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Improving crop rotations and efficient resource distribution for sustainable agriculture growth

Fatholah Karimi[1], Mohammad Ghahderijani[1*], Hossien Bakhoda[1]

[1] Department of Agricultural Systems Engineering, Science and Research Branch, Islamic Azad, Tehran, Iran

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Corresponding author:
Ghahderijani@srbiau.ac.ir

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Abstract

Establishing connections between ecosystems and agricultural mechanization can help address the challenges of poor decision-making in agriculture and prevent further damage to ecosystems. It is essential for agricultural authorities and decision-makers to thoroughly understand ecosystem dynamics and the factors that influence them to develop effective policies for sustainable development. This study focuses on determining optimal conditions for crop patterns and input allocation across fields, specifically in the agricultural landscape of Ilam Province, with an emphasis on technical and energy aspects. The research targets farmers cultivating wheat, barley, fodder maize, and canola in the southern region of Ilam Province, covering Abdanan, Dareshahr, and Dehloran cities. Findings from a survey of 240 farmers reveal significant disparities in machinery, labor, and diesel fuel inputs across the different field levels. Recommendations include adjusting crop patterns by reducing wheat cultivation by 140 hectares and increasing irrigated fodder maize cultivation. Moreover, exploring rainfed cultivation or enhancing rainfed wheat yields is suggested to compensate for the decreased wheat cultivation. Utilizing an objective planning model, the study advocates for a more sustainable cropping model, highlighting wheat, barley, fodder maize, and canola crops. The proposed model introduces 210 additional hectares of irrigated wheat cultivation, along with expansions in irrigated barley and fodder maize cultivation areas. Although rainfed cultivation is uncommon in the area, efforts are directed towards improving the productivity of irrigated crops to support sustainability and enhance agricultural practices in the province.

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Introduction

Governments in the world are grappling with major issues such as growing population, land degradation, ineffective farming techniques, decreasing output and higher costs. Additional concerns include unprofitable crop growth, outdated farming practices, substandard labor conditions, wasteful use of water and soil resources, and lack of attention to appropriate planting patterns (Hatamkhani and Moridi, 2021). To tackle these issues, governments need to enact measures to maximize land utilization and enhance crop yield to adequately feed their people. Crop rotation is a centuries-old farming practice that involves planting different crops on the same piece of land in sequential seasons. This method has long been recognized as a valuable tool for preventing soil nutrient depletion, reducing pest and disease pressure, and improving overall crop productivity (Farvardin et al., 2024). However, with the increasing demands on global food production and dwindling natural resources, there is a need to further optimize crop rotations for sustainable agriculture growth. One way to enhance the effectiveness of crop rotations is by strategically planning the distribution of resources such as water, nutrients, and labor across different crops and seasons. By carefully managing these resources, farmers can maximize crop yields, conserve valuable natural resources, and minimize environmental impacts. Furthermore, innovative farming practices such as incorporating cover crops, intercropping, and agroforestry into crop rotations can further enhance soil health, improve biodiversity, and increase resilience to climate change (Kaab et al., 2023).

The use of Diversified Crop Rotation (DCR) is enhancing farming efficiency globally, with potential benefits including improved soil health and increased system productivity. By incorporating a variety of crops into their rotation, farmers can improve soil attributes such as water uptake and storage and promote a greater diversity of beneficial soil organisms, resulting in improved resilience to challenging growing conditions. DCR not only reduces production risk and uncertainty for farmers, but also promotes soil and ecological sustainability. Additionally, DCR allows farmers to diversify their income sources. The unique plant-soil relationship in DCR systems helps to improve soil health by reducing pest and disease incidence and enhancing soil structure. As DCR becomes increasingly popular for sustainable crop production, this review highlights its importance, challenges in implementation, and potential solutions for widespread adoption (Shah et al., 2021).

The framework was applied to identify promising diversified rotations for Quzhou, a cereal-producing region in North China, considering 11 sustainability indicators. Among 3011 technically feasible rotations generated, none surpassed the prevailing wheat-maize system across all indicators. However, using Pareto-based techniques, 125 (4%) compromise rotations were identified. These compromise rotations were classified into eight clusters representing diverse sustainability priorities, including profitability, nutrition, environmental concerns, and achieving a balance across multiple dimensions. The study suggests that while individual rotations may not address all sustainability conflicts, compromise solutions can cater to various stakeholder needs and offer well-considered choices for future agricultural landscapes. The proposed crop rotation design method can be adapted for other agricultural settings to inform stakeholders and policymakers about potential options and trade-offs in enhancing crop production sustainability (Liang et al., 2023). Crop residues, a byproduct of crop production, are valuable natural resources that can be optimized to enhance input use efficiencies. Managing crop residues is a well-established practice within conservation agriculture, essential for sustainable farming. With the shift towards modern agricultural practices, there has been an increase in crop residue production due to the demand for greater food supplies. Utilizing ecosystem services provided by crop residues can improve soil health and nutrient levels in plants. However, improper management, such as burning residues in-situ, can lead to serious environmental consequences, posing a significant threat to the agricultural sector. This review examines the various aspects of crop residue management, including its impact on crop and soil health, resource recycling, and strategies for residue retention in farming systems. By understanding these findings, stakeholders can develop effective residue management techniques that align with current farming practices while promoting productivity and environmental sustainability (Sarkar et al., 2020).

This novelty involves implementing innovative strategies to enhance crop rotations and optimize the distribution of resources in agriculture to promote sustainable growth. By incorporating diverse crop rotations, farmers can improve soil health, reduce the risks of pests and diseases, and increase overall crop productivity. Additionally, efficient resource distribution, such as water, fertilizers, and pesticides, can help minimize waste and environmental impacts while maximizing yields. This approach can lead to a more sustainable and resilient agricultural system, reducing the reliance on chemical inputs and decreasing the environmental footprint of farming practices. By improving crop rotations and resource distribution, farmers can enhance their profitability, ensure food security, and contribute to long-term environmental sustainability. Ultimately, this novelty aims to promote a more balanced and sustainable approach to agriculture that benefits both farmers and the planet. The aim of this study is to investigate and develop improved crop rotation practices that will lead to more sustainable agriculture growth. By understanding the interactions between different crops and their impact on soil health, pest control, and nutrient cycling, we aim to optimize resource distribution and increase overall productivity. This research will contribute to the development of more efficient and environmentally friendly farming practices that can support long-term agricultural sustainability and food security.

Materials and methods

Study area

This study was carried out in Ilam Province, located on the western slopes of the Zagros Mountain range, where vegetation is influenced by the local climate and precipitation patterns. There is abundant vegetation in the mountainous areas and high altitudes in the north, northwest, northeast, and Kabirkoh regions. Data for the research were collected using questionnaires, interviews, and official statistics from the Ministry of Jihad-e-Agriculture spanning the past decade (Ministry of of Iran, 2021). The questionnaire comprised two sections: the first focused on farmers' personal and professional attributes, while the second included technical, economic, and social indicators of agricultural mechanization to evaluate its impact on agricultural development in the province. The questionnaire's accuracy was validated through input from university professors, graduate students, Jihad-e-Agriculture experts, and research institutions in Ilam Province. The study employed a two-stage simple random sampling technique, known for its simplicity and reliability in generating results that can be extrapolated to the wider population. This method was chosen for its consistency with the methodologies employed by the Iranian Statistics Center and the Management and Planning Organization in the national census. The research targeted farmers cultivating wheat, barley, fodder maize, and canola in the southern part of Ilam Province, specifically in Abdanan, Dareshahr, and Dehloran cities. A sample size of 240 was determined using Equation 1 (Kaab et al., 2019b) at a 95% confidence level, selected through a completely random process.

$$n = \frac{Nt^2S^2}{Nd^2+t^2S^2} \quad (1)$$

Equation 1 utilizes various variables such as N for the statistical population, t for the confidence coefficient, S^2 for the variance estimate, d for probability accuracy, and n for sample size.

Energy

Input for crop production consisted of labor, machinery, fuel, water, electricity, fertilizers, manure, pesticides, seeds, and natural gas. Outputs included wheat, barley, maize, and canola. Energy equivalents for inputs and outputs were determined using specific energy coefficients detailed in Table 1.

Table 1. Energy equivalents for inputs and outputs.

Title Inputs	Unit	Energy content (MJ/Unit)	Refrences
Human labor	h	1.96	(Liu et al., 2010)
Machinery	kg		
Tractor	kg	9-10	
Self-driving combine	kg	8-10	(Ghasemi-Mobtaker et al., 2022)
Other machines	kg	6-8	
Diesel fuel	L	47.8	(Kaab et al., 2019)
Chemical pesticides	kg	120	(Ahmadbeyki et al., 2023)
Fertilizers	kg		
Nitrogen	kg	78.1	
Phosphorus	kg	17.4	(Kazemi et al., 2023)
Potassium	kg	13.7	
Manure	kg	0.3	
Irrigation water	m^3	1.02	(Mohammadi Kashka et al., 2023)
Electricity	kWh	12	(Firouzi et al., 2016)
Seed	kg		
Wheat	kg	13	(Sewchurran and Davidson, 2021)
Barley	kg	13	(Canakci et al., 2005)
Fodder maize	kg	7	(Sun et al., 2022)
Canola	kg	14	(Unakitan et al., 2010)
Outputs	kg		
Wheat	kg	12	(Canakci et al., 2005)
Barley	kg	13	(Canakci et al., 2005)
Fodder maize	kg	5	(Sun et al., 2022)
Canola	kg	14	(Unakitan et al., 2010)

The research investigated energy indicators in specific production systems, important metrics in the energy analysis procedure involving a variety of indicators including energy ratio, energy efficiency, specific energy, and net added energy. These indicators provide a thorough understanding of the energy dynamics in agriculture. The formulas 2-5 were utilized for computing these indicators (Mousavi-Avval et al., 2017).

$$\text{Energy ratio} = \frac{\text{Output energy (MJ/ha)}}{\text{Input energy (MJ/ha)}} \quad (2)$$

$$\text{Energy productivity} = \frac{\text{Yield (Kg/ha)}}{\text{Input energy (MJ/ha)}} \quad (3)$$

$$\text{Energy intensity} = \frac{\text{Input energy (MJ/ha)}}{\text{Yield (Kg/ha)}} \quad (4)$$

$$\text{Net added energy} = \text{Output energy} - \text{Input energy} \quad (5)$$

The energy ratio reflects the connection between the calorific value of output products and the total energy used in production processes. This dimensionless indicator showcases the efficiency of energy utilization in production by revealing the amount of energy gained for each unit of energy consumed. Energy intensity is not constant and varies depending on factors such as crop type, location, and time. It serves as a useful metric for evaluating energy efficiency in different production systems associated with specific crops. In agricultural production, input energy can be divided into two main categories: direct energy and indirect energy. Direct energy includes resources directly or indirectly involved in field work or activities, such as labor, fuel energy, electricity, and irrigation energy. On the other hand, indirect energy is the energy used in producing inputs like chemical fertilizers, pesticides, and animal manure before they are used in the field.

Indirect energy consumption in agricultural production is mainly attributed to fertilizers, notably nitrogen fertilizers.

Results and discussion

Analysis of input-output energy

Wheat and barley are extensively grown in the southern region of Ilam Province, encompassing Abdanan, Dareshahr, and Dehloran cities. Cultivation areas vary significantly in size, with a notable portion being under 1 hectare, some between 1-3 hectares, and a smaller portion exceeding 3 hectares. A study was conducted to examine the impact of field size on energy consumption and to compare the energy efficiency across different field dimensions. Wheat fields in the area were categorized into three groups: small (< 1 hectare), medium (1-3 hectares), and large (> 3 hectares). The study revealed that an average energy input of 1.79 GJ is required to cultivate one hectare of wheat and barley in the region, while the average energy output is estimated at 38.04 GJ ha^{-1}. Statistical analysis indicated no significant variance in total input energy among fields of different sizes, but larger fields exhibited higher energy output compared to smaller ones. The study found that machinery, manpower, and diesel fuel inputs showed the most significant differences among the field sizes, with larger fields being more mechanized and consequently consuming more energy from machines and fuel. Smaller fields relied more on manual labor for operations like fertilization and harvesting. Notably, electricity usage for water pumping highlighted inefficiencies in irrigation practices in smaller fields. The study also showed differences in chemical fertilizer consumption, with smaller fields using greater amounts due to manual application. Efforts aligned with Iran's development plan included reducing chemical fertilizer and pesticide usage, decreasing water consumption, and improving crop yield. The research aimed to optimize farming patterns for wheat, barley, fodder maize, and canola to meet environmental goals and ensure sustainable agricultural development. Data from farmer income and expenses, agricultural organization reports, farmer interviews, and completed questionnaires were leveraged to develop a planning model considering factors such as field area, fertilizer types, pesticide types, labor, water usage, machinery, and capital constraints across the production cycle (Table 2).

Table 2. Energy of inputs and outputs in wheat and barley production in the south of Ilam Province (Abdanan, Dareshahr, and Dehloran cities)

Title	Wheat and barley					Foder maize				
	Land grouping in three sizes			Mean	SD	Land grouping in three sizes			Mean	SD
	Small (1>)	Medium (1-3)	Large (3<)			Small (1>)	Medium (1-3)	Large (3<)		
A. Inputs (GJ ha^{-1})										
1. Machines	1.36^{a}	2.09^{b}	3.12^{c}	1.89	1.14	0.89^{a}	0.92^{b}	0.96^{c}	0.91	0.05
2. Labor force	0.21^{a}	0.14^{b}	0.05^{c}	0.16	0.1	0.42^{a}	0.31^{b}	0.18^{c}	0.35	0.17
3. Diesel fuel	3.12^{a}	3.59^{b}	4.84^{c}	3.56	1.23	3.38^{a}	3.76^{b}	4.29^{c}	3.64	0.69
4. Electricity	39.15^{a}	39.89^{b}	40.17^{b}	39.56	2.09	34.84^{a}	28.79^{b}	19.33^{c}	30.55	11.91
5. Chemical fertilizers										
A) Nitrogen	20.52^{a}	18.35^{b}	17.18^{b}	19.26	5.27	26.53^{a}	21.06^{b}	21.37^{b}	23.57	6.45
B) Phosphate	3.06^{a}	1.98^{b}	2.01^{b}	2.54	1.13	3.65^{a}	3.1^{b}	2.76^{b}	3.32	1.26
C) Potassium	1.75^{a}	1.09^{b}	1.24^{b}	1.45	0.73	1.69^{a}	0.74^{b}	0.56^{b}	1.16	0.76
6. Manure	1.2^{a}	1.32^{a}	1.7^{a}	1.32	1.82	2.04^{a}	2.57^{a}	2.62^{a}	2.34	2.28
7. Chemical pesticides	0.14^{a}	0.21^{b}	0.23^{b}	0.18	0.14	0.36^{a}	0.24^{b}	0.27^{a}	0.37	0.12
8. Irrigation water	6.11^{a}	6.22^{b}	6.26^{b}	6.17	0.33	6.09^{a}	5.03^{b}	3.38^{c}	5.34	۲/۰۸
9. Seeds	3.75^{a}	4.37^{a}	4.27^{a}	4.04	5.24	12.33^{a}	12.12^{a}	12.72^{a}	12.28	۱/۹۹
Total input energy	80.4^{a}	79.29^{a}	81.11^{a}	79.10		92.22^{a}	78.65^{b}	68.44^{c}	83.72	
B. Output (GJ ha^{-1})										
Output energy	31.56^{a}	42.96^{ab}	48.32^{b}	38.04		71.78^{a}	87.94^{b}	111.41^{c}	84.15	

*Superscript letters indicate statistically significant differences between different levels of fields.

Crop cultivation pattern

The unique characteristics of cropping patterns, rotation, tillage schedules, and irrigation practices for various common crops in different regions lead to a wide variety of mixed cropping systems, constraints on arable land, and intense competition for water resources. In this context, mathematical planning models play a crucial role as they can incorporate these complex factors. It is important to note that mathematical programming is not simply a computational tool but rather an analytical approach that can model economic behavior at both individual and systemic levels within economic activities. By operating under optimization assumptions, mathematical programming helps in decision-making by maximizing or minimizing outcomes given certain constraints. While some may debate the appropriateness of this method in economic and management sciences, proponents of normative economics find it justifiable as it aligns with their goal-oriented approach.

When comparing energy indicators for wheat and barley cultivation across different farm sizes, significant differences were noted between small farms and larger operations, with medium-sized farms falling in between (Table 3). Energy ratios also varied accordingly, with smaller fields showing lower values compared to medium and large fields. The analysis underscored the importance of consolidating fields to improve energy efficiency. Additionally, the assessment of fodder maize cultivation at different scales revealed substantial differences in energy indicators, with energy ratios and net energy gains varying significantly across small, medium, and large fields. These findings highlight the need for optimizations in input consumption, particularly for energy-intensive inputs like electricity and nitrogen fertilizers, even in larger fields. The annual assignment of fields to different crops and the choices farmers make regarding crop management are crucial for farm productivity and profitability. Decision support models are developed to help farmers efficiently allocate limited resources, focusing on cropping plans and crop rotation decisions. These decisions include crop selection, spatial distribution within the farmland, and temporal successions over years, impacting resource utilization efficiency and environmental processes. A review of over 120 references incorporating cropping plan and crop rotation decisions in models reveals that these decisions are often treated as static concepts optimized based on a single monetary criterion. Uncertainties are typically addressed as static probabilities without considering dynamic constraints. To better support farmers, it is proposed that cropping plan and crop rotation decisions should be viewed as dynamic processes integrated into planned and adaptive decisions on annual and long-term horizons. New models should potentially simulate farmers' decision-making processes explicitly rather than relying solely on normative approaches (Dury et al., 2012).

Table 3. Energy indicators in the production of studied crops in the south of Ilam Province.

Title	Unit	Wheat	Fodder maize	Barley	Canola
Energy ratio	-	0.45	1.06	0.12	0.17
Energy efficiency	Kg GJ^{-1}	34.1	286.83	143	209.7
Energy intensity	GJ kg^{-1}	0.029	0.003	0.0006	0.005
Net added energy	GJ ha^{-1}	-42.1	0.43	-1515.32	-1098.04

According to Table 4, the cultivation pattern includes wheat, barley, fodder maize, and canola crops. To optimize the cultivation, wheat cultivation area should be reduced by 140 hectares, while fodder maize cultivation in irrigated areas should be increased. Addressing the wheat shortage could involve expanding rainfed cultivation or improving rainfed wheat yield per unit area. Currently, rainfed wheat cultivation covers 11,000 hectares in the Abdanan region. The results from the goal planning model suggest that achieving sustainability may require reducing cultivation diversity and eliminating certain crops. Therefore, transitioning towards sustainability in the region may involve specializing in specific crops that align with the region's resourcesand facilities.

Table 4. The results of the cropping pattern in Abdanan City.

Crop	Area under cultivation (ha)	Pattern		
		Existing area under cultivation (ha)	Ideally optimized area under cultivation (ha)	Deviations
Irrigated wheat	X1	1000	860	$d_1^- = 80.1$
Irrigated barley	X2	0	0	$d_2^- = 502.3$
Fodder maize	X3	0	105	$d_3^- = 98.1$
Canola	X4	5	40	$d_{11}^- = 640.6$

Table 5. The results of the cropping pattern in Dareshahr City.

Crop	Area under cultivation (ha)	Pattern		
		Existing area under cultivation (ha)	Ideally optimized area under cultivation (ha)	Deviations
Irrigated wheat	X1	3000	3210	$d_1^- = 32.48$
Irrigated barley	X2	0	90	$d_2^- = 224.5$
Fodder maize	X3	130	30	$d_3^- = 5.36$
Canola	X4	200	0	$d_{11}^- = 47.2$

Based on Table 5, the cropping model shows the presence of wheat, barley, fodder maize, and canola crops. The irrigated wheat cultivation area is expanded by 210 hectares in the latest model. Rainfed wheat cultivation covers approximately 6300 hectares in the Dareshahr region. With a decrease in fodder maize cultivation from 130 to 30 hectares in the economic model, 90 hectares have been reallocated to barley cultivation for animal fodder. Additionally, 1000 hectares in the region are dedicated to rainfed barley cultivation. The limited impact of canola cultivation due to the rise of medicinal plant cultivation has led to the proposal to eliminate canola cultivation in the economic model. Consequently, the sustainability-focused model suggests a reduction in crop diversity and the exclusion of certain crops from the current agricultural scenario in the region. This implies a shift towards the specialized cultivation of specific crops that align with the region's resources to promote sustainability.

Table 6 illustrates that wheat, barley, fodder maize, and canola crops are present in the current cultivation pattern. Given that rainfed farming is uncommon in this city, the bulk of irrigated wheat cultivation is located in the southern part of the province. Consequently, the area dedicated to irrigated barley cultivation has expanded by over 1400 hectares. Similarly, the acreage for fodder maize has surged from 300 to more than 2400 hectares. The economic model underscores the need to boost animal fodder production, taking into account data from livestock farms. Nevertheless, a decline has been noted in wheat and canola cultivation. This underscores that the shift towards sustainability may lead to a reduction in crop diversity within the region, necessitating the removal of certain crops from the current cultivation model. In essence, transitioning to specialized cultivation of specific crops that align with the region's capabilities is crucial for moving towards sustainability. Moreover, the quantities of phosphate, nitrogen, and potash fertilizers are projected to decrease by 1.8, 12.3, and 3.5 tons, correspondingly. The usage of various chemical pesticides, such as herbicides, insecticides, and fungicides, is also anticipated to decline by 112.6, 213.8, and 86.8 liters, respectively.

Addressing the increasing food production demands of society while also enhancing water quality poses a significant challenge in many watersheds globally. In numerous countries, the traditional approach in agriculture involves farmers deciding what, when, and where to plant based on market forces and the efficient utilization of land resources for their individual farms. On the contrary, the European Union (EU) has investigated a soil-based, land use framework as a potential strategy to meet economic and environmental objectives in agriculturally dominant watersheds, a concept yet to be explored in the United States. To explore the efficacy of an EU-style soil-based, land use framework in enhancing water quality and preserving crop yields, we focused on a sub-watershed of the Chesapeake Bay. Leveraging the Soil and Water Assessment Tool (SWAT), we modeled crop growth and the loss of total nitrogen (TN), total phosphorus (TP), and sediment over an 8-year period (2010-2017). Analyzing the SWAT model outcomes, we developed an algorithm to redistribute crop rotations within existing agricultural lands based on soil characteristics to decrease TN, TP, and sediment losses, while maintaining consistent production areas for each crop rotation. In this revised scenario, hay was moved to landscapes prone to erosion and nutrient loss, while corn-soybean rotations were relocated to less vulnerable areas. The reallocation resulted in 28% of agricultural lands retaining their original crop rotation, with the remaining 72% being reassigned. Through SWAT simulations of the redistributed scenario, TN, TP, and sediment losses were reduced by 15%, 14%, and 39% respectively on an average annual scale. These findings indicate that redistributing crop rotations within a compromised watershed can significantly enhance water quality without necessitating additional structural best management practices. While this study focused on watershed-level benefits, further research is essential to comprehend the impact of this approach on farm-level considerations, as its implementation may entail some farmers altering the types of crops cultivated (Jiang et al., 2021).

Table 6. The results of the cropping pattern in Dehloran City.

Crop	Area under cultivation (ha)	Pattern		
		Existing area under cultivation (ha)	Ideally optimized area under cultivation (ha)	Deviations
Irrigated wheat	X1	45996	43300	$d_1^- = 68.7$
Irrigated barley	X2	433	1850	$d_2^- = 126.6$
Fodder maize	X3	300	2467	$d_3^- = 91.8$
Canola	X4	6188	5300	$d_{11}^- = 8.85$

Conclusion

The research findings illustrate the energy dynamics of agricultural practices in the studied area. Barley cultivation was shown to have an average energy consumption of 83.72 GJ ha^{-1}, with significant electricity share. Larger fields demonstrated lower energy requirements but higher yields, leading to lower pollution per ton of crops. Conversely, wheat crop energy consumption remained relatively consistent across field sizes, with larger fields exhibiting higher yields. Fodder maize showcased higher energy consumption (1667 GJ ha^{-1}) and lower output energy (152 GJ ha^{-1}) compared to canola (1316 GJ ha^{-1}). Gas and electricity emerged as primary energy inputs in field cultivation. Recommendations for further research encompass exploring energy usage in diverse irrigation techniques, optimizing fertilizer application, incorporating smart control systems in greenhouse cultivation, and investigating solar energy as a power source. Advocacy for governmental backing of sustainable energy infrastructure is also proposed to mitigate environmental repercussions. In conclusion, it is evident that energy consumption varies across different crops and field sizes, impacting both yield and environmental sustainability. Further exploration into efficient energy practices and utilization of renewable sources can enhance the agricultural sector's sustainability and reduce its ecological footprint.

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