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RESEARCH ARTICLE

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Environmental impacts of irrigated and rain-fed barley production in Iran using life cycle assessment (LCA)

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Abstract

Current intensive grain crops production is often associated with environmental burdens. However, very few studies deal with the environmental performance of both current and alternative systems of barley production. This study was undertaken to evaluate energy consumption and environmental impacts of irrigated and rain-fed barley production. Additionally, three alternative scenarios were examined for irrigated barley fields including conservation tillage and biomass utilization policies. The findings showed that around 25 GJ/ha energy is needed in order to produce 2300 kg/ha irrigated barley and 13 GJ/ha for 1100 kg/ha rain-fed barley. Life cycle assessment (LCA) results indicated that irrigated farms had more environmental impacts than rain-fed farms. Electricity generation and consumption had the highest effect on the abiotic depletion potential, human toxicity potential, freshwater and marine aquatic ecotoxicity potential. However, alternative scenarios revealed that using soil conservation tillage systems and biomass consumption vs. gas for electricity generation at power plants can significantly mitigate environmental impacts of irrigated barley production similar to the rain-fed conditions while higher yield is obtained.

Additional keywords: *Hordeum vulgare* L.; energy use efficiency; energy productivity; global warming potential.

Abbreviations used: AC (acidification potential), AD (abiotic depletion potential), EU (eutrophication potential), FAET (freshwater and aquatic ecotoxicity potential), FU (functional unit), GHG (greenhouse gas), GWP (global warming potential for time horizon 100 years), HT (human toxicity potential), IF (irrigated farm), LCA (life cycle assessment), MAET (marine aquatic ecotoxicity potential), OD (ozone depletion potential), PhO (photochemical oxidation potential), RF (rain-fed farm), TE (terrestrial ecotoxicity potential).

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Introduction

Agricultural productions are intensively dependent on the energy resources directly or indirectly (Hatirli *et al.*, 2005; Pimentel & Pimentel, 2006). Diesel engines have commonly used diesel directly for farm operations and water pumping. All the farm inputs, *e.g.* fertilizers, chemicals and mechanization infrastructures utilize some forms of energy indirectly for formulation, storage and distribution (Fluck & Baird, 1980; Dyer & Desjardins, 2006; Arbat *et al.*, 2013). Human activities play a key role in total greenhouse gas (GHG) emissions, of which the global food system is responsible for around one third of all (Gilbert, 2012; Houshyar *et al.*, 2012) while cropping systems contribute to 14% of the global net CO_2 emissions (Cooper *et al.*, 2011). Reducing CO_2 emission is a global priority (Yuttitham *et al.*, 2011; Tzanidakis *et al.*, 2013). The most important direct greenhouse gas emissions in fields originates from nitrogen (N) fertilizers, which represent around 20% and 30% of the total GHG emissions from large and small farms, respectively (Lal, 2004). A sustainable food production system with the lowest GHG emissions and environmental footprints can be obtained via efficient energy application (Erdal *et al.*, 2007; Nguyen & Hermansen, 2012; Houshyar, 2012; Mohammadi *et al.*, 2013; Afshar *et al.*, 2013). Although GHG emissions have received considerable attention recently, other potential environmental impacts are associated with energy production (*e.g.* eutrophication, acidification and land use). Such impacts are typically not considered by energy system analysis and a full overview of life cycle is necessary (Tonini & Astrup, 2012).

Life cycle assessment (LCA) is one of the methods used to assess the environmental impact of a product regarding the materials, inputs and emissions associated with each stage of production (Gil *et al.*, 2013). This analysis tool provides information on the full environmental effects of a product, service or system from its cradle to its grave (Brandao *et al.*, 2011). LCA as a suitable method for evaluating the environmental impacts of food and field crops production has been used in many studies. An European study on the Environmental Impact of Products (EIPRO) showed that the "food and drink" sector involves 20-30% of the total environmental impacts of EU consumption, with regard to global warming, acidification, photochemical ozone formation and eutrophication.

Barley (*Hordeum vulgare* L.) is one of the world's main cereal crops, ranking fourth in production after wheat, maize and rice (http://faostat.fao.org). This crop can grow fast, suppress weed pressure and provide high yield in terms of dry weight but protein content of the forage is low (Dhima *et al*., 2007). Barley is an important crop in Iran since its production and price has great influence on the local livestock production capacity. A total of 19.5 million tons grain was produced in Iran in 2015-2016, of which 3.8 million tons were barley grains. Yet, it is estimated that the country needs another 1.3 million tons barley which must be imported (http://www.world-grain.com/Departments/Country-Focus/Country-Focus-Home/Focus-on-Iran-2015.aspx?cck=1).

The two main objectives of this study were: 1) to evaluate the energy efficiency of irrigated and rain-fed barley farming, and 2) to assess the environmental impacts of barley production in different impact categories using LCA approach. To meet the objectives, the indices of energy use and the related CO_2 emission were investigated. Next, the data from the previous step were used to determine environmental impact of barley production from the view point of ten categories. The analyses for irrigated farms (IFs) were made with biomass utilization for electricity generation and without barley biomass utilization; *W.* burning it to assess how biomass management affects the status of barley production.

Material and methods

This study was carried out in the central area of the Fars province, Southwest Iran. The province is located within 27° 03' and 31° 40' N and 50° 36' and 55° 35' E. This area was chosen since it includes around 50% of the province's barley growing farmers and livestock production units in which barley is the main food source. In addition, a study reported that this area is suitable for barley production since it has higher partial benefits compared to other crops such as rice and cucumber (Mohammadi & Boostani, 2009). The area has a moderate temperature in summer, ranging from 15 to 37 ºC (FMB, 2015) and the soil type is silt loam. The production period for barley in the region is around 7-8 months and field preparations for sowing usually are done in early October.

The farmers were selected through a simple random sampling without replacement. The desired sample size was calculated by Eq. [1] (Amidi, 2005):

$$n = \frac{\left[\frac{t.s}{r.y_N}\right]^2}{\left[1+(1/N)\left[\frac{t.s}{r.y_N}\right]^2\right]} \qquad [1]$$

where n is the required sample size; N is the number of holdings in target population; S is the standard deviation of the output energy of the sample; yN is the mean of the output energy of the sample; t is the reliability coefficient (2.576 which represents the 99% reliability); and r is the permissible difference between actual and calculated mean (0.03 in this study).

A primary sample of farmers was selected to calculate the number of farmers required to carry out this study. Accordingly, 30 farmers were selected from irrigated farms and 20 farmers from rain-fed farms (RFs) to obtain S and y_N included in formula [1]. Thus, the S and yN were calculated as 3851.2 and 31026.25 MJ/ha, respectively for IFs and 1421.5 and 17151.34 MJ/ha for RFs from the primary sample of farmers. Finally, from a total of 973 farmers of irrigated barley producers 105 farmers were chosen. From 591 rain-fed barley producers 53 farmers were selected for the study.

Energy consumption in barley fields

A nine-page questionnaire was designed to gather data on the energy inputs of barley production belonged to the production period of 2014-2015. Both validity and reliability of questionnaire were assessed. The validity of the questionnaire was assessed by a panel of agricultural experts affiliated at either universities or agricultural organizations. The reliability of the questionnaire was assessed using Cronbach's alpha coefficient (Amidi, 2005). Revising the questionnaire, the final coefficient was estimated at 0.83 which confirmed the "highly reliable" questions of the questionnaire. The questionnaire consists of two main parts; one part to gather farmers' personal information and one part to gather barley farming inputs and barley grain and straw as outputs. The gathered personal data from the first part of the questionnaire were: farmer's age, farmer's sex, size of farm, farming experience and income.

The amount of each input, including fertilizers, chemicals, human power, electricity for pumping water, fuel for pumping water and farm machinery operations (*i.e.* preparing fields, planting seeds, managing pests and weeds, and harvesting the crop), water for irrigation and seed for planting, was measured per hectare. Correct estimation of fossil energy use from primary data was an important step of the analysis. The conversion factors used for the study and reference sources are summarized in Table 1. The conversion factors were based on a "cradle to grave" estimation approach, meaning that they take into account the direct and indirect embodied energy use for a product or process.

Water may be pumped onto the farms using either diesel engines or electric pumps. Total energy consumption for irrigation is related to quantity and source of water applied, distance from source, and irrigation system type.

Equation [2] was applied in order to estimate the required electrical energy (J/ha) for pumping water from water wells (Badger *et al.*, 1999):

$$E_{el} = \frac{\gamma . g . h . V_A}{\eta P . \eta Pd} \quad [2]$$

Table 1. Applied energy equivalents of inputs and outputs in agricultural production

Input (units)	Energy equivalent (MJ/unit)	Reference
Liquid chemical (L)	102	Chaudhary *et al.*, 2006
Granular chemical (kg)	120	Chaudhary *et al.*, 2006
Human power (h)	1.96	Mani *et al.*, 2007
Machinery (kg)	62.7	Verma, 1987
Nitrogen (kg)	78.1	Badger *et al.*, 1999
Phosphorus (kg)	12.44	Shrestha, 1996
Potassium (kg)	1.15	Shrestha, 1996
Zinc sulphate (kg)	20.9	Verma, 1987
Electricity (kWh)	11.93	Ozkan *et al.*, 2004
Diesel (L)	56.3	Verma, 1987
Barley seed (kg)	1	Ozkan *et al.*, 2004
Water (m^3)	0.63	Yaldiz *et al.*, 1993

where E_{el} is the electricity energy (J/ha); γ denotes the water density (kg/m^3); g is the acceleration in relation to free-fall (m/s^2); H is the total dynamic head (m); V_A is the volume of required water for one cultivating season (m^3/ha); η_p is pump efficiency (70-90%) and η_{pd} is total power conversion efficiency (18-20%) (Ercoli et al., 1999).

The amount of indirect energy use in farm machinery manufacturing was estimated by Eq. [3] (Bockari-Gevao *et al*., 2005):

$$EID = \frac{TW \times CED \times h \times RU}{UL} \quad [3]$$

where EID is the indirect energy used for machinery production, MJ/ha; TW is the total weight of the specific machine, kg; CED is the cumulative energy demand for machinery, MJ/kg; h is the specific working hours per run, h/ha; RU is the number of applications in the considered field operation; and UL is the wear-out life of machinery, h.

Other indirect energy used for fertilizer, chemicals and seed packaging and irrigation equipment were not included in analyses since related data were not available.

Four main energy indices were employed to assess the efficiency of energy inputs (Mani *et al*., 2007) as following:

$$\text{Energy ratio [dimensionless]} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input(MJ/ha)}} \quad [4]$$

$$\text{Specific energy [MJ/kg]} = \frac{\text{Energy input (MJ/ha)}}{\text{Yield output (kg/ha)}} \quad [5]$$

$$\text{Energy productivity [kg/MJ]} = \frac{\text{Yield output (kg/ha)}}{\text{Energy input (MJ/ha)}} \quad [6]$$

$$\text{Net energy gain [MJ/ha]} = \text{Energy output} - \text{Energy input} \quad [7]$$

These indices express the efficiency of energy used in a system.

LCA methodology

Inputs and outputs

The ISO (International Organization for Standardization) has a standardized framework (14040) for LCA, which divides the entire LCA procedure into four distinct phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006). A full LCA includes the four stages (Guinée, 2002). An LCA that is limited to addressing the contribution to climate change is usually called a CF (carbon footprint) or climate change impact assessment (Cederberg *et al.*, 2013). A clear system boundary is essential to include all the emissions caused by inputs that contribute to production (Suh *et al.*, 2004). A cradle to farm gate system was adopted for the study and harvest of barley was defined as the ending point of the system. Indeed, the focus was on the production at the farm level during farming season rather than storage, distribution and consumption.

Ten environmental impact categories were considered in this study including: abiotic depletion potential (AD); acidification potential (AC); eutrophication potential (EU); freshwater aquatic ecotoxicity potential (FAET);global warming potential for time horizon 100 years (GWP); ozone depletion (OD) potential; human toxicity (HT) potential; marine aquatic ecotoxicity potential (MAET); photochemical oxidation potential (PhO); and terrestrial ecotoxicity (TE) potential. For the data analysis, CML 2 baseline 2000 V2/world developed by the Institute of Environmental Science of Leiden University (PRéConsultants, 2003) in SimaPro 8 was applied.

Two main LCA models were provided for each crop; *i.e.* irrigated and rain-fed barley. A sub-model was designed for farm machinery operations including: (a) for irrigated barley: ploughing, chiseling, planting, fertilizing by broadcaster, spraying by field sprayer and harvesting; (b) for rain-fed barley: chiseling, sowing by broadcaster, fertilizing by broadcaster, spraying by field sprayer and harvesting.

The above model was then entered into the main LCA model involving all inputs (*e.g.* fertilizers, pesticides, etc.), barley seed as output and different emissions into the air and water. Transportation of inputs was also considered as ton per kilometer (functional unit FU = tkm) by tractor and trailer. Four additional scenarios were considered for irrigated barley, and suitable LCA models were accordingly designed to analyze how alternative energy use options affected the environmental impacts of this crop. The scenarios were: S1, irrigated barley production as reference scenario; S2, using no-tillage machinery to convert ploughing, chiseling and planting to one operation; S3, using biomass for electricity generation versus gas utilization (as a fossil fuel) at power plants; S4, combination of S2 and S3 to analyze whether environmental impacts can be mitigated by reduction of tillage intensity and gas consumption at electricity power plants. These scenarios were compared to irrigated barley LCA model (S1) as reference scenario.

Three different functional units (FUs) have been proposed for LCA studies (Nemecek *et al*., 2011): 1) the land management function, measuring as cultivated hectare per year (land-based); 2) the financial function expressed as a currency unit; and 3) the productive function described by physical units (*e.g*., kg dry matter yield, MJ net energy for lactation-mass-based). The land-based FU was used in the model for farm machinery operations to calculate environmental impacts per hectare. Then the mass-based FU was employed in the main LCA model to analyze the result based on kg dry barley yield. Application of two or more FUs can better clarify environmental performance (Van der Werf *et al*., 2007).

Emissions

The IPCC (2006) guidelines were used to determine nitrous oxide (N_2O) emission into the air. Accordingly, the application of 100 kg of N-based fertilizers emits 1.25 kg of N_2O into the air. It was assumed that 30% of total N fertilizers leached into groundwater in the form of nitrate (Erickson *et al*., 2001).

The average amount of P leached to groundwater was estimated as 0.07 kg/ha of P-based fertilizers (Nemecek *et al*., 2007). It has been suggested that 30-50% of total sprayed pesticides be considered as emissions into the air (Sahle & Potting, 2013).

The amount of diesel fuel used for farm operations and pumping water and amount of electricity for pumping water were estimated and equivalent CO_2 emission was considered in the model.

Results and discussion

Personal characteristics of the barley producers

Table 2 indicates that the average farmers' ages are not significantly different in IFs and RFs (39.5 and 38.2 yrs old, respectively). Nonetheless, the farming experiences were higher than 2 yr on average in IFs (15.5 *vs*. 13.5 yrs). Another study in the West of Iran by Zarafshani *et*

Table 2. Personal characteristics of barley growing farmers (105 farmers from irrigated (I) and 53 farmers from rain-fed (R) farms). SD: standard deviation

Item	Average		SD	
	I	R	I	R
Age (Yr)	39.5	38.2	2.24	2.95
Farming experience (Yr)	15.5	13.5	1.97	2.05
Farm size (ha)	3.4	5.8	0.36	0.67
Net income ($/ha)	510.5	250.3	58.92	32.51

al. (2017) indicated that canola farmers have higher average age (44.18 yrs) than our barley farmers. Almost all (99.7%) of the barley growing farmers were male. The average size of farming was significantly different between the studied groups (3.4 ha for IFs and 5.8 ha for RFs). However, the net incomes were also significantly different due mainly to different yields in IFs and RFs. The average net income was 510.5 $/ha in IFs and 250.3 $/ha in RFs. Several studies confirmed that farmers' age, experience and net income influenced the agricultural practices enhancement and adoption of new technologies (Adesoji & Farinde, 2006; Dinpanah & Naji, 2012; Shojaei *et al*., 2013).

Output and input energy flow in barley farming systems

The calculated values for energy consumption in the barley fields are given in Table 3. Production of barley in IFs consumed ~ 25,000 MJ/ha, which was twice the energy of rain-fed barley growing systems; the yield of IFs was also twice that of the RFs. Statistical analysis revealed that irrigated and rain-fed barley had significantly different energy input and outputs at a 0.01 level of significance.

Table 3 shows that all energy efficiency indices in IFs were higher than in RFs. Output-input energy ratios were close, 1.33 in IFs and 1.25 in RFs. These values were half of that found by Finnish farmers (Mikkola *et al.*, 2011) and one fifth of Australian farmers (Khan *et al*., 2010). However, net energy gain in IFs was around 8300 MJ/ha, 2.5 times that of RFs. Specific energy consumption for barley cultivation was 3.5-4.5 MJ/kg in Italy (Pellizzi (1992) and 1.62 MJ/kg in Spain (Lechon *et al*., 2005), while in our Iranian barley farms it was much higher (11 MJ/kg). Barley grain yield in IFs was similar to that found by Fallahpour *et al.* (2012) in Khorasan, Northeast Iran, with a similar N consumption (120 kg/ha), whereas the yield of RFs was around twice of Khorasan farms (60 kg/ha N consumption). This shows that our farmers can reach higher yield with almost similar N application.

Fertilizer, diesel fuel and water for irrigation were the main contributors of energy input in IFs (~ 78%).

Table 3. Energy used for barley production (105 farmers from irrigated (I) and 53 farmers from rain-fed (R) farms). SD: standard deviation.

Item	Average		SD	
	I	R	I	R
1-Machinery (MJ/ha)	1163.259 [A]	815.020 [B]	98.41	76.55
2- Diesel fuel (MJ/ha)	5469.906 [A]	4229.136 [B]	325.32	245.66
3- Fertilizers (MJ/ha)	10281.4930 [A]	5561.679 [B]	784.32	305.52
Nitrogen	9360.240 [A]	4680.170 [B]	641.72	298.34
Phosphorous	456.410 [ns]	427.500 [ns]	32.55	30.57
Potassium	464.840 [ns]	454.010 [ns]	24.50	25.45
4- Human power (MJ/ha)	289.655 [A]	176.28 [B]	15.34	13.56
5- Seed (MJ/ha)	1701.976 [A]	2134.380 [B]	105.65	154.23
6- Chemicals (MJ/ha)	186.316 [A]	75.720 [B]	8.45	5.53
7- Water (MJ/ha)	3308.318	—	235.60	—
8- Electricity (MJ/ha)	2434.688	—	155.32	—
- Total energy input (MJ/ha)	24835.612 [A]	12992.217 [B]	1767.58	855.42
-Total output energy (MJ/ha)	33135.882 [A]	16204.599 [B]	2567.24	1755.61
- Output-input energy ratio	1.330 [a]	1.250 [b]	0.012	0.008
- Energy productivity (kg/MJ)	0.091 [a]	0.085 [b]	0.004	0.003
- Specific energy (MJ/kg)	10.990 [a]	11.760 [b]	0.13	0.12
- Net energy gain (MJ/ha)	8300.271 [A]	3212.382 [B]	658.25	235.51
- Yield (kg/ha)	2254.142 [A]	1102.354 [B]	178.32	97.58

Small and capital letters show significant differences between the two farming groups at 0.05 and 0.01 probability levels, respectively (Duncan statistical test).

The share of fertilizer and diesel fuel were also dominant in RFs. Both barley production systems consumed high amount of N with the share of 90% of fertilizer energy factor. Our farmers use around three times more pesticides compared to Finnish farmers.

An experimental study determined in Agramunt (NE Spain) that application of 40 kg N lead to 4.5 and 6.3 ton/ha of barley yield under rain-fed and irrigated conditions, respectively (Cossani *et al.*, 2009). This shows that our farmers apply much more N in their farms. Compared to Finnish farmers (Mikkola *et al.*, 2011), in this work irrigated barley producers consumed ~ 50 kg/ha more N and ~ 20 kg/ha more K. Integrated methods to increase soil fertility can be a useful choice since it has been shown that

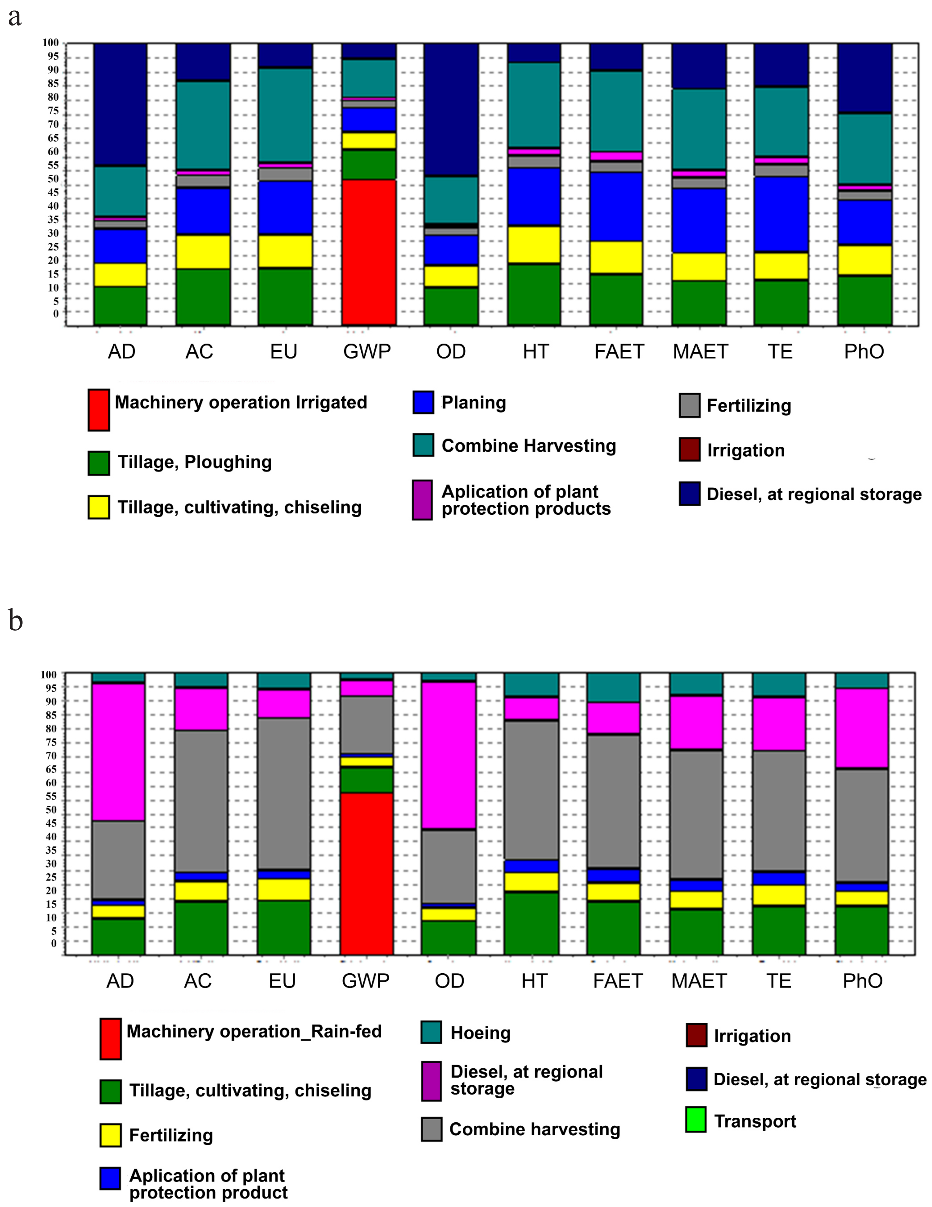

Figure 1. Environmental analysis for machinery operations in irrigated (a) and in rain-fed barley fields (b). AD, abiotic depletion potential; AC, acidification potential; EU, eutrophication potential; GWP, global warming potential for time horizon 100 years; OD, ozone depletion potential; HT, human toxicity potential; FAET, freshwater and aquatic ecotoxicity potential; MAET, marine aquatic ecotoxicity potential; TE, terrestrial ecotoxicity potential; PhO, photochemical oxidation potential.

application of biochar and N fertilizer on a light soil within temperate climate increased by 30% the yield of spring barley compared to N fertilizer only (Gathorne-Hardy *et al*., 2009).

Although some farmers use legal amounts of this input, a large number of them do not usually conduct soil sampling to understand how much and what type of fertilizer should be applied. No green crops such as alfalfa and clover are currently planted in barley farms. The intensive cropping of barley, wheat and corn, especially at IFs farms, has led to continuous soil infertility. The unnecessary use and waste of N is critical since it is very mobile in the soil and embedded high energy and, consequently, it may reduce the sustainability of barley production. The mobility of N can be dangerous in both IFs and RFs; in the IFs, due mainly to leaching into underground water resources and in the RFs due to emissions into the air (Khan *et al*., 2009; Meisterling *et al*., 2009). At global scale, fertilizer-induced N_2O emissions and nitrate leaching have been estimated to be approximately 0.8% and 19% of N fertilizer input, respectively (Kim *et al*., 2015). Using green crops and crop rotation would be useful to maintain soil fertility and to reduce chemical N consumption. Eriksen *et al.* (2015) reported that rotation of barley and ryegrass led to lower nitrate leaching compared to other experiments with barley-pea and old grasslands rotations.

Although less farm operations have been done in the RFs, the share of diesel fuel in energy input was higher than in the IFs (33% *vs* 22%; Table 3). One of the deficiencies in RFs is probably related to the machines used for planting. Technically, the planter should place the seeds into the soil deeper under rain-fed than under irrigated conditions and particular press wheels provides suitable contact between the soil and seeds. In more than 95% of the RFs, seeds are broadcast on the soil surface and then a shallow disking is used to cover seeds. In such situations, germination is not satisfactory to approach higher yield. Near to 85% of available tractors and equipment exceeded the economic and technical life spam and should be replaced by new machines. Using new machines would be useful to increase energy input efficiency. Our observations showed that RFs need more suitable machinery in the region. Additionally, it is recommended that conservation tillage systems such as minimum or no-tillage should be examined locally in the province and be introduced to the farmers.

Energy consumption in the forms of water for irrigation and electricity for pumping water alone accounted for around 23% of total energy input in IFs. It is a critical point since Iran is located in a semi-arid region encountering water shortage. One reason is that most farmers use furrow irrigation systems while more efficient irrigation systems like sprinkler may improve water use efficiency and productivity; *i.e.* less water consumption and higher yield. Water productivity in our IFs was much lower (0.5 kg barley per cubic meter of water) than in Australia (~ 3.5 kg/m^3, Khan *et al*., 2010) or Portugal (1.8 kg/m^3, Paredes *et al*., 2017). Water productivity was also high in China for grain crops (~ 1.58-1.72 kg/m^3) by employing novel irrigation methods (Kang *et al*., 2016). It should be noted that only water from wells were considered in the analysis of IFs to reach correct assessment of energy efficiency and productivity. In the study by Paredes *et al*. (2017), both irrigation and rainfall water were included. Thus, differences in water

Table 4. Comparison of irrigated (I) and rain-fed (R) barley life cycle impact indicators based on 1 kg barley production (105 farmers from irrigated and 53 farmers from rain-fed farms)

Impact category	Unit	Average			SD		
		I	R	S4 [1]	I	R	S4 [1]
Abiotic depletion	kg Sb eq	0.02	0.008	0.007	0.001	0.000	0.000
Acidification	kg SO_2 eq	0.015	0.011	0.012	0.001	0.001	0.000
Eutrophication	kg PO_4 eq	0. 007	0. 004	0. 005	0.000	0.000	0.000
Global warming (GWP100)	kg CO_2 eq	2.35	1.31	1.35	0.17	0.115	0.113
Ozone layer depletion (OD)	kg CFC-11 eq	1.78×10^{-8}	1.19×10^{-8}	9.72×10^{-9}	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	2.71	0.63	0.82	0.208	0.051	0.063
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.624	0.145	0.28	0.069	0.011	0.024
Marine aquatic ecotoxicity	kg 1,4-DB eq	1333.17	325.57	582.5	95.226	28.237	46.310
Terrestrial ecotoxicity	kg 1,4-DB eq	0.015	0.004	0.014	0.000	0.000	0.000
Photochemical oxidation	kg C_2H_4	0.0007	0.0002	0.0003	0.000	0.000	0.000

[1] Scenario 4 for irrigated barley production; *i.e.* no-tillage is used for farm operation and biomass (*vs*. gas) is consumed for electricity generation. SD: standard deviation

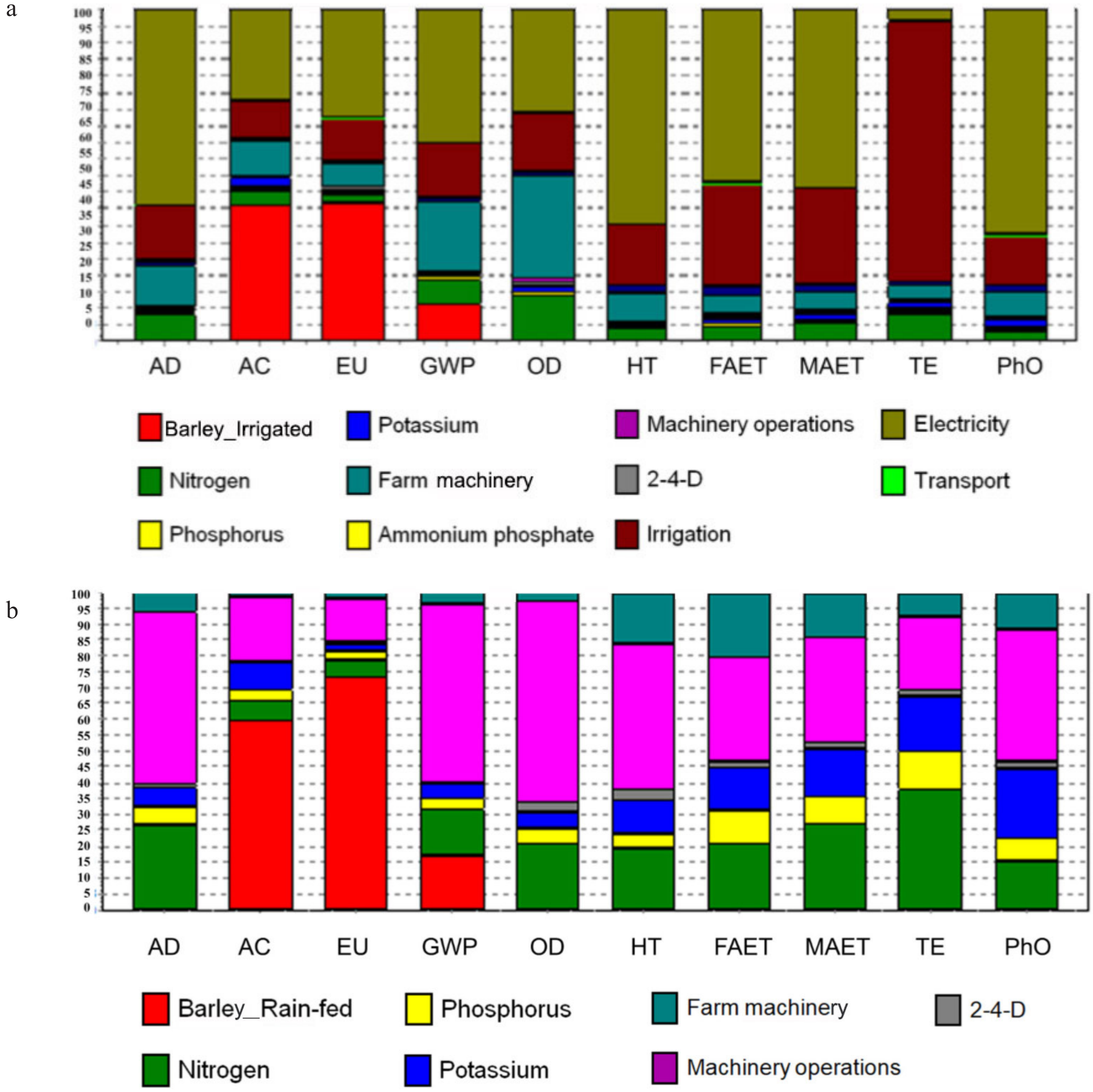

Figure 2. LCA of irrigated (a) and of rain-fed (b) barley fields.

productivity between our farms and the farms in Portugal may be due to different basic assumptions made.

LCA of barley production

Environmental impacts of farm machinery operations

As described before, a separate LCA model was provided for machinery operations to analyze each operation in more detail. Fig. 1 shows that in IFs, chiseling, plowing, planting and combine harvesting had almost similar impacts in all studied LCA categories; *i.e.* AD, AC, EU, GW, OD, HT, FAET and MAET, TE, PhO by around 10% for chiseling, 20% for plowing and planting and 32% for harvesting. Likewise, the impact of chiseling was around 20% and combine harvesting around 50% in RFs (Fig. 1). Emitted heavy metals from direct energy consumption in machines usually contributed to ecological toxicity. Some parts of acidification were also caused by air emissions of SO_2, N_2O and ammonia.

Diesel fuel consumption in farm machines had the highest contributions to AD and OD in both irrigated and rain-fed conditions (~ 45-50%). This is critical since the share of diesel fuel in energy input was also significant (~ 20-30%). Diesel as a source of fossil fuel affected abiotic directly and affected OD by emitting greenhouse gases. Accordingly, the given suggestions to reduce diesel fuel input are emphasized here to mitigate burdens on the environment. Another essential key is that efficient tractors should be applied in farms to reduce diesel inputs. Lares-Orozco *et al*. (2016), using more efficient tractors that decrease diesel inputs, found emissions reduced a major 33% under conventional tillage, and a 24% under no tillage.

Environmental impacts of barley production

The results of LCA for irrigated and rain-fed barley are shown in Fig. 2. Electricity consumption in IFs was responsible for the highest environmental burdens in several impact categories including AD, GW, HT, FAET, MAET and PhO. A direct comparison among the results from different LCA studies is not always straightforward due to the different system boundaries definition and assumptions. Niero *et al*. (2015) reported different results on barley production in Denmark in which environmental impacts of fertilizers, especially N, dominated, Danish farmers consumed around 240 kg of different N fertilizers vs 140 kg in Iran. Rajaniemi *et al*. (2011) reported that Finnish farmers applied ~ 86 kg/ha N to obtain 3380 kg/ha of barley. However, climate conditions, soil type and other variables can have an effect on the different N consumptions.

Abiotic resources are considered as natural resources and energy generation usually affected these resources. Accordingly, abiotic depletion is strongly dependent on electricity generation and consumption. Given the findings of the study, using efficient electrical water pumps at the farm level is essential to mitigate electricity energy consumption and, consequently, environmental impacts. Electricity generation from agricultural waste and biomass can be recommended as an alternative way to reduce the environmental effects of electricity especially on the AD. In IFs, the impact of farm operations on the OD (~ 30%) was similar to that of electricity. However farm operations, compared to electricity and irrigating, had much less impact on AD, AC, EU, HT, FAET, MAET, TE and PhO. Irrigating had similar environmental impacts regarding AD, AC, EU, GW, OD and HT potential. Instead, TE is mainly due to contribution of irrigating life cycle (~ 80%). Impacts of farm machinery operations in RFs were dominant in almost all impact categories (Fig. 2). It seems that farm operations had highest environmental impacts in RFs since no electricity and water from wells were used in these farms compared to IFs.

Urea as an energy intensive input mostly affected terrestrial ecosystem by 40% and abiotic by 28% in RFs. However, the effect of urea on the MAET, OD, HT and FAET was also considerable (~ 20%). Brentrup *et al.* (2004) revealed that increasing N fertilizer rates, which do not result in an equivalent yield increase per ha, lead to increasing CO_2 rates per ton of grain. Accordingly, it is essential to know how much fertilizers are needed for each kilogram of barley in each special farm/region to reduce these environmental impacts.

Impacts of potassium sulphate, ammonium nitrate and agricultural machinery on the FAET, MAET, TE and PhO were similar, achieving values of 10-18%. Meanwhile, transportation and glyphosate consumption had negligible burdens on the environment in all the considered categories. Comparison of environmental impacts of IFs and RFs revealed that IFs burden more the environment than RFs in all impact categories (Table 4). Considering global warming potential, for instance, the emitted kg CO_2 eq. from IFs was around twice of RFs; *i.e*. 2.35 *vs*. 1.31 kg CO_2 eq. (Table 4). This result is consistent with another study in Khorasan, Northeast Iran (Fallahpour *et al*., 2012) which indicated that IFs

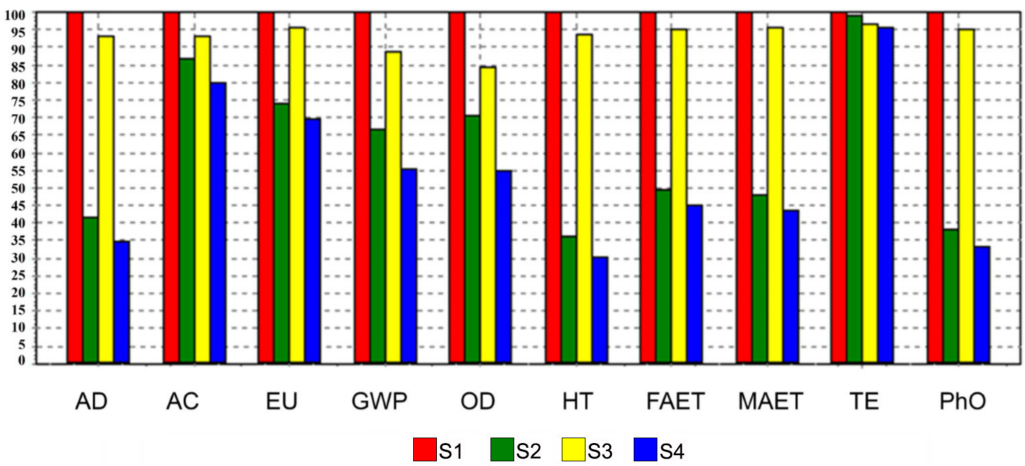

Figure 3. LCA of alternative scenarios: S1, irrigation barley field; S2, irrigation barley field while biomass (vs. gas) is consumed for electricity generation; S3, irrigation barley field while no-tillage is used for farm operation; S4, irrigation barley field while no-tillage is used for farm operation and biomass (vs. gas) is consumed for electricity generation

have higher burdens on the environment compared to RFs.

The emitted kg CO_2 eq. in IFs is 20 times that of irrigated Spanish farms (Lechon *et al*., 2005). It is notable since our energy flow analysis showed that higher energy was consumed and higher yield was obtained in irrigated barley farms, although energy efficiency indices were not significantly different between IFs and RFs. The result of LCA justify that if lower yield in RFs is not a critical point and the country can preserve self-sufficiency in barley production, RF barley production is more beneficial from both energy and environment point of view. Furthermore, selection of the proper cultivars is an effective way to reduce environmental impacts of barley (Niero *et al*., 2015).

The LCA of alternative scenarios for irrigated barley farms

In Fig. 3, the three alternative scenarios were compared to conventional irrigated barley production as reference scenario (S1). All alternatives revealed some reduction of the burdens on the environment. Employing conservation tillage (S3) had the lowest effect on the impacts mitigation. However, it should be considered that Fig. 3 shows the effect of farm operations together with other activities, while these effects were high when farm operations were considered in a separate LCA model. Scenario S3 (using no tillage machinery) revealed some reductions in all environmental impacts compared to S1. A similar study on wheat (Lares-Orozco *et al*., 2016) showed that conventional system contributed to 13% of GWP while no tillage systems contributed to 1% of GWP. In the S3 (using biomass at power plant for electricity generation) and S4 (combination of S2 and S3), environmental impacts were significantly reduced in all categories (50-65%) especially for AD, HT, FAET, MAET and PhO by a considerable amount. Although the reduction of AC and TE were negligible, other categories had some mitigation (20-30%).

The result of S2 confirmed that remained barley straw, as a renewable source of energy, can be successfully used for cleaner energy generation and reduction of environmental impacts. The availability of agricultural waste for bioenergy production and various options in Iran is strongly recommended in different studies (*e.g*. Najafi *et al*., 2009). Scenario S4, which is a combination of S2 and S3 (*i.e*. employing conservation tillage system in farms and using biomass for electricity generation at power plants) can be a promising approach to mitigate environmental impacts of irrigated barley production. As discussed earlier, both the yield and energy consumption of irrigated barley were twice that of rain-fed barley. While LCA analysis revealed that irrigated barley production had more environmental impacts than rain-fed barley. Table 4 shows that most of the environmental impacts from RFs were very close to scenario S4. For instance, the emitting levels of kg SO_2 eq. as a value of acidification was 0.011 in RFs and 0.012 in S4. Furthermore, impact of S4 on the OD was much less than RFs. The consumption from natural resources intensifies the depletion of abiotic resources. S4 had around 60% fewer burden on the AD compared to S1 and S3, since biomass was used in this scenario instead of natural gas. These results are promising since clarify that when S4 is applied, the country can have suitable yield from irrigated barley farms while burdens on the environment is as low as RFs. Nevertheless, increasing yield efficiency is an effective means to reduce environmental impacts. A study in Finland (Virtanen *et al*., 2007) showed that N and P run-offs would decrease by ~ 5.8% and ~ 2.4%, respectively, for a 100 kg/ha barley yield increase.

In summary, the patterns of energy use for irrigated and rain-fed barley and cradle-to-farm gate LCA of both were investigated in this study. Fertilizer, diesel fuel and water for irrigation were the main contributors of energy input in irrigated farms. It is recommended that the use of fertilizer applications, green crops and suitable alternative conservation tillage systems are possible ways to reduce energy inputs. Applying efficient water pumps and farm machines are essential to mitigate both energy consumption and impacts on the environment. Literature reviews showed that other beneficial methods such as data envelopment analysis (DEA) and evolutionary algorithms can be used to further investigate the reasons of energy use inefficiency in barley farms (Houshyar *et al*., 2012). In the current study water obtained from wells was considered in the analyses of IFs. More correct evaluations of water use productivity in IFs can be obtained if water from rainfall is also included in the calculations.

The result of the LCA demonstrated that rain-fed barley production is environmentally more suitable than the irrigated barley. However, lower yield and net-energy gain are critical points of this system. More investigation is necessary to clarify the amount of N fertilizers leached into groundwater in the form of nitrate in barley fields. Alternative scenarios revealed that using conservation tillage systems in farm operations and planting, and biomass utilization for electricity generation can significantly mitigate environmental impacts of IFs. Accordingly, the benefits of irrigated barley production such as higher yields can be maintained for a country's self-sufficiency simultaneously with much lower burden on the environment. Biomass can be used in some other ways; *i.e*. as livestock feed, in mushroom production as a soft bed etc. which would change the environmental effects of biomass that are removed from fields. The investigation on these subjects is recommended for future studies.

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