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Improving the sustainability of agricultural land use: An integrated framework for the conflict between food security and environmental deterioration

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ABSTRACT

In rapidly developing countries, intensive agriculture faces the conflict between food security and environmental deterioration. To improve the sustainability of agricultural land use, this paper proposes an integrated framework for risk assessment and conflict coordination to cope with these salient challenges at the administrative unit level. This framework is demonstrated using a case study conducted in the Dongting Lake area in China. Drawing upon diverse sources of statistical data concerning agricultural inputs and outputs, water resources and natural hazards as well as questionnaire surveys conducted at the household level, this paper uses the Cobb-Douglas production function and the water environmental pressure index to assess food insecurity risk and environmental risk from food production, respectively. A double matrix method is used to characterize the degree of sustainability based on the risk assessment. The results indicate that the overall food security of the region can be maintained in the negligible-risk range. However, rising agro-environmental risks from grain production in the coming years are likely to threaten the sustainability of agricultural land use in most administrative units. It is suggested that optimization of land use patterns and mitigation of natural hazards could be effective approaches to improve the sustainability of local agricultural land use.

1. Introduction

Food insecurity is a key risk to economic development, social stability and national autonomy (Krishnamurthy, Lewis, & Choularton, 2014; Qi, Zhong, & Liu, 2015). In the past several decades, many rapidly developing countries experienced pressure from population growth, urban land expansion, farmland loss, human dietary shifts and the turbulence of global food markets (Huang & Yang, 2017; Huang, Liu, Martin, & Rozelle, 2009; Qiang, Liu, Cheng, Kastner, & Xie, 2013; Seto, Michail, Burak, & Reilly, 2011; Wu & Guclu, 2013). To guarantee food self-sufficiency with limited farmland resources, active promotion of the transformation from extensive to intensive agriculture has become a policy option for many of these countries (Diniz, Kok, & Arts, 2013; Li, Chen, Wang, & Liu, 2014). By relying on increasing input of chemical fertilizers, intensive agricultural land use patterns have significantly increased the national grain output in many areas and caused serious damage to the upstream environment of the agricultural sector, farmland and downstream communities (Gomiero, Pimentel, & Paoletti, 2011; Schreinemachers & Tipraqsa, 2012; Vitousek et al., 2009).

Food security can be measured from various perspectives. Most studies have analyzed food security from availability, access and utilization perspectives and primarily focused on the individual or household level (Ericksen, 2008; Ingram, 2011; Maye & Kirwan, 2013). Food availability refers to the amount, type and quality of food that a unit has at its disposal to consume. Access to food refers to the ability of a unit to obtain the type, quality, and quantity of food it requires. Food utilization refers to individual or household capacity to consume and benefit from food (Ericksen, 2008). Although this analytical framework is insightful and can provide extensive information to evaluate individual or household food security, it has two major flaws. First, it is difficult to collect accurate data to support analysis because the interactions between household food access and food acquisition and household income and food consumption interactions are very complex (Pinstrup-Andersen, 2009). Second, because the framework primarily focuses on an individual's ability to acquire food, it is difficult to evaluate corresponding environmental outcomes.

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Other studies beyond the individual or household level primarily focus on the issue of food security in different administrative units (i.e., national, provincial and municipal units). Using food self-sufficiency or food sovereignty as the evaluation criteria (Pinstrup-Andersen, 2009), they are generally concerned with the issues that may cause food insecurity, such as climate change (Hanjra & Qureshi, 2010; Li, Yang, et al., 2014), natural hazards (Hao, Zhang, & Liu, 2011; Simelton, 2011), resource constraints (Khan, Hanjra, & Mu, 2009; Qi, Vitousek, & Liu, 2015b), labor shortage (J. Chen, 2007; Savary, Castilla, Elazegui, & Teng, 2005), price fluctuation (Byerlee, Jayne, & Myers, 2006; Dawe & Peter, 2012) and consumption growth (Gandhi & Zhou, 2014; Li, Zhao, & Cui, 2013). These studies provide valuable methods for assessing food security at the national or regional levels but the environmental risks arising from intensive agricultural practices to attain food security have been neglected or only briefly discussed.

Numerous studies on the environmental risks related to agricultural land use have been conducted at the watershed or farm scale. The major environmental risk from agricultural land use is non-point source pollution, which arises from excessive use of agrochemicals (Vitousek et al., 2009; Zhuo, Liu, Kuang, & Qi, 2014). To overcome the challenge of monitoring or measuring non-point source pollution, existing studies have mostly used simulation models such as the Soil and Water Assessment Tool (SWAT), the Agricultural Non-Point Source (AGNPS) model and the Agricultural Policy and Environmental eXtender (APEX) model to estimate pollution (Gassman et al., 2009; Haregeweyn & Yohannes, 2003; C. Sun & Ren, 2014; P. Zhang, Liu, Pan, & Yu, 2013). These models are only applicable in specific watersheds or farms due to the high sensitivity of model parameters, which vary with climatic and hydrogeological conditions. Moreover, studies conducted at the watershed or farm scale may not generate useful insights for policymakers because the effects of their policy instruments are confined by administrative boundaries. There is a mismatch between the practical needs of local policymakers and available options developed from previous research.

Considering this research gap, there is great value in developing an integrated framework that is compatible with the boundaries of administrative units and generalizable in addressing the conflict between food security and environmental deterioration. This paper aims to engage in this task and seeks possible policy measures to attain sustainable agricultural development in rapidly developing countries. Because grain is key to ensuring national food security and because environmental risks are mainly derived from excessive chemical inputs under intensive agricultural land use patterns, this study focuses on the inputs and outputs of grain production in the analysis. The remaining sections of this paper are organized as follows. Section 2 introduces the research methods and general analytical procedures. Section 3 introduces the background of the selected case study area and data sources. The results are presented in section 4. Section 5 discusses the main findings and limitations. Section 6 concludes the paper.

2. Methods and procedures

2.1. Analytical framework

Fig. 1 illustrates that both positive (additional food supply) and negative (additional chemical pollutants) effects are produced by intensive agricultural land use patterns. At the national or regional level, food insecurity risk emerges when the food supply fails to meet the demand. To reduce this risk, the main approach is to increase the supply with additional agrochemical input. However, agro-environmental risk arises when non-point source pollution from chemical pollutants exceeds the regional environmental carrying capacity and this risk is intensified by greater agrochemical input for additional food supply due to limitation of the regional environmental carrying capacity. To achieve sustainable development of agriculture, the conflict between these two risks must be coordinated.

There are two approaches to achieve the objective of agricultural sustainability. One is optimization of anthropogenic inputs (especially chemical inputs), which is essential for reducing environmental risk. The other is mitigation of natural hazards, which could directly reduce food insecurity risk. Based on this framework, we propose a three-step approach for our analysis. First, guided by the classical technical guidance of risk assessment (USEPA., 1998), an incorporated risk assessment method that includes risk identification, risk analysis and risk characterization is used to systematically assess the risks from food insecurity and agro-environmental deterioration. Second, based on assessment of the risks, a double risk matrix method is used to evaluate the sustainability status of agricultural land use. Finally, optimization approaches that could improve agricultural sustainability are proposed based on the risk and sustainability status assessment results, current anthropogenic and natural inputs and the regional policy context.

To provide comparable results for regional policy makers who must address the risks from food insecurity and environmental deterioration in the foreseeable future, 2017 and 2020 were selected as the evaluation years for this paper.

2.2. Risk assessment for food insecurity

2.2.1. Risk identification

The sources of food insecurity risk can be divided into natural risk and anthropogenic risk (Qi, Vitousek, & Liu, 2015a; Simelton, 2011). The former mainly refers to natural hazards such as floods, droughts, hailstorms, frosts, pests and disease, which vary across regions, and the latter includes labor, machinery and chemical input constraints and food demand growth.

2.2.2. Risk analysis

Natural hazards usually lead to loss of grain output. Due to the unpredictability and randomness of natural hazards, historic annual average grain losses caused by natural hazards are used to estimate the impact of natural hazards on regional grain output in the evaluation years. The input elements may increase or decrease grain output. Food demand growth in developing countries is mainly due to the combined effect of dietary change (more meat and less grain) and population growth (Qi et al., 2015b; Simelton, 2011). The impacts of these risks on regional food security are analyzed as follows.

Several methods can be used to assess regional food production or consumption status, including fault tree analysis (FTA) (Qi et al., 2015a), data envelopment analysis (DEA) (Mousavi-Avval, Rafiee, & Mohammadi, 2011) and the Cobb-Douglas (C-D) production function (Amaza & Olayemi, 2002). Among these methods, the C-D production function can be used to comprehensively evaluate the impacts of input elements on grain output; it has been widely used in previous studies (Amaza & Olayemi, 2002; Qi et al., 2015b; Sun & Zhu, 2012). Thus, we adopt this method in this paper. With reference to the above studies, seven input elements of the sown grain area, nitrogen fertilizer inputs, phosphorus fertilizer inputs, potassium fertilizer inputs, pesticide inputs, machinery inputs and labor inputs were selected to establish the grain production function. First, the following function is used to eliminate the dimensional difference among these input elements:

$$x_i' = \frac{x_i}{\max x_i} \quad i = 1,2, \ldots n. \tag{1}$$

where x_i and x_i' are the actual value and the dimensionless value, respectively, of an input element in the ith year.

Second, for a specified evaluation unit, the basic C-D production function is as follows:

$$lnG = \beta_0 + \beta_1 lnx_1 + \beta_2 lnx_2 + \beta_3 lnx_3 + \beta_4 lnx_4 + \beta_5 lnx_5 + \beta_6 lnx_6 + \beta_7 lnx_7 + \mu \tag{2}$$

where G represents the grain output, β_0 represents a constant, x_1-x_7