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Analysis

Linkage between crop diversity and agro-ecosystem resilience: Nonmonotonic agricultural response under alternate regimes

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ABSTRACT

This study investigates the dynamic linkage between crop diversity and agro-ecosystem resilience. The analysis estimates a panel data of rice farming in Japan using a time-varying transition probability Markov switching model, capturing (i) the alternate regimes of agro-ecosystems, (ii) the controlling factors affecting the regime shifts of agro-ecosystems, and (iii) the nonmonotonic response of agricultural production under alternate regimes. Results show that the effect of crop diversity on agro-ecosystem productivity differs depending on its regimes. Crop diversity increases productivity during normal periods, a normal regime, while it decreases the productivity during periods exposed to disturbances such as extreme weather events and disease and insect damage, an adverse regime. Further, we find that crop diversity enhances the agro-ecosystem resilience. Thus, it increases the likelihood of the agro-ecosystem remaining in a normal regime and staving off an adverse regime. The crop diversity loss has gradually increased in agro-ecosystems without sufficient understanding about the linkage between crop diversity and agro-ecosystem resilience. Our findings suggest the possibility that the agro-ecosystem resilience would be a key driver of sustainable agriculture under increasing uncertainties. This study gives useful insights on this issue by empirically demonstrating the effects of crop diversity on the agro-ecosystem resilience.

1. Introduction

Agricultural production is affected not only by controllable inputs but also by uncontrollable environmental conditions such as extreme weather events, plant diseases, and insect pests. It has been a long-standing challenge for farmers to mitigate these negative impacts and to adapt their agricultural methods to such risks. However, it is anticipated that farmers will be facing a significantly more difficult situation if these uncontrollable environmental conditions change in an unknown way under climate change (Mestre-Sanchís and Feijóo-Bello, 2009; Schlenker and Lobell, 2010; Lobell et al., 2011; Fisher et al., 2012).

Resilience,[1] which is defined as the ability of the ecosystem to absorb change and disturbance and still maintain the same function and structure (Holling, 1973), has drawn great attention in addressing the increasing uncertainties in agro-ecosystems. Agro-ecosystems might change abruptly if the pressure of disturbance exceeds a certain threshold,[2] resulting in great losses in agricultural production (Walker et al., 2010). At such times, attempted removal of the disturbance from agro-ecosystems is expected. However, this practice is not recommended because such disturbances in nature are not fully under human control and are often necessary for the renewal of ecosystems. Rather, it is preferable to understand the mechanism of the agro-ecosystem, particularly the resilience of the agro-ecosystem under the effects of controlling variables as well as the disturbances. It is important to understand that the controlling variables can sometimes change gradually with time and degrade the resilience of agro-ecosystems before they can be managed, leading to the vulnerability of agro-ecosystems. For effective ecosystem management, we should address the changes in controlling variables that affect resilience rather than merely trying to control the disturbance (Scheffer et al., 2001).

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[1] To be exact, resilience has three components: latitude, which is the maximum amount a system can be changed before losing its ability to recover; resistance, which is the difficulty of changing the system; and precariousness, which is the closeness of the current state of the system to the threshold. The measure of resilience used in this paper is the resistance. Detailed discussions on resilience appear in Arrow et al. (1995); Scheffer et al. (2001); Walker and Meyers (2004); Mäler (2008), and Walker et al. (2010).

[2] These abrupt changes of ecosystems are generally known as regime shifts. Walker et al. (2010) classified the regime shifts of the ecosystem into three types according to its reversibility: reversible, difficult to reverse, and impossible to reverse. Following their classification, we discuss the reversible regime shifts of the agro-ecosystem affected by disturbances such as extreme weather events without feedback changes.

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Diversity is one of the controlling factors affecting agro-ecosystem resilience (Naeem and Li, 1997; Folke et al., 2004). In the literature, it is suggested that ecological diversity contributes to maintaining the ecosystem function and structure through mechanisms such as "insurance hypothesis" and "resource partitioning." Despite its importance, few empirical studies have examined the linkage between resilience and diversity in agro-ecosystems, partly because the regime shifts of agro-ecosystems are unobservable, or the data are limited.[3] The Millennium Ecosystem Assessment (2005, pp5–6) described this situation by stating "there is *established but incomplete* evidence that reductions in biodiversity reduce ecosystem resilience [sic]."

In this study, by using the panel data of rice farming in Japan, we show that the linkage between crop diversity and the resilience of agro-ecosystems can be captured by a time-varying transition probability (TVP) Markov switching model originally proposed by Hamilton (1989) and developed by Filardo (1994) and Kim (1994). The three important features of this econometric model are that it can (i) consider alternate regimes of agro-ecosystems, (ii) explicitly specify the controlling factors affecting the agro-ecosystem resilience, and (iii) describe the nonmonotonic response of agricultural production under alternate regimes. Under actual conditions, we cannot directly observe the regime of agro-ecosystems; therefore, we must guess it indirectly based on agricultural production. We approach this problem by using the concept of likelihood. Resilience is closely related to the regime shifts of the ecosystems; we estimate the likelihood of the agro-ecosystem remaining in the same regime or changing from one regime to another depending on crop diversity. The TVP Markov switching model captures these ecosystem dynamics. From the perspective of policy implications, given the occurrence of regime shifts, the model demonstrates how effective agro-ecosystem management can be achieved under adverse circumstances.

Our empirical findings indicate that the Markov switching model can effectively describe regime shifts of the agro-ecosystem because the alternate regimes of the agro-ecosystem from our model closely represent the difference between normal times and the periods in which the system is exposed to potential risks. We also elaborate on the effects of crop diversity on agro-ecosystem resilience. Crop diversity strengthens the ability of the agro-ecosystem by absorbing the detrimental impacts of disturbances and staving off calamity. Finally, we show that crop diversity has various effects on agro-ecosystem productivity depending on its regime. Crop diversity increases productivity during normal times, but decreases are shown during periods of exposure to certain risks.

These findings have useful implications for sustainable agro-ecosystem management under the current worldwide trend of diversity loss (Van de Wouw et al., 2010; Dyer et al., 2014). Many studies have argued the inclusion of resilience into the inclusive wealth model is considered key to achieving sustainability (Arrow et al., 2003; Mäler, 2008; Walker et al., 2010). However, the issue of resilience quantification and incorporation into the inclusive wealth model remains unresolved. This study, using the concept of likelihood of regime shifts, gives a useful insight into this issue by empirically illustrating the effects of crop diversity on the resilience of agro-ecosystems.

The remainder of this article is organized as follows. Section 2 explains the background of our study on rice farming in Japan. Section 3 introduces an econometric model based on the TVP Markov switching model and its estimation procedure using panel data. Section 4 offers estimation results and draws policy implications. The final section summarizes our conclusions.

[3] Numerous studies have discussed the relationship between diversity and other aspects of agro-ecosystem, i.e., productivity and stability, from various viewpoints, such as Smale et al. (1998); Tilman et al. (1998); Tilman (1999); Weitzman (2000); Mittelbach et al. (2001); Pfisterer and Schmid (2002); Loreau et al. (2003); Di Falco and Perrings (2005); Steiner et al. (2005); Di Falco et al. (2010); van Ruijven and Berendse (2010), and Palatnik and Nunes (2014).

2. Background of Analysis: Rice Farming in Japan

Rice is a staple in the Japanese diet. Its self-sufficiency ratio on a production value basis has been kept at almost 100%. The self-sufficiency ratio of other major crops in Japan is considerably lower. For example, in 2014, those of corn and wheat were 0% and 12%, respectively (Ministry of Agriculture, Forestry and Fisheries, 2016). In dry-field farming, which used for corn and wheat, it is preferable to rotate cultivated crops or leave land fallow in order to avoid replant failure. However, replant failure is irrelevant in wet-rice farming. The feasibility of repeated cultivation is essential in Japanese agriculture for securing stable agricultural production because farmers in Japan have historically been involved in small-scale farming, with 90% of rice farmers cultivating less than 2 ha, which leaves insufficient land for leaving fallow. These unique production conditions make it difficult to substitute different crops for rice.

Fig. 1 shows the trend of climate conditions and rice production in Japan during 1900–2010. Occasional low temperature and high precipitation are likely to cause crop failure. In addition, plant disease and insect pests associated with extreme weather events can spread widely across fields, which results in persistent decreases in rice production over several years. Rice farmers would be exposed to further risks in the long term. The increases in temperature and variation in precipitation experienced in the 20th century are expected to progress in the future (Japan Meteorological Agency, 2014). In fact, the adverse effect of high temperature on rice farming has been observed recently in warmer regions in Japan (Ministry of Agriculture, Forestry and Fisheries, 2007). It is also feared that extreme precipitation causes more severe losses in rice production. Thus, it is becoming more important for rice farmers to adapt to the unpredictable changes of environmental conditions along with climate change.

Fig. 1 shows that rice production rose consistently until the 1960s and, in reversal, decreased since then. In fact, rice production consistently increased throughout the 20th century owing to the expansion of agricultural land, mechanization, the use of chemical fertilizers and pesticides, the installation of irrigation facilities in almost all cultivated area in Japan, and land improvement with governmental support. However, the excessive amounts of rice produced around the 1960s induced the policy shifts from "support" to "adjustment," in which rice farmers were encouraged to reduce the acreage, resulting in gradual decreases in rice production.

Rice farmers have also advanced the monoculture to simplify production management because the timing of planting and harvesting, water management, and mid-season drainage differ among rice varieties. In the early 20th century, 3500 rice varieties were cultivated in Japan (Suge, 1998). However, this number has gradually decreased to 300 as a result of variety selection and breed improvement. Fig. 2 shows the ratios of cultivated land for each rice variety to total cultivated land, focusing on the 10 most produced varieties in Japan plus two formerly used rice varieties. Variety 1 has consistently increased since 1960 to a current level of almost 40 % of cultivated land. Varieties 2 through 10 have appeared since the late of 1980s and have replaced the declining varieties 11 and 12, which used to be the main rice varieties. Currently, only these 10 varieties occupy 83.2% of the total cultivated land, implying a significant loss of crop diversity in rice faming in Japan.

3. Econometric Model

3.1. Data

For our analysis, we use a balanced panel dataset of 46 prefectures in Japan during 1975–2003.[4] The data is consists of statistics published by

[4] We exclude Okinawa Prefecture from our sample because although rice is produced in this prefecture, the amount is little. The sample period is limited by data availability.