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Sustainability assessment of straw utilization circulation modes based on the emergetic ecological footprint

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ABSTRACT

In order to find a reasonable way to return the straw and reduce waste of resources, sustainability assessment of four types of maize straw circulation modes, straw direct returning to the farmland (control), "straw-biogas-straw" (S-B-S), "straw-dairy-straw" (S-D-S) and "straw-dairy-biogas-straw" (S-D-B-S), are analyzed and compared. Based on the Emergetic Ecological Footprint (EEF) method, which is an integration of Ecological Footprint (EF) analysis and emergy accounting, the Footprint Investment per unit of Footprint Delivered (FIFD) was used as an indicator of the sustainability of an ecological system. The results showed that the FIFDs for these straw circulation modes were 0.81, 1.96 and 0.43, respectively, and a sustainability sequence of S-D-B-S>S-B-S>S-D-S, in which S-D-B-S has the highest sustainability and S-D-S is unsustainable. Therefore, the agriculture-biogas mode is better than the agriculture-livestock mode, and longer circulation chains correspond with stronger sustainability. Based on the results, we suggest that integrated-biogas subsystem should be developed and all wastes in agrosystem should be used more efficiently in order to increase the sustainability.

1. Introduction

Resource-circular agriculture is a new type of development model aimed at lowering consumption and pollutant emissions and improving resource use efficiency relative to traditional agriculture (Zhou et al., 2012). China is the most populated country in the world, and the Chinese national economy includes a very high proportion of agriculture (Jun and Xiang, 2011). Three main agricultural circulation modes exist in China (Wu et al., 2015), namely the northern "four in one", the northwestern "five-matching" and the southern "pig-biogas-fruit" or "pig-biogas-fish" modes. Because chemical fertilizers have been widely used for a long time in China, pollution from agricultural production is a serious problem that has led to soil acidification and hardening. Although the quantity of agricultural production in China is large, the quality is poor. Meanwhile, a large amount of straw is generated in China every year. Crop straw is an important renewable resource, which has become widely known in recent years (Wei et al., 2012). Thus, it is important to use straw reasonably and effectively. Soil organic carbon (SOC) is a key factor of soil quality due to its important role in modifying soil physical, chemical and biological properties. Studies have suggested that straw return increases SOC storage in the soil surface (0–20 cm) (Choudhury et al., 2014; Sun et al., 2013). Bhattacharyya et al. (2012) observed that combining straw with inorganic nitrogen fertilization significantly increased the total carbon content in topsoil. Although conventional straw return methods are widely used in some agricultural regions, several drawbacks of these return methods in wheat–maize rotation systems have been shown. For example, conventional straw return shows negative effects on machinery tillage and seedling emergence (with large amounts of crop residues retained on the soil surface) and causes unstable crop yields (Dai et al., 2013). Thus, indirect straw return is studied in this paper.

Abbreviations: EEF, emergetic ecological footprint; EF, ecological footprint; EEF_{inputs}, the total footprint inputs in the circulation mode; EEF_{wastes}, the footprint related to the wastes (cow manure and biogas slurry); $EEF_{materials}$, the footprint associated with the materials consumed within the circulation mode; EEF_{yields}, the footprint outputs from the circulation mode in which production (crops and biogas and milk) is provided to society; FIFD, footprint investment per unit of footprint delivered; GED, global empower density; S-B-S, straw-biogas-straw; S-D-S, straw-dairy-straw; S-D-B-S, straw-dairy-biogas-straw.

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Straw can be used as animal feed; however, a lot of straw is returned to farmland, burned or discarded, so less straw is used for feeding animals (Zheng et al., 2012). Meanwhile, livestock waste abandoned is considered as one of the most significant contributors to environmental problems (Llea, 2009). Dalgaard and Halberg (2007) suggested that the environmental burden of manure production should be considered as a co-product from livestock production. The environmental problems have become very serious. So the number of studies on the reuse of agricultural and urban wastes as substitutions for fertilizers is growing (e.g., Ruggieri et al., 2009). However, these works mainly compare the agronomical benefits of such application (Amiri and Fallahi, 2009), but do not consider sustainability aspects. To propel the sustainable development of rural areas, the Chinese government has continuously endeavored to promote biogas construction through policy, financial support, and technology inputs (Chen and Chen, 2006). Integrated biogas-utilization modes have become popular for household biogas utilization in China (Chen and Chen, 2012). Wu et al. (2015) analyzed the sustainability properties of an integrated "pig-biogas-fish" system. Wang and Wang (2006) analyzed the effects of household biogas systems on farmers' cropping behaviors exploring the use of descriptive statistics and econometric models.

Since the introduction of the EF concept to China in 1999, it has induced vast attention in the academic field and some potential improvements have been proposed in the current EF method (Wu et al., 2015). Zhao et al. (2005) modified the method of ecological footprint calculation. They tried to combine EF with emergy accounting, given the fact that both methods aim to solve the same problem through accounting of sources and throughputs, through estimating the gap between the demand by humanity and available natural services, and finally through evaluating resource utilization by humans. Siche et al. (2010) discussed some weak points found in Zhao's approach, and overcame them through a new approach called Emergetic Ecological Footprint (EEF). The main difference between EEF and Zhao's approach is that the former one accounted for natural capital. Natural capital is an internal storage of natural resources in an area, which includes geology, soils, air, water and all living organisms. Natural capital is may also provide ecosystem services such as recycling waste materials or pollution (or even erosion) control (Siche et al., 2010). Nowadays, all countries, mainly the developing countries, are dependent on natural capital. Chen and Chen (2006) compared emergy-based ecological footprint with EF in a time series (1981–2001) study of the Chinese society, and suggested that EEF is better than EF to illustrate the ecological overshoot of the general ecological system.

In order to find a reasonable agricultural circulation mode and make full use of waste resources, this paper compared the environmental sustainability of 4 different straw utilization modes by using the EEF to provide theoretical support for managers and decision-makers.

2. Materials and methods

2.1. Experimental design

The experiment was conducted from 2012 to 2014 in Pingyuan County, which is located on the Huang-Huai-Hai Plain of China (116°26′ E, 37°09′ N). It has a warm and temperate continental monsoon climate with an annual mean temperature of 12.6 °C, minimum and maximum temperatures of −17.1 °Cand 38.5 °C, respectively, and annual rainfall of 600.75 mm. The main planting system is winter wheat-summer maize rotation in a light salinized meadow soil, containing 12.8 mg kg^{-1} organic matter, 1.38 mg kg^{-1} total N, 26.9 mg kg^{-1} available P, and 145.2 mg kg^{-1} available K, with a pH value of 7.7 in the –20 cm soil layer.

Four circulation modes based on maize straw utilization were compared using the EEF method. The four modes differ as follows (Fig. 1):

- Control mode: all straw was directly returned to the farmland.
- "straw-biogas-straw" (S-B-S) circulation mode: after maize was harvested, the straw was transported to the biogas pool and fermented before the remnants of the biogas slurry were used as fertilizer for the farmland.
- "straw-dairy-straw" (S-D-S) circulation mode: after maize was harvested, the straw was transported to the dairy farm and was processed into silage to feed the dairy cows, and the cow manure was used as fertilizer for the farmland.
- "straw-dairy-biogas-straw" (S-D-B-S) circulation mode: after maize was harvested, the straw was transported to the dairy farm and was processed into silage to feed the dairy cows, and then the cow manure was transported to the biogas pool and fermented before the remnants of the biogas slurry were used as fertilizer for the farmland.

Equal quantities of nitrogen (N) were used in the experimental fields. The N, phosphorus and potassium concentrations in the biogas slurry and cow manure are measured as shown in Table 1. The annual application rates of organic manure and mineral fertilizer for the 4 circulation modes are shown in Table 2.

2.2. Emergy accounting

Emergy is defined as a type of available energy previously used in direct and indirect transformations to make a product or service (Odum, 1988, 1996) and is measured using units of solar emjoule (sej). The emergy could be used to unify all knowledge of energy, material, information and money flows, which currently cannot be compared directly (Brown and Ulgiati, 2004; Lan et al., 2002; Martin et al., 2006). In this study, U can be used as the emergy of the resources, products and waste, and the fundamental equation of emergy analysis is given below.

$$U = \sum U_{i=} \sum p_i \cdot UEV_i \quad (1)$$

where U_i denotes the emergy directly and indirectly associated with the production of the ith product, $P_{i,}$ with the entire circulation mode process. UEV is the emergy transformity, which represents the solar emergy required to make per unit joule or mass of a product or service (Brown and Ulgiati, 2004; Chen et al., 2006; Wu et al., 2014). A latest systematic database of embodied ecological elements intensity, including solar emergy transformity for 135 industry sectors in China has been built by Chen and Chen (2010) and his collaborators via the systems input-output method (Han et al., 2015). This database is therefore used here to explore the average ecological cost of each product or service with relation to local production level.

The global emergy sustaining the biosphere is regarded as the emergy base of reference, which was previously calculated as 9.44E + 24 sej/yr (Odum, 1996) and then updated to 1.58E + 25 sej/yr (Odum and Odum, 2000) and 1.52E + 25 sej/yr (Brown and Ulgiati, 2010). In this study, 1.58E + 25 sej/yr is adopted.

2.3. Emergetic ecological footprint accounting

The emergetic ecological footprint (EEF) could serve as an extended indicator of ecological footprint (EF) (Chen and Chen, 2006). In this paper, the global empower density (GED), the ratio of the annual global emergy consumption to the surface area of the