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Comparing the sustainability of protective agricultural ecosystems based on energy efficiency indicators in wheat, barley and cotton crop rotation (case study: Birjand)

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Abstract

This research was conducted to evaluate the effect of conservation agriculture on energy indicators in common agricultural ecosystems using a split plot design in the form of randomized complete blocks with three replications in the climatic conditions of Birjand, a town in east of Iran. The study investigated the rotation system of wheat, barley and cotton. We used treatments including three levels of conventional tillage methods (plow+disc+leveling+farrower+planting with seeds), reduced plowing (chisel packer or light disc +farrower+ planting with seeds) and no plowing (direct planting with seed drill) in the main plots considering plant residues at three levels: without residues, 30% retention and 60% retention of wheat residues in the secondary plots. The results of variance analysis and statistical analysis of energy indicators showed that in the period under study, the largest share of input was electricity 68.7%, nitrogen 11.9% and fuel 8.9%. The share of direct energy from the total energy input for all three tillage methods was more than 75%. The effect of tillage practices was only significant on the efficiency of energy consumption; so the change of tillage methods from conventional to no tillage and reduced tillage was associated with a decrease in energy consumption by 11.6 and 9.9, respectively. The effect of plant residues and the mutual effect of tillage practices and plant residues on energy indicators were not significant. The results of the energy index analysis indicated that the use of conservation tillage methods is preferable in terms of the superiority of the energy consumption efficiency index for wheat, barley and cotton cropping systems in the climatic conditions of Birjand.

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Introduction

The continuous growth of the global population and the rising demand for food and agricultural products have led to a substantial increase in energy consumption within this sector. The scarcity of energy resources, the escalating global prices of energy carriers, and the growing worldwide focus on sustainable development have prompted researchers to seek solutions for optimizing energy consumption in agriculture (Esfahani, 2022).

The results of research indicate that on a global scale, about five percent of the total energy is used in the agricultural sector, and about 11 percent of greenhouse gas emissions belongs to this sector, which is mainly caused by the consumption of fossil fuels, pesticides and fertilizers. Agriculture is dependent on electricity and tillage operations (Smith et al., 2014). Although energy consumption in agricultural ecosystems has led to increased productivity and economic growth, greenhouse gas production has also increased in intensive agricultural systems that are heavily dependent on chemical fertilizers, pesticides, and inputs such as fossil fuels, electricity and machinery (Li et al. al., 2016).

One of the suitable strategies to increase energy efficiency and reduce the environmental impact of energy inputs is the use of conservation agriculture in crop production systems (Rajaby et al., 2012). Changing the system from conventional agriculture to conservation agriculture saves fuel and energy and reduces the costs of crop production. On the other hand, preserving the residues on the soil surface increases the organic matter of the soil and increases the efficiency of the consumption of nutrients, supports living agents and microorganisms along with the activation of living agents, increases the amount of soil porosity, maintains moisture, prevents erosion, increases production and finally, increases economic and energy productivity (Tavakoli and Ghodsi., 2020).

In a research conducted on the energy flow and emission of greenhouse gases in crop production systems in the Sharifabad plain of Qom Province, the highest energy consumption efficiency was related to barley (*Hordeum vulgare* L.), fodder corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) and the lowest was related to cotton (*Gossypium hirsutum* L.). The share of direct energy was more than indirect energy and the share of non-renewable energy was more than renewable energy. Also, the results of the above research showed that in most products, electricity, diesel fuel, and nitrogen play the largest role in energy input and greenhouse gas emissions (Vafabakhsh & Mohammadzadeh, 2019). In another research, on wheat production in Ardabil Province, input energy of about 38755.34 $MJ.ha^{-1}$ was needed, and among the inputs, nitrogen fertilizer with 37.38% and diesel fuel with 19% contributed the most. The share of direct and indirect energy consumption was 39.88% and 60.12%, respectively, and renewable and non-renewable energies were 31% and 68.99% of the total input energy, respectively. Based on the results of this research and in order to reduce the environmental effects of the wheat production system in Ardabil Province, it was suggested to use crop management methods such as the use of organic inputs, crop rotation, low tillage and no tillage (Taghinazhad et al., 2019). Other researchers have also conducted studies on the evaluation of energy indicators in crop production systems (Razzazi et al., 2015; Omidmehr, 2016; Feiz Bakhsh et al., 2019; Afzalinia, 2020; Fathi et al., 2020).

The results of the research that was conducted in order to evaluate the energy efficiency indicators in three conventional, reduced and no-till tillage methods along with the management of plant residues in three levels: without residues, 30% and 60% of wheat residues indicated that the average energy consumption efficiency index for wheat and barley in the no-till method compared to conventional tillage and reduced tillage showed an increase of 21 and 9 percent, respectively (Tavakoli and Ghodsi, 2020). In a similar study, no-plow and no-residue treatments had the highest energy efficiency, and minimal plowing and conventional plowing without residue treatments were ranked second and third (Moayedi and Zareh, 2019).

The findings from various studies suggest that the energy consumption patterns in agricultural ecosystems are influenced by factors such as the cropping system, cultivation methods, technological advancements, the agricultural workforce, farmers' knowledge, the type and quantity of chemical fertilizers, and crop yields (Mohammadzadeh et al., 2017). Furthermore, a review of these research outcomes reveals significant variations in energy indicators during the agricultural production process across different regions. As a result, this study was conducted to assess the impact of conservation agriculture on energy indicators within the agricultural ecosystems of the Birjand region.

Materials and methods

Location, climatic and agronomic information of the experiment

This research was conducted in 2018 in South Khorasan Province. According to the climate of the region using the Emberger classification system, the study site is considered a dry region. The cultivated area of crops in this province is around 73343.3 hectares, and wheat, barley and cotton occupy the largest cultivated area with 19,605, 18,170 and 7,170 hectares, respectively (Ahmadi et al., 2020).

Experimental design and treatments

This experiment was conducted using a split plot design in the form of randomized complete blocks with three replications in the climatic conditions of Birjand. In the research, the treatments included tillage methods in three levels of conventional tillage methods (plow + disc + leveling + farrower + planting with seeds), reduced plowing (chisel packer or light disc + farrower + planting with seeds) and no plowing. We used direct lanting with seed drill in the main plots with plant residues at three levels: without residues, 30% retention and 60% retention of wheat residues in secondary plots. This study was investigated in the rotation system of wheat, barley and cotton.

Calculation of energy indicators

In order to calculate the energy indicators in the studied products, the energy of the consumed inputs, including human power, fertilizer, machinery, seeds, pesticides, water, etc., which are used during agricultural operations, as well as the yield of the product was calculated according to their energy equivalents as shown in Table 1. Energy indices were calculated based on relationships 2, 3, 4 and 5 (Mohammadi & Omid, 2010):

$$EUE = \frac{\mathrm{EOU}}{\mathrm{EIN}} \tag{2}$$

$$Ep = \frac{\mathrm{Y}}{\mathrm{EIN}} \tag{3}$$

$$NEG = EOU - EIN \tag{4}$$

$$SE = \frac{EIN}{\mathrm{Y}} \tag{5}$$

In these relationships, EUE = energy use efficiency, EOU = energy output (MJ ha^{-1}), EIN = energy input (MJ ha^{-1}), Y = crop yield (kg ha^{-1}), EP = energy efficiency, NEG = net energy and SE = specific energy. The studied input and output energies and the corresponding energy equivalent (in MJ) are presented in Table 1. Input energies in agricultural systems can be divided into two parts: direct and indirect or renewable and non-renewable. Accordingly, direct energy includes human power, diesel fuel, irrigation water, and electricity, and indirect energy includes seeds, chemical fertilizers, animal manure, pesticides, and machinery (Yilmaz et al., 2005). Also, human power, seeds, irrigation water and animal manure are considered as renewable energy and electricity, chemical fertilizers, diesel fuel, pesticides and machinery are considered as non-renewable energy (Esfahani and Rafati, 2022).

Data analysis

Data analysis was conducted by SAS V. 9.2 software and comparison of means was implemented using Duncan's multiple range test at the five percent probability level.

Table 1. Equivalent energy for inputs and outputs

a) Inputs	Unit	Energy equivalents (MJ. Unit^{-1})	Reference
Human labour	hr	1.96	Zangeneh et al. (2010); Ozkan et al. (2004); Yilmaz et al. (2005)
Machinery	hr	62.7	Zangeneh et al. (2010); Ozkan et al. (2004); Yilmaz et al. (2005)
Diesel	l	47.8	Zangeneh et al. (2010); Ozkan et al. (2004); Yilmaz et al. (2005)
Nitrogen	kg	66.14	Singh et al. (2002); Yilmaz et al. (2005); Pervanchon et al. (2002)
Phosphorus (P_2O_5)	kg	11.15	Mohammadi & Omid (2010)
Potassium (K_2O)	kg	12.44	Zangeneh et al. (2010)
Insecticides	l	58	Mohammadi et al. (2014)
Herbicides	l	295	Mohammadi et al. (2014)
Fungicides	l	115	Mohammadi et al. (2014)
Electricity	kwh	11.93	Ozkan et al. (2004)
Irrigation water	m3	0.63	Yilmaz et al. (2005)
Wheat seed	kg	17.7	Vafabakhsh & Mohammadzadeh (2019)
Barley seed	kg	14.7	Vafabakhsh & Mohammadzadeh (2019)
Cotton seed	kg	18	Vafabakhsh & Mohammadzadeh (2019)
b) Outputs			
Wheat grain	kg	14.7	Vafabakhsh & Mohammadzadeh (2019)
Wheat straw	kg	9.25	Vafabakhsh & Mohammadzadeh (2019)
Barley grain	kg	14.7	Vafabakhsh & Mohammadzadeh (2019)
Barley straw	kg	11.6	Vafabakhsh & Mohammadzadeh (2019)
Cotton	kg	18	Vafabakhsh & Mohammadzadeh (2019)

Results and Discussion

The research findings revealed that the total input energy required for cultivating wheat, barley, and cotton was 104205.38, 102120.72, and 145554.22 MJ.ha-1, respectively (Table 2). Among these crops, the highest input energy consumption was attributed to electricity, nitrogen fertilizer, and fuel. Specifically, electricity consumption constituted 59.3%, 60.5%, and 70.8% of the total input energy for wheat, barley, and cotton planting, respectively (Table 2). Furthermore, the analysis of energy input distribution across the studied crop cycles indicated that electricity, nitrogen fertilizer, and fuel accounted for the most substantial shares of consumed energy, averaging 68.7%, 11.9%, and 8.9%, respectively (Figure 1). Notably, fungicides had the lowest share, averaging only 0.01% (Figure 1).

Previous research has also highlighted the predominant roles of electricity, diesel, and nitrogen in input energy for various agricultural products (Vafabakhsh & Mohammadzadeh, 2019). For instance, in a study concerning fodder sorghum production in the Sistan region, it was found that an energy input of 37,695 MJ.ha-1 was required, with electricity, chemical fertilizers, and diesel contributing significantly (Fartout Enayat et al., 2017).

In the assessment of energy indicators and greenhouse gas emissions related to wheat production in Golestan province, it was determined that 16,231 MJ of energy was needed to cultivate one hectare of wheat. Moreover, each hectare of wheat production resulted in the release of 1,414 kg equivalent of carbon dioxide into the atmosphere. Nitrogen fertilizers and fossil fuels accounted for 70% of the total energy consumption and 78% of the total greenhouse gas emissions in this context (Rezvantalab et al., 2019). Similarly, for wheat production in Ardabil province, an input energy of 38,755.34 MJ.ha-1 was essential, with nitrogen fertilizer contributing 37.38% and diesel fuel contributing 19% to this energy demand (Taghinazhad et al., 2019).

Additional research conducted in rapeseed fields of Razavi Khorasan Province indicated that nitrogen, phosphorus, and potash fertilizers collectively accounted for 45%, 38%, and 16% of the global warming potential (equivalent to 1.5 tons of CO2 per hectare). In contrast, chemical pesticides, including fungicides and herbicides, made up only 0.9% and 0.5% of this potential, respectively. Based on these findings, the study recommended considering the use of organic inputs and the introduction of nitrogen-fixing species as ecological alternatives to replace chemical nitrogen fertilizers (Khorramdel et al., 2016).

Table 2. Total amount of input and output energy in studied crop rotation

		Wheat			Barley			Cotton		
	Unit	$A^{\dagger}$ ha^{-1}	$E^{\dagger\dagger}$ MJ. ha^{-1}	$P^{\dagger\dagger\dagger}$ %	$A^{\dagger}$ ha^{-1}	$E^{\dagger\dagger}$ MJ. ha^{-1}	$P^{\dagger\dagger\dagger}$ %	$A^{\dagger}$ ha^{-1}	$E^{\dagger\dagger}$ MJ. ha^{-1}	$P^{\dagger\dagger\dagger}$ %
a) Inputs										
Human labour	hr	92.5	181.3	0.17	92	180.32	0.17	305	597.8	0.41
Machinery	hr	20.5	1285.3	1.23	20	1254	1.22	25	1567.5	1.07
Diesel	l	272.2	13011.16	12.48	232.6	11118.28	10.88	233.4	11156.52	7.66
Seed	kg	220	3454	3.31	200	2940	2.87	80	1440	0.98
Nitrogen	kg	250	16535	15.86	250	16535	16.19	250	16535	11.36
Phosphorus (P_2O_5)	kg	150	1672.5	1.60	150	1672.5	1.63	150	1672.2	1.14
Potassium (K_2O)	kg	75	933	0.89	100	1244	1.21	100	1244	0.85
Herbicides	l	2	590	0.56	2.5	737.5	0.72	2	590	0.40
Insecticides	l	2	46	0.11	1	0	0.05	2	0	0.08
Fungicides	l	0.4	61845.12	0.04	0	61845.12	0	0	103075.2	0
Electricity	kwh	5184	4536	59.34	5184	4536	60.56	8640	7560	70.81
Irrigation water	m^3	7200	116	4.35	7200	58	4.44	12000	116	5.19
Total input energy	MJ.ha^{-1}	-	104205.38	100	-	102120.72	100	-	145554.22	100
b) Outputs										
Grain	kg	3410	50127	-	3190	46893	-	-	-	-
Straw	kg	5558.3	51414.2	-	4178.9	48475.2	-	-	-	-
Cotton	kg	-	-	-	-	-	-	2300	41400	-
Total output energy	MJ.ha^{-1}	-	101541.2	-	-	95368.2	-	-	41400	-

A†: Input per unit area, E††: Equivalent energy, P†††: Percentage of total input energy

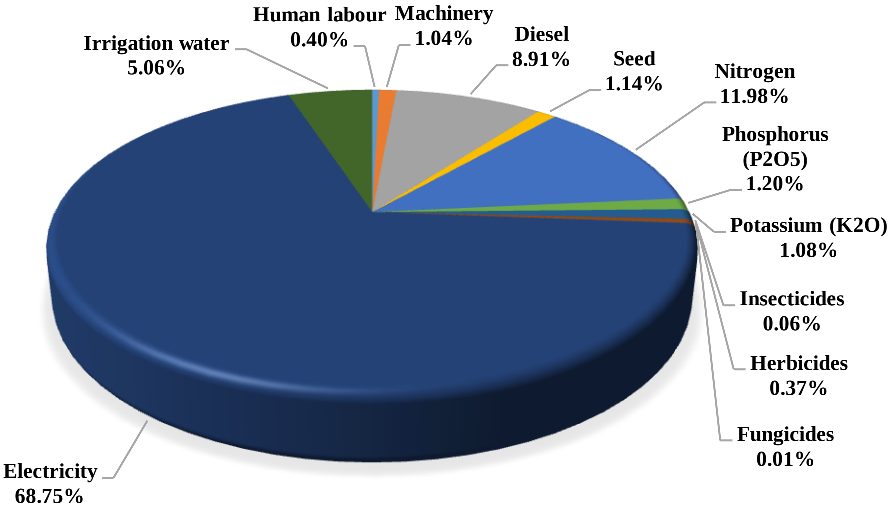

Figure 1. The share of different energy inputs from the total energy input in the studied crop rotation

Input energies in agricultural systems can be divided into two parts: direct and indirect or renewable and non-renewable. Accordingly, direct energy includes human power, diesel fuel, irrigation water, and electricity, and indirect energy includes seeds, chemical fertilizers, animal manure, pesticides, and machinery (Yilmaz et al., 2005). In this study, the results of the investigations showed that the relative share of direct energy from the total input energy of each product in the common cycle for all three tillage methods is more than 75% (Table 3). Also, the results indicated that changing the tillage method from conventional tillage reduced and no tillage decreased the direct energies and increased indirect energies in the rotation of wheat, barley and cotton (Table 3). In a research that was conducted to study the flow of energy in crop production systems in the Sharifabad plain of Qom Province, the share of direct energy was more than indirect energy and the share of non-renewable energy was more than renewable energy (Vafabakhsh & Mohammadzadeh, 2019). In another study, for wheat production in Ardabil Province, the share of direct and indirect energy consumption was 39.8% and 60.1%, respectively, and renewable and non-renewable energies were 31% and 68.99% of the total input energy, respectively (Taghinazhad et al., 2019).

Table 3. Relative contribution of direct and indirect energies in different methods of soil tillage in studied crop rotation

Forms of energy	Wheat (2019-2020)			Barley (2020-2021)			Cotton (2021-2022)		
	CT†	MT††	NT†††	CT†	MT††	NT†††	CT†	MT††	NT†††
Direct energies	84.08	77.28	76.42	84.82	78.28	77.41	89.86	86.36	85.98
Indirect energies	15.92	22.72	23.58	15.18	21.72	22.59	10.14	13.64	14.02
Total (%)	100	100	100	100	100	100	100	100	100

CT†, MT†† and NT†††: represents conventional tillage, minimum tillage and no tillage, respectively.

The analysis of variance for energy indices of wheat, barley and cotton rotation showed that the effect of tillage methods was significant only for the energy consumption efficiency index at the five percent level (Table 4). However, the effect of residues and the interaction between tillage practices and residues were not significant for any of the energy indicators (Table 4).

Table 4. Anova for energy indices of crops in rotation

Sources of variation	Energy use efficiency	Specific energy	Net energy gain	Energy productivity
Tillage (T)				
Wheat (2019-2020)	*	ns	ns	ns
Barley (2020-2021)	*	ns	ns	ns
Cotton (2021-2022)	*	ns	ns	ns
Residue (R)				
Wheat (2019-2020)	ns	ns	ns	ns
Barley (2020-2021)	ns	ns	ns	ns
Cotton (2021-2022)	ns	ns	ns	ns
T× R				
Wheat (2019-2020)	ns	ns	ns	ns
Barley (2020-2021)	ns	ns	ns	ns
Cotton (2021-2022)	ns	ns	ns	ns

n.s and *: are Non- significant and significant at 5% probability level, respectively

The comparison of the average values of the energy consumption efficiency indices in the desired interval showed that the highest and lowest values of this index were observed in the without tillage and continuous tillage methods, respectively. The efficiency index of energy consumption for wheat, barley and cotton in the without tillage method had an increase of 16.6%, 19.2% and 42.3%, respectively, compared to the conventional tillage (Table 5). Also, the results indicated that in the period under study, the lowest efficiency of energy consumption in all three tillage methods belonged to cotton (Table 5). In a research that was conducted in order to study the energy flow in crop production systems of Sharif Abad plain, Qom Province, the highest energy consumption efficiency was related to barley (*Hordeum vulgare* L.), fodder corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) and the lowest was related to cotton (*Gossypium hirsutum* L.) (Vafabakhsh & Mohammadzadeh, 2019). Based on research results for wheat production in Ardabil Province, it was suggested to use crop management methods such as the use of organic inputs, crop rotation, low tillage and no tillage to increase the efficiency of energy consumption (Taghinazhad et al., 2019).

Table 5. Mean comparison of the tillage effect on energy use efficiency of wheat, barley and cotton

Tillage methods	Wheat (2019-2020)	Barley (2020-2021)	Cotton (2021-2022)
Conventional tillage	0.54 ^{b}	0.52 ^{b}	0.26 ^{b}
Minimum tillage	0.59 ^{ab}	0.55 ^{ab}	0.29 ^{ab}
No tillage	0.63 ^{a}	0.62 ^{a}	0.37 ^{a}

Means within a column that have the same letter are not significant at 5% probability level

The results showed that the most consumed energy was related to conventional tillage with an average of 378,788 MJ.ha^{-1}. Changing the tillage method from conventional tillage to minimum tillage and no tillage resulted in a decrease of 9.9% and 11.6% in total energy consumption (Figure 2). Also, the results of the efficiency of energy consumption indicated that in the period under study, the sustainability of no tillage and tillage practices was the least and the least sustainable was the conventional tillage (Figure 2). As such, the efficiency of energy consumption in the minimum tillage and no tillage method was at least 19.8 and 14.5% higher than conventional tillage (Figure 2). The research results showed that the highest efficiency index of energy consumption in wheat, barley, and cotton and wheat rotation was observed in the without tillage and minimum tillage methods and the highest in the conventional tillage method (Tavakoli Kakhki and Ghodsi, 2020). In a research, the energy efficiency of three tillage systems including conventional tillage, minimal tillage and no tillage with winter wheat, barley, spring wheat and Vetiver cultivation were calculated in the North of Madrid in Spain. The results of the study showed that in the method of no tillage and minimal tillage, energy consumption was reduced by 7-11% for cereals and 10-15% for Vetiver. Energy efficiency also showed an increase of 18% and 20% in the method of minimal tillage and no tillage compared to the normal state (Hernanz et al., 1995).

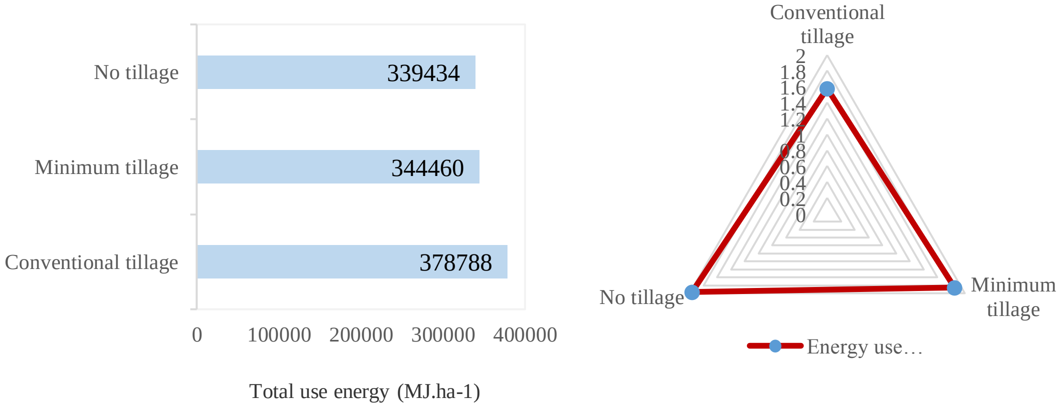

Figure 2. The average efficiency of energy consumption and the total energy consumed in different methods of tillage in the rotation of wheat, barley and cotton

Conclusion

The results of this research showed that in the rotation of wheat, barley and cotton, the largest share of inputs was electricity 68.7%, nitrogen 11.9% and fuel 8.9% respectively. The relative share of direct energies from the total input energy of each product in the common cycle for all three tillage methods was more than 75% and more than the relative share of indirect energies. Also, the results showed that the effect of tillage methods was significant only on the efficiency index of energy consumption; but the effect of plant residues did not have a significant effect on energy indices. Changing tillage practices from conventional tillage to no-tillage and reduced tillage in the studied rotation was associated with a decrease in energy consumption by 11.6 and 9.9, respectively. The results of the energy index analysis indicated that the use of conservation tillage methods is prefered in terms of the superiority of the energy consumption efficiency index for wheat, barley and cotton cropping systems in the climatic conditions of Birjand.

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