

Restructuring lucerne planting can improve production and environmental co-benefits in Northwest China

Huiping Zhou^{a,b}, Xiaowei Ding^{a,b}, Jiabao Chen^{a,b}, David Parsons^c, Liebao Han^{a,b,*}

^a School of Grassland Science, Beijing Forestry University, Beijing 100083, China

^b Engineering and Technology Research Center for Sports Field and Slope Protection Turf, National Forestry and Grassland Administration, Beijing 100083, China

^c Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Umeå 90183, Sweden

ARTICLE INFO

Keywords:

Restructuring planting
Climate change
Lucerne
Yield and quality
Global warming potential

ABSTRACT

As China's cornerstone lucerne production region, Gansu Province plays a pivotal role in sustaining national forage security and livestock systems, yet the climate resilience of this strategic crop remains critically unassessed. Here we present a multi-objective optimization framework integrating process-based modeling and climate change projections under SSP245 and SSP585 scenarios to reconcile lucerne biomass and protein production, irrigation water productivity, and global warming potential from field (GWP-field) trade-offs. We project that lucerne biomass and protein production in Gansu will increase 5.7 %-25.3 % by the 2090 s, but with a 6.0 %-10.1 % decrease in protein concentration, primarily as temperature-affected biomass increases mask the declines in protein concentration. Strategic spatial restructuring of cultivation could achieve synergistic benefits - elevating biomass and protein yield by 1.4 %-2.0 % while simultaneously diminishing irrigation and GWP-field by 1.4 %-3.9 %. The new planting patterns identified 4238–5521 ha of priority expansion in Longzhong and Longdong, where phased cultivar deployment could maximize benefits of production (1.4–2.0 % increase), resource use (3.4–3.9 % decrease), and environmental impact (1.4–1.9 % decrease). However, increasing lucerne production to expand cattle and sheep feeding would result in an additional 17.9–20.0 thousand CO₂-eq of emissions due to enteric fermentation and manure management, even taking into account the benefits of restructuring lucerne planting and irrigation saving on GWP. Our findings underscore the imperative of multi-dimensional optimization in balancing agronomic gains against environmental impacts in cropping systems of arid regions.

1. Introduction

The continuous improvement of living standards has led to a growing demand for livestock products, and the scale of development of livestock industries depends on the supply of sufficient and high-quality forage. Lucerne (*Medicago sativa* L.), is a crucial and high-quality forage crop, which provides essential fiber and protein to livestock (Sanz-Sáez et al., 2012; Feng et al., 2022; Varol et al., 2024). China has increased its alfalfa import, from 19601 metric tons in 2008–1.38 million metric tons in 2018 (Wang and Yang, 2020), demonstrating a large increase in demand. Addressing regional lucerne production to achieve a simultaneous improvement in yield and reduction in GHG emissions and water use remains an urgent scientific issue requiring resolution, especially in the current context of international trade disputes and the pressing need to reduce dependence on imported forage.

The intensity of agricultural practices such as irrigation, fertilization and land use significantly impacts lucerne production, yet it can also lead to excessive resource inputs, inefficient utilization, and increased greenhouse gas emissions (GHGs) (Zhang et al., 2024). Optimizing irrigation and fertilization can enhance lucerne yield, quality, and water use efficiency. However, the quantity and timing of water and fertilizer applications should be adjusted in response to changing climatic factors throughout the growing season (Jia et al., 2024; Zhang et al., 2020). Intensification of agronomic inputs, including irrigation (Varol et al., 2024), fertilization (Macolino et al., 2013), and land management practices (Feng et al., 2022) may induce moderate yield increases; however, those approaches entail significant trade-offs through resource depletion, suboptimal input-use efficiency, and elevated GHG. The resulting long-term and regional variations in production with interannual differences need to be addressed.

* Corresponding author at: School of Grassland Science, Beijing Forestry University, Beijing 100083, China,
E-mail address: hanliebao@163.com (L. Han).

<https://doi.org/10.1016/j.agwat.2025.109927>

Received 24 May 2025; Received in revised form 20 September 2025; Accepted 21 October 2025

Available online 25 October 2025

0378-3774/© 2025 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Spatially optimized restructuring of cultivation has been demonstrated as an effective strategy to enhance the yield potential of crops across diverse agroecological zones in China (Zhang et al., 2018). Planting areas, types, and patterns of crops can be optimized. This can maximize crop yields and bring them closer to their physiological potential which is an effective way to further improve regional production and environmental benefits. This approach allows crops to be cultivated in suitable areas and facilitates the efficient use of key resources such as light, water, and nutrients (Hu et al., 2025; Liu et al., 2023). However, previous planting structure optimization has predominantly targeted ecological restoration (Sun et al., 2024), and grain and vegetable crops (Wen and Chen, 2023), with limited attention to forage crops.

Gansu is one of China's major production areas for lucerne, accounting for a significant proportion of the country's total output (Yin et al., 2022). The abundant sunlight and large diurnal temperature variation provide ideal natural conditions for lucerne growth. However, water resource scarcity has constrained the scale of production and planting (Gu et al., 2018; Yin et al., 2022; Zhou et al., 2024). Previous studies only performed regional-scale simulations of lucerne yield (Azadbakht et al., 2022; Qin et al., 2023; Wang et al., 2021), without addressing protein content or global warming potential, and certainly without conducting crop optimization for specific regions. Making lucerne production more climate resilient in Gansu directly affects regional and even China's livestock security, and restructuring its cultivation is a potentially viable option.

In this study, a calibrated mechanistic model (APSIM) was used to simulate the yield, protein, actual water consumption (ET_a), irrigation water requirement (IWR), and global warming potential (GWP) of lucerne in Gansu Province. The spatial and temporal variability of key variables, trade-off inputs (land and irrigation water), outputs (yield and protein), and costs (GWP) were assessed in response to restructuring of cultivation. The aim was to improve production, conserve irrigation water, improve resource use efficiency, and reduce carbon emissions. We sought to identify dynamic climate adaptation strategies proposed without expanding cultivation to balance the inputs, production, and costs of lucerne.

2. Materials and methods

2.1. Study area

Gansu Province (32°31'–42°57'N, 92°13'–108°46' E), located in Northwest China, spans an area of 42.58×10^4 km² (Fig. 1a) and sustains a permanent resident population of 24.58 million. It encompasses the primary ecological types of the Northwest China, including the Loess

Plateau region (e.g., Qingyang, Pingliang), the Hexi Corridor irrigated agricultural region (e.g., Wuwei, Zhangye, Jiuquan), the northeastern edge of the Qinghai-Tibet Plateau (e.g., Gannan), and the desert and semi-desert region (bordering Inner Mongolia and Ningxia). This arid-to-semiarid region serves as a major cultivation hub for lucerne (*Medicago sativa* L.), producing approximately 33 % of China's total yield, while concurrently maintaining its status as a pivotal animal husbandry base. Provincial livestock inventories rank third and ninth nationally in sheep and cattle populations, respectively, underscoring their strategic importance in China's agricultural ecosystem. The average annual precipitation is 399 mm (spatial range of 50–750 mm), and the average annual temperature is 9.5°C (spatial range of 0–15°C) based on 30 years of municipal meteorological observations (<http://data.cma.cn>). Based on hydrological and geographic factors, Gansu Province is divided into six sub-regions at the city level, namely Shule River Basin, Heihe River Basin, Shiyang River Basin, Longzhong, Longnan, and Longdong (Fig. 1b).

2.2. Flow chart of this study

The flowchart for this study is shown in Figure S1, divided into three parts: APSIM Simulation, Planting reconstruction, and analysis and evaluation. APSIM was calibrated and validated using collected data for grided simulation, with the simulations serving as inputs for lucerne planting reconstruction. The new pattern of lucerne cultivation in Gansu Province was derived, and regional biomass production, protein production, irrigation water requirement (IWR), and global warming potential (GWP, including from field, cattle and sheep breeding, and irrigation-saving) were further calculated, clarifying the livestock potential supported by lucerne production surpluses and its environmental costs.

2.2.1. APSIM simulation

APSIM is a process-based crop model that includes plant, soil, and management modules (Keating et al., 2003). APSIM was used to simulate lucerne biomass yield, protein yield, actual water consumption (ET_a), global warming potential of agro-field soil respiration from field (GWP-field), and consequently to calculate protein concentration, IWR, irrigation water productivity (IWP), and greenhouse gas intensity (GHGI):

$$\text{Proteinconcentration} = (\text{Proteinyield}/\text{Biomassyield}) \times 100 \quad (1)$$

$$\text{IWR} = ET_a - P_{gs} \quad (2)$$

$$\text{IWP} = \text{Biomassyield}/\text{IWR}/10 \quad (3)$$

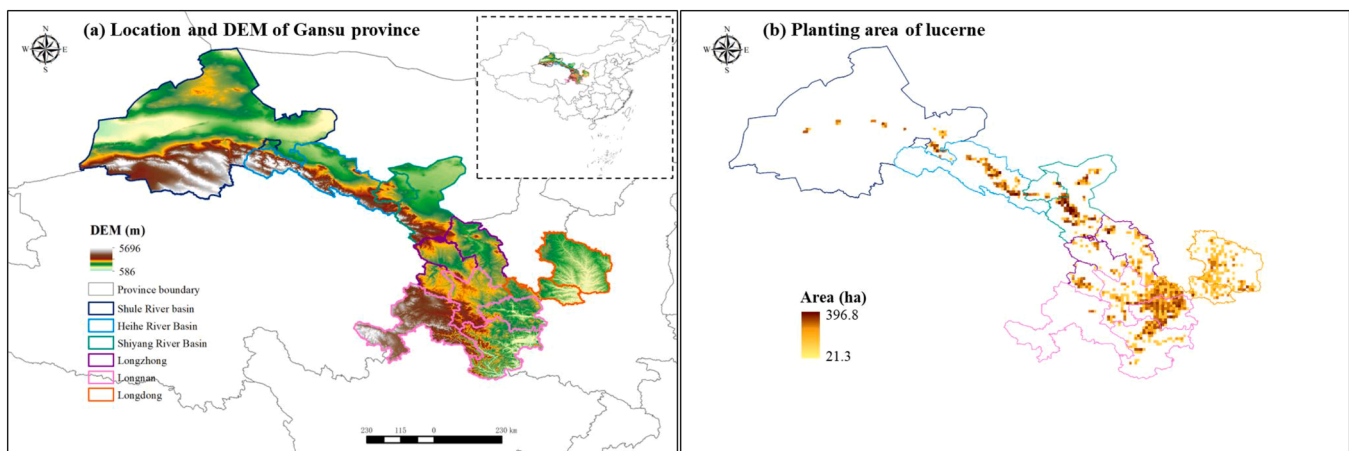


Fig. 1. Location, Digital Elevation Model (DEM), subregions, and lucerne planting area of Gansu Province. Subregions include Shule River Basin, Heihe River Basin, Shiyang River Basin, Longzhong, Longnan, and Longdong.

$$GWP - field = CO_2 + 273 \times N_2O + 27 \times CH_4 \quad (4)$$

$$GHGI = GWP - field / Biomass_{yield} \quad (5)$$

where IWR, ET_a , and P_{gs} are irrigation water requirement, actual crop water consumption, and total precipitation during the growing season in each harvest, mm; IWP is irrigation water productivity, kg/m^3 , and 10 is the conversion coefficient; GWP-field is the global warming potential from field, $kg CO_2 eq/ha$; GHGI is greenhouse gas intensity, $kg CO_2 eq/kg$ biomass. Irrigation water productivity was calculated based on non-deficit irrigation conditions, i.e., IWR. For GWP-field calculations, CO_2 , CH_4 , and N_2O were considered in APSIM, including Carbon_{tot}, C_{atm} (consisting of fom, bom, hum and residue), and N_2O_{atm} (top 30-cm soil depth). GWP-field was calculated based on the molecular weight ratio and conversion factor, as detailed information in Hochman et al. (2017) and Zhou et al. (2025).

The parameters of lucerne in APSIM were calibrated based on measured data from 11 field experiments conducted in Gansu Province (Table S1) by using the CROPTIMIZR package (Buis et al., 2021). The experiments were conducted from 2013 to 2019 in Jiuquan, Wuwei, and Jiayuguan of Gansu Province, incorporating different irrigation and fertilization treatments (Table S1). Coefficient of determination (R^2) and normalized root mean square error (nRMSE) were used to evaluate model performance. The nRMSE is classified as good ($nRMSE \leq 15\%$), moderate ($15\% < nRMSE \leq 30\%$), and poor agreement ($nRMSE > 30\%$), respectively, and R^2 is classified as unsatisfactory ($R^2 \leq 0.6$), satisfactory ($0.6 < R^2 \leq 0.7$), good ($0.7 < R^2 \leq 0.8$), and very good ($R^2 > 0.8$). The calibrated crop parameters are shown in Table S2, which determine crop growth and leaf development processes, radiation use efficiency, and photosynthetic product allocation under changing environment. The performance of calibrated APSIM is shown in Figure S2.

For APSIM modelling, auto-irrigation (Irrigation on sw deficit function) and auto-fertilizer (FerOnSoilNCriteria function) options were used in each grid cell, which meant there was no deficit. Lucerne is a perennial crop that was set up in the model to be resown every 4 years, on May 5th. Harvests were simulated when lucerne growth reached the flowering stage, and harvest times were variable during the years. Biomass yield, ET_a , protein yield and concentration, IWR, IWP, GWP-field, and GHGI were recorded throughout each year.

2.2.2. Planting optimization

A genetic algorithm was used to restructure lucerne cultivation in Gansu Province. The objective functions were maximizing biomass production, maximizing protein production, minimizing IWR and minimizing GWP-field:

$$\max Production - biomass_{sum} = \sum_{i=1}^n (Y - biomass_i \cdot A_i) \quad (6)$$

$$\max Production - protein_{sum} = \sum_{i=1}^n (Y - protein_i \cdot A_i) \quad (7)$$

$$\min IWR_{sum} = \sum_{i=1}^n (IWR_i \cdot A_i) \quad (8)$$

$$\min GWP - field_{sum} = \sum_{i=1}^n (GWP - field_i \cdot A_i) \quad (9)$$

where i is the number of grids ($i = 1, 2, \dots, n$); Y -biomass _{i} and Y -protein _{i} are the biomass yield and protein yield in i^{th} grid, respectively, kg/ha ; A_i is the planting area of lucerne in the i^{th} grid, ha ; IWR_i is the IWR of lucerne in the i^{th} grid, mm ; $GWP - field_i$ is the GWP from lucerne field in the i^{th} grid, $kg CO_2 eq/ha$; $production - biomass_{sum}$, $production - protein_{sum}$, IWR_{sum} , and $GWP - field_{sum}$ are the total biomass production, protein production, IWR, and GWP from field of lucerne in the Gansu Province,

respectively. Biomass production, protein production, IWR, and GWP-field were considered equally important. Research demonstrating agricultural and ecological optimization had shown that strategies derived from equally weighted settings were valuable for practical management (Deléglise et al., 2024; Wang et al., 2019). Therefore, the weight for each of the four objectives was set at 0.25 based on the normalized results as weight scenario I in this study. Simultaneously, the analytic hierarchy process (AHP) method established weighting scenarios II and III by setting biomass production as relatively more important than the other three objectives and as equally important to protein production while being relatively more important than the other two objectives, respectively. This was performed to characterize the impact of varying objective weights on the optimization results.

The genetic was implemented using the scikit-opt package (Head et al., 2020) in Python v 3.9, and the key settings were: the population size was 600, the maximum number of generations was 1000, the proportional selection and single-point crossover were selected, the crossover probability was 0.75, and the probability of variance was 0.01. The convergence curve showed that the algorithm reached stable performance at the 755th generation (Figure S3).

Maintaining the planted area unchanged was the main constraint:

$$\sum_{i=1}^n A_i \leq A_{sum} \quad (10)$$

$$A_i \leq A - grid_i \quad (11)$$

where A_{sum} is the total lucerne planting area in Gansu Province, ha ; $A - grid_i$ is the area of grid, ha . The genetic algorithm was implemented by using the *ga* function in the R package 'GA' (Scrucca, 2013). The main parameters of the genetic algorithm in this study were set as follows: the size of population was 2000, the maximum number of generations was 1000, the crossover method was single-point, the probability of crossover was 0.8, and the probability of variation was 0.01.

2.2.3. Analysis and evaluation

In this study, we hypothesized that lucerne surplus was used for cattle and sheep breeding, with the resulting GWP from enteric fermentation and manure management (GWP-livestock) and the from irrigation-saving (GWP-irrigation) considered alongside GWP-field to calculate carbon reduction potential. When calculating GWP-livestock and GWP-irrigation, factors related to electricity consumption for irrigation wells and enteric fermentation and manure management in cattle and sheep breeding were considered and the corresponding emission factors were referred to IPCC (2023), Gansu Province Statistical Yearbook (<https://tjj.gansu.gov.cn/>), and Database of National Greenhouse Gas Emission Factor (<https://data.ncsc.org.cn/factoryes/index>) (Table S3). A life-cycle assessment was not employed because the distribution of lucerne feed and supply changes after increased production, and carbon emissions from energy consumption, transportation, and additional resource inputs for new livestock farms are highly uncertain.

2.3. Data sources

Given that raster data on lucerne planting area is not currently available, we generated data based on land use and land cover change (LUCC) (<https://www.resdc.cn/Default.aspx>) (1-km spatial resolution) and Gansu Province Statistical Yearbook (<https://tjj.gansu.gov.cn/>). Lucerne is part of an agricultural system, and most of the current plantings in Northwest China are located in areas with well-established irrigation, (<http://nync.gansu.gov.cn/>). We hypothesized that lucerne planting areas only occur where arable land area is aggregated. Therefore, a new blank raster with 5' resolution was generated to count the planting land in LUCC, and then the area in the raster with the planting area in the top 50 % of the whole area was filtered out at first, and then multiplied by 0.3 based on statistical lucerne planting data in Gansu

Province (0.179–0.192 million ha during 2015–2020 ha) to get the raster data of lucerne planting in Gansu Province, which was used as a baseline for the calculation of the production, consumption, and emission.

Soil properties data (bulk density, field capacity, wilting point, saturated water content, saturated hydraulic conductivity, alkali-hydrolysable N, and soil organic matter) were obtained from the Soil Database of China for Land Surface Modeling (30" spatial resolution) (Shangguan et al., 2013) and the China Dataset of Soil Hydraulic Parameters Using Pedotransfer Functions for Land Surface Modeling (30" spatial resolution) (Dai et al., 2013; Shangguan and Dai, 2013). Historical (1981–2020) and future (2021–2100) climate data were obtained from the China Meteorological Forcing Dataset (0.1° spatial resolution) (Yang et al., 2019) and the Impact Model Intercomparison Project (0.5° spatial resolution) (ISIMIP, <https://data.isimip.org/>), respectively, including daily precipitation, minimum and maximum air temperature, specific humidity, wind speed, and downwelling shortwave radiation. Two typical Shared Socioeconomic Pathways, SSP245 (low-emission socioeconomic pathway) and SSP585 (high-emission socioeconomic pathway), and three typical global circulation models (GCMs), Can-ESM5, CNRM-CM6-1, and CNRM-ESM2-1, were used in the APSIM simulation. Simulation results under the three GCMs from the three GCMs were averaged at each grid point annually for analysis and evaluation. Uncertainties from different GCMs are illustrated in Figure S4. A first-order conservative remapping procedure was used to resample the APSIM input data to maintain a uniform 5' spatial resolution.

3. Results

3.1. Spatial and temporal variability of lucerne production

The calibrated APSIM performed well ($R^2 = 0.95$, nRMSE = 20.2 %) when compared to the collected real-world experimental data (Figure S2), which consequently we used for simulation in each grid cell. Variables related to lucerne production (biomass, protein yield, and protein concentration), inputs (IWR), resource use efficiency (IWP), and cost (GWP-field and GHGI) were characterized by strong temporal and spatial variability (Fig. 2–4 and S5–S6). We averaged the annual simulations in 10-year steps at each raster to show trends of all variables over time, with a focus on the spatial distribution at the mid- (2050 s) and late-century (2090 s). Lucerne biomass in Gansu Province ranged from 5422 to 15075 kg/ha (median 9480 kg/ha) during 1980s–2010s, with changes between –21.1–38.8 % and –7.5–41.4 % during 2020s–2090s under SSP245 and SSP585, respectively (Fig. 2 and Figure S5). Protein yield ranged from 1424 to 2837 kg/ha during the historical period (median 2012 kg/ha), with greater variation under SSP585 (between –32.2 % and 34.1 %) than under SSP245 (between –9.4–21.4 %). Protein concentration ranged from 18.3 % to 37.1 % during the historical period (median 20.9 %), with greater variation under SSP585 (–41.7–0.9 %) than under SSP245 (between –21.7 % and 27.8 %).

Over time, the biomass yield generally increased – up from 9480 kg/ha (median) during the historical span of the 1980s to 2010s, to 10512 kg/ha (+10.9 %) and 11874 kg/ha (+25.3 %) by the late century under SSP245 and SSP585, respectively. Protein yield increased from 2012 kg/ha in 1980s–2010s to 2127 kg/ha (+5.7 %) and 2209 kg/ha (+9.8 %) by the late century under SSP245 and SSP585, respectively. Notably, the protein concentration showed a declining trend in the

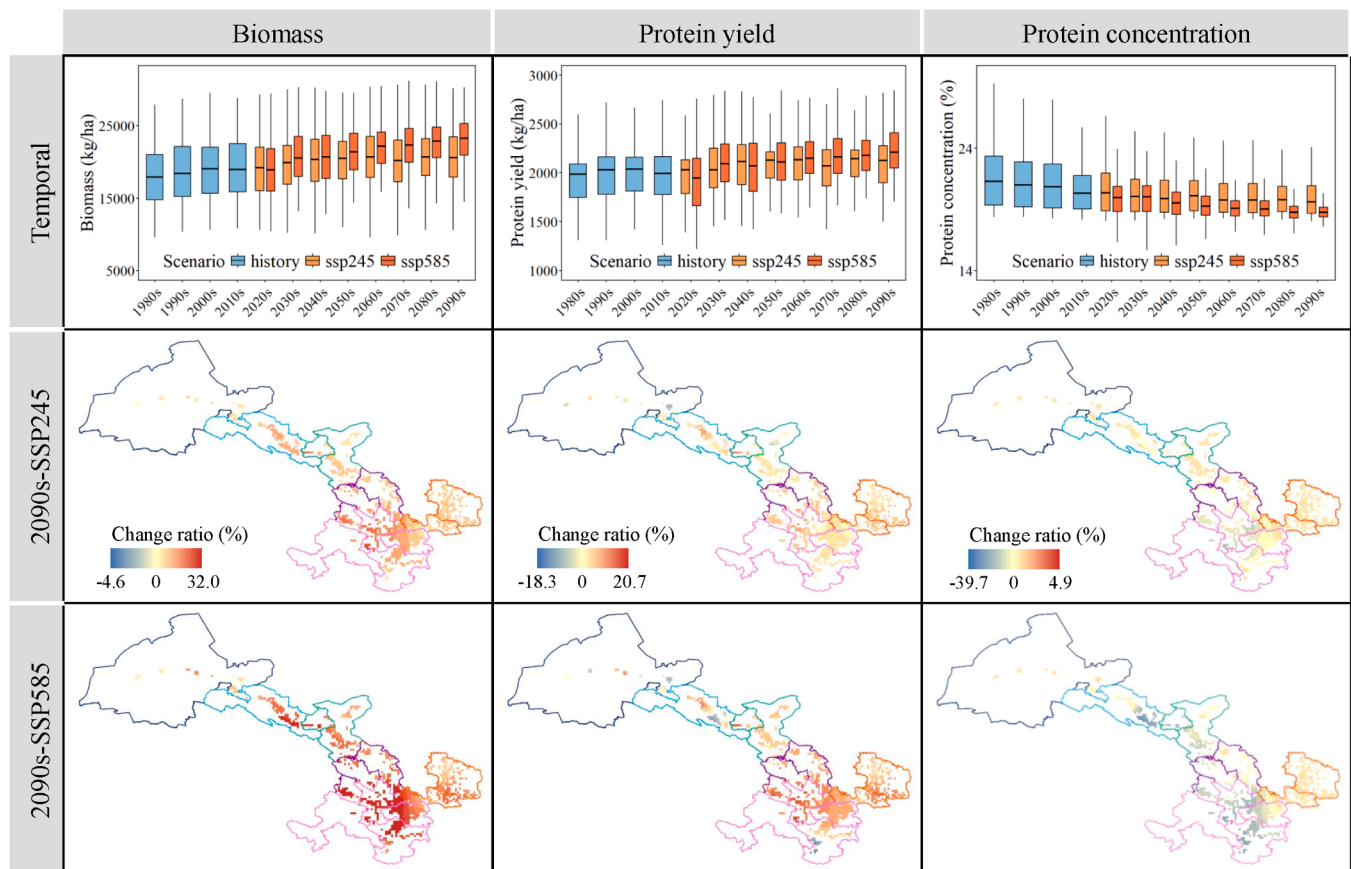


Fig. 2. Temporal variability of lucerne yield, protein yield, and protein concentration and the spatial distribution maps of relative changes in the 2090 s under SSP245 and SSP585.

future, decreasing from 20.9 % in 1980s–2010s to 19.6 % (−6.0 %) and 18.8 % (−10.1 %) by the 2090 s under SSP245 and SSP585, respectively (Fig. 2 and Figure S5).

For IWR and GWP-field, although there were increasing trends over time, the increases were greater under SSP585 than SSP245, with strong spatial variability (Fig. 3 and Figure S6). During the 1980s–2010s, IWR fluctuated between 231 and 490 mm, with a median of 321 mm. Projections for the 2020s–2090 s indicated a range of 227–529 mm under SSP245 and 246–550 mm under SSP585. Compared to the historical period, regional IWR variations were estimated at −19.7–18.3 % under SSP245 and −22.0–33.3 % under SSP585. GWP-field changed from 832 kg CO₂ eq/ha (median, ranged 1531–3260 kg CO₂ eq/ha) during the 1980s–2010s to 1490–3481 kg CO₂ eq/ha and 1441–3527 kg CO₂ eq/ha during 2020s–2090s under SSP245 and SSP585, respectively, with the regional variations ranging from −9.9–22.3 % and −19.5–36.1 %, respectively, compared to the historical period (Fig. 3 and Figure S6). The IWR of lucerne in Gansu Province increased especially under SSP585 where it increased by 8.6 % (3.3 % under SSP245) compared to the historical period. GWP-field showed a slight increase − 9.3 % and 7.2 % by the end of the century (2090 s) under SSP245 and SSP585, respectively.

We focused on IWP and GHGI in terms of resource use efficiency,

which can also be described as production intensity (Fig. 4 and Figure S6). Spatially, the historical IWP ranged from 1.35 to 4.39 kg/m³ (median 2.93) and changed to 1.44–5.03 kg/m³ (changed from −30.9–51.6 %) and 1.27–5.64 kg/m³ (varied from −11.3–83.6 %) in the 2020s–2090s under SSP245 and SSP585, respectively. GHGI fluctuated between 0.15 and 0.40 kg CO₂ eq/kg biomass (median 0.21 kg CO₂ eq/kg biomass) during 1980s–2010s and changed to 0.14–0.49 kg CO₂ eq/kg biomass (changed from −30.4–42.0 %) and 0.14–0.30 kg CO₂ eq/kg biomass (changed from −42.0–12.2 %) during 2020s–2090s under SSP245 and SSP585, respectively (Fig. 4 and Figure S6). Temporally, IWP peaked during the 2070 s under SSP245 (median 3.20 kg/m³, range 1.61–4.41 kg/m³), while under SSP585 the maximum IWP emerged later in the 2090 s with elevated variability (median 3.26 kg/m³, range 2.01–5.61 kg/m³). Concurrently, GHGI showed a decreasing trend, with decreases of 7.2 % and 16.1 % overall in the 2090 s under SSP245 and SSP585 compared to the historical period, respectively.

3.2. Restructuring lucerne planting and the production, inputs and costs thereof

Given that we posited that the total lucerne planting area in Gansu would undergo restructuring without any expansion or contraction, it

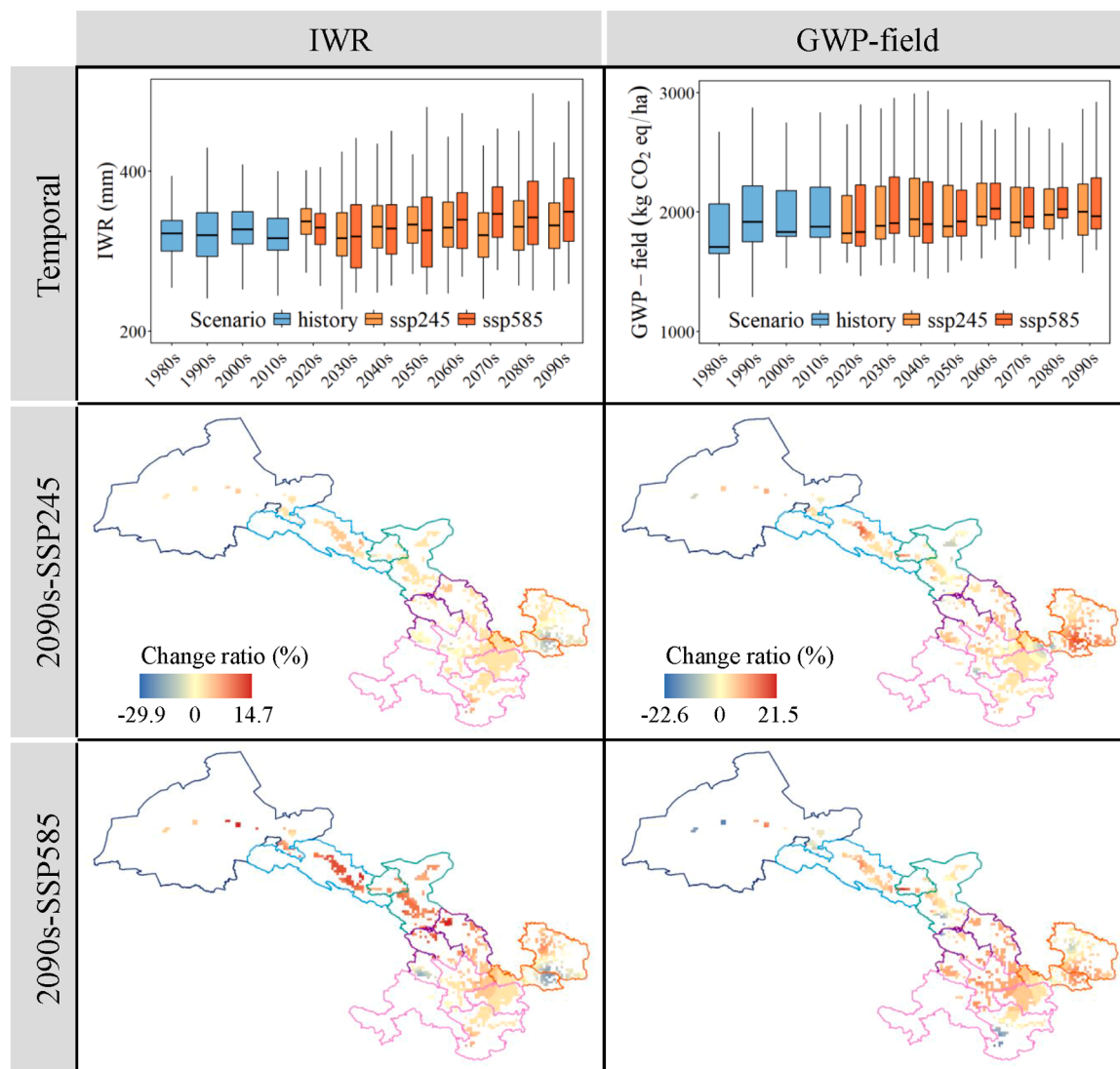


Fig. 3. Temporal variability of lucerne irrigation water requirement (IWR) and global warming potential from field (GWP-field) and the spatial distribution maps of relative changes in the 2090 s under SSP245 and SSP585.

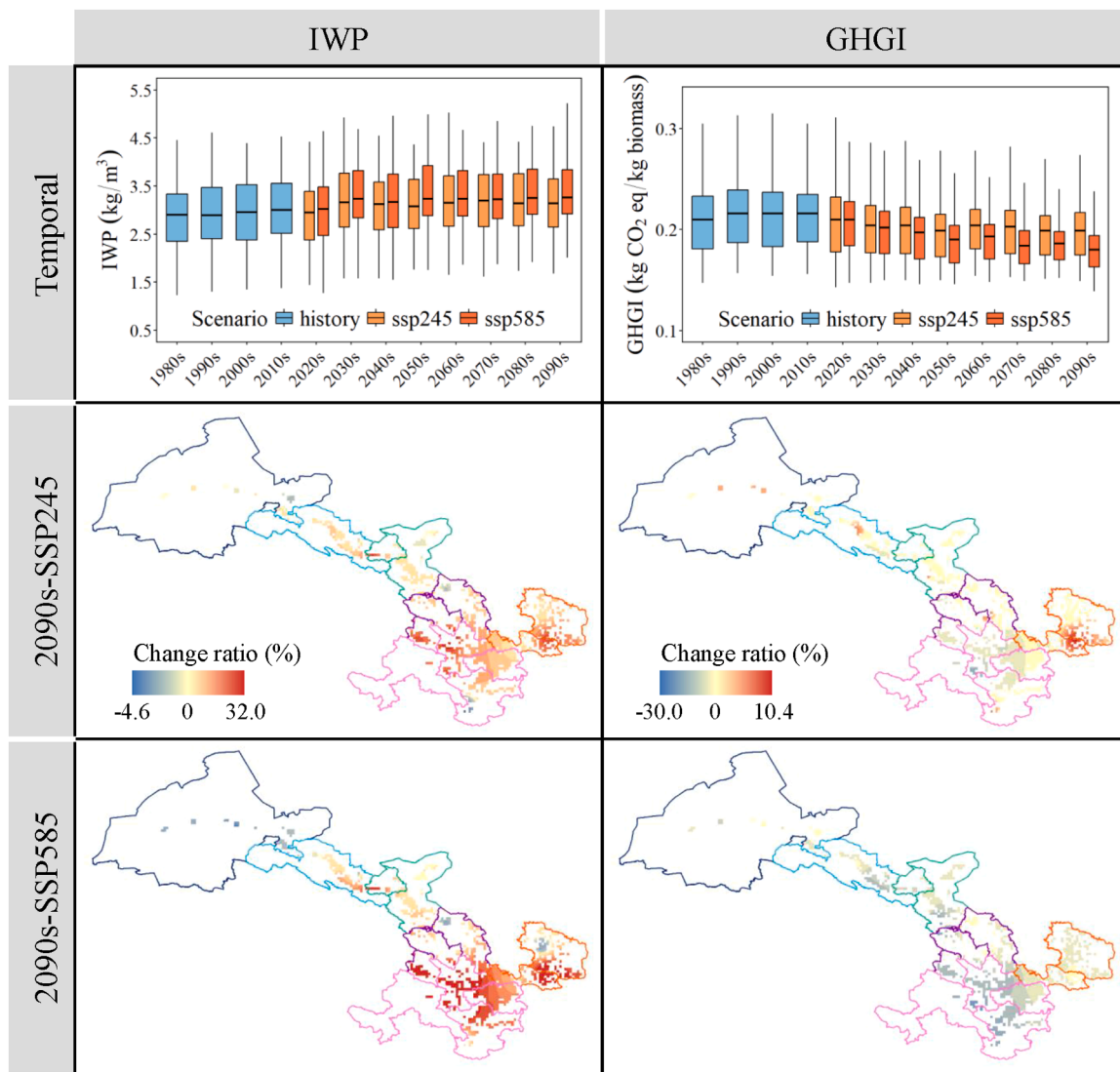


Fig. 4. Temporal variability of lucerne irrigation water productivity (IWP) and greenhouse gas intensity (GHGI) and the spatial distribution maps of relative changes in the 2090 s under SSP245 and SSP585.

follows that the total area remained relatively stable across all years and climate change scenarios. However, regional changes were evident: compared to the historical period, the planting area in Longzhong (832–1740 ha, 3.1 %–6.4 %) and Longdong (2776–4071 ha, 6.7 %–9.8 %) would increase by 3.1 %–9.8 %, the Shule, Heihe, and Shiyang river basins would decrease by 3.7 %–11.8 % (338–3345 ha.), and Longnan would be stable, fluctuating in the range of -1 – 1 % during 2020s–2090s for equal-weight scenario (weight scenario I) under SSP245 and SSP585 (Fig. 5). Although the area changes in sub-regions were not consistent, the major planting sub-region were still Longnan (34.1 % of Gansu Province, same below) and Longdong (24.2 %), followed by Longzhong (15.3 %), Shiyang River Basin (13.6 %), Heihe River Basin (8.3 %), and Shule River Basin (4.5 %) (Figure S7). Optimized planting areas changed over time and climate change scenarios in different grid cells. Planting area in each grid cell ranged from 178.3 to 396.8 ha (median 218.5 ha) during the historical period, and 21.3–324.9 ha (changed between -78.5 % and 435.7 %) and 23.0–321.4 ha (changed between -92.3 % and 538.0 %) under SSP245 and SSP585, respectively. Focusing on the two critical periods of the 2050 s and 2090 s, the planting area was obviously clustered within Longzhong and Longdong. For weight scenario II and III, the restructured area changes ranged from -16.7 – 19.5 % compared to the weight

scenario I in each sub-region (Figure S7). Given the uncertainty surrounding future actual policy interventions, the equal-weight scenario holds greater referential value. Therefore, the subsequent analysis and evaluation will focus on weighted scenario I.

The variables related to lucerne production (biomass and protein production), inputs (irrigation) and costs (GWP-field) changed across regions by restructuring the planting area (Figs. 5 and 6). Biomass production in Longzhong and Longdong increased by 14.2–56.8 million tons (4.8 %–11.1 % increase) compared to the same period without restructuring under SSP245 and SSP585, while protein production increased by 1.3–8.5 million tons (2.1 %–9.6 %), which were both associated with cultivation restructuring and area expansion. Notably, biomass and protein production in Longnan increased by 3.2 and 2.8 (mean values for SSP245 and SSP585) million tons, respectively, even though the planting area was fluctuating during 2020s–2090s. Biomass production and protein production in the Shule, Heihe and Shiyang river basins decreased by 4.4–26.6 million tons and 0.1–3.9 million tons, respectively, a decrease of 0.1 %–10.9 % compared to the same period without planting restructuring. As lucerne planting area and production concentrated in Longzhong and Longdong, IWR and GWP-field increased by 0.9 %–6.1 % during 2020s–2090s under SSP245 and SSP585. In Longzhong, IWR and GWP-field increased by 1.0–4.0 million

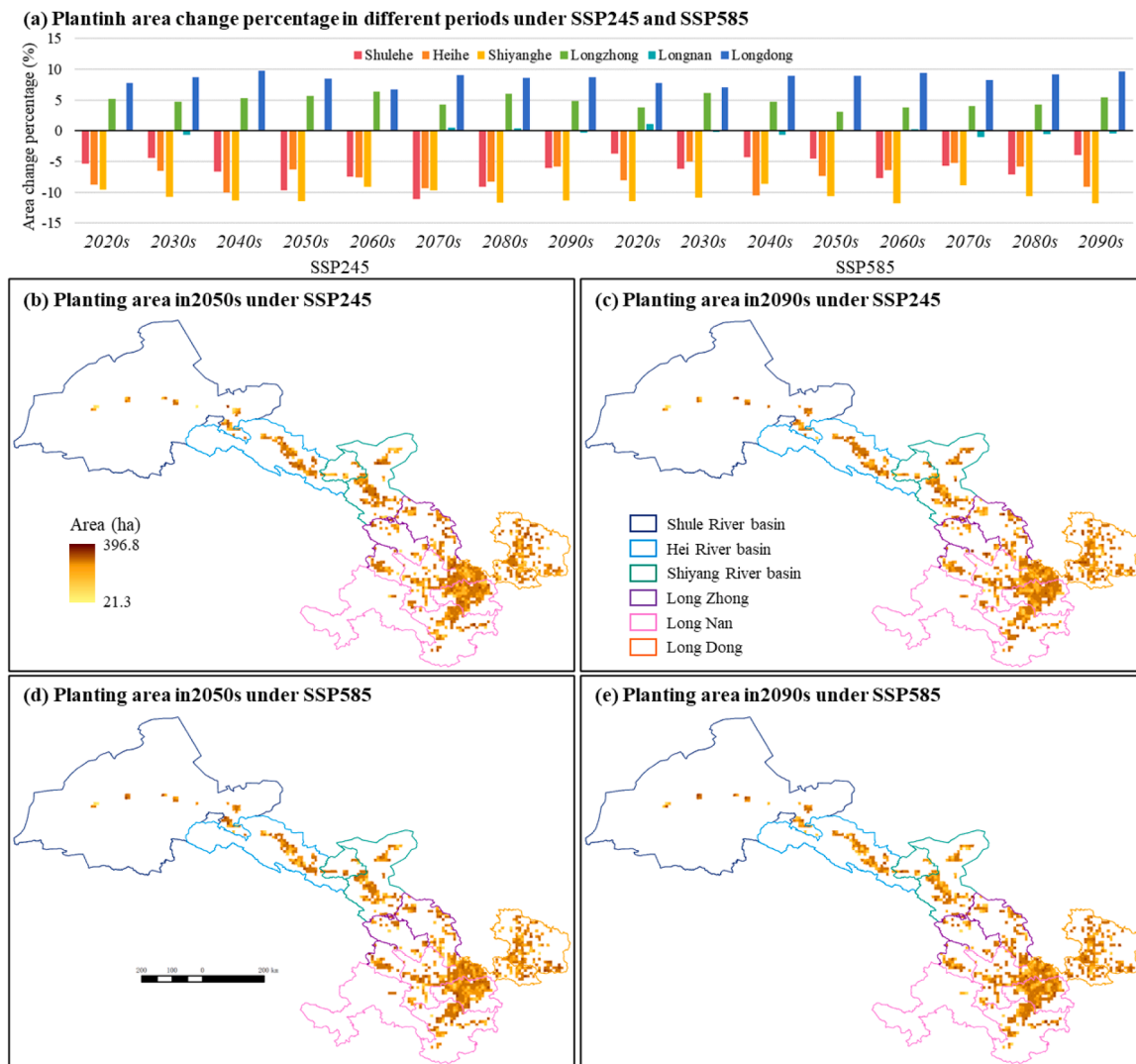


Fig. 5. Spatial and temporal variability of lucerne redistribution under SSP245 and SSP585.

m^3 and 0.6–2.4 thousand tons $\text{CO}_2\text{-eq}$, respectively, while in Longdong, they increased by 1.0–5.0 million m^3 and 2.4–4.7 thousand tons $\text{CO}_2\text{-eq}$, respectively. In the Shule, Heihe and Shiyang River basins, IWR and GWP-field decreased by 3.8–16.5 % (2.3–17.8 million m^3 and 1.0–8.2 thousand tons $\text{CO}_2\text{-eq}$), while in Longnan were fluctuating between –2.8 % and 1.2 %.

Compared to the baseline scenario, restructuring of lucerne cultivation led to an increase in biomass production of 30.6–38.5 million tons (1.4 %–2.0 % increase) and an increase in protein production of 6.5–7.4 million tons (an increase of 1.7 %–1.9 %), while the total planting area remaining essentially unchanged. During the same period IWR decreased by 21.0–24.5 million m^3 (3.4 %–3.9 % decrease) and GWP-field thousand tons $\text{CO}_2\text{-eq}$ (1.4 %–1.9 % decrease) during 2020s–2090s under SSP245 and SSP585 (Fig. 6), respectively.

3.3. Potential contribution of lucerne production to livestock and the impacts on environment

Future lucerne production (2020s–2090s) had a notable surplus compared to historical periods (Fig. 2 and Fig. 6). Thus, we attempted to quantify the potential additional benefits and costs of utilizing it as feedstock for livestock, focusing mainly on cattle and sheep (Fig. 7). The diets of cattle and sheep typically contain 15 %–20 % lucerne. Based on the 10-year statistical data from the Department of Agriculture and

Rural Affairs of Gansu Province (2010–2019), we set the lucerne proportion in cattle and sheep feed to be 18 % and 15 %, respectively. Based on the current ratio, we set the ratio of cattle to sheep to 1:5. The biomass production surplus of lucerne could supply feed to an additional 11.7–14.7 million cattle and 58.3–73.5 million sheep under SSP245 and 11.8–12.9 million cattle and 58.7–64.4 million sheep under SSP585 during the 2020s–2090s, assuming sufficiency of other feed components. Cattle and sheep feeding are a significant source of GHG, so we estimated the GWP due to additional feeding. In our analysis, we integrated multiple factors to calculate the GWP: electricity savings from IWR reductions (GWP-irrigation), GHG emissions from enteric fermentation and manure management of cattle and sheep farming (GWP-livestock, with coefficients in Table S3), and the GWP from fields (GWP-field) modeled using APSIM. Our GWP assessment focused on lucerne production and its consumption to raise additional livestock, while excluding other potential CO_2 - emitting processes like transportation and manufacturing. Results showed that cattle and sheep feeding produced 44.5–56.1 thousand tons and 44.9–49.2 thousand tons $\text{CO}_2\text{-eq}$ under SSP245 and SSP585, respectively, which far exceeded the 17.9–20.0 thousand tons $\text{CO}_2\text{-eq}$ reduction due to planting restructuring and irrigation water savings. Overall, the expanded livestock operations appear to result in an additional 24.9–37.5 thousand tons and 25.6–30.3 thousand tons $\text{CO}_2\text{-eq}$ under SSP245 and SSP585, respectively.

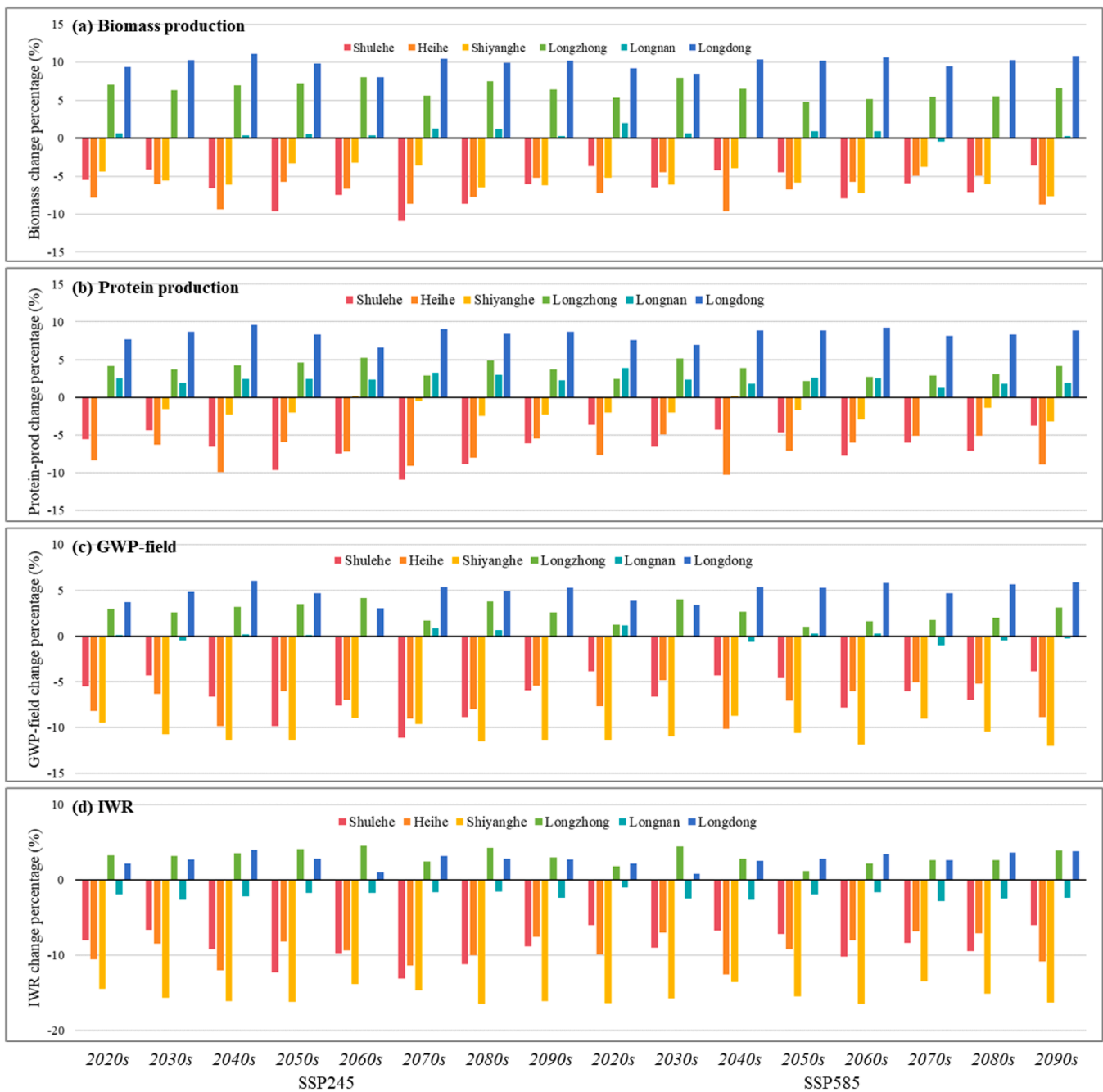


Fig. 6. Changes in lucerne biomass production, protein production, global warming potential from field (GWP-field) and irrigation water requirement (IWR) in different sub-regions before and after restructuring cultivation.

4. Discussion

4.1. Lucerne production under climate change

The impacts of climate change on crop production show strong spatial variability. The main factors driving these impacts differ globally, depending on crop type, regional climate, and the projected extent of climate change (Chen et al., 2023; Ray et al., 2015; Cuniff et al., 2017). Rising temperatures may accelerate spring regrowth, increase the number of harvests, and enhance photosynthetically active radiation reception, thereby boosting lucerne yields in Iran (Pourshirazi et al., 2022). Meanwhile, fluctuations in irrigation water requirements were affected by a combination of temperature, precipitation, and CO₂. Feng et al. (2022) showed the average dry matter yield of lucerne was 11.18

± 6.69 t/ha based on 7166 observations across China, in particular, lucerne yield was significantly and positively correlated with temperature but not significantly correlated with precipitation, which was probably because of the amount of irrigation. The improvement of lucerne yield was also found to varying degrees under elevated temperature conditions (Sanz-Sáez et al., 2012), and reported in other crops under future climate change such as tomato (Zhou et al., 2023), grapevine (Mosedale et al., 2016) and soybean (Guilpart et al., 2022). In a temperate climate, lucerne shoot production increased linearly with total intercepted radiation and temperature. In addition, the seasonal temperature variation changed shoot production efficiency from 0.47 g dry mass/MJ to 1.01 g dry mass/MJ, which was partly due to biomass partitioning changes between shoots and perennial biomass (roots and crowns) (Brown et al., 2006).

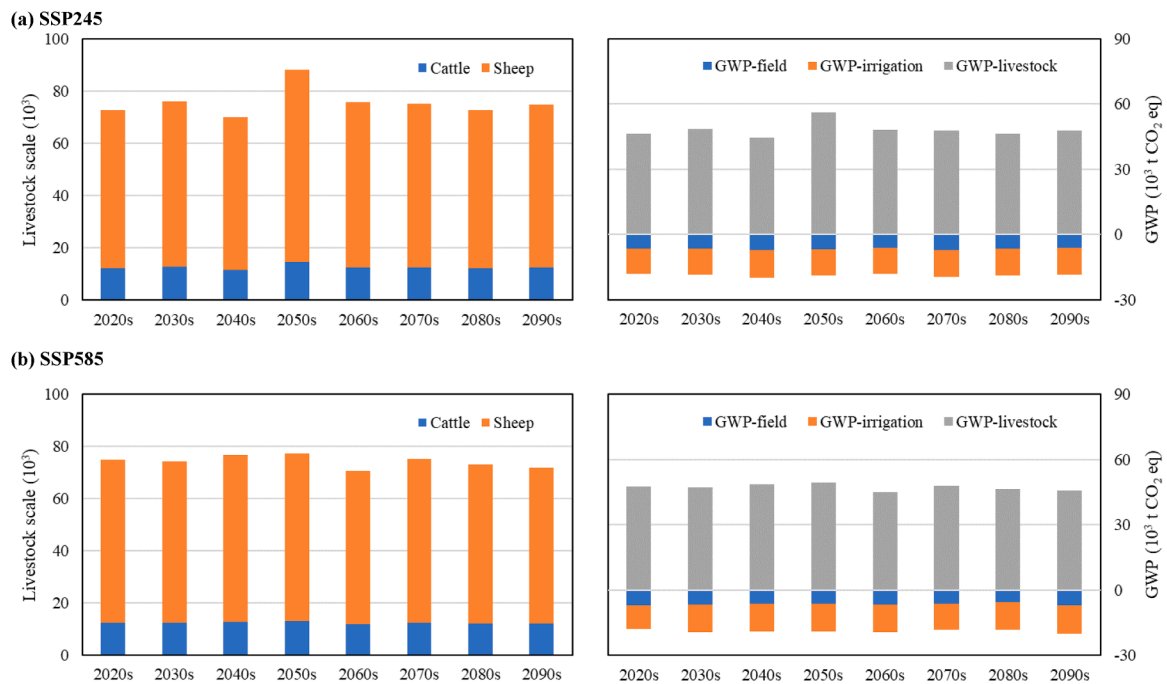


Fig. 7. Scale of the livestock supportable by increased lucerne production and the associated global warming potential (GWP).

The multi-scenario simulation of the model could provide more effective adaptive management and planting strategies for lucerne production than field experiments. Process-based crop models such as APSIM (Pembleton et al., 2016; Watt et al., 2022), STICS (Strullu et al., 2020) and CSM-CROPGRO (Jing et al., 2020) provide useful tools to explore the potential impacts of climate change on forage production. The increase in cutting time due to warmer temperatures may increase the annual yield, whereas little change was observed with increased precipitation in eastern Canada, as a result of already sufficient precipitation in this region (Jing et al., 2020). Simulation in southeastern Australia found a larger range (26 %–932 %) of increased lucerne yield under future climate change scenarios using APSIM (Pembleton et al., 2016).

Protein, a key forage quality indicator, has a more intricate response to climate change than yield. This is due to the complex process of nitrogen transformation in plants as they adapt to environmental changes (Asseng et al., 2019). The average protein concentration of alfalfa in China was 19.05 ± 2.87 % based on the observed data (Feng et al., 2022), and research on its response to climate change (e.g., warming, elevated CO_2 , and changes in precipitation patterns) is lacking. Drought had a negative effect on protein concentration and was found to be inconsistent across seasons (Liu et al., 2018). In our study, the rise in protein yield came mainly from yield benefit rather than higher protein concentration (Fig. 2), possibly due to drought events brought by warming (Liu et al., 2018). Climate change compromises lucerne protein synthesis through rising CO_2 , temperatures, and drought. Although CO_2 was not considered in this study, lucerne biomass and protein yield in Gansu Province showed significant positive correlations with temperature and significant negative correlations with precipitation. This indicated that regional warming remained within the tolerance range for lucerne growth. Notably, protein concentration exhibited a significant negative correlation with temperature and a significant positive correlation with precipitation, contrasting with biomass and protein yield (Figure S8). The decline in future lucerne protein concentration was primarily attributed to the inhibitory effect of elevated temperatures on nitrogen fixation (Sanz-S  ez et al., 2012), which further reduced total amino acid content and available nitrogen (Aranjuelo et al., 2011). High temperature reduced chlorophyll content and the chlorophyll

fluorescence parameter (F_v/F_m), while downregulating key photosynthesis-related proteins. Concurrently, increased malondialdehyde content and electrolyte leakage indicate membrane damage in lucerne under thermal stress (Li et al., 2021). Further Gene Ontology and Kyoto Encyclopedia of Genes and Genomes analyses identified key differentially expressed proteins—such as ATP-dependent zinc metalloprotease FTSH, vitamin K epoxide reductase family protein, and ClpB3—that played crucial roles in the heat stress response. However, a meta-analysis in China revealed a positive correlation between fiber content and mean annual temperature and precipitation, but no significant relationship was found between crude protein content and temperature (Li and Liu, 2024), suggesting that climate impacts on lucerne nutritional quality may involve more complex regulatory pathways.

To mitigate these climate-driven nutritional losses, strategic interventions are necessary. For instance, targeted nutrient management (e.g. selenium or other micronutrients application) could enhance lucerne's stress resilience and protein synthesis under abiotic stress conditions (Abdullah et al., 2025). Exploiting microbial symbiosis (particularly arbuscular mycorrhizal fungi and stress-tolerant rhizobia strains) could improve plant water and nutrient uptake, thereby supporting protein production during drought and heat stress (Liao et al., 2023). Adaptive harvesting strategies, such as adjusting cutting schedules based on heat accumulation to avoid peak stress periods, could help preserve forage quality by capturing the crop at the optimal protein content (Li et al., 2023). As a critical forage species, lucerne demands integrated strategies balancing yield, protein content, and ecological sustainability under climate change.

4.2. Potential of restructuring cultivation to improve production and environmental co-benefits

Restructuring crop cultivation establishes an optimal relationship between resource inputs and agricultural production by reasonably optimizing and adjusting the planting area and spatial distribution, while maximizing regional benefits (Li et al., 2016). Optimizing planting structure is an important way to ensure stable increases in crop production (Yang et al., 2022). The restructuring and even shifting of regional crop cultivation allows for trade-offs between yields, irrigation

water inputs and GHG, offering the possibility of increased production and environmental benefits (Wu et al., 2025). Guilpart et al. (2022) demonstrated that Europe, despite facing similar challenges of soybean import dependency, has significant potential to enhance supply resilience under climate change through strategic expansion of cultivation areas. However, the explicit quantification of agro-ecological trade-offs is lacking, as well as the environmental externalities and land-use change dynamics associated with the expansion of soya bean cultivation. On the other hand, climate change may lead to further shortage of agricultural water resources, and water conservation through restructuring of agricultural cultivation is a viable option. Yu et al. (2021) reported that a 15 % water-saving plan was the best scenario in north China, through a combined approach of reducing irrigated land reduction, controlling crop scale and using water-saving irrigation methods.

Current studies on acreage reconstruction mainly focus on cereals, pulses, and vegetables (Fan et al., 2025; Wu et al., 2025), with limited research on forages such as lucerne. We restructured lucerne cultivation in Gansu - an important region for forage cultivation in China - on the basis of simulating spatial and temporal variability of biomass, protein, and GWP-field under climate change (Figs. 2–4), and found that expanding 4238–5521 ha of cultivation in the Longzhong and Longdong regions (Fig. 5) would lead to higher benefits in production, water use, and the environment for the whole region (Fig. 6). This reconstitution could be interpreted as transferring the cultivation area from the Hexi Corridor (Shule, Heihe, and Shiyang River basins) to Longzhong and Longdong - that is, as we set the total area to remain unchanged. This relocation essentially involved shifting lucerne cultivation to regions with more suitable climate and soil conditions, as Longdong and Longzhong owned temperatures 5.3–44.9 % higher, radiation 1.3–19.6 % lower, saturated hydraulic conductivity 4.9–49.6 % lower, and silt content 3.8–36.6 % higher than other subregions (Figure S9), consistent with the results of the Spearman correlation (Figure S8). However, the additional GWP from additional production of lucerne, if used directly for livestock expansion, would outweigh the GWP reductions from restructuring lucerne cultivation and water conservation (Fig. 7). Reducing direct and indirect carbon emissions from livestock farming can be achieved through feed additives (e.g., antibiotic, phyto-compounds, etc) (Gutierrez-Chavez et al., 2025), biological solutions (e.g., vaccine, rumen microbiome, etc) (Waters et al., 2025), breeding and productivity improvements (e.g., selective breeding, health management, etc) (Zanon et al., 2025), and management optimizing (e.g., improving manure treatment technology can reduce ammonia and methane emissions by more than 33 %.) (Yan et al., 2024). Therefore, livestock should focus on these dimensions to advance low-carbon development through technological innovation to achieve sustainable development of agricultural systems in response to increasing demands for animal products.

4.3. Limitations and future research

Although we quantified the spatial and temporal variability characterizing lucerne yield, protein, water consumption, and GWP in Gansu Province, elevated CO₂ was not considered in this study as it would require further development of the CO₂ effect on the crop model based on extensive experimental data collected from controlled environment (e.g., FACE and OTC). In addition, the main planting areas of lucerne include Inner Mongolia and Hebei, making it crucial to consider broader regional climate and soil heterogeneity when developing regionally distributed lucerne production strategies. Lucerne, as a moderately salt-tolerant crop, should also be quantified and evaluated for its productivity and benefits on marginal lands. However, this also placed higher demands on crop model performance under stress conditions (e.g., salinity and drought stress). Acquiring extensive experimental data to enhance the representation of soil and climate stress effects on crops in model was a crucial pathway to achieving this. The economic analysis of lucerne cultivation and application is a matter of practical concern,

relating to feasibility of the cultivation project. Sprouts, extracts, powders, and dietary supplements are all applications of lucerne beyond its use as feed (Tlahig and Elfalleh, 2025). The labor, equipment, transportation costs, and environmental pressures associated with these applications form a complex industrial chain that requires consideration and calculation from an industry-wide perspective.

5. Conclusion

In this study, we used APSIM to simulate the spatial and temporal variability characteristics of biomass, protein, water consumption, and carbon emissions of lucerne in Gansu Province, and restructured the planting to enhance production, efficiency, and environmental benefits. Results showed that biomass yield, protein yield, IWR, IWP, and GWP-field of lucerne were increased by 17.6 %, 10.0 %, 3.9 %, 12.0 %, and 6.2 % respectively by the end of the century, while protein concentration and GHGI decreased by 6.7 % and 10.5 %, respectively. With the total area unchanged and considering the spatial and temporal variability characteristics of the variables, total biomass and protein were improved by 1.2–2.0 %, irrigation water was reduced by 3.4–3.9 %, and GWP-field was decreased by 1.4–1.9 % by transferring 4238–5521 ha of planting area from the Hexi Corridor to Longzhong and Longdong compared to no change in the lucerne cropping pattern. The surplus lucerne production could support additional feeding of 11.7–14.7 million cattle and 58.3–73.5 million sheep. However, this would result in an extra 44.5–56.1 thousand tons CO₂-eq emissions, which far outweighs GWP benefits of soil respiration and irrigation savings from restructured cultivation (reducing 17.9–20.0 million tons of CO₂-eq emissions) and generating 24.9–37.5 million tons of CO₂-eq emissions. The development patterns of grassland and livestock in Gansu Province, along with the water resource constraints and carbon emission pressures faced, exhibited high homogeneity with other northwestern regions such as Shaanxi, Ningxia, Inner Mongolia, and Xinjiang. Further, the core driving parameters of the simulation and optimization framework proposed in this paper—climate factors, soil attributes, and management practices—were universally applicable. Therefore, the program and methodology for lucerne restructuring proposed in this study not only offered potential solutions for sustainable agricultural development and food security but also established paradigm-setting for soil-water adaptation strategies in arid regions of Northwest China and the world.

CRedit authorship contribution statement

Huiping Zhou: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xiaowei Ding:** Methodology, Data curation. **David Parsons:** Writing – review & editing. **Jiabao Chen:** Validation, Formal analysis, Data curation. **Liebao Han:** Supervision, Project administration.

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.

Acknowledgments

This work was partially supported by the National Natural Science Foundation of China (52309069), the Fundamental Research Funds for the Central Universities (BLX202329).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2025.109927](https://doi.org/10.1016/j.agwat.2025.109927).

Data availability

Data will be made available on request.

References

- Abdullah, Wani, K.I., Hayat, K., Naeem, M., Aftab, T., 2025. Multifaceted role of selenium in plant physiology and stress resilience: a review. *Plant Science (Limerick)* 355, 112456.
- Aranjuelo, I., Molero, G., Erice, G., Avicé, J., Nogués, S., 2011. Plant physiology and proteomics reveals the leaf response to drought in alfalfa (*Medicago sativa* L.). *J. Exp. Bot.* 62 (1), 111–123.
- Asseng, S., Martre, P., Maïorano, A., Rotter, R.P., O'Leary, G.J., Fitzgerald, G.J., Girousse, C., Motzo, R., Giunta, F., Babar, M.A., Reynolds, M.P., Kheir, A., Thorburn, P.J., Waha, K., Ruane, A.C., Aggarwal, P.K., Ahmed, M., Balkovic, J., Basso, B., Biernath, C., Bindi, M., Cammarano, D., Challinor, A.J., De Sanctis, G., Dumont, B., Eyshi, R.E., Fereres, E., Ferrise, R., Garcia-Vila, M., Gayler, S., Gao, Y., Horan, H., Hoogenboom, G., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kassie, B.T., Kersebaum, K.C., Klein, C., Koehler, A.K., Liu, B., Minoli, S., Montesino, S.M.M., Muller, C., Naresh, K.S., Nendel, C., Olesen, J.E., Palosuo, T., Porter, J.R., Priesack, E., Ripoche, D., Semenov, M.A., Stockle, C., Stratonovich, P., Streck, T., Supit, I., Tao, F., Van der Velde, M., Wallach, D., Wang, E., Webber, H., Wolf, J., Xiao, L., Zhang, Z., Zhao, Z., Zhu, Y., Ewert, F., 2019. Climate change impact and adaptation for wheat protein. *Glob. Change Biol.* 25 (1), 155–173.
- Azadbakht, M., Ashourloo, D., Aghighi, H., Homayouni, S., Shahrabi, H.S., Matkan, A., Radiom, S., 2022. Alfalfa yield estimation based on time series of landsat 8 and proba-v images: an investigation of machine learning techniques and spectral-temporal features. *Remote Sens. Appl.: Soc. Environ.* 25, 100657.
- Brown, H.E., Moot, D.J., Teixeira, E.I., 2006. Radiation use efficiency and biomass partitioning of lucerne (*Medicago sativa*) in a temperate climate. *Eur. J. Agron.* 25 (4), 319–327.
- Buis, S., Lecharpentier, P., Vezy, R. CROPTIMIZR: A Package for Parameter Estimation, Uncertainty and Sensitivity Analysis for Crop Models (Version 0.4.0). <https://doi.org/10.5281/zenodo.14145952>.
- Chen, S., Liu, W., Yan, Z., Morel, J., Parsons, D., Du, T., 2023. Adaptation strategy can ensure seed and food production with improving water and nitrogen use efficiency under climate change. *Earth's Future* 11 (2), 2022EF002879.
- Cunniff, J., Jones, G., Charles, M., Osborne, C.P., 2017. Yield responses of wild C3 and C4 crop progenitors to sub-ambient CO₂: a test for the role of CO₂ limitation in the origin of agriculture. *Glob. Change Biol.* 23 (1), 380–393.
- Dai, Y.J., Shangguan, W., Duan, Q., Liu, B., Fu, S., Niu, G., 2013. Development of a China dataset of soil hydraulic parameters using pedotransfer functions for land surface modeling. *J. Hydrometeorol.* 14, 869–887.
- Deléglise, H., Justeau-Allaire, D., Mulligan, M., Espinoza, J., Isasi-Catalá, E., Alvarez, C., Condom, T., Palomo, I., 2024. Integrating multi-objective optimization and ecological connectivity to strengthen Peru's protected area system towards the 30*2030 target. *Biol. Conserv.* 299, 110799.
- Fan, Y., He, L., Wang, S., 2025. Limited improvement of crop nitrogen management sustainability through optimal crop distributions in drylands. *J. Environ. Manag.* 377, 124716.
- Feng, Y., Shi, Y., Zhao, M., Shen, H., Xu, L., Luo, Y., Liu, Y., Xing, A., Kang, J., Jing, H., Fang, J., 2022. Yield and quality properties of alfalfa (*Medicago sativa* L.) and their influencing factors in China. *Eur. J. Agron.* 141, 126637.
- Gu, Y., Han, C., Fan, J., Shi, X., Kong, M., Shi, X., Siddique, K.H.M., Zhao, Y., Li, F., 2018. Alfalfa forage yield, soil water and p availability in response to plastic film mulch and p fertilization in a semiarid environment. *Field Crops Res.* 215, 94–103.
- Guilpart, N., Iizumi, T., Makowski, D., 2022. Data-driven projections suggest large opportunities to improve Europe's soybean self-sufficiency under climate change. *Nat. Food* 3 (4), 255–265.
- Gutierrez-Chavez, V., Gutierrez-Chavez, C., Feregino-Perez, A.A., Gutierrez-Antonio, C., Lomas-Soria, C., Guevara-Gonzalez, R.G., 2025. Capsaicinoids and capsinoids of chili pepper as feed additives in livestock production: current and future trends. *Anim. Nutr.* 22, 483–501.
- Head, T., Kumar, M., Nahrstaedt, H., Louppe, G., Shcherbaty, I., 2020. scikit-optimize/scikit-optimize (v0.8.1). Zenodo.
- Hochman, Z., Horan, H., Reddy, D.R., Sreenivas, G., Tallapragada, C., Adusumilli, R., Gaydon, D.S., Laing, A., Kokic, P., Singh, K.K., Roth, C.H., 2017. Smallholder farmers managing climate risk in India: 2. Is it climate-smart? *Agric. Syst.* 151, 61–72.
- Hu, M., Tang, H., Yu, Q., Wu, W., 2025. A new approach for spatial optimization of crop planting structure to balance economic and environmental benefits. *Sustain. Prod. Consum.* 53, 109–124.
- Intergovernmental Panel on Climate Change (IPCC), 2023. Climate change 2023: synthesis report. IPCC, Geneva, Switzerland, pp. 1–34.
- Jia, Z., Ou, C., Sun, S., Sun, M., Zhao, Y., Li, C., Zhao, S., Wang, J., Jia, S., Mao, P., 2024. Optimizing drip irrigation arrangements to improve alfalfa seed yield in semiarid region. *Agric. Water Manag.* 297, 108830.
- Jing, Q., Qian, B., Bélanger, G., VanderZaag, A., Jégo, G., Smith, W., Grant, B., Shang, J., Liu, J., He, W., Boote, K., Hoogenboom, G., 2020. Simulating alfalfa regrowth and biomass in eastern Canada using the CSM-CROPGRO-perennial forage model. *Eur. J. Agron.* 113, 125971.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., Mclean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., Mccown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18 (3), 267–288.
- Li, M., Guo, P., Singh, V.P., Yang, G., 2016. An uncertainty-based framework for agricultural water-land resources allocation and risk evaluation. *Agric. Water Manag.* 177, 10–23.
- Li, Y., Z., Li, X.R., Zhang, J., Li, D.X., Yan, L.J., You, M.H., Zhang, J.B., Lei, X., Chang, D., Ji, X.F., An, J.C., Li, M.F., Bai, S.Q., Yan, J.J., 2021. Physiological and proteomic responses of contrasting alfalfa (*Medicago sativa* L.) varieties to high temperature stress. *Front. Plant Sci.* 12, 753011.
- Li, S., Liu, Z., 2024. Fertilisation and environmental factors affect the yield and quality of alfalfa in China. *Plant Soil Environ.* 70 (5), 276–286.
- Li, T., Peng, L., Wang, H., Zhang, Y., Wang, Y., Cheng, Y., Hou, F., 2023. Multiple cutting increases forage productivity and enhances legume pasture stability in a rainfed agroecosystem. *Ann. Agric. Sci.* 68 (2), 126–136.
- Liao, X., Zhao, J., Xu, L., Tang, L., Li, J., Zhang, W., Xiao, J., Xiao, D., Hu, P., Nie, Y., Zou, D., Wang, K., 2023. Arbuscular mycorrhizal fungi increase the interspecific competition between two forage plant species and stabilize the soil microbial network during a drought event: evidence from the field. *Appl. Soil Ecol. A Sect. Agric. Ecosyst. Environ.* 185, 104805.
- Liu, Q., Niu, J., Du, T., Kang, S., 2023. A full-scale optimization of a crop spatial planting structure and its associated effects. *Engineering* 28 (9), 139–152.
- Liu, Y., Wu, Q., Ge, G., Han, G., Jia, Y., 2018. Influence of drought stress on alfalfa yields and nutritional composition. *BMC Plant Biol.* 18 (1), 13.
- Macolino, S., Lauriault, L.M., Rimi, F., Ziliotto, U., 2013. Phosphorus and potassium fertilizer effects on alfalfa and soil in a non-limited soil. *Agron. J.* 105 (6), 1613–1618.
- Mosedale, J., Abernethy, K., Smart, R., Wilson, R., Maclean, I., 2016. Climate change impacts and adaptive strategies: lessons from the grapevine. *Glob. Change Biol.* 22, 3814–3828.
- Pembleton, K.G., Cullen, B.R., Rawnley, R.P., Harrison, M.T., Ramlan, T., 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of southeastern Australia using APSIM. *J. Agric. Sci.* 154 (7), 1131–1152.
- Pourshirazi, S., Soltani, A., Zeinali, E., Torabi, B., Arshad, A., 2022. Assessing the sensitivity of alfalfa yield potential to climate impact under future scenarios in Iran. *Environ. Sci. Pollut. Res.* 29 (40), 61093–61106.
- Qin, R., Xu, J., Harrison, M.T., Liu, K., Li, F., Sun, G., Zhang, F., 2023. Assessing perennial alfalfa yield by incorporating physiologically-lucid function into denitrification-decomposition model. *Field Crops Res.* 298, 108966.
- Ray, D.K., Gerber, J.S., Macdonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. *Nat. Commun.* 6 (1).
- Sanz-Sáez, Á., Erice, G., Aguirreolea, J., Irigoyen, J.J., Sánchez-Díaz, M., 2012. Alfalfa yield under elevated CO₂ and temperature depends on the sinorhizobium strain and growth season. *Environ. Exp. Bot.* 77, 267–273.
- Scrucca, L., 2013. GA: a package for genetic algorithms in R.J. *Stat. Softw.* 53, 1–37.
- Shangguan, W., Dai, Y.J., Liu, B.Y., Zhu, A.X., Duan, Q.Y., Wu, L.Z., Ji, D.Y., Ye, A.Z., Yuan, H., Zhang, Q., Chen, D.D., Chen, M., Chu, J.T., Dou, Y.J., Guo, J.X., Li, H.Q., Li, J.J., Lu, L., Xiao, L., Liu, H.P., Liu, S.Y., Miao, C.Y., Zhang, Y.Z., 2013. A China dataset of soil properties for land surface modeling. *J. Adv. Meteorol.* 5, 212–224.
- Shangguan, W., Dai, Y., 2013. A China dataset of soil hydraulic parameters pedotransfer functions for land surface modeling (1980). National Tibetan Plateau Data Center.
- Strullu, L., Beaudoin, N., Thiébeau, P., Julier, B., Mary, B., Ruget, F., Ripoche, D., Rakotovololona, L., Louarn, G., 2020. Simulation using the STICS model of C&N dynamics in alfalfa from sowing to crop destruction. *Eur. J. Agron.* 112, 125948.
- Sun, C., Gao, C., Chen, W., 2024. Unrevealing the water-use strategies for typical ecological restoration plants and cash crops in the eastern Chinese loess plateau region. *J. Hydrol. Reg. Stud.* 56, 102013.
- Tlahig, S., Elfalleh, W., 2025. Alfalfa as a nutritional and functional food resource: applications and health benefits. *Food Biosci.* 68, 106762.
- Varol, I.S., Ünlikara, A., Kaplan, M., 2024. Water productivity, yield response factors, yield and quality of alfalfa cultivars in semi-arid climate conditions. *Environ. Exp. Bot.* 224, 105826.
- Wang, H., Wang, X., Bi, L., Wang, Y., Fan, J., Zhang, F., Hou, X., Cheng, M., Hu, W., Wu, L., Xiang, Y., 2019. Multi-objective optimization of water and fertilizer management for potato production in sandy areas of Northern China based on topsis. *Field Crops Res.* 240, 55–68.
- Wang, Z., Yang, J.Y., Drury, C.F., Jiang, R., 2021. Simulating alfalfa and pasture yields at regional and national scales in Canada from 1981 to 2019. *Agric. Syst.* 191, 103166.
- Wang, Q.B., Yang, Z., 2020. China's alfalfa market and imports: development, trends, and potential impacts of the US-China trade dispute and retaliations. *J. Integr. Agric.* 19 (4), 1149–1158.
- Waters, S.M., Roskam, E., Smith, P.E., Kenny, D.A., Popova, M., Eugène, M., Morgavi, D. P., 2025. International symposium on ruminant physiology: the role of rumen microbiome in the development of methane mitigation strategies for ruminant livestock. *J. Dairy Sci.* 108 (7), 7591–7606.
- Watt, L.J., Bell, L.W., Pembleton, K.G., 2022. A forage brassica simulation model using APSIM: model calibration and validation across multiple environments. *Eur. J. Agron.* 137, 126517.
- Wen, M., Chen, L., 2023. Global food crop redistribution reduces water footprint without compromising species diversity. *J. Clean. Prod.* 383, 135437.
- Wu, H.W., Li, Z.H., Deng, X.Z., Zhao, Z., 2025. Enhancing agricultural sustainability: optimizing crop planting structures and spatial layouts within the water-land-energy-economy-environment-food nexus. *Geogr. Sustain.* 6, 100258.

- Yan, X., Ying, Y., Li, K., Zhang, Q., Wang, K., 2024. A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production. *J. Environ. Manag.* 352, 120028.
- Yang, K., He, J., Tang, W., Lu, H., Qin, J., Chen, Y., Li, X., 2019. China meteorological forcing dataset (1979-2018). National Tibetan Plateau/Third Pole Environment Data Center.
- Yang, S.L., Wang, H.M., Tong, J.P., Bai, Y., Alatalo, J.M., Liu, G., Fang, Z., Zhang, F., 2022. Impacts of environment and human activity on grid-scale land cropping suitability and optimization of planting structure, measured based on the MaxEnt model. *Sci. Total Environ.* 836, 155356.
- Yin, M., Ma, Y., Kang, Y., Jia, Q., Qi, G., Wang, J., Yang, C., Yu, J., 2022. Optimized farmland mulching improves alfalfa yield and water use efficiency based on meta-analysis and regression analysis. *Agric. Water Manag.* 267, 107617.
- Yu, H., Liu, K.L., Bai, Y.Y., Luo, Y., Wang, T., Zhong, J., Liu, S.Q., Bai, Z.Y., 2021. The agricultural planting structure adjustment based on water footprint and multi-objective optimisation models in China. *J. Clean. Prod.* 297, 126646.
- Zanon, T., Baes, C., Miglior, F., Gierus, M., Gauly, M., 2025. Review: effect of breeding strategies, feeding and manure management, to mitigate methane emissions in dairy cattle farming: an overview and the road ahead. *Animal* 19 (9), 101617.
- Zhang, W.H., Hou, L.Y., Yang, J., Song, S.H., Mao, X.T., Zhang, Q.Q., Bai, W.M., Pan, Q.M., Zhou, Q.P., 2018. Establishment and management of alfalfa pasture in cold regions of China. *Chin. Sci. Bull.* 63 (17), 1651–1663.
- Zhang, Q., Liu, J., Liu, X., Sun, Y., Li, S., Lu, W., Ma, C., 2020. Optimizing the nutritional quality and phosphorus use efficiency of alfalfa under drip irrigation with nitrogen and phosphorus fertilization. *Agron. J.* 112 (4), 3129–3139.
- Zhang, J., Mao, Y., Wang, G., Luo, D., Cao, Q., Siddique, K.H.M., Mirzaei, M., Saunders, M., Aghamir, F., Radicetti, E., Xiang, Y., Zhang, Q., Li, Y., Shen, Y., 2024. Enhancing lucerne (*Medicago sativa*) yield and nutritional quality: a meta-analysis of fertilization types and environmental factors in China. *Front. Plant Sci.* 15, 1405180.
- Zhou, H., Chen, J., Ding, X., Qin, Q., Han, L., 2025. Future climate change will strengthen cotton production but have substantial environmental costs—a focus on xinjiang by APSIM modelling. *J. Clean. Prod.* 491, 144803.
- Zhou, H., Kang, S., Génard, M., Vercambre, G., Chen, J., 2023. Integrated model simulates bigger, sweeter tomatoes under changing climate under reduced nitrogen and water input. *Hortic. Res.* 10, uhad045.
- Zhou, Z., Li, J., Gao, Y., Wang, X., Wang, R., Huang, H., Zhang, Y., Zhao, L., Wang, P., 2024. Research on drought stress in *Medicago sativa* L. From 1998 to 2023: a bibliometric analysis. *Front. Plant Sci.* 15, 1406256.