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Comparison of the Sustainability of Bean Production Systems Based on Emergy and Economic Analyses

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Abstract

To address increasing demand, bean producers have intensified agricultural activities by increasing application of industrial inputs. Such intensification can impose environmental risks to vulnerable ecosystems. Emergy and economic analyses were utilized in this study to investigate and comparison of environmental performance of five management patterns specified by differing degrees of intensification, i.e., ecologic, integrated, low-, medium- and high-input production systems at Bean Research Station in Khorram Dasht, Iran. The total emergy supporting these systems was estimated to be $6.52\text{E}+15$, $1.22\text{E}+16$, $6.62\text{E}+15$, $1.10\text{E}+16$ and $1.54\text{E}+16$ sej ha⁻¹ for the ecologic, integrated, low-, medium- and high-input systems, respectively. The purchased emergy inputs accounted for the largest portion of the total emergy inputs to these systems and ranged between 60.84 and 75.80%. The renewable fractions, transformities, emergy yield ratios, environmental loading ratios, emergy sustainability indices, and the economic output to input ratios demonstrate that the ecologic and low-input systems performed well compared to the three more industrial systems when considering their environmental sustainability. However, the more industrial systems had comparatively higher economic output. Generally, the results illustrate that sustainable bean production will depend on the transition from fossil fuel intensive systems to more natural resource intensive ones. To achieve more sustainable systems, applying conservation tillage and replacing chemical fertilizer with organic fertilizer are advocated for use in bean

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production systems. Joint use of emergy and economic evaluation provided different but complementary standpoints for comparison of the five bean production systems examined, and can assist in solving the problems that may occur in decision-making.

Keywords

Cropping systems; Pulse crops; Emergy Synthesis; Environmental Loading Ratio; Economic Output-input Ratio

1. Introduction

The adoption of more sustainable agricultural production systems requires society to face the great global challenges of the present time, including the population explosion, food security and environmental pressures of all kinds (Hole et al. 2005). To maintain high yields, traditional farming systems are dependent on the utilization of increasingly large quantities of fossil fuel and mineral inputs, which are scarce non-renewable natural resources (Rydberg and Haden 2006). The intensive utilization of agrochemicals and other industrial inputs has been accompanied by groundwater mining, soil fertility reduction, soil erosion, fertilizer and pesticide pollution, biodiversity loss as well as global warming that may endanger future production (Foley et al. 2011).

Today, the sustainability of many food production systems is in doubt considering the modern structure of the application of inputs, hence a consolidated systems procedure to quantifying both economic inputs and environmental resources is needed (Jafari et al. 2018; Lu et al. 2018). Agricultural ecosystems are at the border zone between economic and environmental systems being reliant on both human economic inflows, for instance machinery, fertilizers, electricity, fuels, pesticides, and some other agro industrial resources as well as free environmental flows, for instance sun, wind, water and soil organic matter (Rydberg and Haden 2006). Nevertheless, the conventional economic analysis approach does not properly account for nonmarket environmental inputs or outputs (Lu et al. 2014). If free environmental flows are ignored relative to economic ones, managing decisions will be on the basis of imperfect analyses and the optimum use of inputs to support agricultural systems may not be attained (Cheng et al. 2017).

Meanwhile, the technique based upon laws of thermodynamic, e.g., emergy analysis (Asgharipour et al. 2012), exergy accounting (Chen and Chen 2009), emergy synthesis and life cycle assessment (Milà i Canals et al. 2006) are beneficial, because they quantify the share that environmental products and services contribute to production systems in equivalent units with the other inputs (Odum 1986). Within this context, the emergy methodology (Campbell et al. 2005) is a suitable instrument to value renewable and non-renewable flows and services from the environment normally considered 'free' plus exterior flows obtained from the economy (Ulgiati et al. 1994). Emergy is the accessible exergy or energy that was consumed in direct or indirect to produce products or services (Brown and Ulgiati 2004). In emergy synthesis, the amount of all forms of energy and material flows may be transformed to an equivalent unit (solar emjoules, abbreviated as sej) by multiplying by their appropriate transformation coefficients for example, transformity (sej J^{-1}) or

specific emergy (sej g^{-1}) (Cohen et al. 2006; Wu et al. 2013). To evaluate the environmental issues, economic efficacy as well as to quantify the sustainability of the production systems, a series of emergy-based indicators can be calculated (Brown et al. 2000).

Over the last twenty years, emergy synthesis together with its corresponding indices have been widely utilized to assessing ecological sustainability of farming systems of various scales and types. Examples include banana (de Barros et al. 2009), rainfed corn–wheat rotation (Singh et al. 2016), corn production alternatives (Rótolo et al. 2015), grain production systems on large-scale farms (Wang et al. 2014), rice (Ting and Ping-an 2016), coffee (Giannetti et al. 2011), grapes (Kohkan et al., 2017) and date and pistachio (Jafari et al., 2018). The emergy methodology has been applied to compare various natural and agricultural production systems regarding their environmental impact, productivity, sustainability and resource use (Zhang et al. 2007; Campbell et al. 2009). For example, the emergy methodology has also been successfully applied to compare rice and vegetable farming systems in Guangdong province of China (Lu et al. 2010).

Markazi province is one of the main areas of legume crop production in Iran. This region is faced with ecological and economic problems and crop producers are demanding a transition from traditional to eco-friendlier production systems. Since beans are among the paramount legume crops in the world, they can be investigated as a reference crop for ecological–economic evaluation of differing management patterns specified by differing degrees of intensification (industrialization). To the best of our knowledge, no emergy analyses have been carried out thus far for the navy bean (*Phaseolus vulgaris* L. var. Dorsa). A comprehensive emergy analysis of bean cultivation in Iran can provide new insights by analyzing the costs and benefits of managing legume crop production systems. The findings of such a study could demonstrate the potential for advancement toward environmental sustainability and bring up supplementary information to improve bean production. In the present study, based on a one-year research project, emergy and economic indicators are used to assess environmental impact, productivity, resource utilization efficiency, overall sustainability as well as economic performance of five different bean production systems, namely the ecologic, integrated, low-, medium- and high-input systems, which are representative of the main patterns of bean production found around the world.

Pulse crops are considered a profitable choice for enhancing the food of low-income consumers and a vital crop for both poor consumers and producers in developing countries (Singh and Singh 1992). Moreover, in developed countries, pulses serve a particular role in the diet by providing essential amino acids and micronutrients, they are progressively being considered as beneficial foods (Singh and Singh 1992; Hillocks et al. 2006). Therefore, pulse crops offer a great potential to achieve the new sustainable development aims to achieve food and nutritional security and reduce poverty around the world. On average pulses account for around 3% of whole calories used in third world, ranging from 4% in Sub-Saharan Africa, 3% in Latin America and South Asia, 2.5% in North Africa and Middle East and fewer than 1% in Central Asia (Reid 2010).

Bean are the best-known legume crops in human nutrition and more than 300 million people are dependent on it in the world for direct consumption as a primary source of dietary

protein (Jones 1999). The estimated harvested area of bean crop in 2015 was 27 million ha, which produced nearly 29 million tons of dry bean (Akibode and Maredia 2011). South Asia constitutes 33% of the entire area under bean cultivation, followed by Latin America (25%), Sub-Saharan Africa (20%) and Middle East and North Africa (13%). In terms of production, Latin America dominates with 29% followed by South Asia (Akibode and Maredia 2011). Iran is among the leading bean producers in the Middle East with an annual production of 270 thousand tons gained from a total area of 117 thousand ha under cultivation in 2016 (FAO 2017).

Bean crops are produced in a range of environment and cropping systems in South Asia, Latin America, Middle East and Canada, as diverse as highly mechanized systems in developed countries, where beans are produced on medium- and large-scale with high industrial input, to small holders, who usually produce beans on small-scale farms in India, Brazil, Mexico, Central America, Andean Zone, the Caribbean, Africa, Pakistan and Iran with limited purchased industrial-inputs (Akibode and Maredia 2011). Although beans are progressively identified for their nutritive value in human diets as a strategic remedy for healthy eating and hidden hunger, there is a paucity of information on sustainability of bean cropping systems. Such information is vital to assessing alternatives investment to promote beans to combat malnutrition within the framework of urbanization and growing economies.

2. Materials and methods

2.1 Site description

The field experiment was performed in 2016 at Khomein Bean Research Station in Khorram Dasht, Markazi Province, Iran (49.57° N, 33.39° E, which is 1930 m above sea level). The research area has a moderate, semiarid climate with an average annual temperature of 13.7 °C (June and July are the warmest months with average daily temperature of 27.1 °C, while January is the coldest month with mean temperature of 0.7 °C) and the average annual precipitation is 341.7 mm, only 25% of which is concentrated in the bean growth season. The average wind velocity is 2.64 m s⁻¹, the annual sunshine is 2621.4 h and the annual solar radiation is approximately 1256.7 kW m⁻². Table 1 presents the initial physicochemical properties of the experimental plot.

2.2 Description of the different bean production systems

In this study, we chose five different intensities of input including ecologic, integrated, low-, medium- and high-input as representatives of the usual bean production systems in Iran. The input and output characteristics of the production systems correspond to the different scales of bean production in the area. High, medium and low-input systems indicate a shift in energy consumption in the production systems and a conversion from extensive to intensive bean production, a gradient which is characterized by high, medium and low levels of mechanization and industrial agricultural practices, such as the application of mineral fertilizers and agrochemicals, tillage operations, consumption of fuel and irrigation water, etc. The ecologic system is intensive in the application of organic fertilizer and natural resources and uses minimum tillage operations. The integrated system is classified as

combining the application of organic and mineral fertilizers and pest control through chemical and physical methods.

It is worth mentioning that that medium and high-input systems belong to large scale bean production, while ecologic, integrated and low-input systems are classified as household farms of small scale and family operated. Table 2 summarized the treatment details and all the input requirements to the five production systems.

The experimental design for this study was a randomized block design (RBD) with three replicates. Plots were 25-m long and 10-m wide. The bean crop, “navy bean cv. Dorsa”, was sown using a seed drill at 0.50 m row spacing by the first week of June and harvested in the second week of September. Phosphorous and potassium were utilized as the base along with 50% of the nitrogen, while the remaining nitrogen was top-dressed at 45 DAS (days after sowing). Fe was sprayed at the time of the late vegetative stage. In the organic fertilizer containing plots, farm yard manure was broadcast 20–25 days before sowing and incorporated into the soil. Nitrogen was applied as urea, phosphorous as triple super phosphate, potassium as potassium sulfate and Fe as ferrous sulfate. The chemical properties of farm yard manure are shown in Table 3. Irrigation systems were surface drips and the rate of emitter discharge was 1.5 L ha⁻¹.

For weed control, trifluralin (*Treflan*) was utilized at 1 kg ha⁻¹ i.e., as a pre-emergence herbicide in all production systems except the ecologic system. A selective post emergence herbicide, *Basagran* was applied at 1 kg ha⁻¹ a.i., active ingredients and Gallant at 0.5 kg ha⁻¹ a.i. was sprayed at 45 days after sowing in medium and high-input. A mixture of Diazinon and Metasystox was sprayed once, once, twice and three times during the growth season in the integrated, low-, medium- and high-input cultivations, respectively.

To facilitate the calculations and make the flow easily comparable among bean production systems, the quantities of the various items have been standardized for an area of 1 ha.

2.3 Emergy synthesis

The Emergy synthesis procedure is founded on the works of Odum et al. (2000) and Odum (1996, 2000). The initial stage in this method is to characterize the spatial and temporal boundaries of the system and the next is to draw the diagram of Energy Systems Language (ESL) based on the energy systems symbols defined by Odum et al. (2000). This diagram distinguishes the major ingredients of the system, their connections, and the material, energy and economic inflows and outflows. The system inputs are separated into categories and are defined as renewable or non-renewable resources and domestic or external resources. Fig. 1 presents a general conceptual ESL diagram for the bean production systems examined in the research at hand. The inputs driving agricultural systems stem from two kinds of outside resources: free natural resources and purchased resources from the human economy. The rectangle box indicates the system boundary; the environmental resources are presented on the left side of the diagram; the resources from the human economy are shown in approximate order of raising transformity (sej/J) on the upside of the diagram; and finally, useful yields from the bean production systems are shown on the right side of the diagram. For analysis of the production systems and calculation of indices the resources were

aggregated into four categories (Lu et al. 2010): renewable environmental resources (R), for instance sun, wind and rain; potentially renewable local resources that are being utilized in a non-renewable manner (N_0) for instance soil erosion, ground water and inputs used for making processes; renewable purchased resources (F_R), for instance organic manure, seeds and water obtained from out of the system boundary; and non-renewable purchased resources (F_N) for instance electricity, fuel, machinery, fertilizers and pesticides.

In agreement with previous emergy studies (Ulgiati et al. 1994; Lu et al. 2010; Jafari et al. 2018), 90% of labor was considered as being supported by non-renewable inputs and incorporated in F_N , whereas the rest was assumed as renewable and incorporated in F_R .

The fraction of rainwater transpired was 17%, 12%, 17%, 12% and 10%, respectively for the ecologic, integrated, low-, medium- and high-input systems, respectively. Therefore, this fraction was included in R , while the remaining transpiration was considered as being supported by groundwater and included in N . The wind, rain and rainwater transpired are coupled with each other and co-products of the geobiosphere, thus, to prevent double accounting only the greatest value was considered to estimate the entire R (Odum 1996). The emergy of solar radiation supporting photosynthesis was not assumed to double count the heating effects of the sun used to generate rain and wind. This assumption was made, because PAR and the heating effect of solar radiation are based on two different exergies.

After quantifying all energy and materials input and output flows for each production system, these quantities were converted into emergy units (sej) via multiplying by their respective transformities or specific emergies. These transformities and specific emergies for all ingredient originated from earlier researches (Odum 1996; Brandt-Williams, 2002; Lan et al. 2002; Cuadra and Rydberg 2006; Campbell et al. 2005; Lu et al. 2009; Bastianoni et al. 2009). Different transformities for some items had been obtained in various contexts and the calculated transformity has been selected under the most similar situation to those observed in the assessed conditions. Electricity generation in Iran in 2016, accounted for 280.7 billion kWh. Natural gas was the major fuel used to generate electricity in 2016, accounting for an estimated 61.3%, followed by oil at 37.6% and hydro power at 1.1%. In 2016, 6.08 billion L of gasoline, 6.95 billion L of crude oil and 58.42 billion cubic meters of natural gas were consumed to generate 280.7 billion kWh electricity (Iran Statistical Yearbook 2017). An average transformity of $2.31E+05 \text{ sej J}^{-1}$ was determined for electricity generation in Iran. All transformities used in this emergy analysis are based on $12.0E+24 \text{ seJ yr}^{-1}$ planetary baseline (Brown et al. 2016); therefore, values of transformity and specific emergy were converted to this baseline, if they were not in that before.

Many emergy-based indices are employed to assess the ecological, environmental and economic conditions of systems (Lu et al. 2010 and 2018). In this study, transformity (Tr), the renewable fraction of total emergy use (% R), the emergy yield ratio (EYR), the emergy investment ratio (EIR), the standard environmental loading ratio (ELR), modified versions of the ELR (e.g., ELR*), the emergy sustainability index (ESI) and the modified version of the ESI (e.g., ESI*) were applied to compare the properties of the five bean cropping systems (Lu et al. 2009, 2014 and 2017). The major specifications and formulae of the emergy-based indices are presented in Table 4.

2.4 Economic analysis

The input of money and the output of five bean production systems were evaluated using traditional economic analysis methods from data gathered by field research in 2016. Since one-year was the timescale for assessing these production systems, both the inputs and outputs for these systems were transformed to annual flows. The inputs and outputs were computed on the basis of domestic market values and the exchange rate of Iranian Rials to US Dollars in 2017 (42000 IR to 1 USD).

2.5 Data sources

The quantity of inputs and outputs of the five bean production systems were collected using field measurements and observations made by the authors during the entire agronomic year (2016). The raw data on renewable natural inputs, which include incoming solar radiation, precipitation and wind speed were obtained from the weather station located at the agricultural research site. The effective amount of organic fertilizer was directly measured and that of chemical fertilizer needed was acquired from Chen (2011). Entire materials, buildings and machinery utilized in the systems were expressed as yearly flows on the basis of their anticipated life-span. The life-span for machinery was approximated to be 10 years and for buildings 40 years (Jafari et al. 2018).

The total energy inputs were approximated on the basis of appropriate energy coefficients, which were obtained from Khoshnevisan et al. (2013). The energy content of the outputs (grain and straw yields from the beans) were determined as the combustion caloric value using the method defined in ISO, 1928 (ISO 1995).

After each irrigation and rainfall event during the bean's growing season, run-off was measured at 10 a.m. using multi-slot divisors. To measure the collected deposit in the run-off tank of all plot, a 500 ml specimen was taken from the tanks after stirring for 5 min. The resultant suspensions were quickly filtered using a Whatman No. 42 filter paper (International Ltd., Maidstone, UK.). To estimate soil loss data, the sediment on the filter paper was subjected to oven drying at 95 °C for 36 h and weighed.

To determine grain yield at maturity, pods were harvested from the plot area (25 m × 10 m) later than eliminating beans from the 1 m margin of the plot, dried in the sun for 14 days to approximately 15% water content, threshed and weighed. Straw yield from the same plots was measured by collecting all remaining aboveground biomass.

2.6 Statistical analysis

The data collected were subjected to the analysis of variance. *t*-test was carried out to determine the significance of the treatment difference. Comparison of means was done by Tukey's range test at the 5% level of probability.

3. Results

3.1 Energy synthesis and structures of energy input

Table 5 presents the natural and economic input flows for the five bean production systems, while Table 6 summed up the results of the emergy synthesis for the various systems. All the inputs in the tables were transformed to solar energy by multiplying by their respective transformities or other emergy per unit value. In this study, the majority of the transformities were collected from previously published analyses after checking their appropriateness for the specified case being studied. The quantitative flows of inputs were multiplied by appropriate renewability values to classify them into their renewable and non-renewable parts. The total emergy inputs supporting the systems are estimated to be $6.52\text{E}+15$, $1.22\text{E}+16$, $6.62\text{E}+15$, $1.10\text{E}+16$ and $1.54\text{E}+16$ sej ha⁻¹ for the ecologic, integrated, low-, medium- and high-input systems, respectively. These results show that the high-input cultivation method needs the most emergy input and that the total emergy requests from the ecologic, low-input, medium-input, integrated and high-input systems form a gradually increasing series. In general, a higher emergy input value usually reflects the intensification of the studied systems and demonstrates a higher degree of industrialization for the investigated systems (Lu et al. 2010).

By counting the respective portion of each input flow, the inputs are classified into aggregate categories, renewable environmental flows (R), potentially renewable environmental flows that are being utilized in a non-renewable manner (N), purchased renewable resources (F_R) and purchased non-renewable resources (F_N).

3.1.1 Renewable environmental flows—Among the wind, rain and rainwater transpired emergy sources inflowing to the different bean production systems, the rain was the highest for all systems. To avoid double accounting rain plus the emergy of solar radiation taken as total renewable inputs. The renewable emergy flows for the ecologic, integrated, low-, medium- and high-input represented 5.95%, 3.18%, 5.86%, 3.52% and 2.52%, respectively (Table 6). Large variation in the flow of renewable inputs to one hectare of each of the five bean systems was detected and the differences are reflected in the values of total emergy.

3.1.2 Non-renewable environmental flows—The three main inputs of local non-renewable resources are soil erosion, groundwater consumption and groundwater transpired, and their emergy values varied from $1.04\text{E}+15$ up to $1.80\text{E}+15$ sej ha⁻¹ (Table 6). The local non-renewable emergy flows contribute 15.92%, 11.54%, 15.99%, 13.02% and 11.68% of the total emergy inputs for the ecologic, integrated, low-, medium- and high-input, respectively. In spite of low rainfall in the district, the quantity of eroded soil could be regarded as high when compared to the results of emergy synthesis of other agricultural systems. For example, the non-renewable flow by means of soil erosion approximated at a rate of $6.21\text{E}+13$ sej ha⁻¹ yr⁻¹ in a corn field in KS, USA (Martin et al. 2006), and the emergy flows by soil erosion estimated at a level of $2.23\text{E}+13$ sej ha⁻¹ yr⁻¹ in a grape farm in the Chianti area of Italy (Bastianoni et al. 2001).

The high soil erosion rate indicates the fragile nature of the agricultural system in Iran and the serious environmental expenditures for growing bean crops in semi-arid regions such as Khorram Dasht in Iran. It is noteworthy to mention that the soil was supposed to be a non-renewable input. That is because in most cases soil can be regarded to be a reservoir that is damaged or depleted through farming operations and then refreshed only when appropriate agricultural productions are implemented. Nonetheless, given that normally the rate of natural soil reformation is lower compared to its rate of consumption, this input has been regarded as non-renewable.

3.1.3 Purchased resource flows—The major distinctions among the five bean production systems were detected in the utilize of purchased inputs that differed by more than two times from the least flow ($5.09\text{E}+15$ sej ha⁻¹ for the ecologic system) to the largest amount ($1.32\text{E}+16$ sej ha⁻¹ for the high-input system), indicating the levels of cropping intensity in the typology. Despite these variations, the purchased resources made the largest contributions to the total emergy input and they accounted for between 78.10% and 85.65% of the overall emergy used (Table 2). This indicates that the investigated bean systems are exceedingly open systems influenced highly by resources from the human economy. As discussed before, the emergy of purchased inputs was divided into renewable and non-renewable categories. The non-renewable portions of the entire purchased resources are, respectively, 38.9%, 88.0%, 97.2%, 98.5% and 99.0% for the ecologic, integrated, low-, medium- and high-input cropping systems. The structure of purchased emergy inputs to the ecologic and integrated production system differed from that of the other systems. In low-, medium- and high-input systems, the resources used were strongly reliant on the energy of fossil fuel in the form of machinery, pesticides and fertilizers (Table 6). Phosphorous and nitrogen fertilizer are two of the largest emergy flows for the integrated, low-, medium- and high-input systems. Organic fertilizer, however, was an important emergy input into the ecologic systems. Organic fertilizer represents the largest single item of the purchased emergy inputs for ecologic system (56.29% of the total). In addition, the labor force is another weighty item of the emergy inputs to all systems, accounting for 14.44%, 6.39%, 11.47%, 6.90% and 4.81% of the entire emergy inputs for the ecologic, integrated, low-, medium- and high-input systems, respectively. This is because the human labor force is required for soil preparation, sowing, fertilization, field management and other production processes.

3.1.4 Yield and solar transformities—The emergy assigned to yield in bean production systems changed from the least observed amount of $6.52\text{E}+15$ sej ha⁻¹ for the ecologic system to $1.54\text{E}+16$ sej ha⁻¹ for the high-input system (Table 6). The specific emergy and transformity can be utilized as a measure of the emergy efficiency of production (output (in J or g)/ emergy input (sej)). For systems yielding the same outputs, the higher the specific emergy or the transformity, the lower the production efficiency of the process; in other words, more product will be generated for the same quantity of emergy invested, and thus the lower the amount of resources required to yield the same quantity of the same quality product the more efficient the process (Odum 1996; Brown et al. 2000).

Among all the cropping systems, the ecologic system attained the lowest values of transformities and specific emergies of both the economic output ($1.71\text{E}+05 \text{ sej J}^{-1}$ and $2.82\text{E}+09 \text{ sej g}^{-1}$) and straw ($1.48\text{E}+05 \text{ sej J}^{-1}$ and $2.23\text{E}+09 \text{ sej g}^{-1}$) yields of bean production (Table 6). This reflects that the ecologic production system used less emergy input across time and space and was highly efficient in energy transformation compared to the other systems. This indicates that ecologic systems can generate greater amounts of product using the same amount of emergy. The high-input system had the greatest values of transformities and specific emergies for both the economic ($3.02\text{E}+05 \text{ sej J}^{-1}$ and $4.99\text{E}+09 \text{ sej g}^{-1}$) and straw ($2.62\text{E}+05 \text{ sej J}^{-1}$ and $3.94\text{E}+09 \text{ sej g}^{-1}$) yields from bean production, because the higher quality inputs used have transformities that are large compared to the inputs used for other products. Therefore, the higher transformity of the products of this system was due to losses of highquality energy (*e.g.* chemical fertilizer and fuel) that could result in less product formation and thus a higher product transformity all other things being equal in the production process (Vassallo et al. 2007). This condition stemmed from the fact that the high-input system uses large quantities of N and P chemical fertilizer with high solar transformity.

3.2 Emergy-based indices analysis

A comparison of emergy-based indices among the various bean production systems would be beneficial to find out quantitatively their distinctness in causing environmental impacts and in providing ecological and economic profit. Also, this comparison will help identify the best management practices for bean production to move toward the aim of sustainable agriculture. The values of emergy-based indices that were used to determine environmental status, production efficiency and sustainability for the five bean production systems are presented in Table 7.

3.2.1 Renewable fraction (%R)—Dividing the emergy input of resources into renewable and non-renewable fractions demonstrates the maximum pragmatic procedure to address an emergy analysis (Zhang et al. 2013a,b). The renewability fraction (%R) is the portion of renewable energy utilized by the system. Generally, processes or production systems with a higher share of renewable energy resources are probably to be more sustainable and ultimately more successful in economic competition compared to those using a great percentage of non-renewable emergy resources (La Rosa et al. 2008).

The integrated, low-, medium- and high-input systems were driven by a low proportion (3.35–13.39%) of renewable indigenous sources and have a greater dependency on non-renewable emergy support (Table 6). by contrast, the flow of renewable emergy resources are estimated to be 53.69% in the ecologic production systems. The ecologic cropping systems consumed a large quantity of organic fertilizer to supply the demand for nutrients. These results indicate that the ecologic system is more reliant on local renewable inputs and that they used minimum non-renewable inputs. The adoption of more ecologic methods by producers, who could benefit from greater use of renewable energy sources, would improve the sustainability of their production systems. The enhancement in the integration of agricultural systems, the cascade of energy, etc., are some of the initial stages that must be taken to advance in the orientation of sustainability.

3.2.2 Emergy yield ratio (EYR)—The emergy yield ratio (EYR) is the proportion of entire emergy yield to the emergy acquired from the external economy that is extensively utilized as a benchmark for the capacity of a process to capture local renewable and non-renewable inputs through investment on economic inputs from the outside (Odum 1996). For greater EYR, a greater share of free inputs to the emergy consumed in the process is a necessity (Zhang et al. 2007). The least achievable value of the EYR is one, which demonstrates that the share of local resources is zero and the process is entirely reliant on purchased inputs.

The amounts of EYR are estimated to be 1.28, 1.17, 1.28, 1.20 and 1.17 for the ecologic, integrated, low-, medium- and high-input systems, respectively. The EYR obtained for the soybean in south Tuscany of Italy was in the range of 1.98–2.32 (Panzieri et al. 2000), for the soybean in several cases studied in Brazil was in the range of 1.18–1.78 (Ortega et al. 2002) and for corn in Italy was in the range of 1.19–1.53 (Ulgiati et al. 1994). The EYR attained for the bean evaluated in this study do not indicate a very good capacity to make and exploit local sources accessible by outside investment of resources; therefore, bean production systems in this area require additional improvement. However, by taking more benefit of the accessible energy of local resources, the ecologic and low-input systems had higher EYRs compared to the other systems. by contrast, EYR values for the high-input and integrated production systems were lower than the other systems. This means that these two systems have a higher economic cost and depend more on purchased emergy inputs. As nutrient supply is among the major limitations for plant growth and production in industrial systems, the application of N and P fertilizer in unreasonable quantities has resulted in heavy dependence on purchased resources, thereby increasing the EYR. Undoubtedly, ecologic and low-input cropping systems compared to the industrialized agricultural systems have good capacity to utilize local free inputs of the system. It shows the level of dependency of the agricultural system with respect to the environment.

3.2.3 Emergy investment ratio (EIR)—The emergy investment ratio (EIR) used here is the proportion of the emergy input received from the outside economy to the emergy supplied by the natural resources or free environmental emergy of the system. In other words, it demonstrates the level of dependence of the agricultural system on natural resources and the degree of economic development (Wang et al. 2014). Thus, EIR and EYR are similar indices expressed in different manners. However, a very low EIR represents an extreme dependence of the system on environmental resources and a smaller level of economic costs (Odum 1996; Lan et al. 2002). The application of EIR in emergy analysis, facilitates the understanding from the viewpoint of the economic investment relative to the environmental resource base and it makes the discussion clearer compared to using the EYR alone (Brown and Ulgiati 2004).

The EIRs of the five investigated systems were in the range 3.57–6.03, with the high-input and integrated systems having the largest EIR and the ecologic and low-input system the lowest. This means that more purchased inputs were invested in the high-input and integrated systems, while the ecologic and low-input systems used more indigenous and local environmental inputs (Yang and Chen 2014), possibly making them more attractive for further economic investments. The EIR value of these bean production systems is

comparable to other agricultural products, for example wheat (3.2), sugar cane (7.0) and rice (2.7) (Odum 1996).

Current trends in the world demonstrate that low-cost energy probably has no future (Campbell and Laherrere 1998). Therefore, under these conditions, systems based more on non-renewable inputs cannot compete with production systems that rely more on renewable inputs, which require less economic and fossil energy investment and more contributions from nature. The investment ratios for those systems that will be competitive and sustainable in the future may be lower than those that we observe today.

3.2.4 Standard environmental loading ratio (ELR) and modified

environmental loading ratio (ELR*)—The Standard environment loading ratio (ELR), $(F+N)/R$, (Brown and Ulgiati, 1998) is an indicator of ecosystem stress because of economic production operations, and might be regarded as a measure of the possible anthropogenic impacts that a transformation process puts on the environment around the system (Lu et al. 2017). The modified edition of the environmental loading ratio (ELR*) suggested by Ortega et al. (2002) and shown in table 4 is the relationship between emergy from the entire non-renewable emergy resource and the emergy from the entire renewable resource. That is an inverse measure of sustainability (Campbell and Garmestani 2012). The greater the ELR, the more serious the environmental pressure on local ecosystems due to utilizing non-renewable resources (Odum 1996; Lu et al. 2014). The concept of ELR* obviously focuses on the dissimilarity between non-renewable and renewable resources, and therefore it may complement the evidence supplied by transformity (Martin et al. 2006).

The ELRs and ELR*s of the investigated systems are as follows, respectively: ecologic (16.81 and 0.86), integrated (31.35 and 6.47), low-input (17.09 and 11.47), medium-input (28.40 and 20.00) and high-input (39.66 and 28.61). In general, ELRs of lower than two represent relatively low environmental pressure, ELRs that are greater than three and below ten indicate a moderate environmental pressure and ELRs higher than ten demonstrate much higher environmental stress (Wei et al. 2009). Larger environmental stress could be due to loading a non-renewable investment into a small area, which cannot dilute the pressure (Cavalett et al. 2006). The greater quantities of ELR and ELR* for the intensive production systems were as a result of a large dependence on the flows of non-renewable inputs, for instance groundwater, electricity and inorganic fertilizer. While, the relatively high renewable input of organic fertilizer led to the ecological and integrated system exerting the minimum level of potential stress on the environment.

The ELR obtained for the corn production in northeast China was 10.62 (Wang et al. 2014), for the integrated grains, pig and fish system in the South Brazil, it was 3.13 (Cavalett et al. 2006), for corn production in Italy, it was in the range of 2.49–5.63 and for wheat production in Italy it was 3.4 (Ulgiati et al. 1994). Under the assumption that a load with a large flow of concentrated non-renewable emergy is tolerable, if it is close to local renewable resources, the two less-intensive systems are well-integrated into a local series of flows, while instead the three intensive systems are away from being a satisfactory balance with the local environment (Ulgiati and Brown 1998). These conditions are not necessarily regional, but could be related to the wider scale on which the resources originated. This study showed that

the use of ELR and ELR* together could clearly distinguish between the ecologic and low intensity production modes regarding their relative sustainability (respectively, 0.35 vs. 1.63), while showing that their potential environmental impacts were similarly low (3.14 vs. 3.20) compared to the impact of the other production modes.

3.2.5 Standard energy sustainability index (ESI) modified energy sustainability index (ESI*)

—The standard energy sustainability index (ESI) and the modified energy sustainability index (ESI*) are compound indicators obtained from the ratio of EYR to ELR and or ELR* (Lu et al. 2010 and 2017). On the one hand, the ELR measures the beneficial yield per unit of the potential environmental damage done to a system and can be used to assess the sustainability of a study area (Li et al. 2011). On the other hand, ELR* compares the beneficial yield of the system to an inverse measure of system sustainability based on the ratio of non-renewable to renewable energy use in the system. In other words, ESI demonstrates the system profit to expense ratio; namely, the profit a process provides to the economy in association to the contribution that the user makes to the pressure on the environment, whereas ESI* shows the system benefit gained in relation to the relative sustainability of the system. ESI and ESI* both consider the economic and ecological compatibility of production processes, but from a different perspective. However, in both cases the higher ESI and ESI*, the greater the sustainability of the system of concern. The value of the ESI and ESI* can vary from 0 to ∞ . According to Ulgiati and Brown (1998) ESIs from 1 to 10 demonstrate a system or process with good potential for sustainability, whereas those below 1 are indicative of a highly consumptive system that is running out of production with large environmental impact and will require large energy inputs to be maintained.

Among all the bean cropping systems, the ecologic non-intensive system had the highest ESI and ESI* (0.08 and 1.48), which helped to demonstrate the less environmental stress of these production systems of the research at hand. While the ESI of the four other systems were all below 0.1, from 0.07 for the low-input system to 0.03 of the high-input system and the ESI* of these systems were all below 0.2, from 0.18 for the integrated system to 0.04 of the high-input production system (Table 6), demonstrating that they were all unsustainable systems that deplete resources and exert great pressure on the environment Zhang et al. 2013a,b). These production systems supply a low energy returning on investment at the expense of great pressure exert on the environment, in comparison with other agricultural production options with higher marketable resources. Our ESI values fall in the range 0.10–0.45 of Hu et al. (2010) and 0.18 of Wang et al. (2018) for wheat–corn rotation in China.

3.3 Economic analysis

The environmental accounting of bean production systems is augmented by an economic analysis, as shown in Table 4. In this table the total annual economic inputs and outputs were computed on the basis of the local market prices of products in 2017. It should be noted that the prices of the outputs in the market rely primarily on aesthetic aspects of the bean grains. In other words, there is no economic incentive in the market to produce more ecological and environmentally friendly products. The highest economic cost in all bean production systems was human labor with a share of 45–60% of the total production cost,

followed by irrigation cost with share of 17–19% except for the ecologic system where seed cost ranks second with a share of 17%.

Among the five bean production systems, the high-input system had the highest economic input (US\$2006.0 ha⁻¹) which was 1.17, 1.22, 1.38 and 1.53 times that of the medium-input, integrated, ecologic and low-input production systems, respectively (Table 5). The dissimilarities between the five cropping systems regarding the economic values of the output were also high, namely the economic output of the high-input system was 1.18, 1.18, 1.34 and 1.79 times that of the integrated, ecologic, medium- and low-input systems, respectively. Lastly, the output to input ratio of the high-input system was 0.86, 0.96, 1.14 and 1.17 times that of the ecologic, integrated, medium-input and low-input system.

4. Discussion

4.1 Integration of emergy and economic results

The composition of the emergy inputs and the emergy-based indices analysis of the five different bean production systems provided major support for the significance of an environmentally-friendly agricultural orientation and for sustainable land management. Nevertheless, to achieve a holistic perception of the farmer's economic benefit considering the driving forces producing and integrating emergy synthesis with economic indicators is essential. Although emergy synthesis is a more comprehensive technique of accounting for ecological–economic production systems than economic evaluation, joint use of emergy and economic evaluation can contribute to a more comprehensive perspective on different views of environmental sustainability and productivity for the investigated systems.

As shown in Table 8, the high-input system had greater economic profit compared to the other systems. The reason was because both the grain and straw yield from the high-input system considerably exceeded that of the other systems. However, EYR, ESI and the economic productivity of the high-input system were less compared to those of the ecologic system, denoting that both the emergy and economic sustainability indices of the high-input system were lower compared to those of the non-industrial systems. Meantime, considering the values of ELR and ELR*, it's not difficult to discover that the ecologic and low-input system had lower environmental stress generation and emergy sustainability than the other systems. Since the high-input, integrated and medium-input production systems consumed large quantities of chemical fertilizer obtained from the economy, they had lower EYRs compared to other cropping systems.

In this study, the comparatively greater amounts of products and economic profits achieved from the high-input system were at the expense of using a large quantity of industrial products. In addition, the financial price of a product only considers the contributions of human economic service in its value and does not reflect the work of the environment. Nevertheless, within the last 20 years, non-industrial bean production in the region has been substituted by intensive production systems on larger areas (Shahgholi 2017). This trend is seen because local farmers searching to maximize their own temporary interests can profit from the greater rewards of selling more products, albeit this action reduces ecological sustainability and increases the environmental stress on the region.

The improved durability of bean cultivation in the region will depend on the transition from a high consumption of fossil fuels to an intensive natural input that increases the share of indigenous renewable inputs. There are numerous ways to compensate for the comparatively less monetary profit of the non-industrial cropping system, for instance improvement of marketing expertise to achieve greater prices for ecologic products and providing government subsidies for promoting conservation practices, as in European countries (Prager and Posthumus 2010).

4.2 Implications of the study and recommendation for policy, practice and research

To promote eco-friendly agricultural practices in production of beans in the western region of Iran, the purchased non-renewable inputs needs to decreased to reduce the environmental stress of the industrial production system. As the inorganic fertilizer constitutes the greatest contributions of entire input of resources to the bean cropping system, special methods such as precise measures of farm management, comprising improved water irrigation, rotations and timely sowing (Murphy 2008; Nemecek et al. 2008; Wang et al. 2016), a fertilizer application recommendation program, new chemical components, soil testing (Sun and Huang 2012) could be implemented in this area. Furthermore, attempts must be made to be less dependent on stressful non-renewable resources, for instance fossil fuel, heavy machinery, electricity, inorganic fertilizer and chemicals. Meanwhile, more consideration should be given the use of renewable resources, for instance human labor and organic fertilizers.

Based on emergy synthesis results, promoting intensive natural and semi-natural bean production systems in the west of Iran has a good possibility of success in the future. Bean production using local natural resources may have a comparative advantage over the low-, medium- and high-input production systems in both environmental and economic performance by means of achieving greater economic output to input ratios, EYR and ESI.

The ecologic system expends comparatively few non-renewable inputs compared to the other systems and therefore possesses a lighter impact on the environment. The low-input system performs moderately well on environmental sustainability and economic production among the systems, and it also has a good potential for further development in the future. However, in the light of the conventional scale of production, the two non-industrial systems are less likely to be chosen by farmers than most of the industrial farming systems in Iran (Shahgholi 2017), thus, the production pattern for the ecologic and low-input systems should change. Furthermore, the government needs to supply some political support to expand intensive natural systems, which could ensure a continuous improvement in the income of farmers in the region. Nonetheless, to incorporate the effects of other off-site aspects of these production systems, such as, groundwater contamination and land use change, as well as the incorporation of other negative externalities associated with the system using a larger scope of analysis is essential.

5. Conclusion

This study was conducted to compare the environmental sustainability and resource use of five bean production systems in the Khorram Dasht region of Iran, including the ecologic,

integrated, low-, medium- and high-input systems using an emergy-based approach with the complementary examination of economic indicators. The results of the analysis point the way toward methods to more ecologically design crop production systems that can maximize the emergy benefit to ecosystems and the economic and emergy benefits to the human economy.

A summary of our results and the main conclusions are given below:

- (1) The systems are approximated to be supported by a total emergy of $6.52\text{E}+15$, $1.22\text{E}+16$, $6.62\text{E}+15$, $1.10\text{E}+16$ and $1.54\text{E}+16$ sej ha⁻¹ for the ecologic, integrated, low-, medium- and high-input, respectively. The main difference among the five bean production systems was in the purchased resources from the human economy. All cropping systems strongly relied on purchased emergy inputs, with a share ranging from 68.07–83.48% of the total emergy inputs. Chemical fertilizer, especially N and P fertilizer makes the greatest share to the whole emergy input in all the investigated system, except for the ecologic system where organic fertilizer constitutes the greatest portion of whole emergy input.
- (2) The high-input system gained greater yields and economic advantages in comparison with the other systems. But the larger quantity of products and economic outputs from high-input system are obtained at the expense of using higher emergy inputs of chemical fertilizer, labor and irrigation water in the pre-sowing and growth stages of bean production, which increase the environmental burden and degrade environmental sustainability. As shown by the transformities, ELR, ELR*, ESI and ESI*, it can be obviously demonstrated that the three intensive systems, i.e. low-, medium- and high-input systems do not have a sustainable production pattern. Such condition is derived from the huge quantities of chemical fertilizers and pesticides used. While, more environmentally sound cropping systems, i.e. ecologic and integrated systems have better emergy and economic sustainability compared to the other cropping systems, as demonstrated by their better performance with respect to ELR, ELR*, ESI and ESI* and their higher economic output to input ratios.
- (3) To attain environmental sustainability of crop production, clean energy supposed to be used in the cropping system. Nevertheless, more attention should be paid to enhancing the share of natural renewable inputs used, and reducing the share of purchased resources. Furthermore, improvement in the productivity of industrial input agriculture by using emergy and economic efficiency analyses need to be further explored to optimize current agricultural practices.
- (4) This work is a general attempt to fill the gap in the evaluation of pulse crop production in the west of Iran and in similar environments elsewhere in the world. The emergy and economic assessments in this study, can provide more information to guide human activities to encourage transition to more sustainable agro-ecological systems. Emergy synthesis together with economic assessment provide an appropriate combined methodology to evaluate agricultural production processes. Nevertheless, for a more comprehensive

study, the findings of this investigation could be compared with other customary methods, in particular exergy analysis and Life Cycle Analysis (LCA) that are frequently applied to explore materials flows, but often do not include information and services.

Appendix A: The details of natural and economic flow calculation

procedure of each system:

Ecologic system:

Solar energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (during growth season, 2.9E+09 J m⁻²) $\times$ (1-albedo, 0.8) = 2.32E+13 J

Wind, kinetic energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (air density, 1.3 kg m⁻³) $\times$ (drag coefficient, 0.002) $\times$ (geostrophic wind, 10/6 $\times$ 2.64 m s⁻¹)³ $\times$ (growth season, 9.42E+6 s) = 1.08E+09 J

Rain, chemical potential energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (evapotranspiration, 0.341 m yr⁻¹) (density, 1,000 kg m⁻³) (Gibbs free energy, 4,740 J kg⁻¹) = 1.62E+10 J y⁻¹ for precipitation

Precipitation evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.117 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.54E+09 J

Ground water evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.612 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 2.90E+10 J

Soil erosion = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (soil loss rate, 1.63 kg m⁻²) $\times$ (organic matter content, 0.51%) $\times$ (5400 kcal kg⁻¹) $\times$ (4186 J kcal⁻¹) = 1.88E+09 J

Integrated system

Solar energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (during growth season, 2.9E+09 J m⁻²) $\times$ (1-albedo, 0.8) = 2.32E+13 J

Wind, kinetic energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (air density, 1.3 kg m⁻³) $\times$ (drag coefficient, 0.002) $\times$ (geostrophic wind, 10/6 $\times$ 2.64 m s⁻¹)³ $\times$ (growth season, 9.42E+6 s) = 1.08E+09 J

Rain, chemical potential energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (evapotranspiration, 0.341 m yr⁻¹) (density, 1,000 kg m⁻³) (Gibbs free energy, 4,740 J kg⁻¹) = 1.62E+10 J y⁻¹ for precipitation

Precipitation evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.117 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.54E+09 J

Ground water evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.860 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 4.08E+10 J

Soil erosion = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (soil loss rate, 1.73 kg m⁻²) $\times$ (organic matter content, 0.51%) $\times$ (5400 kcal kg⁻¹) $\times$ (4186 J kcal) = 1.99E+09 J

Low-input system

Solar energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (during growth season, 2.9E+09 J m⁻²) $\times$ (1-albedo, 0.8) = 2.32E+13 J

Wind, kinetic energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (air density, 1.3 kg m⁻³) $\times$ (drag coefficient, 0.002) $\times$ (geostrophic wind, 10/6 $\times$ 2.64 m s⁻¹)³ $\times$ (growth season, 9.42E+6 s) = 1.08E+09 J

Rain, chemical potential energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (evapotranspiration, 0.341 m yr⁻¹) (density, 1,000 kg m⁻³) (Gibbs free energy, 4,740 J kg⁻¹) = 1.62E+10 J y⁻¹ for precipitation

Precipitation evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.117 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.54E+09 J

Ground water evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.613 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 2.91E+10 J

Soil erosion = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (soil loss rate, 1.70 kg m⁻²) $\times$ (organic matter content, 0.51%) $\times$ (5400 kcal kg) $\times$ (4186J Kcal⁻¹) = 1.96E+09 J

Medium-input system

Solar energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (during growth season, 2.9E+09 J m⁻²) $\times$ (1-albedo, 0.8) = 2.32E+13 J

Wind, kinetic energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (air density, 1.3 kg m⁻³) $\times$ (drag coefficient, 0.002) $\times$ (geostrophic wind, 10/6 $\times$ 2.64 m s⁻¹)³ $\times$ (growth season, 9.42E+6 s) = 1.08E+09 J

Rain, chemical potential energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (evapotranspiration, 0.341 m yr⁻¹) (density, 1,000 kg m⁻³) (Gibbs free energy, 4,740 J kg⁻¹) = 1.62E+10 J y⁻¹ for precipitation

Precipitation evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.117 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.54E+09 J

Ground water evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.858 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 4.07E+10 J

Soil erosion = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (soil loss rate, 1.87 kg m⁻²) $\times$ (organic matter content, 0.51%) $\times$ (5400 kcal kg⁻¹) $\times$ (4186J Kcal⁻¹) = 2.16E+09 J

High-input system

Solar energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (during growth season, 2.9E+09 J m⁻²) $\times$ (1-albedo, 0.8) = 2.32E+13 J

Wind, kinetic energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (air density, 1.3 kg m⁻³) $\times$ (drag coefficient, 0.002) $\times$ (geostrophic wind, 10/6 $\times$ 2.64 m s⁻¹)³ $\times$ (growth season, 9.42E+6 s) = 1.08E+09 J

Rain, chemical potential energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (evapotranspiration, 0.341 m yr⁻¹) (density, 1,000 kg m⁻³) (Gibbs free energy, 4,740 J kg⁻¹) = 1.62E+10 J y⁻¹ for precipitation

Precipitation evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 0.117 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.54E+09 J

Ground water evapotranspiration energy = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (transpiration, 1.073 m yr⁻¹) $\times$ (density, 1,000 kg m⁻³) $\times$ (Gibbs free energy, 4,740 J kg⁻¹) = 5.09E+10 J

Soil erosion = (area, 1 ha) $\times$ (10,000 m² ha⁻¹) $\times$ (soil loss rate, 2.42 kg m⁻²) $\times$ (organic matter content, 0.51%) $\times$ (5400 kcal kg⁻¹) $\times$ (4186 J Kcal⁻¹) = 2.78E+09 J

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Fig. 1.
Summary diagram of the energy flow in bean cropping systems.

Table 1-

Physicochemical properties of soil before planting (0–30 cm)

EC	pH	N	P	K	Zn	Mn	Fe	Cu	O.C.	Soil texture
dSm ⁻¹		%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%	
1.9	7.54	0.07	14.5	280	1.18	7.68	2.68	1.37	0.51	Clay loam

Table 2-

Description of the five different bean production systems

		Ecologic	Integrated	Low-input	Medium-input	High-input
1- Land preparation operations						
Plow	No.	1	1	1	1	2
Disk	No.	0	1	1	2	2
Leveler	No.	0	1	0	1	2
Boundary	No.	1	1	1	1	1
2- Seeding rate	kg ha ⁻¹	69.0	51.7	57.5	51.7	46.0
3- Fertilizer						
Nitrogen (N)	kg ha ⁻¹	0	150	75	150	225
Phosphorous (P ₂ O ₅)	kg ha ⁻¹	0	100	50	100	150
Potassium (K ₂ O)	kg ha ⁻¹	0	10	5	10	15
Micro	kg ha ⁻¹	0	5	2.5	5	7.5
Organic fertilizer	kg ha ⁻¹	12400	4650	0	0	0
4- Weed management						
Herbicide application	kg ha ⁻¹	0	1	1	2	3
Hand weeding	No.	3	1	2	1	0
5- pest control (If applicable)	kg ha ⁻¹	0	1	1	2.5	2.5
6- Irrigation	m ³ ha ⁻¹	4300	6040	4310	6030	7540

Table 3-

The chemical properties of farm yard manure

EC (ds.m ⁻¹)	pH	Humidity (%)	Organic matter (%)	Nitrogen (mg kg ⁻¹)	Phosphorous (mg kg ⁻¹)	Potassium (mg kg ⁻¹)
6.6	7.6	55.59	26.5	17.1	7.2	25.9

Table 4-

Specifications and formulae of the energy-based indices used in the evaluation of bean production systems

Indices	Formula	Specifications
Renewable environmental inputs	R	Renewable flows from free local resources
Non-renewable environmental inputs	N_0	Local potentially renewable flows from free local resources that are being used in a non-renewable manner
Renewable purchased inputs	F_R	Renewable flows from purchased resources
Non-renewable purchased inputs	F_N	Nonrenewable flows from purchased resources
Total energy input	$U = R + N + F_R + F_N$	Total energy resources required to support the production system
Total energy output	$Y = R + N_0 + F$	Total energy of system products
Emergy density	$ED = U/\text{area}$	Total emergy currently required for a unit area of a production. The intensity of emergy invested in a unit area
Transformity	$Tr = U/AE$	Amount of emergy required to produce an output unit in joules, a measure of system efficiency. AE is the accessible energy of the product.
Specific emergy	$SE = U/W$	Amount of emergy required to produce an output unit measured in grams. W is the accessible weight of the product.
Emergy renewability	$\%R = (R + F_R)/U$	Percentage of renewable emergy used by the system
Emergy yield ratio	$EYR = Y/(F_R + F_N)$	Ability of a process to use local renewable and nonrenewable resources when economic resources from outside are invested in the system as a capital input.
Emergy investment ratio	$EIR = (F_N + F_R)/(R + N_0)$	The ratio purchased to free emergy indicates the intensity of economic investment and its matching to the free renewable and nonrenewable resources of the local environment.
Emergy loading ratio	$ELR = (N_0 + F_R + F_N)/R$	The ratio of purchased and non-renewable emergy to the renewable inputs from the local environment. This index is a measure of loading on the local environment.
Emergy loading ratio*	$ELR^* = (N_0 + F_N)/(R + F_R)$	The ratio of nonrenewable emergy to renewable emergy used by the system. This ELR is an inverse measure of the sustainability of the system.
Emergy sustainability ratio	$ESI = EYR/ELR$	The ratio of system yield per unit of purchased input to the total loading on the local system. Systems with higher yields and lower loadings are more sustainable.
Emergy sustainability ratio*	$ESI^* = EYR/ELR^*$	This index shows the system yield in relation to an inverse measure of system sustainability, ELR^* . A system with a higher ESI^* is more sustainable.

Table 5-Natural and economic flows and renewability of different bean production systems in units' ha⁻¹

	Unit	Symbol in diagram	Renewability factor	Ecologic	Integrated	Low-input	Medium-input	High-input
Renewable environmental inputs								
Solar energy	J	J ₁	1	2.32E+13a	2.32E+13a	2.32E+13a	2.32E+13a	2.32E+13a
Wind, kinetic energy	J	J ₁	1	1.08E+09a	1.08E+09a	1.08E+09a	1.08E+09a	1.08E+09a
Rain, chemical	J	J ₁	1	1.62E+10a	1.62E+10a	1.62E+10a	1.62E+10a	1.62E+10a
Precipitation evapotranspiration	J	J ₁₅	1	5.54E+09a	5.54E+09a	5.54E+09a	5.54E+09a	5.54E+09a
Non-renewable environmental inputs								
Ground water evapotranspiration	J	J ₁₅	0	2.90E+10c	4.08E+10b	2.91E+10c	4.07E+10b	5.09E+10a
Soil erosion	J	J ₅	0	1.88E+09c	1.99E+09b	1.96E+09b	2.16E+09b	2.78E+09a
Groundwater	J	J ₂	0	1.28E+08e	2.34E+08c	1.83E+08d	2.89E+08b	3.59E+08a
Purchased inputs								
Human labour	J	J ₁₁	0.1	4.24E+08a	3.51E+08b	3.42E+08b	3.42E+08b	3.34E+08b
Machinery	g	J ₁₂	0	9.40E+03e	1.69E+04c	1.50E+04d	2.26E+04b	3.10E+04a
Fossil fuel and lubricant	J	J ₇	0	2.29E+09e	4.14E+09c	3.76E+09d	5.60E+09b	7.67E+09a
Nitrogen fertilizer	g	J ₈	0	0.00E+00d	1.50E+05b	7.50E+04c	1.50E+05b	2.25E+05a
Phosphorus fertilizer	g	J ₈	0	0.00E+00d	1.00E+05b	5.00E+04c	1.00E+05b	1.50E+05a
Potash fertilizer	g	J ₈	0	0.00E+00d	1.00E+04b	5.00E+03c	1.00E+04b	1.50E+04a
Micro fertilizer	g	J ₈	0	0.00E+00d	5.00E+03b	2.50E+03c	5.00E+03b	7.50E+03a
Organic fertilizer	g	J ₆	0.8	1.24E+07a	4.65E+06b	0.00E+00c	0.00E+00c	0.00E+00c
Pesticide	g	J ₁₃	0	0.00E+00d	1.00E+03c	1.00E+03c	2.00E+03b	3.00E+03a
Herbicide	g	J ₁₃	0	0.00E+00c	1.00E+03b	1.00E+03b	2.50E+03a	2.50E+03a
Electricity	J	J ₉	0.01	2.51E+03c	3.52E+03b	2.51E+03c	3.52E+03b	4.40E+03a
Seed	g	J ₁₀	0.43	6.90E+04a	5.17E+04c	5.75E+04b	5.17E+04c	4.60E+04d
Output								
Economic yield	g	J ₁₆		2.31E+06d	3.19E+06a	2.07E+06e	2.88E+06c	3.08E+06b
Economic yield	J	J ₁₆		3.81E+10d	5.27E+10a	3.41E+10e	4.76E+10c	5.09E+10b
Straw yield	g	J ₁₇		2.92E+06d	4.04E+06a	2.62E+06e	3.65E+06c	3.90E+06b
Straw yield	J	J ₁₇		4.39E+10d	6.06E+10a	3.93E+10e	5.48E+10c	5.86E+10b

Means in each row followed by similar letter(s) are not significantly different at 5% probability level, using Tukey's range test at 5% level of probability.

Energy equivalent for bean grain is 16.51MJ/kg

Energy equivalent for bean straw is 15.01MJ/kg

Table 6-

Emergy synthesis of different bean production systems (sej ha⁻¹) except as noted.

	Transformity (sej unit ⁻¹)	Refs. for transformity	Ecologic	Integrated	Low-input	Medium-input	High-input
Renewable environmental inputs							
Solar energy	1.00E+00	Definition	2.32E+13a	2.32E+13a	2.32E+13a	2.32E+13a	2.32E+13a
Wind, kinetic energy	1.25E+03	Campbell, and Erban, 2017	1.35E+12a	1.35E+12a	1.35E+12a	1.35E+12a	1.35E+12a
Rain, chemical potential	2.25E+04	Campbell (man.)	3.65E+14a	3.65E+14a	3.65E+14a	3.65E+14a	3.65E+14a
Precipitation evapotranspiration	2.88E+04	Campbell (man.)	1.60E+14a	1.60E+14a	1.60E+14a	1.60E+14a	1.60E+14a
Subtotal			3.88E+14a	3.88E+14a	3.88E+14a	3.88E+14a	3.88E+14a
Non-renewable environmental inputs							
Ground water evapotranspiration	2.88E+04	Campbell (man.)	8.35E+14c	1.18E+15b	8.38E+14c	1.17E+15b	1.47E+15a
Soil erosion	9.46E04	Brandt-Williams, 2002	1.78E+14d	1.88E+14c	1.85E+14c	2.04E+14b	2.63E+14a
Groundwater	1.92E+05	Cuadra and Rydberg, 2006	2.46E+13e	4.49E+13c	3.51E+13d	5.55E+13b	6.89E+13a
Subtotal			1.04E+15	1.41E+15	1.06E+15	1.43E+15	1.80E+15
Purchased inputs							
Human labour	2.22E+06	Lu et al., 2009	9.41E+14a	7.79E+14b	7.59E+14b	7.59E+14b	7.41E+14b
Machinery	1.01E+10	Campbell et al., 2005	9.49E+13e	1.71E+14c	1.52E+14d	2.28E+14	3.13E+14ab
Fossil fuel and lubricant	8.60E+04	Bastianoni et al., 2008	1.97E+14e	3.56E+14c	3.23E+14d	4.82E+14b	6.60E+14a
Nitrogen fertilizer	3.09E+10	Brandt-Williams, 2002	0.00E+00d	4.64E+15b	2.32E+15c	4.64E+15b	6.95E+15a
Phosphorus fertilizer	2.82E+10	Brandt-Williams, 2002	0.00E+00d	2.82E+15b	1.41E+15c	2.82E+15b	4.23E+15a
Potash fertilizer	2.23E+09	Brandt-Williams, 2002	0.00E+00d	2.23E+13b	1.12E+13c	2.23E+13b	3.35E+13a
Micro fertilizer	3.91E+09	Lan et al., 2002	0.00E+00d	1.96E+13b	9.78E+12c	1.96E+13b	2.93E+13a
Organic fertilizer	2.96E+08	Odum, 1996	3.67E+15a	1.38E+15b	0.00E+00c	0.00E+00c	0.00E+00c
Pesticide	1.90E+10	Brandt-Williams, 2002	0.00E+00d	1.90E+13c	1.90E+13c	3.80E+13b	5.70E+13a
Herbicide	1.90E+10	Brandt-Williams, 2002	0.00E+00c	1.90E+13b	1.90E+13b	4.75E+13a	4.75E+13a
Electricity	2.31E+05	This work	5.81E+08c	8.13E+08b	5.81E+08c	8.13E+08b	1.02E+09a
Seed	2.73E+09	This work	1.88E+14a	1.41E+14b	1.57E+14b	1.41E+14b	1.26E+14b
Subtotal			5.09E+15d	1.04E+16b	5.18E+15d	9.19E+15c	1.32E+16a
Total			6.52E+15d	1.22E+16b	6.62E+15d	1.10E+16c	1.54E+16a
Output transformities							
Economic yield	sej g ⁻¹	This work	2.82E+09d	3.81E+09b	3.20E+09c	3.82E+09b	4.99E+09a
Economic yield	sej J ⁻¹	This work	1.71E+05d	2.31E+05b	1.94E+05c	2.31E+05b	3.02E+05a
Straw yield	sej g ⁻¹	This work	2.23E+09d	3.01E+09b	2.53E+09c	3.02E+09b	3.94E+09a
Straw yield	sej J ⁻¹	This work	1.48E+05d	2.01E+05b	1.69E+05c	2.01E+05b	2.62E+05a

The transpiration is an integrated measure of all the renewable inputs required to support plant production (Odum, 1996), therefore it was chosen to represent R, to avoid double counting. The emergy of the groundwater transpired must also be included for a complete accounting of the emergy of transpiration supporting bean production.

^b Means in each row followed by similar letter(s) are not significantly different at 5% probability level, using Tukey's range test at 5% level of probability.

Table 7-

Emergy-based indices of different bean production systems

	Ecologic	Integrated	Low-input	Medium-input	High-input
R (%)	53.69	13.39	8.02	4.76	3.35
EYR	1.28	1.17	1.28	1.20	1.17
EIR	3.57	5.77	3.58	5.05	6.03
ELR	16.81	31.35	17.09	28.40	39.66
ELR*	0.86	6.47	11.47	20.00	28.81
ESI	0.08	0.04	0.07	0.04	0.03
ESI*	1.48	0.18	0.11	0.06	0.04

Table 8-

Economic indices of different bean production systems

	Yield (kg ha ⁻¹)		Economic input (US\$ ha ⁻¹)	Economic output (\$ ha ⁻¹)	Output to input ratio	Net income (\$ ha ⁻¹)
	Beans	Straw				
Ecologic	2310	2924.1	1458.0	5767.1	3.95	4309.1
Integrated	3190	4038.0	1640.8	5781.5	3.52	4140.7
Low-input	2067	2616.5	1315.2	3824.7	2.90	2509.5
Medium-input	2884	3650.6	1707.5	5084.4	2.97	3376.9
High-input	3084	3903.8	2006.0	6830.1	3.39	4824.1