 24 \times 10 \quad (1)$$

where CE is the soil CO<sub>2</sub> emission (kg C ha<sup>-1</sup>), F<sub>C</sub> is the soil CO<sub>2</sub> emission flux (μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>), *i*+1 and *i* are the current and the last monitoring dates, respectively, *t* is the number of days after wheat emergence, 0.1584 is a conversion factor for mol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> to g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, and 0.2727 is a conversion factor for g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> to g C m<sup>-2</sup> h<sup>-1</sup>.

ii. Soil nitrous oxide (N<sub>2</sub>O): Static chambers and gas chromatography were adopted to measure the soil N<sub>2</sub>O emission flux (F<sub>N</sub>). One chamber was placed on a stainless-steel frame that was pushed 2–3 cm into the soil of each plot. A measurement chamber was placed in each strip for intercropping. Gas samples were collected with 50 ml plastic syringes and then injected into an evacuated 50 ml bag at 0, 5, 10, and 15 min following chamber closure. The gas samples were collected from 9:00 to 11:00 in the morning. We used gas chromatography (Agilent 7890A, Agilent Inc., USA) to analyze the gas samples. The soil N<sub>2</sub>O emission flux (mg·m<sup>-2</sup>·hour<sup>-1</sup>) was determined by the following formula (Cui et al. 2019):

$$F_N = \frac{273}{273 + \theta} \times 14 \times \frac{2}{22.4} \times 60 \times 10^{-3} \times h \times \frac{dc}{dt} \quad (2)$$

where F<sub>N</sub> is the soil N<sub>2</sub>O emission flux (mg·m<sup>-2</sup>·hour<sup>-1</sup>), θ is the air temperature in the chamber at the sampling time, 14 is the molecular weight of N, 2 is the number of N molecules in N<sub>2</sub>O, 22.4 is the molar volume of an ideal gas, *h* is the height of the static chamber (cm), *dc/dt* is the slope of the regression curve of the N<sub>2</sub>O concentration in the static chamber over time. The soil N<sub>2</sub>O flux of the intercropping system was calculated as the average of the value for the wheat or green manure crop strip and the maize strip.

The soil N<sub>2</sub>O emission (NE) was calculated based of F<sub>N</sub> using the formula of Cuello et al. (2015):

$$NE = \sum \frac{F_{N_{i+1}} + F_{N_i}}{2} \times (t_{i+1} - t_i) \times 0.24 \quad (3)$$

where NE is the soil N<sub>2</sub>O emission (kg N<sub>2</sub>O ha<sup>-1</sup>), F<sub>N</sub> is the soil N<sub>2</sub>O emission flux, *i*+1 and *i* are the current and the last monitoring dates, respectively, *t* is the number of days after wheat emergence, 0.24 is a conversion factor for mol N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup> to g N<sub>2</sub>O m<sup>-2</sup> day<sup>-1</sup>.

The direct soil GHG emission (GHG<sub>d</sub>) is the sum of the CO<sub>2</sub> equivalent of soil CO<sub>2</sub> and N<sub>2</sub>O and was calculated as:

$$GHG_d = CE + NE \times 298 \quad (4)$$

where GHG<sub>d</sub> is the direct soil GHG emission (kg CO<sub>2</sub>-eq ha<sup>-1</sup>) caused by the soil CO<sub>2</sub> and N<sub>2</sub>O emissions, CE is the soil CO<sub>2</sub> emission (kg ha<sup>-1</sup>), NE is the soil N<sub>2</sub>O emission (kg N<sub>2</sub>O ha<sup>-1</sup>), 298 is the global warming potential indicator for N<sub>2</sub>O over a period of 100 years (Akhtar et al. 2020).

### 2.3.3 Indirect GHG emissions

During the experimental period, data for fertilizer, plastic film, diesel fuel, pesticide, electricity used for irrigation, labor, and seeds were recorded for field management. The inputs to all cropping systems in this study are shown in Table S1. Crop residue, nitrate leaching, ammonia volatilization, and synthetic N in the soil background converted to N<sub>2</sub>O emission are relatively low (Yao et al. 2017). Therefore, these parts of N<sub>2</sub>O emissions were not included in this study. The following formula indicates how the indirect GHG emissions for all these inputs were calculated (Zhang et al. 2018):

$$GHG_i = \sum I_i \times C_i \quad (5)$$

where GHG<sub>i</sub> is the indirect GHG emission (kg CO<sub>2</sub>-eq ha<sup>-1</sup>), I<sub>i</sub> is the amount of input, and C<sub>i</sub> is the index of CO<sub>2</sub> equivalent emissions. The amount of every input and its index of CO<sub>2</sub> equivalent emission in this study is shown in Table S1.

### 2.3.4 Variation in soil organic carbon storage

Soil samples from the 0–20 and 20–40 cm layers were collected before crop seeding in 2018 and after the green manure was returned to the soil in 2020. The soil bulk density of the 0–20 and 20–40 cm layers was measured at the same time for calculating soil organic carbon content (SOC) storage. The SOC was determined by using the potassium dichromate wet combustion method (Bao 2005). For intercropping, the SOC of the wheat or green manure crops strips and maize strips was determined from soil samples collected for each of the intercrops. The SOC of the intercropping system was calculated as the average of the wheat or green manure crop strip and the maize strip. The variation in SOC storage in the topsoil for the different treatments is shown in Fig. S3. The SOC storage and the variation in SOC storage (ΔSOC) were calculated as (Sun et al. 2021):

$$SOC \text{ storage} = \sum_{i=1}^n (C_i \times BD_i \times Z_i) \times 10 \quad (6)$$

$$\Delta SOC = \frac{SOC_a - SOC_b}{3} \times \frac{44}{12} \quad (7)$$

where C<sub>i</sub> is the SOC concentration of the *i*th layer (g kg<sup>-1</sup>), BD<sub>i</sub> is the bulk density of the *i*th layer (g cm<sup>-3</sup>), and Z<sub>i</sub> is the depth of the *i*th layer (cm). The ΔSOC is the variation in the

soil organic carbon storage ( $\text{kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ ), and the  $\text{SOC}_b$  and  $\text{SOC}_a$  are the values of the SOC storage in the 0–40 cm topsoil layer before crop seeding in 2018 and after the green manure was returned to the soil in 2020, respectively. The number 3 represents the experimental duration, and 44/12 is a conversion factor for C to  $\text{CO}_2$ .

### 2.3.5 Net soil GHG balances

Farmland is both a source of GHG emissions and a pool for carbon sequestration. The net soil GHG balance (NGHGB) estimates the capacity for carbon sequestration of the different cropping systems and was defined as the net soil GHG emissions source (positive) or the soil GHG sink (negative) (Wang et al. 2021). In this study, we calculated the NGHGB for each cropping system based on direct soil GHG emissions and variation of the soil organic storage carbon. Thus, we estimated the NGHGB by the following formula:

$$\text{NGHGB} = \overline{\text{GHG}_d} - \Delta\text{SOC} \quad (8)$$

where the NGHGB is the net soil GHG balances of each cropping system ( $\text{kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ ), the  $\overline{\text{GHG}_d}$  ( $\text{kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ ) is the average of direct soil GHG emissions of each cropping system in three years, the  $\Delta\text{SOC}$  is the variation in the soil organic carbon storage during the study period.

### 2.3.6 Grain yield and energy yield

The grain yield and wheat biomass were determined for a 2.5  $\text{m}^2$  area and for 6 m of two rows. The common vetch biomass was determined from a 4  $\text{m}^2$  area. Ears of wheat and maize were hand-harvested from quadrants in all cropping systems, air dried, threshed, and weighed. The grain yield of each crop was determined based on the air-dried weight obtained for a given plot, and the biomass of each crop was oven-dried to a constant weight at 80°C.

Energy yield (EY): For each crop, the energy yield ( $\text{GJ ha}^{-1}$ ) was calculated by multiplying the grain and straw yield ( $\text{kg ha}^{-1}$ ) by their corresponding calorific values ( $\text{MJ kg}^{-1}$ ). This parameter provides a measure of the system productivity in a cropping system that includes different crop species. The formula is (Chai et al. 2013):

$$\text{EY} = (Y_g \times E_g + Y_s \times E_s + Y_m \times E_m) \times 10^{-3} \quad (9)$$

where  $Y_g$  and  $Y_s$  are the grain and straw yield of wheat or maize, and  $E_g$  and  $E_s$  are their calorific values, respectively.  $Y_m$  and  $E_m$  are biomass of common vetch and its calorific value, respectively. The grain calorific value for wheat and maize is  $16.3 \text{ MJ kg}^{-1}$ ; the straw calorific value for wheat, maize and common vetch is  $14.6 \text{ MJ kg}^{-1}$  (Chen 2002).

### 2.3.7 Carbon footprint

We estimated the carbon footprint of different cropping systems from multiple perspectives, including the carbon footprint per unit area ( $\text{CF}_A$ ), per kg grain yield ( $\text{CF}_{GY}$ ), per unit of energy yield ( $\text{CF}_{EY}$ ), and per unit of total economic output ( $\text{CF}_{EC}$ ). The total economic output of the primary crop was calculated according to its grain and straw yield ( $\text{kg ha}^{-1}$ ), multiplied by its annual price ( $\text{\$ kg}^{-1}$ ). The total economic output, production cost, and net economic output are shown in Table S2. The grain prices of wheat and maize were respectively 0.331 and 0.302  $\text{US\$ kg}^{-1}$ , and the straw prices of wheat and maize were 0.075 and 0.030  $\text{US\$ kg}^{-1}$ , where 1  $\text{US\$}$  is equal to 6.809 (<http://olap.epsnet.com.cn>). The calculation formulas are:

$$\text{CF}_A = \text{CE}_d + \text{CE}_i - \Delta\text{SOC} \quad (10)$$

$$\text{CF}_{GY} = \frac{\text{CF}_A}{\text{Grain yield}} \quad (11)$$

$$\text{CF}_{EY} = \frac{\text{CF}_A}{\text{Energy yield}} \quad (12)$$

$$\text{CF}_{EC} = \frac{\text{CF}_A}{\text{Economic output}} \quad (13)$$

where  $\text{CF}_A$ ,  $\text{CF}_{GY}$ ,  $\text{CF}_{EY}$ , and  $\text{CF}_{EC}$  are the carbon footprint for each cropping system per unit area ( $\text{kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ ), per kg grain yield ( $\text{kg CO}_2\text{-eq kg}^{-1} \text{ year}^{-1}$ ), per unit of energy yield ( $\text{kg CO}_2\text{-eq GJ}^{-1} \text{ year}^{-1}$ ), and per unit of total economic output ( $\text{kg CO}_2\text{-eq US \$}^{-1} \text{ year}^{-1}$ ), respectively.

### 2.3.8 Sustainability evaluation

A sustainability index (SI) for each cropping system was created based on the carbon footprint, the output, and the soil organic carbon storage integrated as a whole. The SI was used to determine the cropping system that had the highest productivity with the lowest carbon footprint; a cropping system with a higher index is more environmentally friendly and more sustainable. To ensure that the evaluation component could be compared quantitatively, the variables were non-dimensionalized. Three equations were used to determine the SI (Chai et al. 2013):

$$\alpha_1 x_{ij} = \frac{x_{ij}}{x_{\max}} \left( \begin{array}{l} i = 1, 2, 3, 4, 5 \\ j = 1, 2, 3, 4 \end{array} \right) \text{ or } \alpha_2 x_{ij} = \frac{x_{\min}}{x_{ij}} \left( \begin{array}{l} i = 1, 2, 3, 4, 5 \\ j = 5, 6, 7, 8, 9 \end{array} \right) \quad (14)$$

where  $\alpha x_{ij}$  is a standardized value ( $0 < \alpha x_{ij} \leq 1$ ) at the  $i$ th treatment and the  $j$ th parameters in Fig. 5b, where EC, GY, EY and  $\Delta\text{SOC}$  are assigned to  $j$  ( $= 1, 2, 3, 4$ ) or  $\text{CF}_A$ ,  $\text{CF}_{GY}$ ,  $\text{CF}_{EY}$ ,  $\text{CF}_{EC}$  and NGHGB are assigned to  $j$  ( $= 5, 6, 7, 8, 9$ ),

respectively.  $x_{ij}$  is the corresponding actual value for the treatment  $i$  and parameter  $j$ ; and  $x_{max}$  and  $x_{min}$  are the maximum and minimum values for each evaluation component.

$$\beta_{x_{ij}} = \frac{1}{\alpha_1 x_{ij}} \times \sqrt{\frac{1}{m} \sum_{i=1}^m (\alpha_1 x_{ij} - \alpha_2 x_{ij})^2} \left( \begin{array}{l} i = 1, 2, 3, 4, 5 \\ j = 1, 2, 3, \dots, 8, 9 \end{array} \right) \quad (15)$$

where  $\beta_{x_{ij}}$  is the coefficient of variation for each parameter and  $m$  is the maximum number for  $i$  or  $j$ .

$$SI = \sum_{j=1}^m \left( \alpha x_{ij} \times \frac{\beta_{x_{ij}}}{\sum_{j=1}^m \beta_{x_{ij}}} \right) \left( \begin{array}{l} i = 1, 2, 3, 4, 5 \\ j = 1, 2, 3, \dots, 8, 9 \end{array} \right) \quad (16)$$

## 2.4 Statistical analysis

The SPSS 26.0 software (SPSS Institute Inc, USA) was used to analyze the experimental data. The experimental data were subjected to an analysis of variance (ANOVA) individually for each year. The least significant difference (LSD) test was used to compare the treatment means with  $p < 0.05$ .

## 3 Results and discussion

### 3.1 Soil direct GHG emissions

#### 3.1.1 Soil direct GHG emissions of different cropping systems during the entire growth period

The weighted average calculation indicated that increased crop diversity mitigated the total direct GHG emissions during the entire growth period (Table 1). There was no difference in soil GHG emissions between the W-G/M and W/M treatments over 3 years. Except in 2018 when soil GHG emissions of the W-G/M and W-G treatments showed no significant differences, soil GHG emissions for the W-G/M treatment were 16.2% and 12.2% less in 2019 and 2020, respectively, than soil GHG emissions for the W-G treatment. The total direct GHG emissions for the W-G/M and W/M treatments were respectively 9.9–14.2% and 9.3–15.7% lower than that of the M treatment for 3 years. The W-G treatment showed significantly increased total soil GHG emissions of 21.7% and 31.6% in comparison to the W treatment in 2019 and 2020, respectively. The results indicated that increased crop diversity due to intercropping reduces direct soil GHG emissions in comparison to monoculture and multiple cropping

during the entire growth period. This is consistent with the findings of Cui et al. (2019), who reported that the carbon emissions of maize-based intercropping systems were respectively reduced by 38.0% and 15.3% in comparison to monoculture and rotation systems. Conversely, however, other studies observed that the soil GHG emissions of intercropping systems may increase soil GHG emissions (Raji and Drsch 2020; Wang et al. 2021). These contrasting results might be possibly due to different growth periods and inputs of organic matter that were derived from the selection of diversified intercropped crops (Gentsch et al. 2020).

#### 3.1.2 Soil direct GHG emissions of farmland for different growth periods

The soil cumulative GHG emissions for the wheat production period (WP) and the non-wheat production period (NWP) for the two-component crop farmlands under different cropping systems are shown in Table 1. For all cropping systems, most of the GHG emissions occurred during the NWP, accounting for 55.2–66.1% of total soil GHG emissions. The WP and NWP respectively resulted in 40.1% and 59.9% of total GHG emissions for the W treatment. The WP and NWP respectively resulted in 41.7% and 58.3% of the total GHG emissions for the M treatment. The presence of wheat in two intercropping systems decreased the proportion of GHG emissions during the NWP and increased the proportion of GHG emissions during the WP compared to monocultured wheat. The presence of maize in the W-G/M treatment decreased the proportion of GHG emissions during the NWP and increased the proportion of GHG emissions during the WP compared to monocultured maize. No difference in the proportion of GHG emissions during the WP and the NWP between the maize in the W/M and M treatments was seen.

Over the 3 years, increasing crop diversity via intercropping mitigated direct GHG emissions of the component crop (Table 1). The cumulative soil GHG emissions of maize in the W-G/M and W/M treatments were respectively 5.8–11.0% and 5.3–11.7% lower than that of the M treatment. The cumulative soil GHG emissions of wheat (common vetch) in the W-G/M treatment were 8.4–17.3% lower than that of the W-G treatment, and no difference in the cumulative GHG emissions of wheat was observed between the W/M and W treatments during the 3 years, which showed that a diversified cropping system mitigated soil GHG emissions during the high emission period compared cropping systems with less crop diversity. Additionally, increased crop diversity has contributed to lower soil GHG emissions in the maize and wheat strips simultaneously. These trends may be key considerations in reducing farmland soil GHG emissions by implementing diversified cropping systems. Lisa et al.

**Table 1** Soil cumulative direct GHG emissions of different cropping systems in 2018, 2019, and 2020. WP is the wheat production period; NWP is the non-wheat production period and EGP is the entire growth period of crops. In non-wheat production period, wheat strip represented common vetch strip and summer fallow strip in two intercropping systems, respectively. Total GHG emissions are the weighted average

of the emissions by the two-component crop. W-G/M is spring wheat-common vetch/maize double relay cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat- common vetch multiple cropping, W is monoculture spring wheat. The value of LSD was for all the treatments in the column ( $p < 0.05$ ).

Year	Treatment	WP kg CO <sub>2</sub> -eq ha <sup>-1</sup>			NWP kg CO <sub>2</sub> -eq ha <sup>-1</sup>			EGP kg CO <sub>2</sub> -eq ha <sup>-1</sup>		
		Maize	Wheat	Total	Maize	Common vetch/Fallow	Total	Maize	Wheat	Total
2018	W-G/M	2508	2113	2311	3534	2850	3192	6042	4963	5502
	W/M	2574	2148	2361	3630	2808	3219	6204	4956	5580
	M	2729		2729	3687		3687	6416		6416
	W-G		2268	2268		3284	3284		5552	5552
	W		2204	2204		3188	3188		5392	5392
	LSD (0.05)	213	214	178	108	170	189	206	475	354
2019	W-G/M	3261	2614	2938	4578	5026	4802	7839	7640	7740
	W/M	2941	3135	3038	4508	4346	4427	7449	7481	7465
	M	3263		3263	4969		4969	8232		8232
	W-G		3799	3799		5443	5443		9242	9242
	W		2965	2965		4630	4630		7596	7596
	LSD (0.05)	377	389	216	171	351	335	374	448	412
2020	W-G/M	3317	3699	3508	4288	4599	4443	7605	8297	7951
	W/M	3349	3344	3346	4192	3716	3954	7541	7060	7301
	M	3671		3671	4872		4872	8543		8543
	W-G		3698	3698		5360	5360		9058	9058
	W		2988	2988		3896	3896		6884	6884
	LSD (0.05)	317	476	472	473	451	312	826	703	833

(2012); Qin et al. (2013) also observed that soil GHG emissions of intercropped crops were mitigated compared with monoculture systems. We speculated that the differences in direct GHG emissions from the various cropping systems were possibly caused by interspecific interactions in the diversified cropping systems because interspecific interactions could improve resource utilization efficiency spatially and temporally (Li et al. 2001), which contributed to the mitigation of soil GHG emissions (Hu et al. 2013; Zhang and Li 2003). Diversified cropping systems such as wheat-maize intercropping could decrease nitrate accumulation in the soil profile compared to a monoculture system (Zhang and Li 2003), thus reducing the substrates for soil respiration and nitrification (Gao et al. 2020). Previous studies also have demonstrated that intercropping and rotation reduce soil GHG emissions, related to the higher efficiency of recapturing NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> (Shen et al. 2018). With increasing facilitation interactions, diversified cropping systems could use soil moisture more effectively (Hu et al. 2017), and optimize soil aggregates stability and soil organic sequestration (Zhang and Li 2003; Zhang et al. 2021). Furthermore,

an increase in crop diversification could stimulate specific functional traits of soil microbial (Duchene et al. 2017; King and Hofmockel 2017).

In the present study, spring wheat-common vetch multiple cropping increased direct GHG emissions for a longer time compared with monoculture spring wheat. These results are in accord with those of previous studies (Kim et al. 2013; Yao et al. 2017), which also reported that the application of green manure crops drastically increased soil GHG emissions. Moreover, other researchers believed that the application of green manure caused substantial soil N<sub>2</sub>O emissions because it created a pool of readily available N due to the incorporation of leguminous green manure (Fan et al. 2021; Haque et al. 2015). The leguminous green manure could have resulted in a high release of root exudates in monoculture and multiple cropping systems in the absence of interspecific interactions (Miyazawa et al. 2009), thus promoting soil respiration and nitrification (Kim et al. 2013). Nonetheless, integrated green manure crops into a wheat-maize intercropping system may contribute to the reduction of soil GHG emissions due to



interspecific interactions resulting in a higher soil nutrient utilization efficiency in the diversified cropping systems.

### 3.2 Indirect GHG emissions

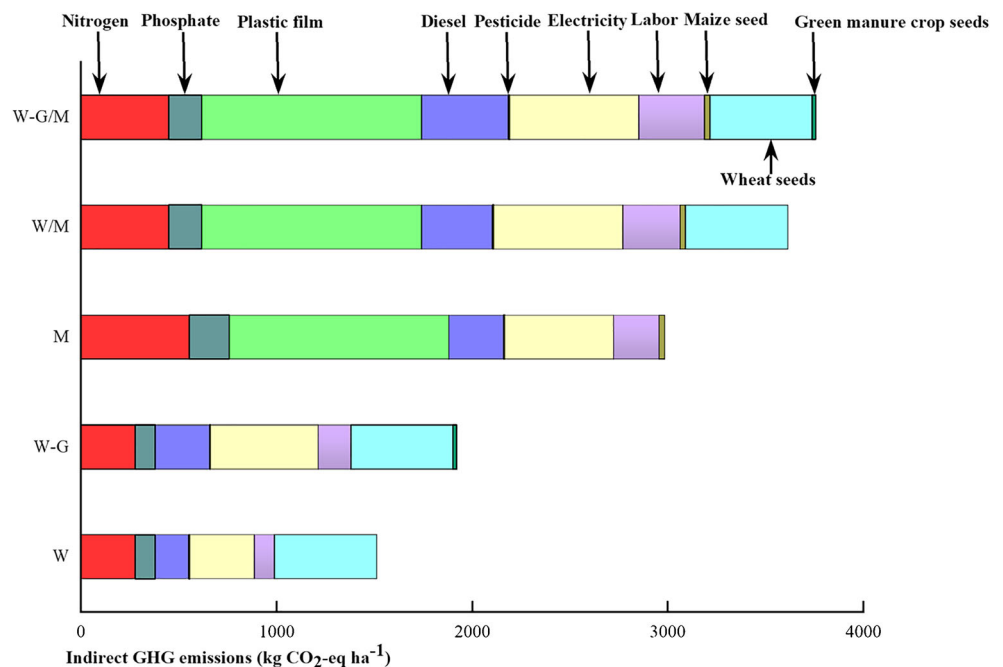
In addition to direct GHG emissions from soil, various agricultural operations such as the labor expended for sowing and harvesting, the electricity used for irrigation, and the inputs of all agricultural materials also indirectly contribute to GHG emissions (Liu et al. 2016; Taki et al. 2018). In the present study, crop diversification increased indirect GHG emissions compared with monoculture (Fig. 2). The indirect GHG emissions of the W-G/M treatment were only 3.3% higher than that of the W/M treatment, while the W-G treatment increased the indirect GHG emissions by 27.4% compared to the W treatment. The magnitude of the indirect GHG emissions increased by 26.4% and 21.6% in the W-G/M and W/M treatments, respectively, compared with the M treatment. Cui et al. (2019) reported that maize-based diversified cropping systems increased indirect GHG emissions by 65.2% compared with a monoculture maize system. These differences were mainly due to different amounts of electricity for different amounts of irrigation. Furthermore, the use of plastic film leads to higher indirect emissions, accounting for 29.1–37.8% of total indirect emissions in intercropping and monoculture maize systems. Higher chemical fertilizer input is one of the reasons for the high indirect GHG emissions of monoculture maize, accounting for 25.4% of the total indirect GHG emissions. Higher inputs of chemical fertilizer and wheat seeds were

responsible for higher indirect GHG emissions in the W-G and W treatments, respectively, accounting for 19.1–25.5% and 27.3–34.8%. Sun et al. (2020) reported that indirect GHG emissions of maize-based intercropping systems were higher by 31.3% in northwest China because of higher inputs of plastic film and electricity in diversified cropping systems. Conversely, studies from North America and the Canadian prairie have found that the diversified cropping systems could decrease agricultural production inputs and reduce indirect carbon emissions (Zentner et al. 2011; Zhou et al. 2012). These contrasting results regarding indirect GHG emissions might be due to the different types of diversified crops resulting in differences in agricultural inputs in various study areas. In arid irrigation areas, plastic film mulching and irrigation are vital for crop production and might increase indirect GHG emissions (Yin et al. 2017; Zhou et al. 2012).

### 3.3 Crop productivity

Crop diversification has attracted increasing attention as an effective strategy to improve or maintain crop productivity (Agegnehu et al. 2008; Beillouin et al. 2021). Intercropping systems as a spatial diversification practice have been widely demonstrated to improve grain yield by 20% (Li et al. 2001; Wang et al. 2021; Chai et al. 2021). Our results also show that diversified cropping systems promote crop productivity in arid irrigation areas. Increasing crop diversity via intercropping significantly increased crop productivity compared to other cropping systems in this study (Table 2). No differences in the total grain yield were found between the W-G/M and W/M

**Fig. 2** Contributions of the different inputs of indirect GHG emissions in different cropping systems. W-G/M is spring wheat-common vetch/maize double relay cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat-common vetch multiple cropping, W is monoculture spring wheat.



treatments in 2018 and 2019, except in 2020 when the total grain yield of the W-G/M treatment was 8.7% higher than that of the W/M treatment. Over the study period, the total grain yield was increased by 9.2–17.0% for the W-G/M treatment and 7.2–11.1% for the W/M treatment in comparison to the M treatment. No differences in grain yield were observed among the W-G and the W treatments in 2018 and 2019, except in 2020 when the total grain yield of the W-G treatment was 15.1% higher than that of the W treatment. The energy yield of the W-G/M treatment was 9.5–25.1% greater than the energy yield of the W/M treatment, and 19.4–65.8% and 12.6–48.9% higher than that of the M treatment over the 3 years. The W-G treatment had a higher energy yield of 23.5–30.0% than the W treatment over the 3 years. These results indicated that the W-G/M treatment could increase crop yield if the experiment duration was extended, compared to the W/M treatment, because the W-G/M treatment introduced a green manure crop during the fallow period. The planting of leguminous green manure crops has been widely demonstrated to improve primary crop productivity (Haque et al. 2013; Fan et al. 2021;). It is possible that leguminous green manure introduced during the fallow period could improve the soil microbiome and consequently, soil health (Plaza-Bonilla et al. 2016; Wang et al. 2022), which would increase primary crop productivity.

Compared with the W-G treatment, the grain yield of the intercropped wheat in the W-G/M treatment was improved by 44.6% and 25.5% on the same area basis in 2018 and 2019, respectively, and no differences in the grain yield of wheat were found for the W-G/M and W-G treatments in 2020 (Table 2). Compared with the M treatment, the grain yield of the intercropped maize was increased by 46.4–82.5% and 51.9–64.7% for the W-G/M and W/M treatments on the same area basis, respectively. Particular crops in diversified cropping systems showed significantly higher grain yields over cropping systems with less crop diversity. The increases in grain yield in diversified cropping systems are primarily due to complementary effects when diverse crops are planted in the same field annually (Zhang and Li 2003; Chai et al. 2021).

### 3.4 Net soil GHG balances and carbon footprint

#### 3.4.1 The NGHGB of different cropping systems

An effective method to estimate the carbon budget of an agroecosystem is to calculate the net soil GHG balance (NGHGB), which reflects the capacity for carbon sequestration in a farmland (Wang et al. 2021). Our results showed that all the cropping systems functioned as net GHG emissions

**Table 2** The grain yield and energy yield of maize, wheat, and green manure crops in different cropping systems in 2018, 2019, and 2020. Total yields are the sum of the yields produced by the two-component crop. W-G/M is spring wheat-common vetch/maize double relay

Year	Treatment	Grain yield (kg ha <sup>-1</sup> )			Energy yield (GJ ha <sup>-1</sup> )			
		Maize	Wheat	Total	Maize	Wheat	Common vetch	Total
2018	W-G/M	9839.5	4840.1	14679.6	210.5	168.7	58.1	437.3
	W/M	10255.3	4671.9	14926.2	262.7	136.8		399.5
	M	13441.5		13441.5	353.5			353.5
	W-G		6696.6	6696.6		190.3	112.8	303.1
	W		6675.9	6675.9		233.4		233.4
	LSD (0.05)	1166.2	450.5	682.1	97.8	56.2		36.8
2019	W-G/M	9591.3	4118.7	13709.0	298.5	135.3	47.6	481.5
	W/M	9051.4	3731.9	12782.4	285.5	165.2		450.7
	M	11920.2		11920.2	403.4			403.4
	W-G		6588.1	6588.1		270.3	68.5	338.8
	W		6203.0	6203.0		274.2		274.2
	LSD (0.05)	2122.3	513.8	1133.2	126.1	58.3		28.9
2020	W-G/M	10907.2	3071.4	13978.6	340.1	185.0	56.3	581.5
	W/M	9840.4	3016.6	12855.9	273.3	191.4		464.7
	M	11952.0		11952.0	313.0			313.0
	W-G		6761.2	6761.2		256.2	65.8	322.0
	W		5874.2	5874.2		25.0		250.1
	LSD (0.05)	1337.3	407.4	781.6	10.9	5.8		69.1

cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat-common vetch multiple cropping, W is monoculture spring wheat. The value of LSD was for all the treatments in the column ( $p < 0.05$ ).

resources (Fig. 3). The NGHGB of the W-G/M treatment was respectively 15.1% and 18.4% lower than the NGHGB of the W/M and W-G treatments. The NGHGB of the W-G/M treatment was 35.4% lower in comparison to the M treatment. No difference in the NGHGB was seen between the W-G and W treatments, indicating that increased crop diversity due to intercropping contributed to mitigating the NGHGB and improving soil carbon sequestration.

### 3.4.2 Carbon footprint of different cropping systems

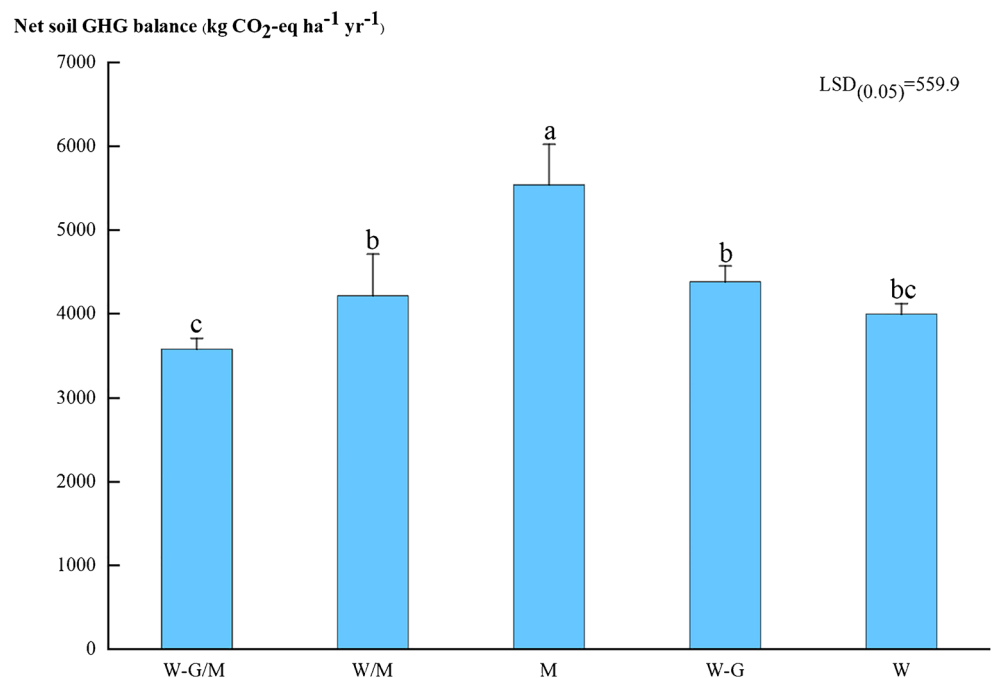
Evaluations from multiple perspectives have been widely used for the analysis of the carbon footprint and sustainability of different cropping systems (Huang et al. 2019; Sun et al. 2021). We determined that the carbon footprint of each cropping system from an integral agroecosystem perspective ( $CF_A$ ,  $CF_{GY}$ ,  $CF_{EY}$ ,  $CF_{EC}$ ) to lower applying single index trade-offs lead to one-sided conclusions (Huang et al. 2019; Liu et al. 2016). The  $CF_A$ ,  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  of the W-G/M treatment were respectively 5.3%, 14.3%, 16.4%, and 7.4% lower than those of the W/M treatment (Fig. 4). Compared with the W-G treatment, the  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  of W-G/M treatment were respectively decreased by 51.2%, 30.9%, and 33.6%. Additionally, the  $CF_A$ ,  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  of the W-G/M treatment were respectively decreased by 12.2%, 27.9%, 37.6%, and 29.6% in comparison to the M treatment. The  $CF_A$ ,  $CF_{GY}$ , and  $CF_{EC}$  of W-G treatment were respectively increased by 22.6%, 14.8%, and 17.3% compared with the W treatment. No difference

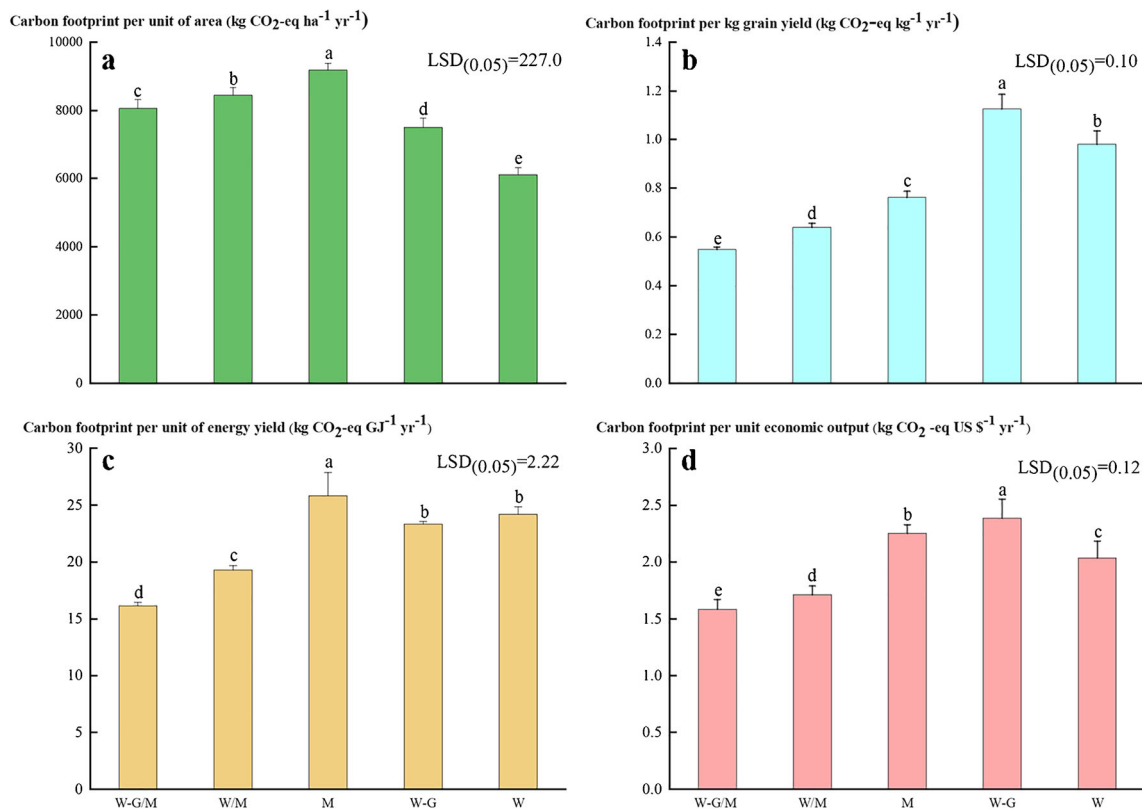
was seen for the  $CF_{EY}$  for the W-G and W treatments. These results demonstrated that increased crop diversity due to intercropping can significantly mitigate the carbon footprint of cropping systems. A number of studies have reported that crop diversification could decrease the carbon footprint for several reasons (Rodriguez et al. 2021; Sun et al. 2021; Yang et al. 2014). Firstly, more diversified cropping systems had lower direct GHG emissions than cropping systems with less diversity. Secondly, more carbon was returned to the soil, supplying abundant carbon resources for crops in diversified cropping, thus promoting soil carbon sequestration (Ceschia et al. 2010; King and Hofmockel 2017). Thirdly, diversified cropping systems produced higher yields and had a greater economic output than that of less diverse cropping systems. Overall, our study confirmed that increased crop diversity due to intercropping mitigate the carbon footprint by reducing direct GHG emissions, and enhancing crop productivity.

### 3.5 The sustainability of cropping systems

Sustainable crop production is essential for agriculture, and more researchers are paying attention to the environmental costs of crop production (Viguier et al. 2021). However, most published studies generally focus on grain yield, economic output, or soil nutrients, which may limit the promotion of the potential advantages of cropping systems (Agegnehu et al. 2008). Focusing on total grain yield per unit of land alone is contrary to the goals of

**Fig. 3** Net soil GHG balance (NGHGB) of different cropping systems. W-G/M is spring wheat-common vetch/maize double relay cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat-common vetch multiple cropping, W is monoculture spring wheat. The error bars indicate the standard errors of the means ( $n=3$ ). The value in the figure is the least significant difference (LSD) of all treatments. The different lowercase numbers above indicate significant differences between treatments ( $p < 0.05$ ).



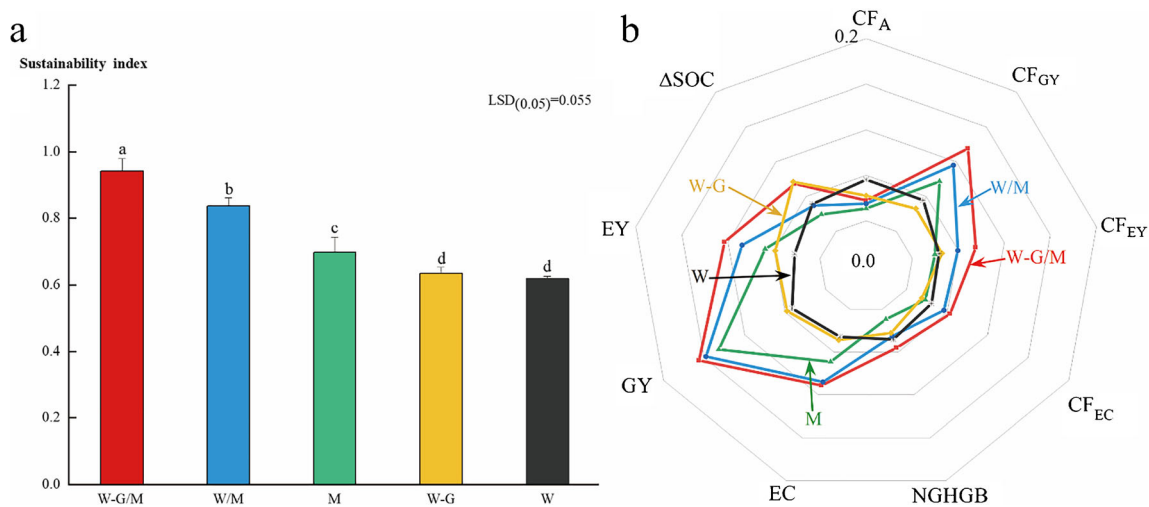


**Fig. 4** Annual average carbon footprint per unit area (a), per kg grain yield (b), per unit of energy yield (c), and per unit economic output (d) for different cropping systems from 2018 to 2020. W-G/M is spring wheat-common vetch/maize double relay cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat-common

vetch multiple cropping, W is monoculture spring wheat. The error bars indicate the standard errors of the means ( $n=3$ ). The value in each figure is the least significant difference (LSD) of all treatments. The different lowercase numbers above indicate significant differences between treatments ( $p < 0.05$ ).

sustainable agriculture (Chai et al. 2013; Lithourgidisa et al. 2007). Specifically, studies that comprehensively assess the performance of diversified cropping systems in crop production are lacking, and this has been believed to seriously hinder the development of diversified cropping systems (Meynard et al. 2018; Viguier et al. 2021). Previous studies have also confirmed that crop diversification measures may not always be positive and might lead to environmental damage (Kim et al. 2013). Therefore, a suitable integrated index based on multiple factors is urgently needed to avoid the use of a single factor that would lead to biased results regarding diversified cropping systems. In the present study, we integrated nine key crop productivity- and carbon footprint-related factors to determine a sustainability index (SI). We used the SI to evaluate the sustainability or effectiveness of various cropping systems currently adopted in the arid inland areas of northwest China. The W-G/M treatment had the highest SI (0.94) (Fig. 5a), which was respectively 12.6%, 35.0%, and 48.5% higher than that of the W/M, M, and W-G treatments. The SI of the W/M treatment was 19.9% higher than that of the M treatment. In terms of

components, the M, W-G, and W treatments had lower crop productivity and a relatively higher carbon footprint (Fig. 5b). On the contrary, the W-G/M and W/M treatments alleviated the environmental impacts present in the other treatments and had relatively lower carbon footprints, along with higher productivity and economic output. Accordingly, increasing crop diversity via intercropping significantly improved the SI of cropping systems. The W-G/M treatment could maintain the economic output since it achieved comparable or better crop yield than the W/M treatment (Fig. 5b and Table S2), implying that the yield increases of the primary crops offset the negative effect of common vetch as green manure, which was unprofitable and only generated costs. The W-G/M treatment was more sustainable and effective. These results confirmed our hypothesis that increasing crop diversity on the same plot promoted crop productivity without increasing the environmental risk. We propose that integrating common vetch as green manure into a wheat-maize intercropping system is a promising approach for safeguarding crop productivity while reducing the carbon footprint in arid irrigation areas.



**Fig. 5** The sustainability index of different cropping systems (a), and performance of evaluated components for different cropping systems using radar chart (b).  $CF_A$ , carbon footprint per unit of area;  $CF_{GY}$ , carbon footprint per kg grain yield;  $CF_{EY}$  carbon footprint per unit of energy yield;  $CF_{EC}$  carbon footprint per unit economic output; NGHGB, net soil GHG balance; EC, total economic output; GY, grain yield; EY, energy yield;  $\Delta SOC$ , variation in SOC storage. W-G/M is

spring wheat-common vetch/maize double relay cropping, W/M is wheat-maize intercropping, M is monoculture maize, W-G is spring wheat-common vetch multiple cropping, W is monoculture spring wheat. The error bars indicate the standard errors of the means ( $n=3$ ). The value in figure a is the least significant difference (LSD) of all treatments. The different lowercase numbers above indicate significant differences between treatments ( $p < 0.05$ ).

### 3.6 The limitation and outlook of this study

Some limitations might apply to the results of this study. Due to the lack of local carbon emission factors to estimate indirect GHG emissions, the emission factors we used in our study were integrated with international emission factors (Gan et al. 2011; Liu et al. 2013; Huang et al. 2019). Also, some uncertainties are inherent in the carbon footprint calculations. For instance, many types of plastic film and pesticides are being used, and have no exact emission factors. The indirect carbon emissions caused by the depreciation of farm machinery, various farm operations, and labor are not negligible in an LCA approach (Sun et al. 2021; Yang et al. 2014). The calculated carbon footprint of this study could change if these undefined energy terms were considered in the system boundary. Soil carbon sequestration could have great potential to mitigate the carbon footprint (Petersen et al. 2013). In this study, only the NGHGB was used to estimate the capacity for carbon sequestration in farmland. Net ecosystem production (NEP) was not used to calculate carbon balance for the agroecosystem (Yin et al. 2017), which would affect the carbon balance calculation.

This study only evaluated the sustainability of cropping systems under conventional field management, but diversified cropping systems can achieve much higher sustainability if variety optimization, better fertilizer management, and better tillage practices are employed (Rodriguez et al. 2021). Furthermore, a sustainability evaluation of diversified cropping systems as affected by irrigation water consumption and labor use should be considered in future research.

Although 3 years is a short time for a sustainability evaluation, the simplified index we determined bodes well for long-term sustainability, evaluated by considering more comprehensive components of diversified cropping systems.

## 4 Conclusions

This study analyzed four carbon footprints of diversified cropping systems in arid irrigation areas. The results confirmed that increasing crop diversity on the same plot annually could increase crop productivity per unit of arable land, and the NGHGB and direct GHG emissions were also lower. Accordingly, diversified cropping systems significantly reduced the carbon footprint when compared to cropping systems with less diversification. In 2020, the total grain yield of the W-G/M treatment was 8.7% higher than that of the W/M treatment. The energy yield of the W-G/M treatment was 9.5–25.1% greater than the energy yield with the W/M treatment over 3 years. The  $CF_A$ ,  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  of the W-G/M treatment were respectively lower by 5.3%, 14.3%, 16.4%, and 7.4% compared to the W/M treatment. Additionally, the W-G/M treatment respectively reduced the  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  by 51.2%, 30.9%, and 33.6% in comparison to the W-G treatment. Compared with the M treatment, the  $CF_A$ ,  $CF_{GY}$ ,  $CF_{EY}$ , and  $CF_{EC}$  of the W-G/M treatment were respectively lower by 12.2%, 27.9%, 37.6%, and 29.6%. It is worthwhile to mention that the W-G/M system achieved the highest sustainability index (0.94) due to improved crop productivity and a lower carbon footprint than the other systems. In conclusion,

increasing crop diversity on the same plot annually has been demonstrated to be an effective and sustainable practice for crop production. The novelty of this study is showing that integrating green manure into a wheat-maize intercropping scheme may achieve emissions reduction and increase productivity in arid irrigation areas.

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**Authors' contributions** Conceptualization, Z.W.G. and Q.C.; Methodology, Q.C. and W.D.C.; Investigation, Z.W.G., W.Y., and A.E.A.; Writing—original draft, Z.W.G. and W.Y.; Writing—review and editing, Z.W.G. and Q.C.; Funding acquisition, Q.C. and W.D.C.; Resources, Z.L.F. and W.Y.; Supervision, Z.W.G., Q.C., and W.D.C.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** All the authors whose names appeared on the submission approved the version to be published and agreed to be accountable for all aspects of the work in ensuring that the questions related to the accuracy of the integrity of any part of the work were appropriately investigated and resolved.

**Conflict of interest** The authors declare no competing interests.

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