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Emergy analysis of grain production systems on large-scale farms in the North China Plain based on LCA

Xiaolong Wang, Yuanquan Chen *[,1], Peng Sui [1], Wangsheng Gao, Feng Qin, Jiansheng Zhang, Xia Wu

College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China

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ABSTRACT

Traditionally, primary grain production systems in China have been on a small scale and are associated with high costs and low labor productivity. Therefore, the substitution of small-scale farming with large-scale farming has been discussed in recent years. The North China Plain (NCP) is one of the primary grain production areas in China, and the winter wheat–summer maize double-cropping system dominates the region. Emergy evaluation based on life cycle assessment (LCA) was introduced in a farm case study to explore the ecological and economic effects of the wheat–maize double-cropping system on large-scale grain production compared with small-scale production. The results indicated that the emergy efficiency of maize production on the large-scale farm was 67.4–88.5% higher than that of common maize production systems, and the emergy efficiency of wheat production in the same farm decreased by 23.5–43.0% compared to other wheat production systems. The emergy sustainability index (ESI) of the double-cropping system was 64.0–84.5% lower than that reported by household farms. This is caused by large-scale farming requiring enormous emergy inputs from irrigation, fertilizers, and labor at the pre-sowing and growth stages of wheat production. Nevertheless, the scenario analysis results showed that the emergy efficiency and ESI of wheat production could be improved by 14.7–59.1% and 18.2–123.3%, respectively, using appropriate water, nutrient, and agronomic management measures. We found that the emergy efficiency of wheat production in this large-scale farm was 41.5% higher than in household farms in the same area if comprehensive improvement measures were applied. In conclusion, the ESI value of the double-cropping system in the NCP needs to be modified to increase the emergy efficiency of large-scale grain production farms. If this is accomplished, the large-scale farming pattern may be applicable for grain production in the NCP.

1. Introduction

An agroecosystem is defined as a seminatural ecological and economic system controlled by humans. Field management involves the input of artificial energies such as tillage, irrigation, and fertilizer, which influence crop growth. Improving energy output efficiency and sustainability in an agricultural ecosystem has been explored in previous studies.

Emergy theory and methodology was first proposed in the 1980s (Odum, 1996) as a concept that combines energetics and systems ecology. Emergy evaluation addresses the weaknesses of traditional energy analysis and describes variable energy forms using a common physical basis, namely, solar emergy. Moreover, it takes into account aspects of energy use that are not usually considered in other evaluation methods such as natural resources, labor, and ecosystem services. Therefore, emergy analysis has been widely applied to different agricultural ecosystems and products in recent years (Cavalett and Ortega, 2009; Ghaley and Porter, 2013; Giannetti et al., 2011; Jiang et al., 2007; La Rosa et al., 2008; Martin et al., 2006). Grain production, as one of the most important functions of an agricultural ecosystem, has been examined previously using emergy evaluation (Lefroy and Rydberg, 2003; Liu and Chen, 2007; Lu et al., 2010; Ortega et al., 2005; Ulgiati et al., 1994).

During the past three decades, with changes in cropping systems, an increased grain yield has been achieved in China at the cost of significant consumption of nonrenewable resources and environmental degradation (Hu et al., 2010; Yang et al., 2006). The North China Plain (NCP) is one of the major grain production areas in China. With rapid population growth, the main type of cropping system in the NCP has changed from single-cropping in the 1950s to double-cropping, the present winter wheat–summer maize production system. This highly intensive grain production

* Corresponding author. Tel./fax: +86 010 62731163.
E-mail addresses: 33629914@qq.com (Y. Chen), wshgao@sohu.com (W. Gao).
[1] These authors contributed equally to this study.

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system demands more energy to maintain crop yield. The annual water demand for crop production in the NCP increased from 300 to 400 mm to more than 850 mm (Hu et al., 2010; Liu et al., 2002), but the mean annual precipitation is only 500–700 mm in the area, which has decreased by about 43.9 mm over the past 40 years (Fu et al., 2009; Hu et al., 2010). Groundwater has become the primary source of irrigation water to meet the water requirements of crops in the NCP. At the same time, the amount of applied chemical fertilizer has increased from 7.3 kg/ha in the 1950s (Chen et al., 2008) to 1869 kg/ha in 2006 (Ma, 2006). The consumption of electricity and fuel for irrigation and machinery has also increased significantly. Clearly, the double-cropping system on the NCP is a high-energy system that relies heavily on the consumption of nonrenewable resources such as groundwater and fossil fuels. These inputs have increased the grain yield and met the immediate need to support a large population with limited arable land. However, this grain production system cannot support sustainable development over the long term, indefinitely. Therefore, reducing energy consumption and improving the efficiency and sustainability index of the grain production systems in the NCP is important.

As a developing country with a population of 1.3 billion and only 0.101 ha of arable land per capita (Feng, 2007), China has traditionally employed labor-intensive cultivation practices compared to developed countries. Chinese agriculture has developed as a series of highly self-sufficient family-operated farms (Chen et al., 2006). This farm type is small scale, with high cost and low labor productivity. Grain production of this household farms depends on a large amount of chemical energy and labor, and the high costs of purchased materials reduce the income of farmers. Thus, modifying this type of grain production is important to improve efficiency and reduce the environmental pressure of grain production in China. In recent years, developments in Chinese society, including accelerated urbanization and profound changes to the political system, have encouraged farmers to move to cities for work. As a result, the ownership of farmland has become more concentrated under the control of a few individuals and companies. Consequently, many large-scale farms have emerged in China. Some experts have indicated that large-scale farming has the following advantages for grain production compared with household farmers: increased total yield and commodity of grain, improved labor productivity and reduced cost, increased level of agricultural mechanization, and promotion of new agricultural technologies (Pan, 2012; Wang, 2004). At the same time, the concentration of farmland and the development of large-scale farms unleash immense labor potential and accelerate the pace of urbanization in China. Moreover, under the current background of sustainable agriculture development, grain production is gradually becoming an integrated component in the agricultural industry chain for many large-scale farms that usually manage planting, livestock, and renewable energy production together. Some experts have suggested that the development of agriculture in China has to emphasize this combination to balance food security and sustainable development (Xing, 1999). Therefore, developing large-scale grain production for the modernization and sustainable development of Chinese agriculture is important in the future. However, all current evaluations of the grain production system in China have focused almost exclusively on household farms (Hu et al., 2010; Liu and Chen, 2007; Lu et al., 2010), and the assessment of large-scale grain production systems in China has been rarely reported.

Moreover, few previous studies have analyzed the efficiency and sustainability of crop production at the field level. The majority of studies on agricultural production have considered the energy input–output ratio, environmental influences, and agricultural development strategies from a macroscopic perspective at regional scales. However, the steps in the process of agricultural production that consume the most energy and cause the most environmental damage remain unclear. Therefore, resolving these issues is important to reduce emergy consumption and improve the sustainability of grain production systems.

According to the above considerations, emergy evaluation based on life cycle assessment (LCA) was introduced in a farm case study. The LCA method in agriculture focuses primarily on the environmental impact of emissions and nonrenewable energy inputs of agricultural processes over a product's life cycle, from the extraction of natural resources to the use and disposal of the product (Pizzigallo et al., 2008). Note that we did not consider further transportation, transformation, consumption, and waste disposal of the grain production system in this study. We analyzed the grain production system of a large-scale farm in the NCP based on an LCA methodology, which involved dividing the agricultural process into production steps and analyzing the emergy inputs and utilization of each step. Our results can be applied to improve the grain production system of large-scale farms in the NCP. A summary of our objectives are as follows: (1) an emergy assessment of the wheat–maize double-cropping system in the NCP, (2) comparisons of emergy indices to those from previous studies on smaller-scale production systems, and (3) scenario analysis of how changes in management practices could modify the performance of large-scale grain production.

2. Methods

2.1. Study sites

We selected a farm (Jinglong Company) in Jingxian County (37°58′N, 115°99′E) of Hebei Province, which is located in the northwest NCP. This farm has a temperate semiarid monsoon climate with a mean annual temperature of 12.5 °C and mean annual precipitation of 554 mm.

This farm was considered representative of the region's large-scale farms performing conventional crop production in the NCP for the following reasons. First, the planting pattern of the farm was a typical winter wheat–summer maize double-cropping system, which was the main grain production mode in this region, providing about 61% and 33% of the national total wheat and maize yield, respectively (Cui et al., 2008). Considering field management, the characteristics of irrigation and chemical fertilizer use in the grain system coincided with the conventional field management of wheat and maize production in the NCP. In addition, the yield level of the grain system in this farm conformed to the average level of wheat and maize in the area. These three characteristics showed that the planting level of this system could represent the overall situation of grain production in the NCP. Similar to other large-scale farms, almost each production step of the planting system was completed by machines, excluding irrigation and maize straw disposal. At the same time, the extensive management of this farm reflects characteristics of the current development of large-scale farms in China, which are mostly at the primary stage of agricultural industrialization. Moreover, the grain production scale of this farm has met the governmental standard and has been certified as a national grain production model, and the farm also integrated livestock and renewable energy production; these industries constituted "agricultural ecological engineering." The "ecological agriculture mode" represented the direction of development of agriculture in China. Therefore, the production and management characteristics of this farm were representative of this type of system in the NCP.

It should be noted that although the farm was involved in livestock production and three biogas projects digesting the excreta of livestock, these two systems did not use the same land as the grain