Resources, Conservation and Recycling 117 (2017) 114–124

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Sustainability evaluation of recycling in agricultural systems by emergy accounting

Xiaolong Wang[a,b], Zhejin Li[a], Pan Long[a], Lingling Yan[a], Wangsheng Gao[a], Yuanquan Chen[a,*], Peng Sui[a,*]

[a] College of Agronomy and Biotechnology, China Agricultural University, Beijing 100193, China
[b] College of Agriculture, South China Agricultural University, Guangzhou 510642, China

ARTICLE INFO

Article history:
Received 1 July 2016
Received in revised form 3 November 2016
Accepted 4 November 2016
Available online 9 November 2016

Keywords:
Recycling agricultural systems
Emergy evaluation
Agricultural waste
Emergy loss
Recycled biomass

ABSTRACT

Recycling wasted biomass as organic fertilizer has been an important road to develop sustainable agriculture. Emergy evaluation (EME) is a widely used method to evaluate sustainability of agricultural systems. However, the contribution of recycled biomass on emergy efficiency and sustainability of investigated systems cannot be comprehensively and reasonably represented, to some extent, by the currently used forth emergy rule. In this study, therefore, an "*emformation*" concept is introduced to illustrate that the recycled biomass derived from different agricultural processes only contains the emergy stored in its organic matter. Meanwhile, a formulas is designed to account the energy contribution of recycled biomass for recycling agricultural systems. A case study on wheat-maize double-cropping systems fertilized by crop straw (CS), pig manure (PM), wine residue (WR), biogas residue (BR) and mushroom residue (MR) in the North China Plain is performed to compare with the system only applying mineral fertilizer (CK). Several emergy-based indices, such as unit emergy value (UEV), nonrenewable resource efficiency (NRE), recycle yield ratio (RYR), emergy yield ratio (EYR), emergy loading ratio (ELR) and emergy sustainability index (ESI) are calculated, in which the EYR and ESI are modified to reflect the influence of applying recycled biomass on the sustainability of recycling agricultural systems. Result shows that the UEVs and NREs of the CS, PM, WR, BR and MR are 22.0%–77.3% higher than that of the CK, the RYR of the CS is 31.6% lower than that of the PM, WR, BR and MR, the modified EYRs of the CS, PM, WR, BR and MR increase by 67.6%–81.4% compared to the CK, the ELR are 8.4%–75.4% higher for the PM, WR and MR but 6.7%–29.1% lower for the CS and BR than that of the CK, the modified ESI of the CS, PM, WR, BR and MR increase by 3.5%–136.8% compared to the CK. Generally, the results illustrate that the modified approach contribute to achieving more reasonable evaluation results for agricultural systems involving recycled biomass. The wheat-maize systems fertilized by recycled biomass consume the more emergy and nonrenewable resources to generate the unit product. The recycling agricultural systems show the higher sustainability, in which recycling biogas residue into field as organic fertilizer shows the best recycling benefits.

1. Introduction

Global challenges including food security, population explosion and environmental pressures require widespread actions to develop global sustainable agriculture (Foley et al., 2011; Tilman et al., 2011). As a large developing country, China is faced with greater pressure due to these challenges. Chinese cereal grain yields increased by 10% from 1996 to 2005, while the use of chemical fertilizers increased by 51% (Chen et al., 2011). There were 4.14×10^8 t of straw resources and 3.97×10^9 t of poultry and livestock manure generated in China in 2007, but the majority of them were burned or discharged into rivers, causing serious environmental issues (Zhang et al., 2009). Therefore, China must explore a sustainable direction in agricultural development. Through years of practice, various integrated agricultural models have been extensively developed in different areas of China, such as the "rice–fish (duck)" (Xie et al., 2011), "pig–biogas–fish" (Wu et al., 2014) and "cattle–biogas–vegetable" models (Wu et al., 2013). These models

---

* Corresponding authors.
E-mail addresses: usosky2011@sina.com (X. Wang), 674318078@qq.com (Z. Li), 155163275@qq.com (P. Long), 627413814@qq.com (L. Yan), wshgao@cau.edu.cn (W. Gao), rardc@163.com, 33629914@qq.com (Y. Chen), suipeng@cau.edu.cn (P. Sui).

http://dx.doi.org/10.1016/j.resconrec.2016.11.009

aim to achieve sustainable goals by reducing the excessive discharge of agricultural wastes, lowering the demand for purchased materials and energy, and increasing the fertility of arable land. Some recent studies have analyzed these models from the perspective of their economic benefits (Sun et al., 2015; Wu and Li, 2008; Zhou et al., 2004), although information on the energy efficiency and sustainability of these models has been relatively lacking.

Emergy evaluation (EME) is a widely used method to analyze energy efficiency and sustainability of complex systems by expressing and accounting different forms of energy on a common physical basis, specifically, solar emergy. During recent decades, EME has been widely applied in various fields, such as the electricity generation (Brown and Ulgiati, 2002), environmental accounting (Lomas et al., 2008), e-waste treatment (Song et al., 2012), bioenergy production (Wang et al., 2014a), industrial products (Puca et al., 2016) and eco-industrial park (Taskhiri et al., 2011). An agricultural system is very suitable for the application of the EME, because this method is particularly appropriate for evaluating systems at the interface between "natural" and "human" spheres (Castellini et al., 2006). Therefore, the EME has been an important measure for assessing the energy efficiency and sustainability of agricultural systems (Ghaley and Porter, 2013; Giannetti et al., 2011b; Jaklic et al., 2014; Wang et al., 2014b, 2015).

In recent years, recycling agricultural models have received increasing attention in their use of the EME (Cavalett et al., 2006; Wei et al., 2009; Wu et al., 2015a; Zhang et al., 2014). Broadly speaking, most of these studies demonstrated that a recycling system had better energy efficiency and sustainability compared to separated production systems. However, the published papers usually viewed the recycling system as a "black box". This implies that the evaluators did not stress the internal dynamic flows within the systems, because the objectives of their works allowed this consideration. Generally, most of the papers followed the fourth emergy rule, as it states, "emergy cannot be counted twice within a system: (a) emergy in feedbacks cannot be double counted; (b) coproducts, when reunited, cannot be added to equal a sum greater than the source emergy from which they were derived" (Brown and Herendeen, 1996). The rule actually implies that the emergy of recycling flows in a complex system should be viewed as zero when calculating the emergy yield of the system. Consequently, the benefits of recycling systems are only reflected by the reduction of purchased energy, and the contribution of recycled biomass is always not showed on the EME results. The reason is that, until now, emergy theory still lacks clear rules regarding recycle, and a key issue studying recycling under an emergy accounting perspective is to know and understand what is the emergy intensity of the recycled material (Agostinho et al., 2013).

Essentially, the primary objective for the analysis of recycling agricultural systems is to understand the role of recycled biomass in complex systems, because applying recycled biomass to agricultural fields is an important and essential road to connect various separated agricultural systems. Regardless of its source, the ultimate destination for recycled biomass (agricultural waste) is farmland where it is used as organic fertilizer. Therefore, determining how to allocate emergy on recycled agricultural biomass in recycling systems is important for the EME application on agricultural systems assessments. Hau and Bakshi (2004) indicated that allocation was probably the most confusing aspect of emergy analysis, particularly to researchers who focus on systems that involve recycled products. Many researchers have identified the challenges of recycling flows in EME and have made great efforts to resolve the problem (Agostinho et al., 2013; Amponsah et al., 2011, 2012; Brown and Buranakarn, 2003; Gala et al., 2015; Lazzaretto, 2009; Tilley, 2011; Winfrey and Tilley, 2012); however, the ideas and approaches are not in agreement thus far. Moreover, all of the studies focused primarily on industrial processes, whereas the information on how to deal with recycled biomass in agricultural systems has been lacking.

In this study, therefore, a wheat-maize double-cropping system fertilized by different sources of recycled biomass in the North China Plain is took as case to allow a discussion regarding the issue in the EME about how to account the emergy of recycled agricultural biomass and to reflect the contribution of them for the recycling agricultural systems.

2. Method

2.1. System description

A long-term field experiment on a wheat-maize double-cropping system is chosen as the case to be studied. The experiment was performed at Wuqiao Experimental Station, Hebei Province (37°41′02″N, 116°37′23″E). The area has a temperate, semiarid monsoon climate with a mean annual temperature of 12.9 °C and annual precipitation of 682.5 mm. The average total annual sunlight is 2614.9 h and the perennial average wind speed is 2.6 m/s.

The field experiment was established in 2010. It includes a control (CK) that only applied chemical fertilizers and five treatments that applied chemical and organic fertilizers including crop straw (CS), biogas residue (BR), mushroom residue (MR), wine residue (WR), and pig manure (PM). Table 1 shows the topsoil features, fertilization, and yield of the six treatments. It is should be noted that the CS, PM, WR, BR and MR also received the same amount of mineral fertilizers than CK, but also they received a surplus of nutrients from the recycled biomass. All of the raw data are obtained by on-site observations and measurements taken by the authors in 2010 and 2014. The details on the experiment are shown in Long et al. (2015).

Table 1
Details on characteristics of topsoil, fertilization and yield of different treatments.

Treatments[a]	Organic matter (g/kg)		Bulk density (g/cm^3)		Chemical fertilizer (kg/h/year)[c]			Organic fertilizer		Yield (kg/ha)
	Oct. 2010	Oct. 2014	Oct. 2010	Oct. 2014.	N	P_2O_5	K_2O	Recycled waste (kg/ha/year)	Energy contribution [b] (J/ha/year)	
CS	6.95	10.95	1.44	1.23	300.00	52.00	248.00	15530.26	22.59	17025.65
PM	7.40	12.96	1.40	1.23	300.00	52.00	248.00	32264.89	20.04	18903.11
WR	7.41	11.66	1.45	1.24	300.00	52.00	248.00	18373.81	22.33	18780.42
BR	7.95	14.83	1.44	1.24	300.00	52.00	248.00	39037.50	18.46	18520.91
MR	6.88	14.79	1.44	1.13	300.00	52.00	248.00	27462.83	18.74	17726.52
CK	7.21	6.85	1.45	1.30	300.00	52.00	248.00	0.00	1.76	16185.45

[a] Control treatment (CK) only applied chemical fertilizers, crop straw (CS), biogas residue (BR), mushroom residue (MR), wine residue (WR), pig manure (PM).

[b] The energy contributions from organic matter used for crop farming are accounted for based on Eq. (6) in Section 2.5.

[c] The CS, PM, WR, BR and MR also received the same amount of chemical fertilizers than CK, but also they received a surplus of nutrients from the recycled resources.