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Evaluating sustainable intensification levels of dryland agriculture: A focus on Xinjiang, China

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ABSTRACT

Adequate tools for evaluating the Sustainable Intensification of Agriculture (SIA) level are crucial, especially in drylands with limited resources. Based on emergy indices and environmental footprints, We propose an evaluation framework for the case of major crop intensification in Xinjiang, China, and examine the local SIA from 2001 to 2020. The results show that increases in emergy input (EI) of the crop system were achieved with simultaneous increases in water consumption and carbon emissions. The most EI to the system is from economically non-free non-renewable resources (75.1 %), and only 5.4 % from environmentally free renewable resources. The emergy output (EO) of cotton was less than 80 % of wheat and maize, but the carbon footprint (CF) and water footprint (WF) of cotton were much higher than wheat and maize (>1.18 times and > 5.01 times, respectively). We group historical results covering emergy indices, CF, WF, and other production indicators into five dimensions and comprehensively evaluate the level of SIA in Xinjiang according to the changes in the five dimensions. It was found that raising the SIA depended on improving management, productivity, and environmental impact dimension from 2000 to 2005. After 2005, the SIA's down-turning was due to the trade-offs between management, environmental dimensions, and their indicators and the continuous reduction of sustainability of other dimensions. In addition, the progress and realization of SDG 2, SDG 6, SDG 7, SDG 8, SDG 11, and SDG 12 can effectively improve the SIA. Our study serves as a helpful example for evaluating the level of sustainability of intensive agricultural policies not just in Xinjiang but also in other drylands of the world.

1. Introduction

Efficient resource management is critical to sustainable development in the Anthropocene era (Hoekstra, 2014). The United Nations recognized this imperative and introduced the 17 Sustainable Development Goals (SDGs) in 2015. These goals represent a concerted effort to address the long-term challenges of social stability, economic development, and ecological security (Reyers and Selig, 2020). The intensification of agriculture, driven by the green revolution, has been triggered by rising labor opportunity costs and significant increases in commercial water and energy consumption (Armanda et al., 2019). However, this intensification poses a significant threat to biodiversity and the delivery of essential ecosystem services (Decocq et al., 2016). As a response to these challenges, Sustainable Intensification of Agriculture (SIA) has been identified as a fundamental solution. The underlying premise of SIA is to increase productivity and economic value while adopting environmentally sustainable practices that consider both biophysical processes and social factors (Bernard and Lux, 2017). Achieving these goals requires a paradigm shift in the resource base for crop production. With resource reserves being limited and their consumption resulting in a high

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environmental cost, it is imperative that people prioritize alternative energy sources and improve resource efficiency through technological and policy incentives (Ngan et al., 2019). Adopting SIA practices and transitioning to alternative energy sources and resource-efficient technologies are crucial steps toward achieving SDGs.

To select appropriate indicators for assessing the SIA, Emergy Analysis (EmA) is a reliable method that can quantify both "free" and " non-free" input indicators in agricultural intensification, whose unit is solar emjoule (sej), to solve the problem of incomparability in different evaluation dimensions of the disunity (Brown and Herendeen, 1996; Lyu et al., 2022). Previous studies have confirmed that EmA can describe the input–output flow of farming systems and assess the efficiency of intensification (Rodríguez-Ortega et al., 2017; Xie et al., 2021). In addition, sustainability studies of intensification have mainly focused on specific indicator systems, such as water and nitrogen balance indicators (Chukalla et al., 2020). Energy and agrochemical risk indicators can also evaluate the SIA (Pittelkow et al., 2016). However, there are currently few successful cases of comprehensive SIA assessments in arid regions, particularly involving the integration of multiple inputs and social indicators. In EmA, the input part can well include the above indicators. Arid regions cover a third of the global land area. Some governments have had higher competing demands for farming in drylands, namely the need to increase productivity to feed a growing population while minimizing footprints (Jiao et al., 2018; Chouchane et al., 2020). The blue water generally accounts for 70 % to 90 % of the total Water Footprint (WF) in drylands (Tian et al., 2020; Hai et al., 2020; Xu et al., 2019). Similarly, the impact of the Carbon Footprint (CF) on sustainable intensification cannot be ignored. For example, changes in farmland types could significantly increase the carbon debt (Chen et al., 2021). Rational fertilization coupled with a supplemental irrigation regime can mitigate CF and substantially improve intensification (Ahmad et al., 2022). Footprint accounting (FA) is a cradle-to-gate approach that examines the inputs consumed during the product or service's life cycle and assesses their usefulness and scarcity (Elbeltagi et al., 2020a; Elbeltagi et al., 2020b; Fang et al., 2021). FA can quantify pressure along the supply chain and help evaluate trade-offs and synergies with different SDGs (Vanham et al., 2019; Hoekstra et al., 2019; Fang, 2022). However, the results obtained by different FA studies may need more standardized procedures (Zadgaonkar and Mandavgane, 2020). In contrast, EmA can view the system as embedded in the more extensive natural system that supports it and includes all inputs that converge to sustain it over spatiotemporal scales (Raugei et al., 2014; Nadalini et al., 2021). Arguably, WF and CF are critical points for measuring the sustainability of dryland agricultural systems, and EmA provides useful supplements to existing FA with a comprehensive donor-side perspective and presents a standardized procedure for the SIA focus. Therefore, in arid regions with limited resources and fragile ecological environments, it is necessary to unify EmA and FA indicators into the framework of SIA.

In recent years, heightened awareness of issues such as ecological vulnerability and water scarcity in drylands has driven significant advancements in research on the sustainability of dryland agriculture. Scholars have made noteworthy progress by simulating the impact of agricultural production on dryland ecosystem services (Xue et al., 2022). By establishing an evaluation system that incorporates the evenness of progress toward SDGs, researchers have unveiled the intricate relationship between dryland water resource pressure and the achievement of SDGs. This underscores the imperative for comprehensive measures, including those addressing environmental impact, resource consumption, and regional planning (Zhu et al., 2023). Against the backdrop of global drylands governance, there is a growing recognition of the importance of studying the impact of dryland SIA on human livelihoods (Li et al., 2023). An increasing number of voices advocate creating a dryland governance system characterized by nested multi-dimensional settings. Emphasis is placed on the nuanced application of these dimensions in agricultural intensification, specifically addressing facets such as food security, production efficiency, and management sustainability (Stafford-Smith and Metternicht, 2021). Consequently, for policymakers at the local level, there is an urgent need to establish a research framework that integrates multi-dimensional assessments. This framework aims to tackle the challenges of dryland agricultural production and contribute to advancing regional sustainable development. As the largest arid administrative region in China, Xinjiang experiences climate conditions marked by frequent droughts and extreme temperatures, making sustainable agricultural production practices imperative. The rapid agricultural development in Xinjiang has also transformed traditional agriculture into intensive production. Specifically, this transformation can be traced back to the late 1970 s when the Chinese government implemented the policy of reform and opening up, providing more funding and technical support for Xinjiang's agriculture. In 2020, the total crop irrigation area was 6.28×10^6 ha, among which cotton, wheat, and maize were representative crops in Xinjiang, covering over 80 % of the sowing area (Long et al., 2021). Cotton production in Xinjiang has received significant attention due to the substantial increase in production scale, especially in recent years, with yield per unit area gains attributed to improved agronomic techniques and management combined with developed high-yielding varieties (Long et al., 2020). However, the contribution of resource inputs and emissions to production management and social development still lacks an accurate understanding of the evaluation framework for SIA in Xinjiang, and quantification is particularly challenging. Hence, the combination of challenging climatic conditions, rapid development, and the influential role of the government in shaping agricultural policies and practices distinguishes Xinjiang as a compelling research location. We selected Xinjiang as the research area to conduct a comprehensive assessment of SIA, highlighting its representativeness. We tracked Xinjiang's progress towards achieving SIA at the dryland levels by evaluating the intensification indicators over time (see details in the Materials and Methodology). We addressed four problems. First, how has the emergy flow of representative crop systems and their products in Xinjiang, as measured in terms of the Emergy Input (EI) and Emergy Output (EO), evolved at the landscape level? Second, how has the spatiotemporal structure of the WF and CF of these systems varied across Xinjiang's administrative regions over time? Third, how has the SIA in Xinjiang evolved under the incorporated influence of EmA, FA, and other socioeconomic metrics? And Fourth, how to establish the relationship between SIA in drylands and different SDGs?

To address these questions, we utilized annual time-series data pertaining to SIA in Xinjiang at the regional level from 2001 to 2020. The SIA comprehensive index was calculated using 20 SIA indicators across five evaluation dimensions. Emergy flows, WF, and CF were quantified for representative crop systems in Xinjiang. An SIA evaluation framework was constructed that incorporated EmA, FA, economic, and productivity indicators. This comprehensive framework enabled us to examine the SIA in Xinjiang from 2001 to 2020. Additionally, we discussed the relationship between crop intensification in Xinjiang and SDGs and explored the synergies and trade-offs resulting from agronomic and policy changes over the past two decades.

2. Materials and methodology

2.1. Study area

The present study focuses on Xinjiang, China, an autonomous region in northwestern China with an area of more than 1.6 million square kilometers in Eurasia. Its jurisdiction includes 14 administrative districts (Fig. 1), with agriculture as its primary economic sector. This region cultivates both food crops (wheat, maize, rice, soybeans) and cash crops (cotton, oil plants, sugar beets, vegetables, melons, potatoes, alfalfa, grapes, apples, fragrant pears, and red jujube), but cotton, wheat, and maize are the major crops, occupying more than 80 % of the cropland area from 2001 to 2020. Additionally, these crops accounted for over 85

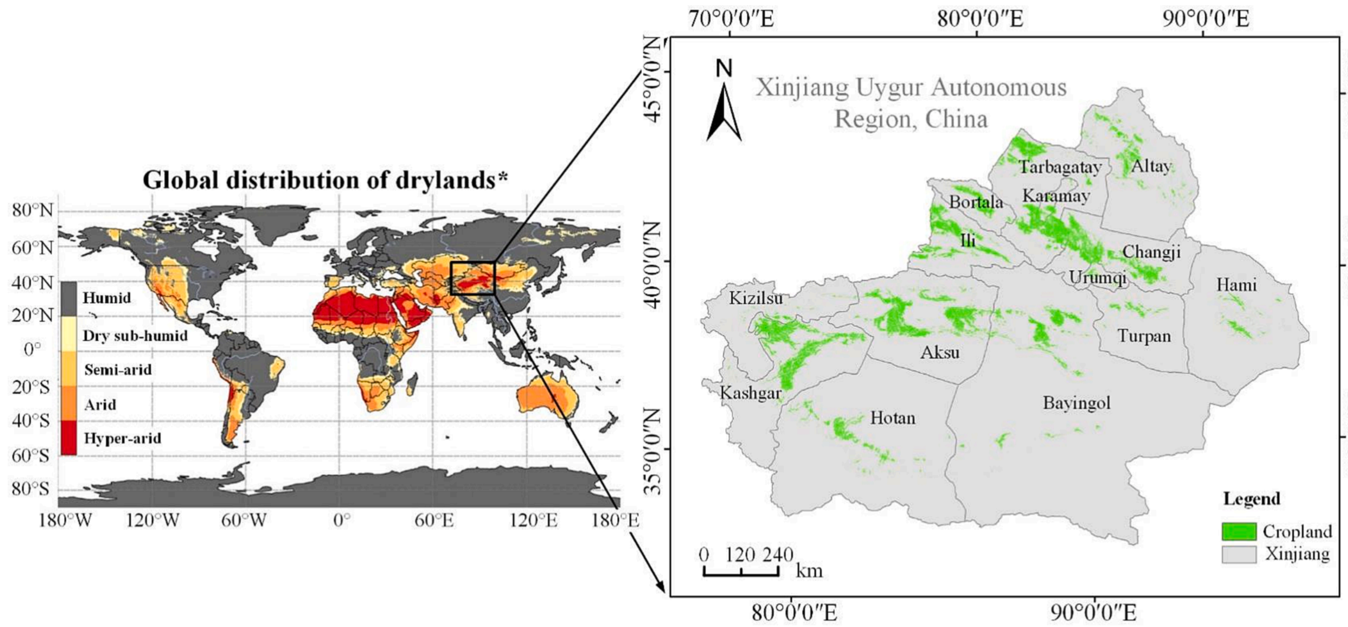


Fig. 1. Geographical location map of Xinjiang and main cropland locations, *data from Abatzoglou et al., 2018.

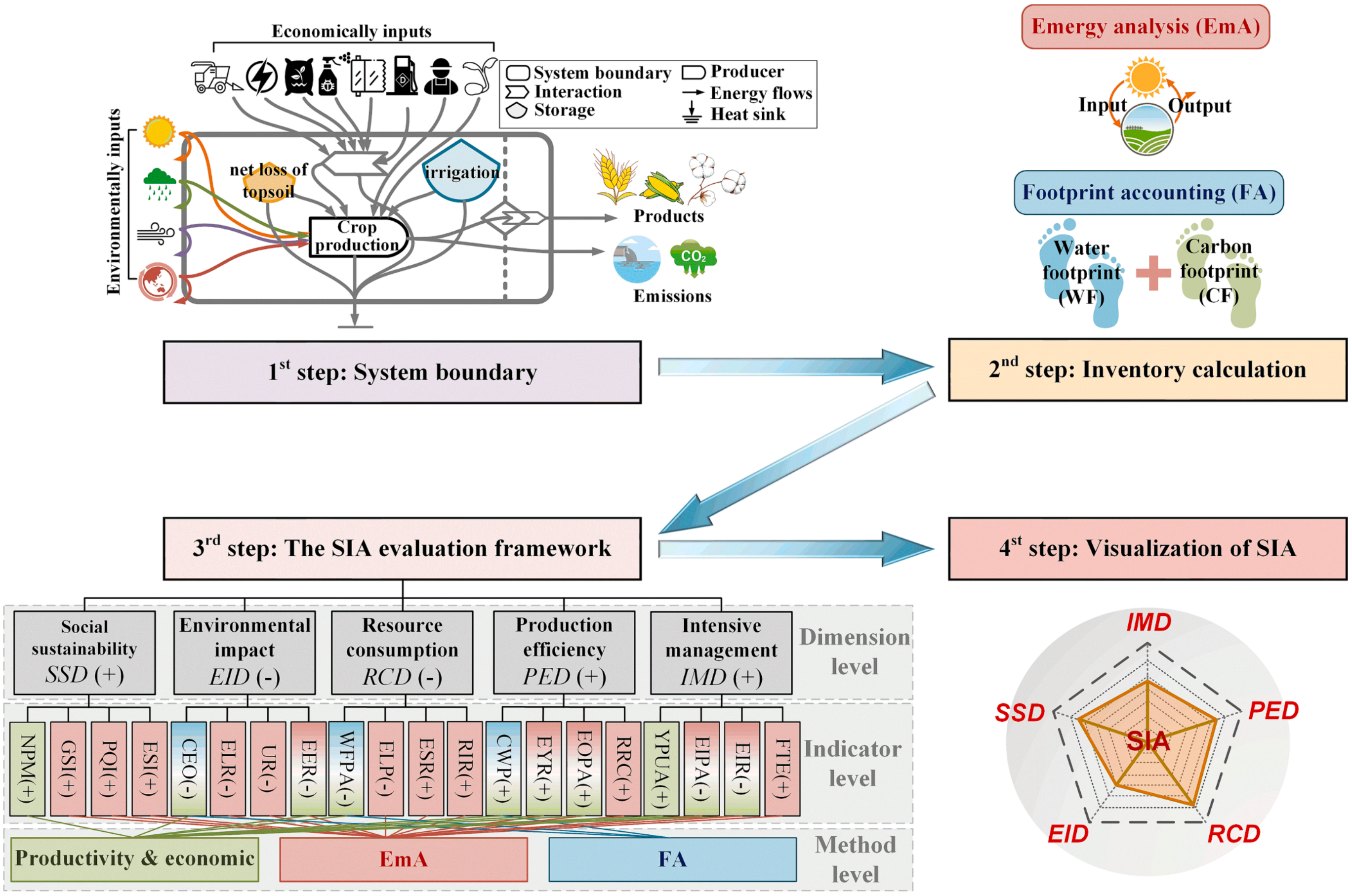


Fig. 2. System boundary and evaluation framework. Note: ① (+) denotes a positive effect on the evaluation level and (-) denotes a negative effect on the evaluation level. ② The evaluation indices: Net profit margins (*NPM*), Grain self-sufficiency index (*GSI*), Product quality index (*PQI*), Emergy sustainable index (*ESI*), Carbon emission per output value *(CEO)*, Environmental load ratio (*ELR*), Unrenewable input ratio (*UIR*), Environmental economic efficiency (*EEE*), Water footprint per unit area (*WFPA*), Emergy loss percent (*ELP*), Emergy self-sufficiency ratio (*ESR*), Renewable input ratio (*RIR*), Crop water productivity (*CWP*), Emergy yield ratio (*EYR*), Emergy outputs per area (*EOPA*), Renewable resource contributions (*RRC*), Yield per unit area (*YPUA*), Emergy inputs per area (*EIPA*), Emergy investment ratio (*EIR*), Farming tillage efficiency (*FTE*).

% of the fertilizers used in crop production during the same period. Consequently, we selected these crops for our study, given their high input consumption. Climatically, Xinjiang experiences a continental climate. The region has limited rainfall; most areas receive less than 200 mm of rainfall annually. Rivers and glaciers provide essential sources of water for local agricultural production. As a means of characterizing the spatial and temporal distribution of agriculture systems, we defined three broader regions in Xinjiang (northern, southern, and eastern), based on the Tianshan Mountains as the boundary, to examine the contribution of crop production to environmental emissions and resource consumption in different regions. Annex 1 in the Supplementary Information provides more details about the classification of these regions. We also investigated the degree of intensification of major crop systems in Xinjiang from the perspective of crop productivity and profitability and found that it has increased over the past 20 years. Please refer to Annex 2 for the detailed survey results.

2.2. Evaluation framework, EmA and FA

Considering the connotation of intensive production and its alignment with the SDGs, this study has established an SIA evaluation framework by fusing EmA, FA, productivity, and economic indices. The overarching aim is to achieve a more efficient and sustainable crop system, including three sub-aims: resource, socio-economic, and ecological benefits. The latter is measured across five dimensions: Resource consumption (*RCD*), Intensive management (*IMD*), Production efficiency (*PED*), Social sustainability (*SSD*), and Environmental impact (*EID*). Each dimension comprises four evaluation indices. The values of each dimension are standardized and used to calculate the comprehensive SIA index. A pentagon is constructed by combining five index triangles, and the visualization of SIA results was obtained by calculating the areas of each triangle and adding them. Due to the limited space in this paper, the detailed calculation process on indices selection, explanation, expression, classification, the SIA composite index calculation, SIA results normalization, and visualization was shown in Annex 3. Fig. 2 illustrates the SIA evaluation process based on the above-mentioned content.

Energy is a fundamental aspect of the structure and function of crop systems, with solar energy serving as the foundation for all forms of energy on Earth. The application of EmA facilitates the comprehensive evaluation of various input sources and material outputs within the crop production process. The complex energy, material, and information flows within crop systems can be quantitatively analyzed by converting disparate energy and substance types into the same standard solar emergy. This analytical approach allows for the comprehensive and objective measurement of the structural and functional characteristics of crop systems and their economic and social benefits (Odum, 2002). Then, the system diagram of EmA was established based on the above information (See the first step in Fig. 2 for details). The crop system boundary was defined from seed sowing to product harvesting in accordance with the EmA methodology (Wang et al., 2021a; Wang et al., 2021b). The input items in the intensive production involve environmentally free renewable resource inputs (sunlight, rainwater or green water, wind, and earth rotation), environmentally free non-renewable resource input (net topsoil loss), economically non-free non-renewable resource inputs (machinery, electricity, diesel, fertilizer, pesticide, plastic mulch, and irrigation water or blue water), economically non-free renewable resource inputs (labor and seeds), and direct emissions to air and water. In tandem with the inexorable waste and losses of energy, a fraction of the energy input into the system is retained within the topsoil, most of which participates in intensive production and is converted into crop energy. For detailed EI, emergy waste and loss, EO, and corresponding solar emergy transformity values see Table A2 in Annex 4. Drawing upon pertinent literature on EmA (Wang et al., 2021a; Wang et al., 2021b) and calculations in paper called *Emergy Analysis of Ecosystems* by Lan and Qin (2001), the solar emjoules (sej) can convert the materials, energy, and services in the input and output of the crop systems according to Equations (1) and (2). Based on these two equations, the emergy transformity calculations are listed in Table A3-A5 of Annex 4.

solar emergy (sej) = *energy* or *weight* (J or kg) × *solar emergy transformity* (sej/J or sej/kg) (1)
solar emergy (sej) = *matter* (unit) × *energy conversion coefficient* (J/unit) × *solar emergy transformity* (sej/J or sej/kg) (2)

In Xinjiang, water is scarce in the long run, and the local ecosystem is delicate. For the SIA of the local crop systems, we need to consider not only its energy use but also its water consumption and environmental emission impact. To do this, we have chosen the WF and CF from the footprint family as the critical quantitative indicators for analyzing the sustainability of local intensive production (Yin et al., 2017; Zhang et al., 2020). To quantify the WF of crop systems, we employed the ISO standard-based WF Accounting and utilized the Penman-Monteith method and CROPWAT model recommended by FAO and USDA-SCS, respectively, to estimate the blue and green WF (Pfister et al., 2017; Hoekstra, 2017). Additionally, the grey WF was assessed using Hoekstra's WF method and the "short board principle" to determine pollutant concentration based on the concentration of pollutants with the largest amount of dilution water (Mekonnen and Hoekstra, 2011). See Annex 5 for the detailed WF accounting process. We conducted CF Accounting following the Life Cycle Assessment (LCA) process outlined in *IPCC Guidelines for National Greenhouse Gas Inventories* to account for carbon emissions during crop-intensive production. As xerophytes, combined with data limitations, greenhouse gases from the straw burning of wheat, corn, and cotton stubble were not considered (Wang et al., 2016). We assumed that the CH_4 emissions were negligible and only thought of the direct and indirect N_2O emissions and presented the specific formulas, symbol meanings, and carbon emission factors of different inputs and sources for CF accounting in Annex 5.

2.3. Data description

This study analyzes the EI, EO, WF, and CF of intensive crop production, focusing on the principal crops of wheat, maize, and cotton in Xinjiang from 2001 to 2020. To gather comprehensive data, we utilized a range of sources, the details of which are included in Table 1.

3. Results

3.1. EmA of intensive production

Fig. 3(a), 3(b), and 3(c) illustrate the driving forces behind the flows of both EI and EO in the crop system within the study area. Both EI and EO followed a similar pattern, exhibiting an initial increase and then an overall decrease. The average EI and EO were estimated to be approximately 1.60×10^{22} sej and 1.68×10^{22} sej per year, respectively. Notably, the crop system relied heavily on economic inputs, 63.2 % of which were non-renewable, including the largest proportion of fertilizers, accounting for 33.4 % of the non-renewable inputs, while irrigation water input accounted for 11.9 %. A mere 5.4 % of the emergy came from local environmentally renewable resources, highlighting the system's low self-sufficiency. The crop system's reliance on economic non-renewable inputs led to significant waste, with fertilizers being the main source of losses (~98 %). The cotton's annual average EO being 27.5 %, lower than 36.8 % and 35.7 % of wheat and maize, respectively.

Fig. 3(d) illustrates the relationship between the net emergy output (NEO) and the emergy input–output ratio (EIOR) in the crop system. A higher EIOR signifies lower utilization efficiency of the system for all inputs. Between 2001 and 2016, the EIOR slowly increased with a rising NEO. After 2016, the NEO demonstrated a declining trend year-on-year, but the EIOR increased significantly compared to pre-2016 levels,

Table 1
Data collection and sources for this study.

Data information	Unit	Data source
Population	person	Xinjiang Statistical Yearbook
Irrigation water consumption and wastewater discharge	m^3	Xinjiang Water Resources Bulletin
Crop planting area and yield	ha; t	Xinjiang Statistical Yearbook
Fertilizers and pesticide usage	t	China Agricultural Products Cost-Benefit Compilation of Information; First National Census of Pollution Sources
Crop producer prices, profitability data, seeds, and labor costs	yuan; person; day	Agricultural Products Business Information Public Service Platform
Machinery, electricity, diesel, and agricultural film usage	horsepower; kwh; kg	China Agricultural Product Price Survey Yearbook; Agricultural Products Business Information Public Service Platform (https://nc.mofcom.gov.cn/)
Meteorological data (precipitation, humidity, wind speed, solar duration, evaporation, and temperature)	mm; %; m/s; h; mm; ℃	77 meteorological stations supplied by China Meteorological Data Sharing Service Network (https://data.cma.cn/)
Crop coefficients for cotton, wheat, and maize	Dimensionless	Food and Agriculture Organization of the United Nations (https://www.fao.org/)
Background emission inventories of inputs for crop production	t CO_2 eq / unit	Ecoinvent Database 2.2; Chinese Life Cycle Database; Günther et al. (2017); Wang et al. (2018)

suggesting the crop system's increasing dependence on purchasing inputs in response to mounting environmental stress. It is worth acknowledging that local crop production heavily relied on external inputs, resulting in low self-sufficiency and significant waste.

3.2. Structural features of CF and WF

Fig. 4 illustrates the variations in CF and WF for the main crops in Xinjiang. In this result, the units of CF and WF are $kgCO_2$-eq ha^{-1} and $m^3 \cdot kg^{-1}$, respectively. Because CF is often used to measure the impact of land use or management practices on GHGs, on the other hand, WF is primarily employed to measure the water utilization efficiency required to produce a particular product or service and the amount of water consumed in the production. Therefore, from 2001 to 2010, the CF of wheat (CF_{wheat}), maize (CF_{maize}), and cotton (CF_{cotton}) gradually ascended with a slight discrepancy among them. The CF_{cotton} was slightly higher than CF_{wheat} and CF_{maize}. Subsequently, the yearly increment of CF_{cotton} surpassed the other two crops, peaking at approximately 6.99 × 10^3 $kgCO_2$-eq ha^{-1}, while the CF_{wheat} and CF_{maize} remained around 5.72 × 10^3 $kgCO_2$-eq·ha^{-1} and 5.91 × 10^3 $kgCO_2$-eq·ha^{-1}. The WF of wheat (WF_{wheat}) and maize (WF_{maize}) had minor fluctuations during the study period, hovering around 1.18 $m^3 \cdot kg^{-1}$ and 0.80 $m^3 \cdot kg^{-1}$, respectively. In contrast, the cotton WF (WF_{cotton}) exhibited variations ranging from 4.28 $m^3 \cdot kg^{-1}$ to 8.70 $m^3 \cdot kg^{-1}$, about 5.01 to 7.38 times higher than WF_{wheat} and WF_{maize}.

Fig. 5 illustrates the interconnectedness among crop production, WF, and CF across diverse regions. The findings suggest an overall increase in annual GHG emissions and water consumption in most administrative regions, with the highest levels recorded in the southern areas of (k) Kashgar and (i) Aksu. Conversely, (a) Urumqi, (b) Karamay, (f) Altay, and (m-n) eastern Xinjiang had comparatively lower levels of GHG emissions and water consumption. The crop CF in most parts of Xinjiang increased while the crop WF decreased with stable wave-type development. (m) Turpan in the east and (b) Karamay in the north have dramatic changes in their crop CF and WF. These two regions have more minor production scales and a drier climate than others. The disparity in crop structure among areas is reflected in the size of CF and WF. Cotton, being a resource-intensive crop, was the primary contributor to the CF and WF of the crop systems in (h) Bayingol, (i) Aksu, (k) Kashgar, and (c) Changji. Thus, the spatiotemporal characteristics of GHG emissions and water consumption in crop systems are closely linked to production scale, while regional differences in crop structure also play a crucial role in determining the size of the CF and WF.

3.3. Levels difference of SIA indicators

We incorporated the EmA and FA results into the unified evaluation framework of SIA, converting all initial negative indicators into positive ones (refer to Annex 4). Fig. 6 illustrates the modifications in 20 indicators across the five SIA evaluation dimensions. Of the 20 evaluation indicators, 3 indicators demonstrated improvement, 5 indicators exhibited no clear trend of change, and the remaining 12 indicators declined over time. Notably, the higher the value of the positive indicator, the closer the evaluation unit moves toward sustainable development. Therefore, the top 5 indicators with the most substantial decrease in values, ranked by greatest to least rangeability, were Net Profit Margins (*NPM*, down 44.9 %), Emergy Sustainable Index (*ESI*, down 62.1 %), Environmental Load Ratio (1/*ELR*, down 43.4 %),

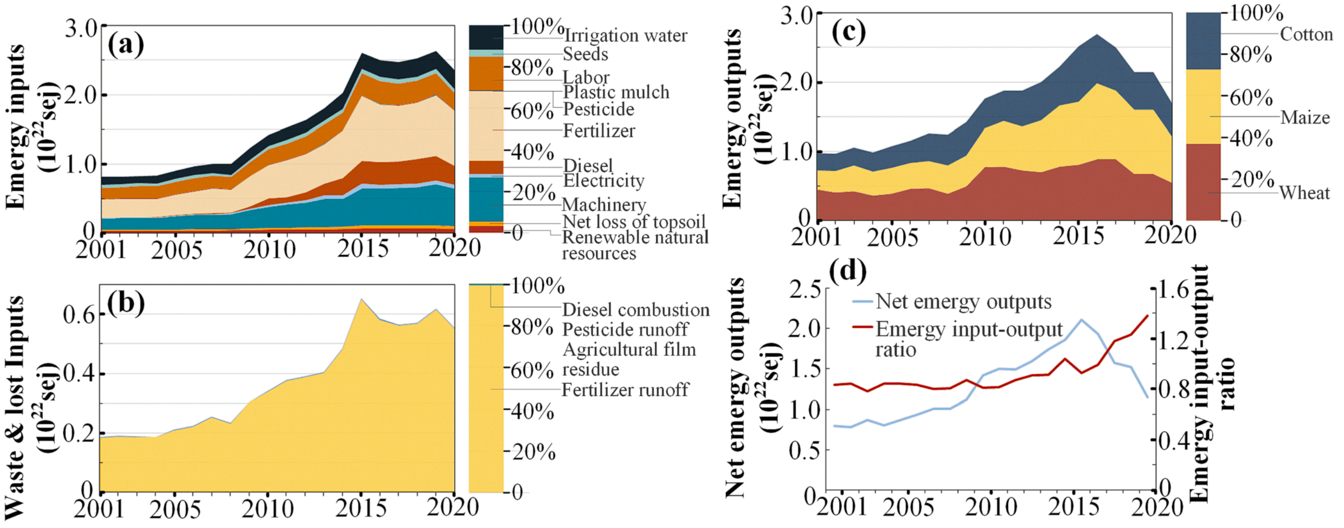


Fig. 3. The inter-annual variability of (a) EI, (b) waste and lost inputs, (c) EO, and (d) the relationship between NEO and EIOR in the crop systems over 2001–2020.

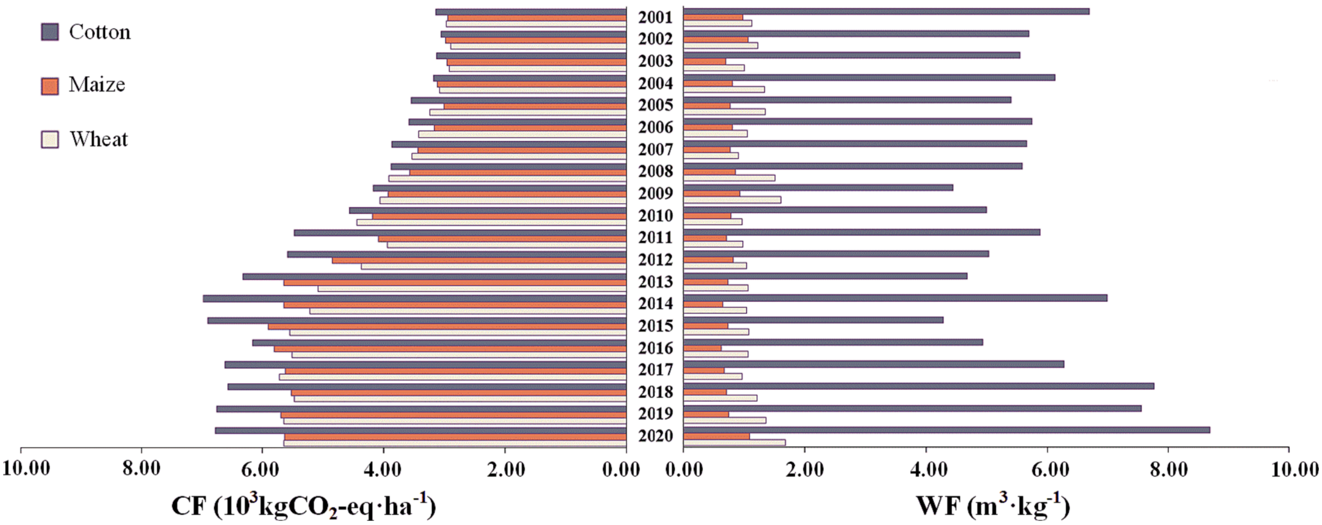


Fig. 4. FA results of major crops in Xinjiang.

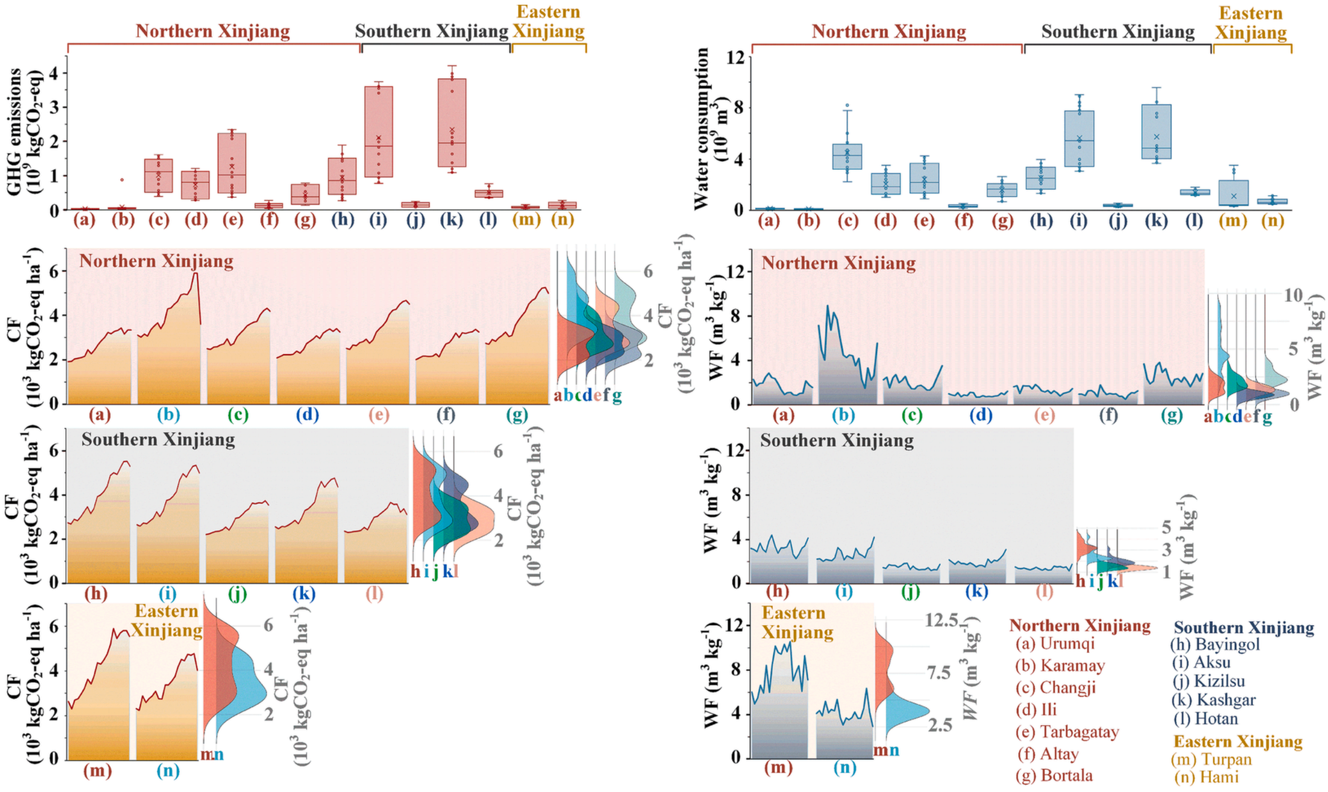
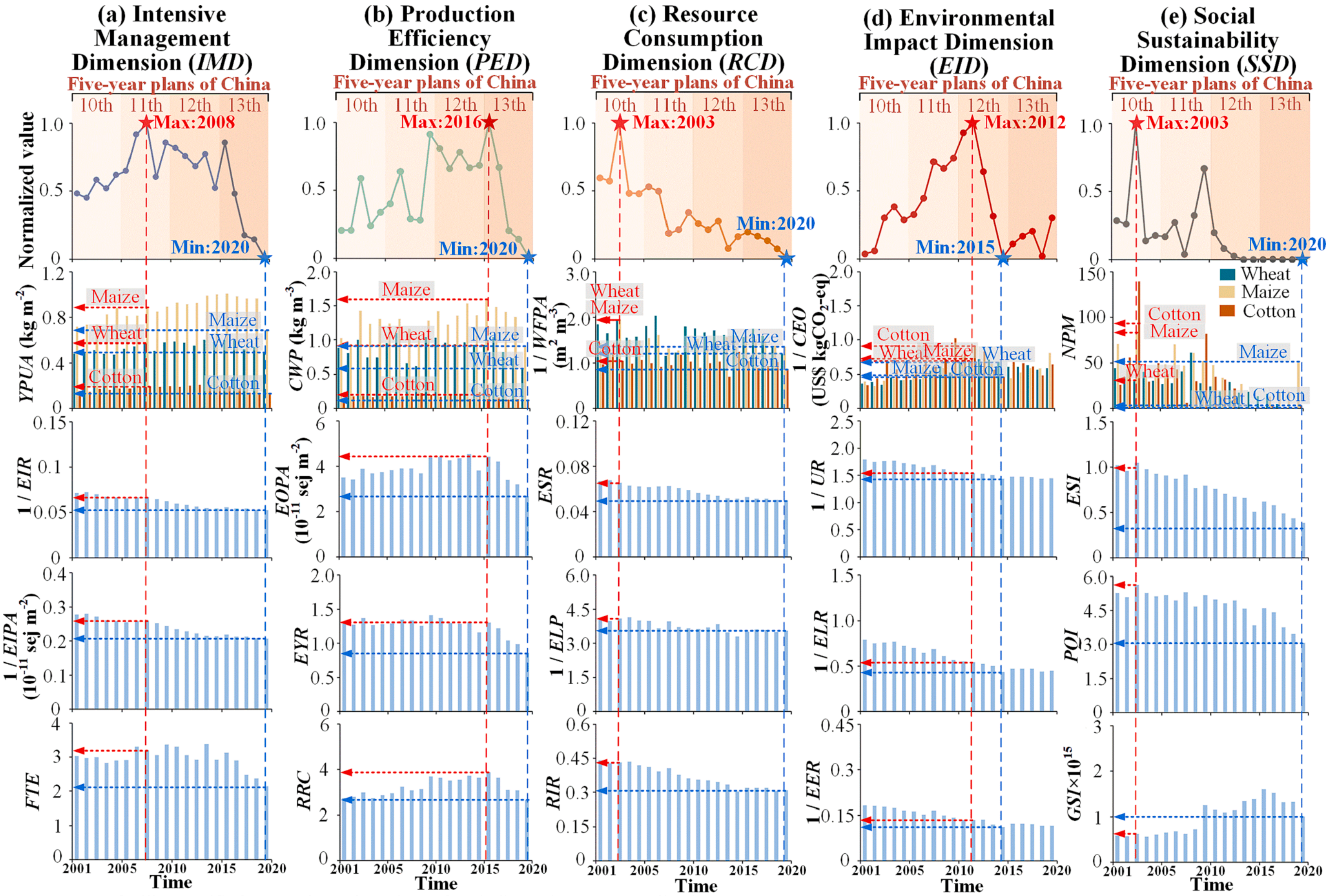


Fig. 5. Interannual variations of WF and CF in different regions of Xinjiang from 2001 to 2020 based on FA.

Product Quality Index (*PQI*, down 41.8 %), and Environmental Economic Ratio (1/*EER*, down 36.4 %). Three evaluation indicators that demonstrated improvement were Yield per Unit Area (*YPUA*), Renewable Resource Contributions (*RRC*), and Grain Self-Sufficiency Index (*GSI*). Between the 10th and 12th plans, the Production Efficiency Dimension (*PED*) and Environmental Impact Dimension (*EID*) gradually moved towards a more sustainable direction and were leading contributors to SIA. The changing Intensive Management Dimension (*IMD*) exhibited relatively volatile trends during this period. Following the 12th plan, with the exception of *EID*, which experienced an upturn during the 13th plan, the other dimensions declined. The Resource Consumption Dimension (*RCD*) and Social Sustainability Dimension (*SSD*) generally developed in an unfavorable direction and became the biggest constraint on SIA's effectiveness.

3.4. Integrating evaluation of SIA

Fig. 7 depicts the changes in the SIA composite index under different Five-year plans of China. Simultaneously considering all results, this study concludes that the SIA composite index increased from the "10th Plan" to the "11th Plan," suggesting an improvement in SIA's level. During this period, the average SIA composite index rose from 0.41 to 0.51. The *IMD*, *PED*, and *EID* contributed to this improvement, but evident trade-offs between the *RCD* and *SSD* and SIA occurred. From the



Note: To facilitate unified comparison, the values of each dimension are normalized.

Fig. 6. Estimated the indicators for Xinjiang's SIA, including a) *IMD*, b) *PED*, c) *RCD*, d) *EID*, and e) *SSD*. Lines depict the change in values calculated for each indicator on an annual basis.

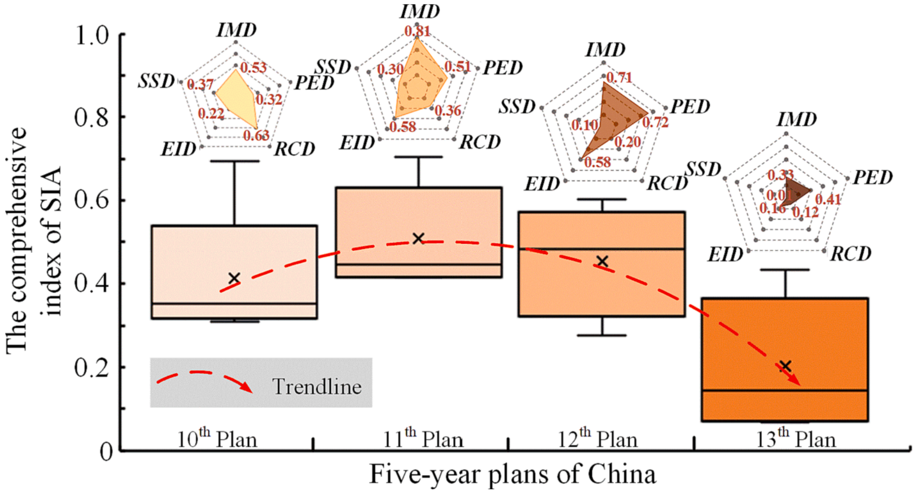


Fig. 7. Distribution of SIA comprehensive index values in different periods.

"11th Plan" to the "13th Plan," although the *PED* demonstrated slight improvements in sustainable development over the previous decade, the SIA composite index declined, mainly due to the decline in the other four dimensions. The *IMD* and *EID* exhibited similar dynamics as the SIA composite index. Concerning the average level of change in each period of the five dimensions, the *SSD* demonstrated the least sustainability, lagging behind the other four dimensions. The sustainability of Xinjiang's agricultural intensification poses significant areas of concern. These findings highlight the limitations of relying on a single EmA or FA metrics to make informed decisions and demonstrate the necessity of quantifying a range of agricultural system outcomes to develop a holistic understanding of the synergy between various dimensional indicators and SIA.

4. Discussion

4.1. Importance of EmA and FA for developing SIA evaluation framework and policymaking in dryland

The comprehensive representation of resource consumption in agricultural production through EmA is of great significance. Despite the lower unit emergy flows of agricultural production compared to traditional secondary industry, the lack of integration of resources and technology may hinder sustainable farming development (He et al., 2019). Thus, increasing the boundaries of EmA of agricultural systems could give rise to interesting cooperation strategies between the government and farmers, favoring the sustainability of local intensification. In the case of Xinjiang's agricultural products, cotton production has a larger scale and unit EI, but lower emergy efficiency than wheat and maize. While the local cotton's emergy efficiency seems slightly higher than that of rice, soybean, and wheat reported in the literature (Wang et al., 2014; Ferraro and Benzi, 2015; Zhang et al., 2016), cotton still exhibits lower energy productivity than food crops. At the level of agricultural products in Xinjiang, compared with wheat and maize, cotton production has a larger scale and unit EI but has lower emergy efficiency. Our emergy efficiency for local cotton seems slightly higher than other values found in literature, around 0.74 for rice (Zhang et al., 2016), soybean (Ferraro and Benzi, 2015), and wheat (Wang et al., 2014). However, these results are similar to LCA studies. That is, cotton shows lower energy productivity than food crops. From the FA results, cotton's CF and WF were higher than food crops. Because cotton is a water-intensive crop, its production per unit area needs to buy more energy and materials and will produce more carbon emissions (Tuninetti et al., 2019). To gain a more holistic understanding of the biophysical overload process caused by agricultural intensification, more footprint indicators such as agricultural PM_{10} footprint, land footprint, and biodiversity footprint need to be incorporated into future studies (Wu et al., 2021). In Xinjiang, cotton-intensive production depended more on economically non-renewable inputs. Appropriate expansion of food crop production to replace cotton production is an effective measure to meet food demand and mitigate environmental burdens. The policymakers need to call for other actions, such as considering economic benefits, land types, and planting structure optimization.

The SIA heavily influences the variation in the CF and WF across Xinjiang. The arid climate and scarce water resources in Eastern Xinjiang make it more suitable for small-scale planting of economic crops, such as grapes and red jujube, which are conducive to sugar accumulation and easy to manage (Yu et al., 2020). Conversely, the relatively abundant water and cultivated land resources in northern Xinjiang make it a favorable region for developing agricultural intensification, especially in Ili and Changji, where blue water resources can be obtained from mountain glaciers and snowmelt (Li and Deng, 2021). Although Bayingol, Aksu, and Kashgar do not lack land resources in southern Xinjiang, preliminary judging from the results of CF and WF, their sustainable and intensive agricultural development lags behind that in northern Xinjiang. The rapid expansion of cotton planting in Xinjiang was mainly driven by local market demand, leading to increased environmental vulnerability and ecological pressure (Zhang et al., 2021). By integrating EmA and FA results into the SIA evaluation, we found a trade-off between *RCD* and SIA during the 10th to 11th Five Year Plan (2001–2010), while the evaluation results show a trade-off between *EID* and SIA during the 12th Five Year Plan (2011–2015). These trade-offs can compromise the continuity of agricultural systems with low purchasing inputs and the ecosystem services they provide. However, improving production efficiency may sometimes aggravate the consumption of economic inputs, as evidenced by the Jevons Paradox, which highlights the need for better management and progressive *SSD* to reduce wastage, loss of inputs, and disorderly emissions (Wang et al., 2020; Fei et al., 2021). For simplicity, in measuring the sustainability and profitability of agricultural systems, the SIA evaluation framework should specifically consider the results of EI, EO, and environmental footprint. Xinjiang's agricultural-intensive production has long been heavily reliant on external inputs, rendering them economically susceptible to sudden market instabilities, such as the impact of Covid-19 on global food security. Additionally, they are vulnerable to water stress and environmental emissions intensity, including extreme variability in drought events (Elbeltagi et al., 2020a; Elbeltagi et al., 2020b). To influence policymakers and farmers, we suggest two complementary strategies based on these aspects. Firstly, the government could develop subsidy policies that promote intensive actions based on local renewable natural resources and incentivize *IMD* and *PED* improvements through water rights trading and carbon emission permit trading. These approaches hold significant potential to improve the sustainability of *SSD*, accelerate the transition to sustainable intensification, and facilitate the introduction of crop varieties with lower management intensity into the industrial structure adjustment. Secondly, the product's embodied EmA or FA results could be incorporated into agricultural product labels. These labels should present reliable sustainability indicators, such as *RCD* and *EID*, in clear and meaningful units for consumers, such as "solar joules" and "WF and CF.".

Our study does not explicitly assign weights to the indicators under consideration. Our focus has primarily been assessing the effectiveness of the *IMD*, *PED*, *RCD*, *EID*, and *SSD* in enhancing SIA in Xinjiang's drylands and examining the challenges posed by unsustainable agricultural intensification. Therefore, the decision to refrain from assigning weights is rooted in our intention to maintain a balanced understanding of all considered indicators that affect changes in the comprehensive index of SIA. While we acknowledge that indicator weighting can effectively capture data characteristics in specific evaluation methodologies (Yang et al., 2020; Dong et al., 2023), we emphasize identifying the impact of status changes in the five dimensions. This approach ensures an equal evaluation of the effectiveness of the SIA decision-making system and allows for their visualization in a time series.

4.2. Relationship between dryland SIA evaluation framework and SDGs

We utilized a combination of existing literature, expert judgments, and keyword comparisons to identify the SDGs related to SIA evaluation at the policy implementation level (Wang et al., 2022). While the subjective nature of existing literature is acknowledged, we believe incorporating expert judgments and transparent methods can enhance the validity and reliability of our findings. Furthermore, we encourage scholars and stakeholders to use our evaluation as a starting point to improve upon it based on new scientific literature and their expertise. Out of the 17 SDGs, 15 relate to the SIA (Fig. 8). Our evaluation identified 69 targets that we categorized as high, moderate, or low relevance for SIA (See the explanation in Annex 6). Specifically, we identified 19 highly relevant targets that directly contributed to SIA, 15 moderately relevant targets that involved changes in management strategies and input patterns during agricultural intensification or actions to address climate and environmental changes, and 29 targets of low relevance that involved indirect interventions. We found that six SDGs, namely SDG 2, 6, 7, 8, 11, and 12, are particularly important for the five dimensions of SIA evaluation. SDGs 6 and 7 are especially relevant, with seven and six targets, respectively, that are highly or moderately related to SIA. Hence, in instances when the comprehensive index of SIA experiences a decline in Xinjiang, as observed during the 11th to 13th Five-Year Plan (2010–2020), policymakers can prioritize the achievement of SDGs 6 and 7. The improvement or deterioration of the sustainability level of the five dimensions in SIA is directly associated with the highly relevant SDGs. For example, SDG 2 has three highly relevant targets that affect all indicators of *IMD*, while SDG 8 has three highly relevant sub-targets (SDG 8.1, SDG 8.2, and SDG 8.4, respectively) that impact the *FTE* of *IMD*, the *WFPA* of *PED*, and the *NPM* and *PQI* of *SSD*. Our research findings indicate that the gradual unsustainable trend of *SSD* in Xinjiang over the past 20 years is directly influenced by *NPM* and *PQI*.

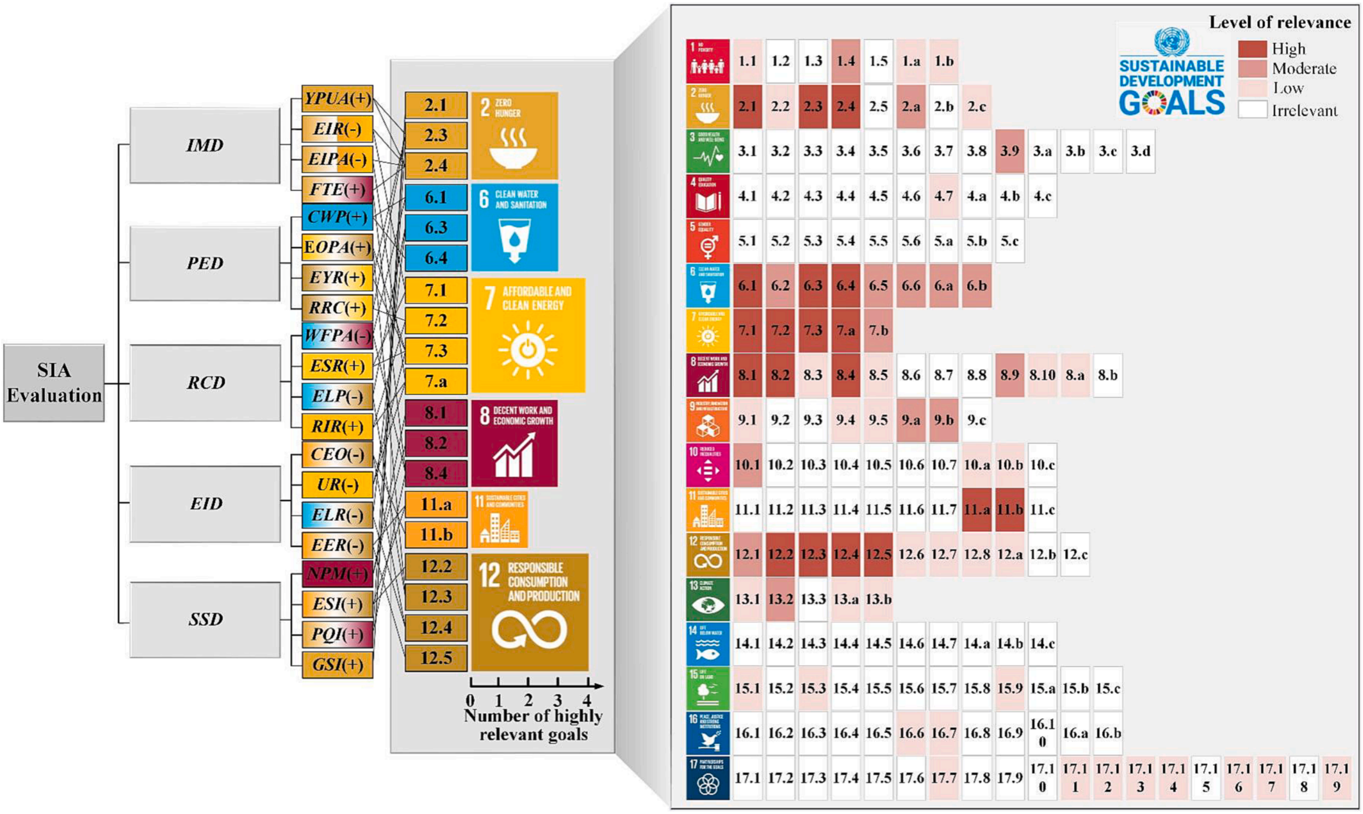


Fig. 8. The relationship between SIA and SDGs.

Policymakers can take specific appropriate measures, such as creating job opportunities and promoting decent work, supporting entrepreneurship and small to medium-sized enterprises, and fostering financial inclusivity. Implementing these measures can narrow the gap between the decline in *SSD* sustainability and achieving the mentioned subtargets under SDG 8. Furthermore, SDG 12 has four highly relevant targets that affect all dimensions except for *IMD*. Additionally, SDG 11 strengthens the linkages between the SIA's environment, economy, and society and mainly affects *EID* and *SSD*. On the other hand, the remaining SDGs have only moderate or low-relevance targets for agricultural intensification. However, they contribute to the overall development of SIA by improving infrastructure, governance, equity, justice, education, and financial support. To establish a concrete connection between SIA evaluation results and the attainment of the SDGs, we recommend that researchers prioritize these SDGs in their studies. Meanwhile, our evaluation provides a valuable framework for policymakers and stakeholders to design and implement policy goals that support SIA in Xinjiang.

4.3. Limitations and future research

Future research is crucial to address the challenges posed by unsustainable agricultural intensification and to assess the effectiveness of EmA and FA indicators in enhancing SIA evaluation in Xinjiang's drylands. In this context, our study confronts three primary limitations. Firstly, the case only focused on drylands in Xinjiang, which may limit the generalizability of our findings to other dryland regions. Future research should expand the scope and include dryland cases in different geographical contexts to enhance the applicability of SIA evaluation indicators. Secondly, the availability of long-term data at the administrative region levels and the coordination of expertise in agricultural resource management and the ecological economy are valuable for SIA research. Future research should strive to explore alternative data sources to mitigate data constraints and enhance the robustness of SIA evaluations. Lastly, differences in indicator adaptability present a challenge, introducing complexity to SIA evaluations in different dryland regions where determining indicator thresholds and calculating parameters (e.g., emergy transformity values) may vary. Future research could adopt more nuanced methods, such as planetary boundaries and on-site monitoring, which may be necessary to comprehensively evaluate the sustainable development space and the socio-economic constraints resulting from agricultural intensification.

5. Conclusion

Over the past two decades, the agricultural systems in the study area have exhibited lower economic and environmental compatibility. While short-term crop yield has improved dramatically, this system needs to provide considerable benefits to the regional economies in long-term sustainability. The agricultural system relies heavily on economic inputs and underutilizes local environment resources. Cotton production is highly consistent with the CF and WF, but its EO is less than 80 % of wheat and maize. Further optimization of the structure of three crops, rural areas, and management practices may be the primary way to improve agricultural production efficiency.

Our evaluation of Xinjiang dryland SIA incorporates EmA and FA results into five dimensions. Although the *IMD* has slightly improved before the "11th Five Year Plan," the development trend of dimension indicators, such as the *EIR* and *EIPA*, has declined significantly. The level of sustainability of the local *EID* tends to increase during the same period, while the *UIR*, *ELR*, and *EEE* declined significantly. Local intensification's sustainability level tends to decline due to trade-offs between dimensions and indicators, especially after the 11th Five-Year Plan. Thus, there is a need to promote vertical integration of each dimension to reduce negative environmental impacts while enhancing agronomic technology and net product profit. At the same time, increased fertilizer inputs and the intensive use of film have increased environmental risks and are potential areas of concern. It is also essential to consider the high mechanization of resource-intensive crop cultivation and larger farm sizes when determining the extent to which these results apply elsewhere.

After discussion, we believe that several SDGs, including “SDG 2,” “SDG 6,” “SDG 7,” “SDG 8,” “SDG 11,” and “SDG 12,” are highly relevant to dryland SIA and can provide actionable guidance to decision-makers in formulating SIA-related policies. The ultimate goal of dryland SIA is not to maximize utilitarian benefits but to seek the actual responsibility of developers while maintaining the dynamic balance between agricultural intensification and SDGs. To achieve sustainable development, it is necessary to understand the current and past use of resources and environmental pressures on drylands and how much sustainable environmental work needs to be done.

6. Author statement

J.Y. and P.O. designed the research. J.Y. and P.O analyzed the emergy flows, CF, and WF, A.L., X.G., and T.H. conducted a comprehensive evaluation of SIA, X.L., A.E., P.O. reviewed and commented on these results, and J.Y. and P.O discussed the relationship between SIA and SDGs. J.Y. drafted the first version of the manuscript. X.L., X.D., P. O., A.E., and H.C. contributed to the interpretation of the results, critical revision of the manuscript, and approval of the final version.

CRediT authorship contribution statement

Jiawen Yu: Writing – original draft, Funding acquisition, Conceptualization. **Aihua Long:** Supervision, Data curation. **Xiaoying Lai:** Writing – review & editing. **Ahmed Elbeltagi:** Validation, Software, Methodology. **Xiaoya Deng:** Resources, Methodology. **Xinchen Gu:** Visualization. **Tong Heng:** Software, Investigation. **Hui Cheng:** Validation, Formal analysis. **Pieter van Oel:** Writing – original draft, Review & editing, and Formal analysis.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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