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Soil carbon sequestration, climate change mitigation, nitrogen pollution and agro-food supply: navigating trade-offs in future cropland management strategies

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Abstract

Model-based scenarios are essential for assessing the potential of agricultural management strategies to achieve sustainable development goals. However, to date, knowledge of the trade-offs and synergies between greenhouse gas (GHG) emissions and nitrogen (N) reduction, carbon sequestration, and food provisioning under different agricultural practices remains limited, with most studies focusing on global and national scales. The present study implements the generalized representation of agro-food system model coupled with the soil organic carbon (SOC) AMG model in the Tuojiang River Basin, China, to assess the effects of 24 agricultural scenarios on SOC stock, the GHG budget, nitrogen (N) surplus, and export capacity at the county level in 2035. We considered viable options by modifying four levers: (i) synthetic fertilizer inputs, (ii) livestock population size and the fraction of animal proteins in the human diet, (iii) the share of legumes in crop rotation, and (iv) the proportion of straw used for bioenergy production. We found that the potential of biofuels to substitute fossil fuel emissions remains low across all scenarios, reducing by 2.9%–5.3% of current emissions. Our results also reveal synergies in reducing GHG emissions and N pollution, with reductions of 39%–43% and 26%–52%, respectively, under agro-ecological scenarios with zero N fertilizer application and halving of the livestock population. In contrast, trade-offs were identified between SOC sequestration and export capacity, both of which were lower in agro-ecological scenarios than in the others.

1. Introduction

Agriculture accounts for more than a quarter of global greenhouse gas (GHG) emissions (Laborde *et al* 2021). Croplands are vital for addressing the dual challenges of mitigating climate change, and ensuring both the quantity and quality of food (Hasegawa *et al* 2015, Frank *et al* 2017). Effective climate change mitigation strategies in cropland management include GHG reduction and carbon (C) sequestration (Fawzy *et al* 2020). Recognized as a nature-based solution, soil C sequestration offers significant potential for mitigating climate change while enhancing food security (Tang *et al* 2019).

However, a tradeoff exists between the environmental benefits of agriculture. Unsustainable agricultural practices and the excessive use of chemicals in crop production have raised significant concerns in recent decades because of their substantial GHG emissions and N pollution, leading to eutrophication with high economic and environmental costs (Zeng *et al* 2021). Increases in cropland soil organic carbon (SOC) stocks are largely driven by enhanced net primary productivity and intensified livestock farming, which provide large amounts of manure (Zhao *et al* 2018, Li *et al* 2021, Wang *et al* 2024). However, agricultural intensification has also led to 'hidden C emissions' from fossil fuel use in agricultural mechanization, fertilizer production, and livestock farming with high methane emissions. Additionally, cropland dedicated to livestock feeding (Garnier *et al* 2019, Crippa *et al* 2021) further offsets C sequestration benefits. Since the mid-20th century, increased soil C sequestration in croplands has heavily relied on non-solar energy, a phenomenon known as the 'fossil fuel-driven C sink' (Gingrich *et al* 2007). Therefore, a holistic assessment of the ability of croplands to mitigate climate change through C sequestration must also consider the GHG emissions resulting from livestock breeding and fossil fuel use for fertilizer application in agricultural production. Substituting fossil fuels by biofuels can reduce GHG emission reduction by 'avoided emissions' (Jeswani *et al* 2020). Technologies and strategies aimed at enhancing C sequestration and reducing emissions in agriculture may impact food production. However, efforts to boost food production often led to increased GHG emissions (Wheeler and Von Braun 2013). Total GHG emissions are typically lower under organic management practices, such as fertilizer reduction, which also reduces energy use by avoiding the use of synthetic fertilizers (Seufert and Ramankutty 2017). However, uncertainties remain regarding the potential for C sequestration in organic agriculture, which may offset the benefits of climate change mitigation (Maenhout *et al* 2024). Additionally, although fertilizer use has accelerated agricultural development, it has also caused a cascade of environmental issues. Studies have indicated that increases in cropland SOC are linked to higher N emissions, particularly through nitrate leaching and the subsequent N cascade generating air and water pollution as well as N_2O emissions, which may undermine efforts to mitigate climate change via C sequestration (Pohanková *et al* 2024).

Scenario analysis has become a critical method for evaluating the impact of changes in agricultural practices on agro-environmental performance at different scales (Merante *et al* 2015, FAO 2018, Le Noë *et al* 2019, Xia *et al* 2023). An increasing number of studies have employed scenario-based approaches to explore the implications of combining specific agricultural levers for food security, while preserving ecosystems (Erb *et al* 2016, Billen *et al* 2018, Le Noë *et al* 2018, Turner *et al* 2020, Billen *et al* 2021, Le Noë *et al* 2023). However, these studies often focused on one environmental indicator in relation to food production, while trade-offs exist between several ecosystem services in agriculture. However, these complex tradeoffs have rarely been systematically investigated. In addition, these scenario analyses are often conducted at global (Erb *et al* 2016, Muller *et al* 2017), continental, (Billen *et al* 2021, Billen *et al* 2024) or national levels (Billen *et al* 2018, Le Noë *et al* 2018, 2023). However, agricultural practices occur locally, and these environmental impacts (e.g. C sequestration from cropland and GHG emissions) highly depend on local conditions (Xia *et al* 2017, Sun *et al* 2020). Therefore, the regional-scale analysis is more suitable for exploring the impacts of scenarios on various environmental and agronomic indicators, although research at this scale remains limited (Le Noë *et al* 2019).

Over the past decades, agricultural production systems worldwide have addressed growing demand through intensification and specialization (Billen *et al* 2014, Lassaletta *et al* 2014, 2016). Since the 1990s, Chinese agriculture has shifted from a diverse resource-recycling model to a specialized, high-input, and resource-intensive mode (Chen 2020). This shift has boosted cropland SOC stocks while significantly contributing to regional and global GHG emissions (Hong *et al* 2021). China's second national survey of pollution sources indicated that agriculture contributed 47% of N losses, with crop planting and livestock breeding responsible for 93% of these losses (Deng *et al* 2024). In particular, in the traditional agricultural region of the Tuojiang River Basin in Southwest China, intensive fertilizer input and livestock expansion have led to the highest N load in the upper Yangtze River, significantly contributing to eutrophication and acidification (Wang *et al* 2020). This has created a dual challenge for the region's agriculture: sustaining productivity, while reducing GHG emissions and other environmental impacts. Achieving this balance requires sustainable practices, and exploration of diverse biophysical scenarios for cropland systems.

In this context, this study seeks to answer two fundamental questions: (i) what are the trade-offs among agro-environmental indicators across diverse scenarios targeting specific agricultural practices? (ii) Which agricultural pathways are most likely to balance food production, cropland SOC sequestration, agricultural GHG reduction, and minimize N surplus, based on the analysis of three contrasting scenarios and the spatial distribution of key environmental indicators? To answer these questions, we combined two approaches: (1) the generalized representation of agro-food system (GRAFS), which provides a framework for understanding the agro-food system from the perspective of nutrient and C flows (Le Noë *et al* 2019); and (2) the AMG model, a simple mechanistic model that requires only readily available soil and climate data (Autret *et al* 2016, Clivot *et al* 2019, Wang *et al* 2023b). In contrast to more complex higher-order models that demand extensive parameters and input data, first-order models such as AMG are more reliable for SOC prediction at the field and regional scales with limited data (Luo *et al* 2016, Shi *et al* 2018, Menichetti *et al* 2019). By integrating the GRAFS method with the AMG model, we aimed to predict the SOC stocks, GHG emissions, N surplus, and export capacity in the cropland of the Tuojiang River Basin under various agricultural development scenarios for 2035. Through this comparison, we sought to identify sustainable development pathways that achieve C sequestration, emission reduction, and food provisioning goals, while minimizing N loads in croplands.

2. Methods and data

2.1. Study area

The Tuojiang River Basin in southwestern China, which covers approximately 27 900 km^2 of cropland, serves as a case study of intensive agriculture in a humid, temperate climate. The region experiences annual rainfall ranging from 870 mm to 1700 mm, with average temperatures between 15.7 °C and 18.2 °C. Situated within the Sichuan Basin, the Tuojiang River Basin has a high population density, with cropland covering more than 80% of the total area. The predominant soil types are Argosols, Entisols, and Ferralosols (according to the Chinese soil taxonomy) (Li *et al* 2019). Livestock farming primarily involves pigs and cattle and intensive agricultural activities exert substantial pressure on aquatic environments (Xiao *et al* 2024).

2.2. Principles for GRAFS approach

The GRAFS methodology quantifies nutrient fluxes in key agricultural activities, including crop production, livestock production, and food consumption (Le Noë *et al* 2017, 2018). This has been extensively verified and applied to various geographical contexts and spatial scales (Lassaletta *et al* 2014, Billen *et al* 2018, Billen *et al* 2024). This method provides a detailed analysis of how croplands receive N from fertilizers, organic manure, atmospheric deposition, and symbiotic N fixation, convert it into harvestable crops, and estimate environmental surpluses. Additionally, livestock feed is partially derived from harvested crops or imported feed. The dietary intake and excretion of residents, linked to the consumption of animal and plant products, also affects crop and livestock production. A further interpretation of the GRAFS model and parameters can be found in the supplementary materials.

2.3. SOC stocks modeling

The AMG model detailed by Clivot *et al* (2019) was employed to estimate the evolution of topsoil SOC stocks (0–30 cm) in the croplands. The AMG model has been rigorously calibrated and validated through multi-decadal field experiments across the Tuojiang River Basin (Wang *et al* 2023b) and various agro-ecosystems worldwide (Saffih-Hdadi and Mary 2008, Autret *et al* 2016, Clivot *et al* 2019, Mary *et al* 2020). The details of the AMG model can be found in SM2.

Specifically, future humified C inputs to croplands were first estimated using the GRAFS model, followed by SOC stock simulation using the AMG model. In the biomass energy utilization scenario, biogas residue was treated as an exogenous C input to the cropland. The formula for calculating the exogenous C input is as follows:

$$TC_p = B_{mi} \times B_{ci} \times C_c \quad (1)$$

where TC_p represents the total C input from applied biogas slurry (t C ha^{-1} y^{-1}). B_{mi} represents the biomass of crop residues *i* (t ha^{-1} y^{-1}). B_{ci} represents the C content of crop residues *i* (t C t^{-1}), and C_C is the C conversion coefficient in biomass energy production (the percentage of by-product carbon relative to the initial C content of the biomass), with a value of 0.33 (Díaz *et al* 2023).

2.4. Data sources

2.4.1. Climate data

The decomposition rate of SOC is highly sensitive to temperature and precipitation (Dash *et al* 2019), making it essential to account for future climate change factors. Future climate trajectories for temperature and precipitation with a 1 km resolution from 2021 to 2035 were represented using three global circulation models (EC-Earth3, GFDL-ESM4, and MRI-ESM2-0) (Peng *et al* 2019). These datasets were generated from the coupled model intercomparison project 6 and included different representative concentration pathways (RCPs) (Eyring *et al* 2016). In this study, we used RCP 4.5 (an intermediate pathway with moderate GHG emissions) to model SOC changes from 2021 to 2035.

2.4.2. Soil data

The cropland SOC stock data in 2010 in the Tuojiang River Basin were derived from our previous study (Wang *et al* 2024). The dataset was generated from 1068 soil samples collected in 2017, in combination with AMG model simulations. These 1 km grid-scale SOC stock data were aggregated to the county scale using an area-weighted averaging method.

2.4.3. Other data

Agricultural census data for each county in the Tuojiang River Basin from 2010 to 2020 were obtained from the Sichuan Agricultural Statistical Yearbook (2010–2020). This data included information on cropland area, population size, urbanization rate, fertilizer input, crop yield, planting area, livestock numbers, and fossil energy consumption in the agricultural sector. Additionally, data and coefficients for estimating C and N fluxes, including cropland

SOC stocks, climate data, N content in harvested crops, and livestock GHG emission factors, were used (see supplementary SM1).

2.5. Scenario settings

Based on an analysis of policies and government reports, the biophysical option for the cropland system was explored by considering four levers: (i) synthetic fertilizer inputs, (ii) livestock population size and share of animal protein in the human diet, (iii) share of leguminous crop rotation, and (iv) proportion of straw used for bioenergy. In line with *the Action to Achieve Zero Growth of Chemical Fertilizer Use by 2020* issued by China's Ministry of Agriculture (Shuqin and Fang 2018), we established three scenarios to represent possible futures for agri-food systems: one with current fertilizer use levels, one with zero fertilizer input as an extreme alternative, and a middle scenario combining elements of both approaches. Studies have indicated that livestock farming in the Tuojiang River Basin has greatly exceeded the environmental carrying capacity, resulting in severe non-point source pollution risks and a high dependency on feed imports (Liu *et al* 2021, Xiao *et al* 2024). Per capita meat consumption, particularly pork, has more than doubled the recommended level in the Chinese Dietary Guidelines for 2022 (Ren *et al* 2023). Considering future dietary shifts and pollution control needs, livestock populations were set to either remain at the current level or be reduced by half. Organic cropping systems typically involve diversified rotations with a higher percentage of legumes, commonly ranging from 20% to 30% in organic rotations (Garnier *et al* 2023, Billen *et al* 2024). The planting frequency of leguminous crops was set to either 25% or remained at the current level to represent the two extreme orientations. To represent the two extreme orientations. Given the significance of the Tuojiang River Basin and Sichuan Province for straw and livestock manure recycling, we incorporated a biogas biomass energy scenario. This approach aligns with the *Technical Guidelines for Agriculture Green Development (2018–2030)* (Wang *et al* 2020). Using this approach surplus straw can be converted into energy products through biomass processing, with the byproduct biogas residue used as an exogenous organic input to enhance SOC stocks (supplementary SM1). The specific settings are listed in table 1.

Using agricultural data from to 2010–2020 as a baseline, the GRAFS model was driven by the input parameters defined by the outlined scenarios. Simulations were conducted at the county scale to model the cropland SOC stock dynamics under 24 scenario combinations from 2021 to 2035.

2.6. Sensitivity analysis

We selected five key input parameters for the sensitivity analysis based on their impact on nutrient flow and the large uncertainty in their values (Papangelou and Mathijs 2021). Parameters with low uncertainty, such as data from official agricultural censuses, were excluded from analysis. In this study, we employed the one-factor-at-a-time method (Zhang and Yu 2020) to investigate the sensitivity of five key parameters: $Y_{\max}$, the carbon conversion coefficient in biomass, ammonia volatilization coefficients, symbiotic N fixation coefficients, and livestock CH_4 emission coefficients. An uncertainty range of $\pm 20\%$ was applied to all these five parameters. To evaluate the results quantitatively, we calculated the relative sensitivity index (SI) (Stehfest *et al* 2019), considering parameters with an SI greater than 10% as sensitive (Yadav and Wang 2021).

Table 1. The scenario settings of the main model parameters.

Main variables	Scenario settings		
Synthetic fertilizer inputs	Business as usual	50%	0
Livestock population size and the fraction of animal proteins	Business as usual	50%	/
Legume rotation rate	Business as usual	25%	/
Bioenergy use proportion	0	50%	/

3. Results and discussion

3.1. Current trend of agro-food systems in the Tuojiang River Basin

The current agricultural system patterns in the Tuojiang River Basin over the last decade reflect the impact of agricultural intensification (figure 1). From 2010 to 2020, livestock density declined from 2.08 to 1.29 Livestock Unit/ha, primarily due to the regulation of livestock farming influenced by non-point source pollution control policies (Zhu *et al* 2022). As a result of fertilizer use reduction policies in the 2010s and improvements in fertilizer use efficiency (Xin 2022), cropland N inputs have significantly decreased since 2010 (figure 1(c)). These changes occurred together with a slight decrease in the crop harvested N yield (figure 1(b)), in line with the established relationship between total N fertilization and crop production (see equation (S1)). This region relies heavily on livestock feed imports, which exceed protein crop exports (figure 1(d)). Total GHG emissions and N surplus were closely aligned with livestock density and N fertilizer inputs, both showing a declining trend from 2010 to 2020 (figures 1(e) and (f)). Due to sustained C inputs in cropland, the cropland SOC stock continued to increase, rising from 42.52–48.40 tC ha^{-1} during 2010–2020.

The spatial distributions of seven main agricultural indicators in each county of the Tuojiang River Basin are shown in figure 2. High livestock densities were concentrated in both the upper (e.g. Jinyang county) and lower (e.g. Zigong County) streams of the basin. Crop N yield is closely linked to total N

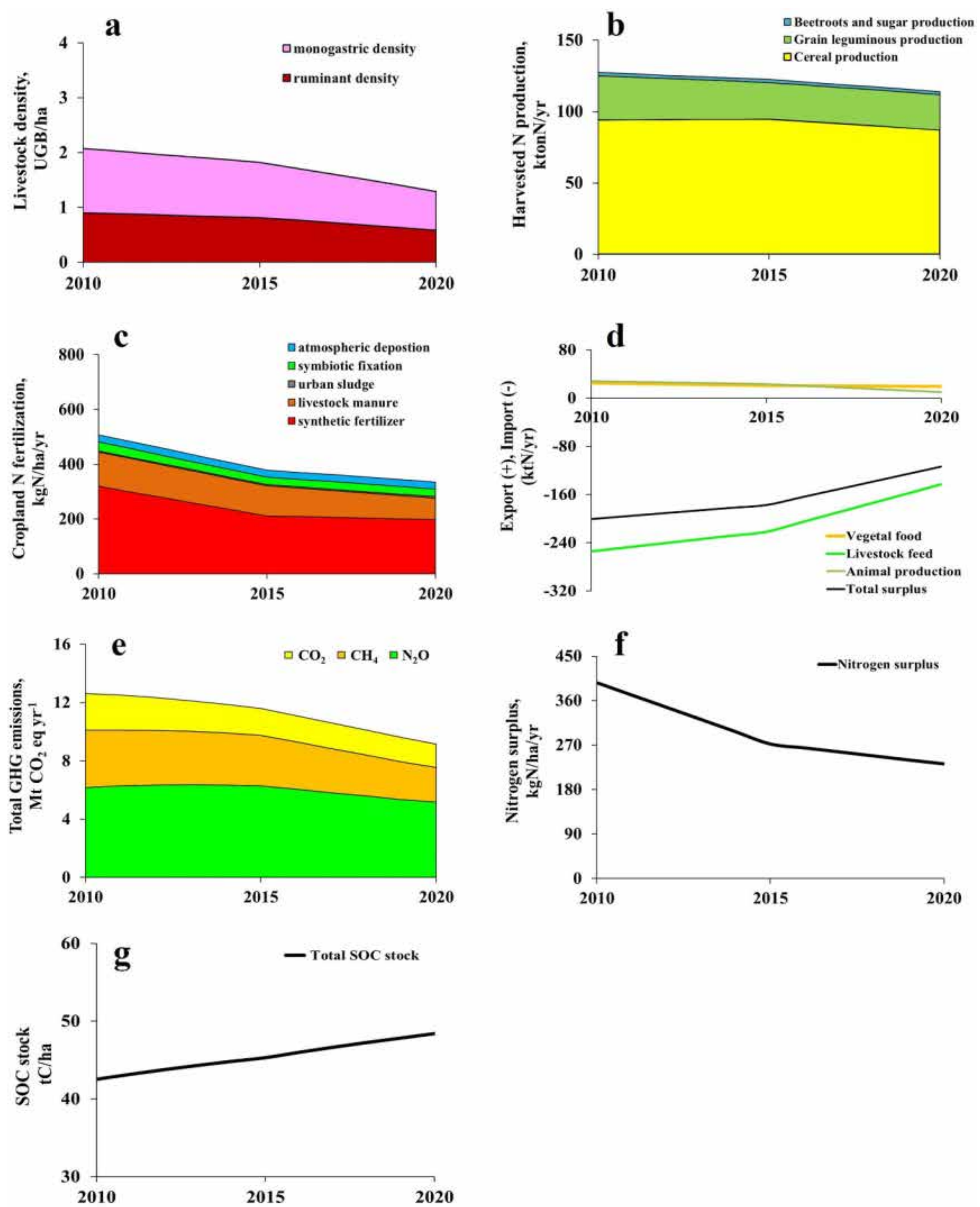

Figure 1. Trajectories of agro-food systems in Tuojiang River Basin through seven main indicators: (a) livestock density, (b) harvested nitrogen production of different crop types, (c) total nitrogen inputs to cropland soils, (d) exports and imports capacities, (e) agricultural greenhouse gas emission budget, (f) cropland nitrogen surplus, (g) cropland SOC stock.

inputs (Liu *et al* 2015), showing a distinct north–south gradient due to variations in crop residue and manure inputs. All counties require feed imports ranging from 2.70 to 10.14 ktN yr^{-1}. Seventy percent of the counties have an N surplus exceeding the recommended maximum threshold of 190 kg N ha^{-1} yr^{-1} for China's cropping systems (Zhang *et al* 2019), indicating a high risk of agricultural non-point source pollution. Croplands in the upper Tuojiang River Basin generally have the highest SOC owing to their flat terrain, fertile soil, dense river network, and favorable climate. In the northwestern region, where urbanization and population density are the highest, the extensive use of chemical fertilizers since the 1980s has significantly enhanced crop productivity and increased carbon inputs from crop residues through practices such as straw return (Wang *et al* 2023a). Consequently, the SOC stocks in this area have remained high over the past few decades (Wang *et al* 2024). In contrast, warmer and wetter conditions

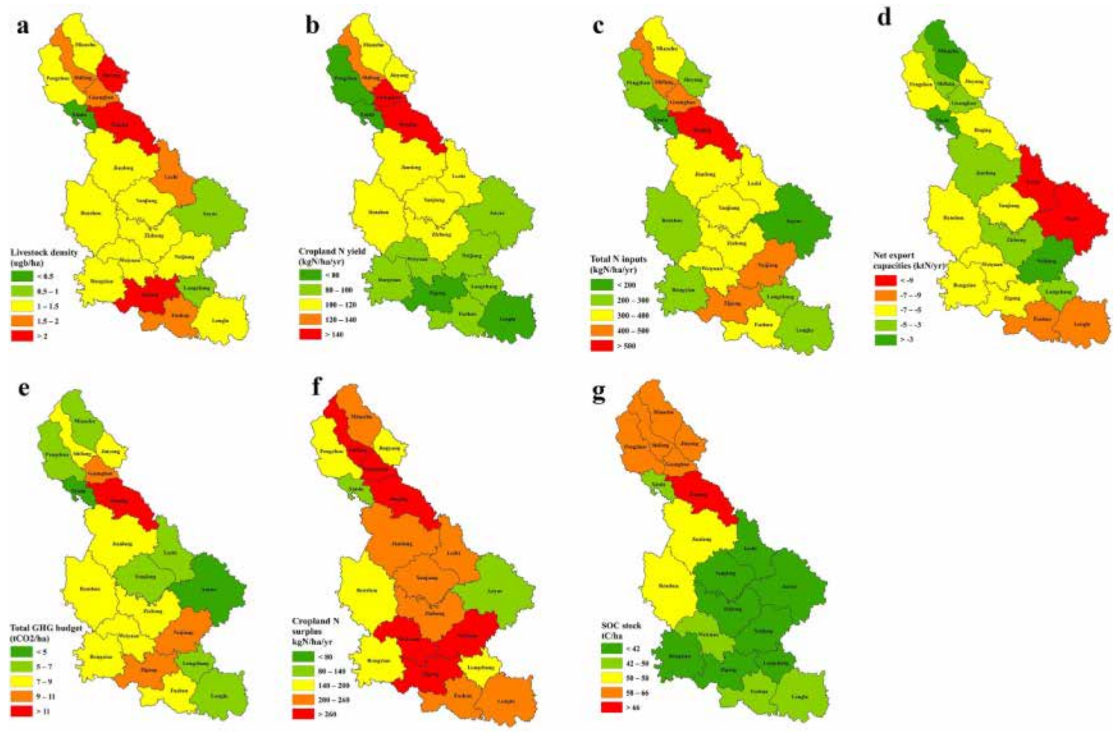

Figure 2. Current (in 2020) characteristics of seven main agricultural indicators for each county in Tuojiang River Basin: (a) livestock density, (b) crop N yield, (c) total nitrogen inputs to cropland soils, (d) exports and imports capacities, (e) agricultural greenhouse gas emission budget, (f) cropland nitrogen surplus, (g) cropland SOC stock.

in the downstream regions reduce agricultural productivity by increasing crop mortality and accelerating SOC decomposition, resulting in lower SOC levels (Wang *et al* 2023a).

3.2. Biophysical option spaces under different scenarios

Figures 3(a)–(c) illustrate the GHG emissions (CO_2, CH_4, and N_2O converted to CO_2 equivalents), net GHG emissions (including SOC dynamics), and N surplus from croplands in the Tuojiang River Basin under the 24 scenarios projected for 2035. Scenarios maintaining current fertilizer input and livestock populations exhibited the highest GHG emissions, exceeding 9 Mt CO_2 equivalents and N surplus 21%–30% above the recommended maximum threshold of 190 kg N ha^{-1} yr^{-1}. In contrast, intermediate scenarios with adjusted livestock populations and fertilization demonstrated significantly lower GHG emissions and N surpluses. Halving both fertilizer input and livestock population reduces GHG emissions by 39%–43% and lowers N surplus by 26%–52%, bringing it within the recommended range for optimal N management. The lowest GHG emissions and N surplus were observed in scenarios with zero fertilizer input and a halved livestock population, achieving 60%–65% and 75%–84% reductions, respectively. Bioenergy measures further reduce GHG emissions by 2.9%–5.3% if bioenergy replaces fossil fuels. Adjusting the legume crop rotation frequency had a minor impact, with slightly higher emissions at altered rotation frequencies compared to current practices. Net GHG emissions followed the same patterns as GHG emissions (figure 3(c)), indicating that SOC sequestration does not counteract GHG emissions from livestock breeding and fossil fuel inputs in croplands. Therefore, the tradeoff between climate change mitigation and C sequestration require careful evaluation. Overall, the results revealed a synergistic effect between GHG emissions, net GHG emissions, and the N surplus.

In contrast, the scenarios revealed at least partially antagonistic effects on SOC sequestration and export capacities. Figure 3(d) indicates that the highest SOC sequestration occurred under the current scenario, whereas scenarios with zero fertilizer input and a halved livestock population with a fraction of animal proteins in the diet resulted in agricultural soils acting as C sources. This suggests that SOC sequestration does not reverse the pattern of GHG emissions (figure 3(a)) although it offers benefits beyond climate change mitigation. Figure 3(e) shows that maintaining current fertilizer inputs, halving the livestock population, and reducing animal protein intake in the human diet decreased dependency on feed imports by 34%–75%. Conversely, reducing fertilizer input while maintaining the current livestock population increases feed import needs by 7%–30%,

Figure 3. Cropland (a) greenhouse gas emissions, (b) net greenhouse gas budget, (c) nitrogen surplus, (d) SOC emissions, and (e) food net export capabilities within Tuojiang River Basin in 2035 under different scenarios.

because of the high reliance of livestock farming on feed imports, making the region a net importer of proteins (figure 1(d)).

The tradeoffs between these sustainability indicators are discussed in the following section.

3.3. Environmental co-benefits under typical scenarios at the county level

To further analyze the trade-offs between the various sustainability indicators, we compared three contrasting scenarios: the business-as-usual scenario (S1), the intermediate scenario (S2) (halving fertilizer use and livestock population size, maintaining the current legume crop rotation frequency, and using 50% straw for biomass energy), and the agro-ecological scenario (S3) (characterized by zero fertilizer use, halved livestock population size, 25% legume crop rotation frequency, and 50% straw utilization for biomass energy (figure 3). The agro-ecological scenario (S3) represents a comprehensive transition to organic agriculture with substantial structural changes in the agro-food system. Given that this is a drastic shift, we also explored a more feasible intermediate transition scenario (S2) as a step toward agro-ecological practices. Figure 4 illustrates the regional patterns of cropland SOC stocks and environmental benefits under the three scenarios.

Scenario S1 significantly increased agricultural SOC stocks but resulted in the highest GHG emissions and N surplus. While current practices enhance SOC due to high crop residue and manure inputs, intensive farming and livestock systems drive notably higher GHG emissions than other scenarios. Excessive N inputs can lead to soil acidification and non-point source pollution (Fang *et al* 2014, Khatri-Chhetri *et al* 2022), primarily due to chemical fertilizer production and livestock manure, resulting in a high N surplus, while also contributing substantially to C emissions (Liu and Zhang 2011, Bellarby *et al* 2013). In Scenario S1, 90% of the counties in the Tuojiang River Basin experienced an increase in SOC stocks from 2020 to 2035 (figure 4(d)). However, net C emissions exceeded 6 t CO_2/ha in these counties, with the highest GHG emissions by 2035 concentrated in the upstream (e.g. Shifang) and downstream (e.g. Zigong) regions. These elevated emissions result from intensive livestock farming and heavy fertilizer use, driving excessive N surplus and non-point source pollution risks.

In contrast, scenario S2 increased the SOC stock while reducing GHG emissions by 39% and feed import dependence by 58%. Lower agricultural intensity significantly reduces both direct and indirect energy consumption, including emissions from production. Furthermore, the agricultural N surplus decreased by 52% compared to the baseline, reducing non-point source pollution risks. Scenario analyses indicated that halving N fertilizer use resulted in a modest 1% increase in SOC sequestration by 2035. With China's fertilizer application rate at roughly 2.7 times the global average (120 kg ha^{-1}) (Zuo *et al* 2023), reducing N inputs while maintaining food security is essential to enhance SOC sequestration and reduce GHG emissions and point-source N pollution (Li *et al* 2021). Although reduced crop residue and organic fertilizer inputs may slightly diminish soil C sequestration, this scenario will sustain the soil C sequestration capacity in the Tuojiang River Basin until 2035. This result is consistent with those of other studies at larger geographical scales with similar scenarios (Garnier *et al* 2023, Sanz-Cobena *et al* 2023, Billen *et al* 2024). A moderate organic farming scenario has proven to be both biogeochemically feasible and capable of ensuring food autonomy

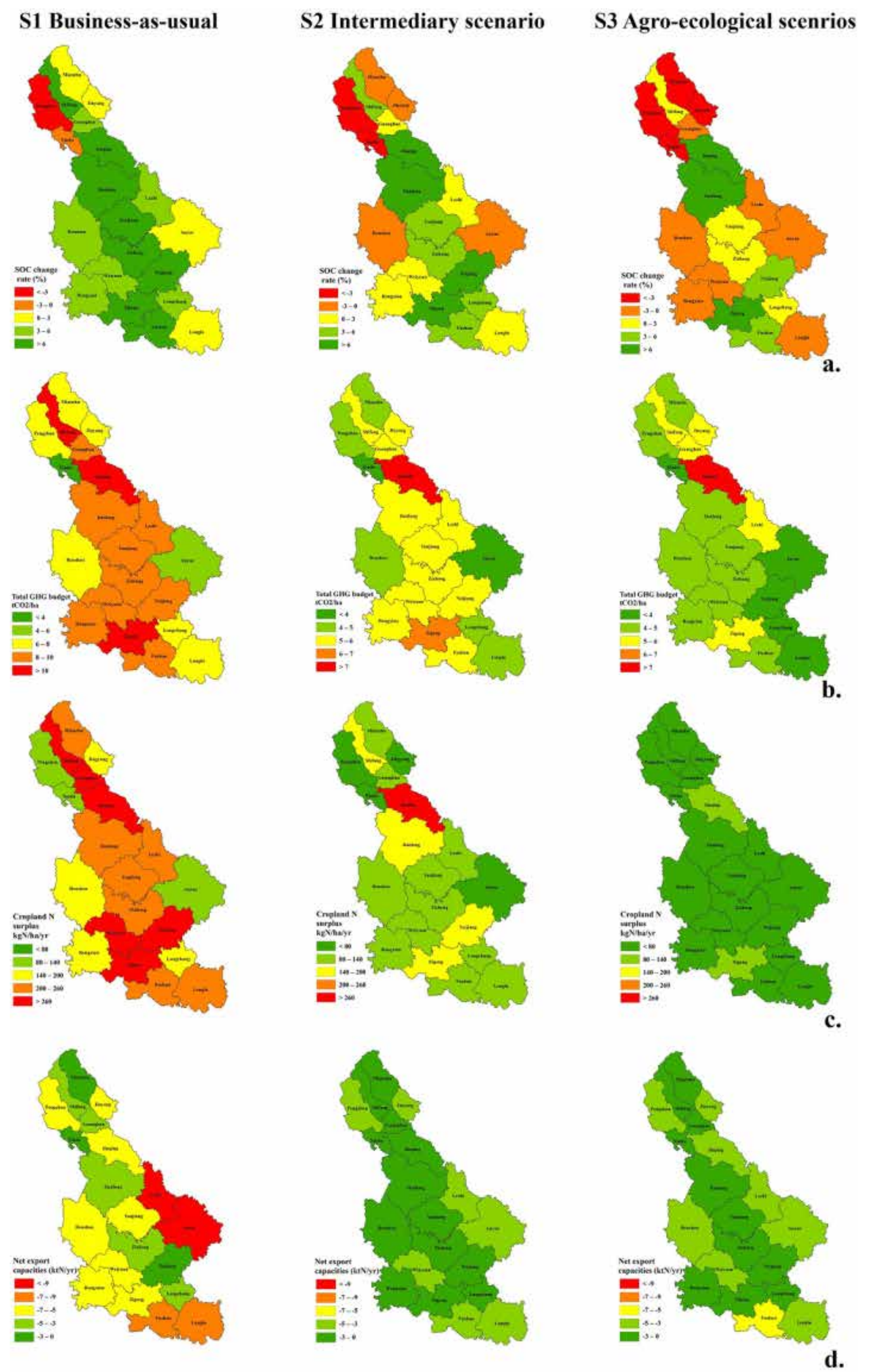

Figure 4. Spatial variability of (a) the change rate of cropland SOC stock from 2020 to 2035, (b) the net GHG emissions budget in 2035, (c) the cropland nitrogen surplus in 2035, and (d) the net export capacities in 2035 under three different scenarios in the Tuojiang River Basin.

(Billen *et al* 2021, Garnier *et al* 2023), and our results underscore its environmental advantages. Our results show that, to reach the carbon peak and neutrality targets proposed by the Chinese government without requiring large additional food imports, a shift in diet structure, including reducing the consumption of animal products, has a strong potential to promote green agricultural development (Yu *et al* 2023). In Scenario S2, 70% of the counties showed an increase in agricultural SOC stocks. Net C emissions fell between 4 and 6 t CO_2/ha in most regions, with only 10% of counties exceeding 6 t CO_2/ha, a reduction of 80% compared with scenario S1. The number of counties with high GHG emissions and N surplus also decreased, with total GHG emissions in Shifang, Neijiang, and Weiyuan counties decreasing by over 25% and the N surplus decreasing from 22.1% to 45.2%.

Scenario S3 achieved 46% and 75% reductions in net GHG emissions and N surpluses from croplands, respectively. Contrary to field observations reporting a high C sequestration potential in organic farming (Seufert and Ramankutty 2017), our results show that a full transition to agro-ecological agriculture transforms cropland soil from a C sink to a C source. Our results, in line with other studies, indicate that this reversal from the C sink to the C source stems from the drastic reduction in soil C inputs, primarily crop residues, due to lower N fertilization, which in turn lowers crop yields and manure as a result of halving the livestock population (Barbieri *et al* 2021, Gaudaré *et al* 2023). Our findings on the limited SOC benefits align with those of a recent meta-analysis, suggesting that organic farming may not increase SOC stocks relative to conventional farming without carbon transfer from other agroecosystems (Alvarez 2021). According China's '2020 Zero Growth Action Plan for Fertilizer Use', substituting chemical fertilizers with organic ones is a feasible strategy to boost crop yields and contribute to SOC accumulation (Zuo *et al* 2023). Scenario S3 achieved the lowest net C emissions and agricultural N surplus across counties, largely because of practices such as fertilizer elimination, which sharply reduces CO_2 from production and N_2O from manure application, and organic fertilizer inputs, which reduce CH_4 emissions. Despite these benefits, Jinniu District and Qingbaijiang counties still report high net C emissions of 11.7 t CO_2/ha due to dense livestock farming and high manure inputs, which leads to significant GHG emissions. Additionally, self-sufficiency in production reduces feed imports and the associated C emissions. However, more than half of the counties experienced a decline in agricultural SOC stocks from 2020 to 2035, highlighting the trade-offs of agro-ecological agriculture for soil C sequestration, N pollution limitation, and reduction of GHG emissions.

3.4. Limitation and prospects

The strength of our approach lies in the integration of a comprehensive scenario analysis of agro-food systems at the county level. However, some input data (e.g. agricultural energy consumption) are subject to uncertainties owing to data availability, which can only be derived from provincial or national studies. The sensitivity indices of the five main input parameters are listed in table S4. The variation in all variables for the five environmental indicators remained within ±10%, except for Y_{max}, which significantly impacted food net export capabilities, resulting in changes of −12.63% and 14.27%, respectively. Notably, the variation in ammonia volatilization and livestock CH_4 emission coefficients exceeded 5%, suggesting that these two factors are potential sensitivity factors (Wang *et al* 2016, Prade *et al* 2017, Zhao *et al* 2021). Previous research indicates that future technological advancements are likely to focus on mitigating the negative impacts of climate change (Billen *et al* 2021). These findings suggest that while the fixed coefficients introduce some level of uncertainty, they do not significantly alter the overall trends, reinforcing the robustness of our results. Furthermore, it is technically challenging to predict the spatial and temporal changes in emission factors and key agricultural management parameters because these do not evolve over time in the model owing to limited county-specific data in southwest China. Although further studies on the temporal dynamics of these parameters would enhance accuracy (Hergoualc'h *et al* 2019), a sensitivity analysis using Monte Carlo methods in a previous study showed that adjustments to individual parameters do not significantly alter total GHG emissions estimates (Hu *et al* 2023).

Currently, the N surplus is based on county-level balances and does not specifically account for upstream-downstream linkages. However, a high N balance in upstream areas can significantly affect downstream regions in terms of nitrogen pollution. Riverine N degradation is influenced by multiple factors, including N load, transport, and transformation processes, particularly in large basins (Wang *et al* 2020). In future studies, a distributed pollution model, such as the geomorphology-based nonpoint-source model, could be integrated to simulate N migration and transformation from hillslopes to rivers, accounting for the spatial and temporal variability in large watersheds.

Further, uncertainty concerns the cost and profitability of these pathways for farmers (Huang and Yang 2017). To assess the feasibility of future optimization measures, it is necessary to incorporate a cost analysis and evaluate whether they can be accepted by smallholder farmers or need stronger public policy support. In the future, policy support, compensation mechanisms and carbon markets in China could incentivize farmers to adopt GHG reduction practices (Nsabiyeze *et al* 2024). Incorporating ecological metrics, such as Marginal Abatement Cost Curves, could help quantify the balance between costs and environmental benefits, facilitating coordinated environmental and economic development (Zou *et al* 2023). Lastly, promoting the reduced consumption of animal products could play a role in lowering GHG emissions, underscoring the need for policies that encourage dietary shifts toward grains and other plant-based options to meet nutritional needs.

4. Conclusion

This study assessed the trade-offs among agro-environmental indicators at the county level in the heterogeneous Tuojiang River region by integrating the GRAFS method with the AMG model based on projected agricultural development scenarios for 2035. Our findings indicate that strategies, such as reducing fertilizer use, moderating livestock intensity alongside dietary shifts toward less animal protein, and partially adapting crop straw for biomass energy, can achieve an equitable balance between GHG reduction, C sequestration, productivity, and sustainability in croplands. However, caution should be taken to prevent potential C source effects in croplands, as the full transition toward organic agriculture has resulted in lower crop production and thus lower residue input to the soil, resulting in SOC losses according to our simulations. Future research could incorporate the spatiotemporal parameters of agricultural practices and perform cost analyses to better evaluate the trade-offs among strategies and their environmental benefits. This approach is broadly applicable to other contexts where data are available, offering valuable insights for policymaking by informing a wide range of scenarios.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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