Assessment of Agricultural Farming Systems Sustainability in Hamedan Province Using Ecological Footprint Analysis (Case Study: Irrigated Wheat)

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ABSTRACT

Ecological footprint analysis in agriculture is a new and evolving subject. The main purpose of the study was to assess environmental sustainability of conventional and conservation tillage systems using ecological footprint analysis in Hamedan Province. Global hectares (gha) were used to measure the ecological footprint unit. Data was collected through questionnaires and use of cross-sectional multi-stage cluster sampling in 2013-2014 cropping year. Results revealed a significant difference in global hectares (gha) between ecological footprints in conventional (2.96) and conservation (2.84) systems. Both cropping systems used agricultural lands more than the ecologically productive land required to offset the environmental impact of different farming activities, and are therefore considered unsustainable. However, conservation systems proved to be more environmentally sustainable. The ecological footprint of fuel factor (gas oil and electricity) in both cropping systems had the highest impact on environmental sustainability: 49.70% and 47.22 percent of global hectares; respectively. Although environmental pollution was reduced slightly by the conservation system, estimated footprint based on gha was worrying. Addressing these challenges requires a national commitment which would not be possible without government intervention.

Keywords: Carbon footprint, Global hectare, Tillage systems, Sustainable agriculture.

INTRODUCTION

With the advent of the industrial age, external inputs have been particularly emphasized in agricultural activities; chemicals such as fertilizers and pesticides and machineries have increased agricultural activity and, therefore, have caused an overexploitation of land and natural resources (Passeri et al., 2013). In previous decades, environmental issues in various fields such as agriculture and industry attracted greater attention due to the followings: the book entitled Silent Spring, which dealt with the use of fertilizers and chemical pesticides (Carson, 2002), the economic theory of non-renewable resources put forward by Meadows (1972), and the concept of sustainability in the report entitled ‘Our Common Future’ (Gerbens-Leenes et al., 2003). Given the diversity of environmental impact of agriculture such as destruction of natural resources (water and soil), pollution, loss of biodiversity of agricultural ecosystems, increased natural hazards (e.g. global warming) with its associated impacts (e.g. droughts, climate change, floods), and their aggregate effects on food quality and consumer health (Punkari et al., 2007). However, in Iran, there have been so far no serious endeavors and research to

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undertake the environmental impact assessment of the various practices affecting the resources (Aghnoum et al., 2014). Several methods for assessing these impacts have been proposed (Wiedmann and Minx, 2008; Panko and Hitchcock, 2011; Agostinho and Pereira, 2013). These methods were developed taking into consideration objectives, concepts, levels of impact and potential application. One of the most important quantitative methods in this respect was the Ecological Footprint Analysis (EFA).

The concept of footprint, which was derived from ecological footprint, was first introduced into the scientific community by Rees and Wackernagel (1996). Subsequently, a variety of footprint indicators were proposed to complete the ecological footprint. The most important ones are energy footprint (Rees and Wackernagel, 1996), water footprint (Hoekstra and Hung, 2002), “energy” footprint (Zhao et al., 2005), “exergy” footprint (Chen and Chen, 2007), carbon footprint (Wiedmann and Minx, 2008), ecological footprint of different species of life (Yaap et al., 2010), chemical footprints (Panko and Hitchcock, 2011), phosphorus footprint (Wang et al., 2011), and nitrogen footprint (Leach et al., 2012). The ecological footprint has been proposed as a powerful communication tool to inform people about the environmental impact caused by excessive production and consumption. The ecological footprint is defined as the area of productive land and water required by the ecosystem to produce resources and assimilate the wastes (Cerutti et al., 2013). In this study, ecological footprint is defined as the area of productive land required to compensate the environmental impact of different farming activities.

Ecological footprint methodology is based on integrating detailed available data. There are two main methods for calculating the ecological footprint: Life Cycle Assessment (LCA) and Input-Output Analysis (IOA) (Agostinho and Pereira, 2013). These two methods have been criticized recently because of the fact that assessment of the ecological footprint requires a different approach at macro- compared to micro-levels like a city, province and, for particular agricultural activities, on a farm. Therefore, in the first decade of the 21st century, Place–Oriented Approach (POA) as a new method of ecological footprint was proposed by scientists like, Kissinger and Gottlieb (2012) and Guzman et al. (2013). This method combines the two previous techniques and focuses more specifically on a particular place. In addition to being flexible, it is able to calculate the footprints using data from different locations; which is an aspect considered in this study.

Using the ecological footprint analysis in agriculture is a new and evolving subject. Ecological footprint indicator is an appropriate index for agricultural production and a good criterion for evaluating energy consumption, greenhouse gas emissions, nitrates’ contamination from fertilizers and pesticides, land and water use in agriculture (Anielski and Wilson, 2010). Ecological footprint can assess the sustainability of agricultural systems (Cerutti et al., 2013). From an environmental point of view, sustainable agricultural activity occurs when long-term use of resources is induced by the environmental carrying capacity. Therefore, ecological footprint evaluation of agriculture is the first step in the overall assessment of agricultural sustainability (Payraudeau et al., 2005). Several studies have used the ecological footprint as an indicator for assessing sustainability of agriculture in order to determine the environmental impact of agricultural activities (Passeri et al., 2013; Crishna, 2007; Cheng et al., 2011; Xu et al., 2013). The main components of this approach, particularly in agricultural activities, are consumption of fuels, inputs, labor, agrochemicals, pesticides, machinery as well as productions and waste products. In general, research in this area can be classified into several categories: studies dealing with the impact of management practices on environmental effects of agricultural activities by using ecological footprint analysis (Passeri et al., 2013; Azad and Ancev, 2010; Phong et al., 2010; Crishna, 2007); works calculating ecological footprint based on energy consumption and products (Tittonell and Giller, 2013; Dong et al., 2013; Anielski and
Wilson, 2010; Cheng et al., 2011); inquiries studying the agricultural ecological footprint and its suitability based on the Life Cycle Assessment (Gan et al., 2011; Schafer and Blanke, 2012; Knudsen et al., 2013); studies considering biodiversity in agricultural activities and then evaluation of the footprint (Galli et al., 2014; Ridoutt and Pfister, 2013; Gan et al., 2012); and finally, those calculating the ecological footprint based on cropping succession (Xu et al., 2013; Wood and Dey, 2009). Each of these studies evaluates the sustainability of agriculture using ecological footprint analysis in different ways.

There are studies that have specifically examined the ecological footprint of wheat production (Gan et al., 2012; Gan et al., 2011). In these studies, the Energy Efficiency Index (EEI) was used to determine the sustainability. In all of these studies, global hectare was used to demonstrate the ecological footprint unit. The global hectare is a term derived from a method presented by Rees and Wackernagel (1996). A global hectare (gha) is a common standard for footprint comparisons between various land use types in the world (Anielski and Wilson, 2010).

In this research, the ecological footprint was used as a criterion to calculate the ecological footprint in wheat production. This method has been developed and evaluated for comparing the sustainability of conventional and conservation tillage systems based on energy consumption by using place-oriented method proposed by Kissinger and Gottlieb (2012) and Guzman et al. (2013).

MATERIALS AND METHODS

The Area of Study

Hamedan Province is located in the west of Iran and has a cold semi-arid climate with an annual rainfall of 340 mm. The study area lies between latitude 33° 59’ and 35° 48’ N and longitudes 47° 34’ and 49° 36’ E Greenwich meridian (Figure 1).

In Iran, wheat is the most important crop and is cultivated in almost 50 percent of total arable land every year (Zeinali, 2009). Annual total products of agricultural sector...
in Hamedan was more than 5 million tons, constituting 5 percent of agricultural production of Iran (Hamedan Jihad of Agriculture Organization, 2014). Hence, agriculture is the main economic activity and principal land use with main crops being wheat and barley in the study area (Hamedan Provincial Government, 2011). Hamedan’s annual cropping plan of wheat in the crop year 2013-2014 is illustrated in Table 1.

Research Methodology

In this cross sectional and descriptive research, the target population consisted of farmers who were members of agricultural production cooperatives (N= 6,673) in Hamedan Province. These farmers followed both farming practices of conventional and conservation tillage systems. A total of 370 farmers were selected for the study based on the Krejcie and Morgan (1970) sampling table via a random sampling method. The research instrument was a self-made questionnaire, of which the validity was approved by a panel of experts; while the pretest-posttest method was utilized to secure its reliability. Due to the nature of questions and low literacy level of the participants, questionnaires were filled through face to face interviews by trained staff in order to collect more robust data. The comparison criterion for ecological sustainability in this study was the global hectares in which each hectare of land had the ability to absorb 1.8 tons of carbon (Guzman et al., 2013). When the ecological footprint of agriculture is more than the stated amount, it is considered environmentally unsustainable. The ecological footprint model has been developed and evaluated for comparing the sustainability of conventional and conservation tillage systems based on energy consumption by using place-oriented method proposed by Kissinger and Gottlieb (2012) and Guzman et al. (2013) as shown below.
\[
EF_i = \sum_{i=1}^{n} EF_i = \left( \frac{E_i \ast T}{C_o} \right)
\] (1)

\[
E_i = F_i \ast EQF \ast 1000
\] (2)

\[
T = \left( \frac{P_c}{C_i \ast O_c \ast K} \right)
\] (3)

Where, \( EF_i \) is ecological footprint in terms of global hectares; \( F_i \) is factor of \( i \) component; \( E_a \) is energy \( i \) component in kJ, \( EQF_i \) is equivalent factor for \( i \) component; \( E_c \) is ability to generate energy per gram of coal (20 kJ), \( O_c \) is percentage of coal output by plants (0.314%) in grams; \( P_c \) is percentage of the carbon in coal (85%) in grams; \( K \) is constant coefficient to convert grams to tons (1000, 0000), and \( C_o \) is the ability of a hectare of land to absorb carbon in tons (1.8 tons, Guzman et al., 2013)

In this model, Equivalence Factors (EQF) were used to convert effective land in global hectares (gha) proposed by Anielski and Wilson (2010) shown in Table 2.

RESULTS

EF Evaluation in the Conventional Tillage System

The ecological footprint in terms of energy consumption was derived from environmental indicators such as seeds, chemicals, fertilizers (nitrogen, phosphorus), fuel, electricity and labor estimated for conventional and conservation tillage systems shown in Table 3. According to this model, the ecological footprint related to irrigated wheat production was estimated at 2.96 of gha. The fuel component (gas oil and electricity) with more than 53 percent had the greatest impact on ecological footprints in this system. The following model demonstrates the ecological footprint of conventional tillage systems. (see Equation 4)

\[
\text{EF Evaluation in the Conservation Tillage System}
\]

The model below shows the ecological footprints of tillage farming practices. According to this model, the ecological footprint related to wheat production equals 2.84 global hectares (see Table 3). The fuel component (gas oil and electricity), with over 51 percent, had the greatest impact on ecological footprints. The following model demonstrates the ecological footprints of conservation tillage systems. (see Equation 5)

Independent sample \( t \)-test was used to compare the conventional and conservation tillage systems. The results showed that there was a significant difference between ecological footprints of the conventional and conservation tillage systems (see Table 4). It seems that the conservation tillage system was more sustainable than the conventional cropping system.

\[
EF_{\text{Conventional}} = \sum_{i=1}^{n} EF_i = \left( \frac{39372.78MJ \ast 1000 \ast \frac{0.85}{20 \ast 0.314\% \ast 1000000}}{1.8_{\text{tons}}} \right)
\]

\[
EF_{\text{Conventional}} = \left( \frac{39372780kJ \ast 0.000000130}{1.8_{\text{tons}}} \right) = 2.96 \text{ gha}
\] (4)
\[
EF_{\text{Conservation}} = \sum_{i=1}^{5} EF_i = \frac{3783.18 \times 0.85}{1.8 \text{ tons}} \times \frac{1000}{20 \times 0.314 \times 1000000}
\]

\[
EF_{\text{Conservation}} = \frac{3783.18 \times 0.000000130}{1.8 \text{ tons}} = 2.84 \text{ gha}
\]

Table 2. EQF for inputs and outputs used in the production of irrigated wheat.

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Equivalent factor</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>kg</td>
<td>15.7</td>
<td>Tipi et al. (2009)</td>
</tr>
<tr>
<td>Labor</td>
<td>hour</td>
<td>1.96</td>
<td>Ozkan et al. (2004)</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>kg</td>
<td>60.6</td>
<td>Akcaoz et al. (2009)</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>kg</td>
<td>11.1</td>
<td>Akcaoz et al. (2009)</td>
</tr>
<tr>
<td>Potassium</td>
<td>kg</td>
<td>6.7</td>
<td>Akcaoz et al. (2009)</td>
</tr>
<tr>
<td>Gasoil</td>
<td>liter</td>
<td>38</td>
<td>Kaltas et al. (2007)</td>
</tr>
<tr>
<td>Petrol</td>
<td>liter</td>
<td>37</td>
<td>Kaltas et al. (2007)</td>
</tr>
<tr>
<td>Electricity</td>
<td>kw.h</td>
<td>12.1</td>
<td>Kaltas et al. (2007)</td>
</tr>
<tr>
<td>Herbicides</td>
<td>kg of active ingredient</td>
<td>278</td>
<td>Tzilivakis et al. (2005)</td>
</tr>
<tr>
<td>Fungicides</td>
<td>kg of active ingredient</td>
<td>99</td>
<td>Strapatsa et al. (2006)</td>
</tr>
<tr>
<td>Pesticides</td>
<td>kg of active ingredient</td>
<td>237</td>
<td>Tzilivakis et al. (2005)</td>
</tr>
<tr>
<td>Wheat</td>
<td>kg</td>
<td>14.7</td>
<td>Tipi et al., (2009)</td>
</tr>
<tr>
<td>Straw</td>
<td>kg</td>
<td>9.25</td>
<td>Tabatabaeefar et al. (2009)</td>
</tr>
</tbody>
</table>

Table 3. The ecological footprint of tillage systems.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Energy (MJ)(^a)</th>
<th>Percentage (^b)</th>
<th>Footprint (gha)(^c)</th>
<th>Percentage (^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed</td>
<td>3807.88 3805.5</td>
<td>9.67 10.06</td>
<td>9.80 9.86</td>
<td>0.64 0.67</td>
</tr>
<tr>
<td>Labor</td>
<td>254.8 235.2</td>
<td>0.65 0.62</td>
<td>0.68 0.70</td>
<td>0.02 0.02</td>
</tr>
<tr>
<td>Fertilizer Nitrogen</td>
<td>12726 12726</td>
<td>32.32 33.64</td>
<td>32.43 33.80</td>
<td>0.64 0.70</td>
</tr>
<tr>
<td>Fertilizer Phosphorous</td>
<td>1054.2 1054.5</td>
<td>2.67 2.79</td>
<td>2.70 2.82</td>
<td>0.08 0.08</td>
</tr>
<tr>
<td>Chemical pesticides and herbicides</td>
<td>475.2 475.2</td>
<td>1.21 1.26</td>
<td>1.35 1.41</td>
<td>0.04 0.04</td>
</tr>
<tr>
<td>Chemical pesticides and herbicides</td>
<td>17860 16340</td>
<td>45.36 43.19</td>
<td>45.27 42.96</td>
<td>0.24 0.24</td>
</tr>
<tr>
<td>Fuels</td>
<td>3194.4 3194.4</td>
<td>8.11 8.44</td>
<td>8.11 8.45</td>
<td>0.10 0.10</td>
</tr>
<tr>
<td>Total</td>
<td>39372.78 37833.18</td>
<td>100 100</td>
<td>100 100</td>
<td>1.16 1.04</td>
</tr>
</tbody>
</table>

\(^a\)The energy of each component and its footprint was estimated for a hectare. \(^b\)Conventional system. \(^c\)Conservation.

**DISCUSSION**

**Ecological Footprint Analysis**

The results showed that the ecological footprint (gha) in the conventional tillage was higher than the conservation system. It was 2.96 and 2.84 ton per hectare in the conventional and conservation farming systems; respectively, far beyond the ecological capacity needed to absorb environmental pollution in one hectare of productive land in wheat production considered to be 1.8 global hectares. As a result, in none of the above systems wheat production was environmentally sustainable. In other words, each system needed an area equivalent to 0.64 and 0.57 of hectares more land in order to absorb the 1.16 and 1.04 tons per hectare of environmental pollution, respectively. In general, as the results were based on EFA with regard to energy consumption, it indicated that the
environmental impact of conventional system was higher than the conservation system. Meanwhile, the conventional cropping system had less energy efficiency compared to conservation tillage system. The findings of the study are consistent with previous studies on the sustainability of conservation tillage systems undertaken by Gan et al. (2011), Cheng et al. (2011), and Knudsen et al. (2013).

High ecological footprints in the traditional system often result from higher usage of machinery fuel in land preparation stage of wheat cultivation. However, less machinery traffic, higher speeds, and lighter gears in conservation system reduces fuel consumption. This has led to a reduction of environmental pollution and has improved the ecological footprint of wheat per hectare (gha). In fact, the main difference in energy consumption could be summarized in fuel consumption. Among the factors related to wheat production in Hamedan Province, like many other studies (Galli et al., 2014; Gan et al., 2012; Xu et al., 2013), fuel consumption had the highest energy consumption, and eventually the highest ecological footprint. However, contrary to previous studies (Phong et al., 2010; Dong et al., 2013; Crishna, 2007), energy consumption of fertilizers (nitrogen and phosphorus) were higher than fuel. It might be due to aging diesel machinery and pumps used in cultivation and irrigation which are highly polluting.

Thus, it is necessary to replace current pumps with electric ones that are less polluting. It is worth noting that although the conservation tillage system reduced environmental pollution, the estimated ecological footprints were still worrying.

### Table 4. Independent sample t-test of conventional and conservation tillage systems. *

<table>
<thead>
<tr>
<th>Tillage systems</th>
<th>Mean</th>
<th>SE</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>2.95</td>
<td>0.02</td>
<td>2.94</td>
<td>0.003</td>
</tr>
<tr>
<td>Conservation</td>
<td>2.85</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Levene's test for equality of variances: F= 0.022, Sig= 0.883.

### CONCLUSIONS

Based on findings of this study, it can be concluded that modernization theory as a dominant notion has established in the farming systems of the study area. Hence, soil, land, and other inputs have been exploited without considering their externalities. In other words, the investigated area was strongly affected by the farmers’ excessive use of chemicals (fertilizers and pesticides), high yielding varieties, cultivation and harvesting machineries. Farmers, with the aim of gaining higher profits, have continuously destroyed their environment. So, most of the prevailing farming practices were unsustainable, even those that stressed conservation farming methods. It seems that the popular conservation farming was more a fantasy and symbolic action. Because of the fact that energy, land, and water resources in most farms were being misuse and overused, resource management must become a dominant notion and planning priority for practitioners and actors. As sustainability in itself has a holistic nature, efficient management of farm resources would require economic, social, and environmental externalities to be considered in all management alternatives. This implies consideration of technical, economic, social, institutional, and environmental issues in line with participation of all stakeholders in the decision-making process. Endogenous agricultural developments in general, and participatory approaches in particular, are to be recommended. They have been developed to empower farmers by inducing positive change...
in harmony with the ecological capacity. Local NGOs, self-help groups and/or producer organizations, and local stakeholders need to become more involved in agricultural management structure, from diagnosis and policy formulation to application of farming practices. Participatory approaches will hopefully lead to a decision-making structure that is more informed and equipped to resolve problems; and consequently more accountable. Iranian ministry of Jihad of Agriculture should prepare a comprehensive and detailed plan on administrative and technical aspects of achieving sustainable development in agriculture. In this proposed plan, optimizing scheme for better use of pesticides and fertilizers, increasing performance and safeguarding the environment by using sound technologies (organic-based, ecologically sound manure system and internal input) will be necessary to maintain soil productivity for the future, however in agricultural sector coerce regulations on "sustainable management and use" of resource not applicable.

Therefore, extension systems would have a critical role to play in transferring appropriate technologies, helping farmers learn the importance and know-how of sustainable land, soil, and water utilization practices, and then maintaining the natural resources. Meanwhile, most farmers are not sufficiently aware of their actions’ consequences. Farmers declared low-tillage direct seeding machines to be very expensive and difficult to find in the local market. Diversification of rural economy (such as introducing off-farm businesses) is another complementary recommendation that could be offered to prevent excessive degradation of soil resources.

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تحقیق نشان داد که تفاوت معناداری بین نمره کل رده‌بندی اکولوژیکی بر حسب هکتار جهانی در شیوه زراعی مرسوم (٢،٩٦) و حفاظتی (٢،٨٤) وجود داشت. به طوری که شیوه زراعی حفاظتی از پایداری زیست محیطی بیشتری برخوردار است. با توجه به فاکتور هکتار جهانی، هر دو شیوه زراعی بیش از توان اکولوژیکی یک هکتار زمین مورد نیاز برای جنگ اثرات زیست محیطی، از زمین بهره برداری می‌نمایند، بنابراین بر اساس روابط جهانی رتیا، هر دو شیوه زراعی ناپایدار محسوب می‌شوند. ردیاب اکولوژیکی فاکتور سوخت در هر یک از شیوه مرسوم و حفاظتی به ترتیب برای با ٤٩،٧ و ٣٧،٢ درصد هکتار جهانی، بیشترین تأثیر را بر پایداری زیست محیطی داشته است. شیوه خاکورزی حفاظتی توانسته است مقدار کمی از میزان آلودگی های زیست محیطی را کاهش دهد، اما میزان ردیاب برآورد شده براساس هکتار جهانی رقمی نگران کننده است. رفع این جنایت نیازمند یک عمل ملی است، به‌طوری‌که دخالت دولت امکان پذیر نخواهد بود.