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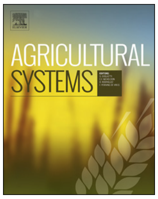

Environmental costs and mitigation potential in plastic-greenhouse pepper production system in China: A life cycle assessment

Xiaozhong Wang[a,b,c], Bin Liu[a], Gang Wu[d], Yixiang Sun[d], Xisheng Guo[d], Zhenghui Jin[e], Weining Xu[e], Yongzhi Zhao[f], Fusuo Zhang[a], Chunqin Zou[a,*], Xinping Chen[a,b,c]

[a] *Center for Resources, Environment and Food Security, China Agricultural University, Beijing, 100193, China*
[b] *Academy of Agricultural Sciences, Southwest University, Chongqing 400716, China.*
[c] *College of Resources and Environment, Southwest University, Chongqing 400716, China*
[d] *Soil and Fertilizer Research Institute, Anhui Academy of Agricultural Sciences, Hefei 230031, China*
[e] *Anhui Sierte Fertilizer Industry Co., Ltd., Ningguo 242300, China*
[f] *Beijing Soil Fertilizer Extension Service Station, Beijing 100029, China*

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ABSTRACT

Intensive vegetable system is commonly considered as high environmental costs due to high inputs, thus quantifying the mitigation potential of various environmental impacts, and developing strategies to improve the sustainability of this system was critical. Here we used partial life cycle assessment (LCA) to quantify the environmental impacts of a plastic-greenhouse pepper production system in China, and then employed an environmental impact gap methodology to analyze the mitigation potential of various environmental impacts and to establish better management strategy. The results showed that the global warming, acidification, eutrophication potentials and energy depletion of 160 farm-gate analysis were in average of 6.4 metric tons CO_2-eq ha^{-1}, 54.5 kg SO_2-eq ha^{-1}, 50.9 kg PO_4-eq ha^{-1}, and 57.3 GJ ha^{-1}, respectively. Fertilizer accounted for 64.4%, 78.6% and 97.9% for the global warming, acidification, and eutrophication potential, respectively, while structural materials for greenhouse accounted for 58.6% of the total energy depletion. Based on analysis of yield gap and environmental impact gap by survey date grouping, the results showed that the pepper yield of the 1st quartile (best 25%) was 26.6% higher compared to the mean of all 160 farmer yields due to better nutrient and crop management. And at meantime, on per metric ton of pepper production, the global warming, acidification, eutrophication potentials and energy depletion were lower by 23.9%, 25.0%, 25.7%, and 23.2% in this system, respectively. In conclusion, the integrated nutrient-crop management strategies based on best famers' practices could close the gap of environmental impacts significantly.

1. Introduction

Sustainable intensification of agriculture is currently one of the main concerns of scientific and public community. In general, the intensive vegetable system is commonly considered as high environmental costs, especially greenhouse vegetable system, which has increased vegetable yield significantly by extending growing seasons and intensifying cultivation (Costa and Heuvelink, 2004;Chang et al., 2013). However, due to the excessive material inputs (Chang et al., 2013; Khoshnevisan et al., 2014), this system also resulted in significant environmental impacts, such as greenhouse effect (He et al., 2009; Chang et al., 2013), soil and groundwater pollution (Ju et al., 2007; Muñoz et al., 2008; Song et al., 2009). Quantitative understanding of the trade-offs between environmental impacts and vegetable yield is essential for developing management strategies that not only increase vegetable yields but also significantly reduce the environmental costs for greenhouse vegetable system.

Life cycle assessment (LCA) is a methodological framework for evaluating environmental effects for a product, process, or activity throughout its life cycle or lifetime, which is known as a 'from cradle to grave' analysis (Rebitzer et al., 2004; Hellweg and Canals, 2014). Since 1990s, the LCA has demonstrated to be a useful tool to assess environmental impacts for a large number of agricultural products. The previous studies had mainly focused on methodology establishment,

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Abbreviations: LCA, life cycle assessment; N, nitrogen; P, phosphorus; K, potassium; FU, functional units; PE, polyethylene; MS, agricultural materials stage; F, arable farming stage; CI, confidence intervals of mean

[*] Corresponding author.

E-mail address: zcq0206@cau.edu.cn (C. Zou).

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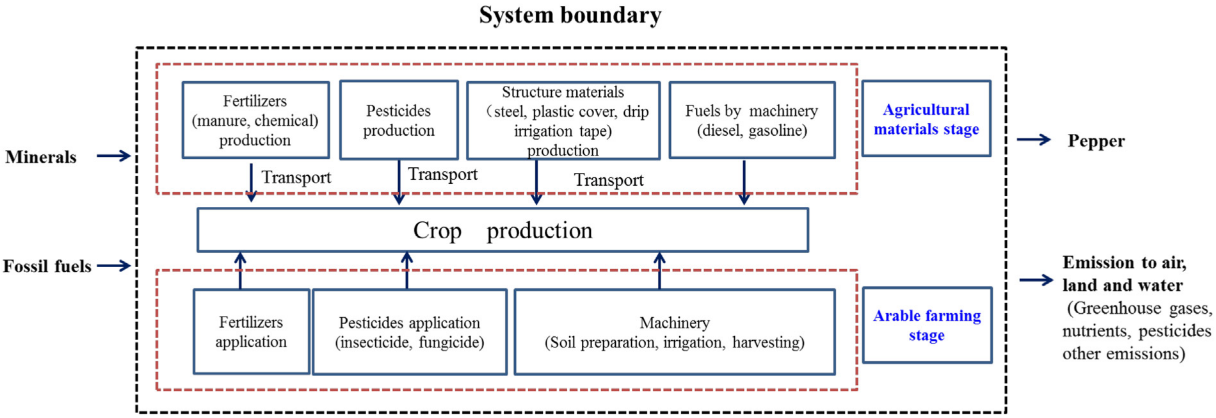

Fig. 1. Flow diagram stages of for pepper production system.

parameters, and system evaluation (Rebitzer et al., 2004; Guinée et al., 2011). Recently, more studies had focused on quantifying various environmental impacts and identifying the contributions of each life-cycle step in given regional-specific and crop-specific system to those impacts (Bojacá et al., 2014; Perrin et al., 2014; Adewale et al., 2016; Clune et al., 2017). In addition, other studies had also demonstrated the difference in environmental impacts of different systems, e. g. organic and conventional systems (Venkat, 2012; He et al., 2016; Goossens et al., 2017; Longo et al., 2017). Those studies indicated that the environmental impacts could be significantly different among regions, crops and systems (Perrin et al., 2014; Clune et al., 2017). And they clearly identified the role of nitrogen (N) fertilizer to global warming and acidification potentials (Yan et al., 2015b), phosphorous (P) fertilizer to eutrophication potential (Bojacá et al., 2014), and structural materials to energy depletion in greenhouse system (Torrellas et al., 2012; Bojacá et al., 2014).

However, LCA should be further developed to access the mitigation potential under different farm practices and eventually be used for establishing the optimum management practice. In today's farm practice, large yield gaps exist due to variation of management practices (Tittonell et al., 2008; Meng et al., 2013; Zhang et al., 2016). Fermont et al. (2009) have showed that yield gap could be closed significantly and rapidly if optimum famers' practices is adapted in a given region, especially for smallholder farmers' system. Here we hypothesize that the methodology of yield gap analysis could be modified and used for environmental impact gap, incorporated with LCA assessment, to analyze the mitigation potential of various environmental impacts, and to establish better strategies to close the gap of environmental impacts.

Pepper (*Capsicum annuum* L) is a typical and important vegetable in China and worldwide. Because of growing demand for fresh, off-season or high-quality vegetables, the total area of pepper production covered by plastic greenhouse has rapidly increased in China (Chang et al., 2011, 2013). Consequently, the aims of this study are to (a) quantify the environmental impacts (global warming potential, acidification potential, eutrophication potential and energy depletion) of pepper production in plastic-greenhouse system in China and identify the contributions of each life-cycle step to various environmental impacts based on 160 farmers survey and LCA methodology and (b) establish an environmental impact gap methodology to analyze the mitigation potential and thereby to find effective strategies to improve the sustainability of agricultural system.

2. Materials and methods

2.1. Study area and data sources

In this study, we present results from a survey conducted in 2015 covering 160 farmer households from 8 villages in Hexian county (118°04′ - 118° 29′ E;31°22′ - 32°03′ N), Anhui province. 60 thousand farmers producing pepper in this county, where represents one of the most important pepper production areas in the Yangtze River Basin with smallholder farmers. To ensure adequate samples, 8 villages were randomly selected from whole county, and 20 farmers from each village were randomly surveyed (Wu et al., 2014). Interviews with farmers were conducted face-to-face, and questions were designed to capture relevant data regarding their pepper production.

Important data collected from the interviews included: 1) sowing area, cultivar, sowing and harvesting dates, density of peppers, fruit yield; 2) amount and time of irrigation, fertilizers (N, P and potassium (K)) and pesticides application; 3) structure materials include amount and type of steel, and plastic, drip irrigation tape; 4) fuel and electricity consumption for field management and irrigation.

2.2. Life cycle assessment

The various environmental impacts were calculated by LCA methodology in accordance with ISO standards 14,040 and 14,044 (ISO, 2006a; b).

2.2.1. System boundary and functional units

This study focused on the pepper production. The LCA analysis for the pepper production system was divided into two stages: the agricultural materials stage and the arable farming stage (Fig. 1). And the impacts of seed production (and distribution) were not considered due to their low mass of pepper seeds, even if the seeds travelled long distances (Keskitalo, 2009). The functional units (FU) for analysis were per hectare and per metric ton of peppers, as these two FUs could better clarify environmental performance (Van der Werf et al., 2007).

2.2.2. Impact categories

A lot of impact categories have been considered to evaluate the environmental impacts by the LCA methodology (Torrellas et al., 2012; Khoshnevisan et al., 2014; Abeliotis et al., 2016). Global warming potential and energy depletion for agricultural production systems have always garnered more attention, and recently more and more studies have focused on acidification and eutrophication potential resulted from fertilizer inputs in the agriculture production (Khoshnevisan et al., 2014; Perrin et al., 2014; He et al., 2016). Therefore those four impact categories were considered as the indicators and impact categories for the analysis in this study. The global warming potential (CO_2 eq $Unit^{-1}$) and nonrenewable energy were estimated according to IPCC (2014) and Frischknecht et al. (2004), respectively. The acidification (SO_2 eq $Unit^{-1}$) and eutrophication (PO_4 eq $Unit^{-1}$) potentials were computed according to the Hauschild and Wenzel (1998). According to Huijbregts et al. (2000), Deng and Wang (2003), the equivalent coefficient of CO_2, CH_4, and N_2O emission for 100-year global warming