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Spatial emergy analysis of agricultural landscape change: Does fragmentation matter?

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ABSTRACT

Approximately 17% of agricultural lands in the western plain of Taiwan were converted to other uses during 1971–2006 due to rapidly industrial and urban development and high population density. Previous studies on the loss of farmland due to urbanization have focused on changes in the agricultural landscape such as fragmentation and irregular shape of farmlands. The shrinkage and fragmentation of agricultural land due to urbanization not only reduces food production but also results in the decrease and degradation of other agro-ecosystem services. Emergy synthesis has been used to assess land use changes in agricultural lands. However, the relationship between farmland fragmentation and the energy flows in agricultural systems has not been studied. This paper investigates empirically how ecological energetic flows of agricultural land were affected by landscape change in the western coastal plain of Taiwan by using emergy synthesis to assess the changes in ecological energetic flows of agricultural systems in each township from 1971 to 2006. Landscape metrics were also chosen to analyze the agricultural landscape change in each township. These metrics were then correlated with the results of emergy synthesis to study the relationship between farmland fragmentation and energy flows in the agricultural system. The results show that the fragmentation of farmlands tends to intensify the inflows of goods and services from the human economic system for farmland operations. For the counties closer to metropolitan areas, maintaining larger farm sizes and preventing farmland fragmentation decreases the proportion of resource inflows from the economic system and mitigates environmental loading in agricultural systems.

1. Introduction

Urbanization has significant impacts on earth's landscape. Owing to urbanization, the land use and land cover changes are the major cause of converting agricultural areas into built-up areas (Du et al, 2014; Pribadi and Pauleit, 2015; Thompson and Prokopy, 2009). Fragmentation of farmland has become one of the most significant results of urbanization, with impacts on ecosystem services over entire landscapes (Pauchard et al., 2006). Farmland contributes to food production, air cleansing, flood control, and water filtration, cultural services, as well as, its inherent societal value as open space (Nelson, 1992; Zhang et al., 2007) and enhanced supporting services (Swinton et al., 2007). Furthermore, the land cover transformed from farmland to built-up land is now considered an irreversible process (Haygarth and Ritz, 2009; Seto et al., 2011; Skog and Steinnes, 2016).

Landscape mosaics are mixtures of natural and human-managed patches that differ in size, shape, and configuration (Forman and Godron, 1986). It is known that the ecological functions and processes and the landscape pattern deeply interact (Alberti et al., 2007; Forman, 1995). Urban expansion can cause fragmented landscape resulting in habitat shrinkage and disturbances on ecological communities. The impacts of urbanization on agricultural land have been addressed in many studies (Chen, 2007a,b; Huang et al., 2012; Jiang et al., 2012; Su et al., 2014). Accelerating urbanization results in degradation of agricultural landscapes, which influences not only food production but also a variety of ecological processes. All of these impacts eventually poses a threat to farmland sustainability.

From 1970 to 2000, the rapid economic growth in Taiwan transformed the country from a rural to an industrialized economy (Huang et al., 2007). Huang et al. (2009) used landscape metrics to assess the spatial and temporal changes of landscape pattern of peri-urban areas of northern Taiwan and the results showed that the agricultural landscape has become significantly fragmented in the non-urban planned areas. The loss of farmland due to urban sprawl in peri-urban areas of Taoyuan County in Northern Taiwan not only resulted in the loss of farm ponds but also decrease the connectivity and circuitry between irrigation ponds and canals (Huang et al., 2012). The resilience of ecological and social systems to typhoons in Northern Taiwan was also

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examined by Wang et al. (2012) and the results indicated that the loss of farmland due to peri-urbanization had degraded the regulatory function of agricultural ecosystem services. Lee et al. (2015) assessed ecosystem services of farmland landscape in Taiwan's western coastal plain by using landscape metrics. Their work demonstrated that farmland loss eventually results in a reduction of agro-ecosystem services.

Previous emergy synthesis studies of farmland systems were frequently done using resource inflows to the total area of farmland in a given study area. However, from a landscape ecology perspective, both the composition and configuration of land cover types affects the ecological functions of a landscape. The spatial differences of emergy flows due to the spatial heterogeneity of landscape characteristics should receive more attention. The relationship between farmland fragmentation and the emergy flows in agricultural energetic systems has yet to be studied. In order to study the relationships between landscape change of paddy rice fields in Taiwan's western coastal plain and its ecological economic effects, Lee (2013) selected seven research sites along the western coast of Taiwan and examined the relationship between their landscape metrics and emergy indices. The results revealed that the characteristics of energetic flows of paddy rice fields were related to the spatial arrangement of paddy rice fields. Failure to preserve agricultural land and prevent the paddy rice field from fragmentation tends to increase energetic inflows from the economic system and decreases the environmental sustainability in agricultural landscapes. To further study the environmental implications of farmland fragmentation, this study expanded the study area to include all agricultural fields in Taiwan's western coastal plain and uses emergy synthesis and landscape metrics to study how farmland fragmentation impacts emergy flows in an agricultural energetic system. Under the premise that maintaining larger farmlands in agro-environment would help agricultural landscape systems capture more renewable energy flows, this paper analyzes the performance of landscape metrics and emergy indices of agricultural landscape to address the following research questions:

- Does the shrinkage and fragmentation of farmlands intensify the resource inflow of goods and services from the economic system to the agricultural landscape system?
- Do agricultural landscapes with irregular shapes or smaller farmland sizes have higher environmental loadings?

2. Material and methods

The study area of this paper includes the entire western coastal plain of Taiwan with the unit of analysis being the 251 townships within the 16 cities/counties in this region (Fig. 1). Taiwan's geography is characterized by its mountainous landscape in the central part of the island, with approximately 70% of the total land area exceeding slopes of 15%. Almost 90% of population in Taiwan resides along the western coastal plain; the population had grown from 12.7 million in 1971 to 21 million in 2010. Several landscape metrics were chosen to study agricultural landscape change in each township. In order to study how fragmentation would affect emergy flows in agricultural landscapes, emergy synthesis was used to evaluate differences in ecological energetic flows of the agricultural system in each township in 1971 and 2006 (Fig. 2). The results of landscape metrics and emergy synthesis were then compared for the cities or counties with land use of farmland greater than 20 percent to study the relationships between landscape fragmentation and characteristics of energetic flows in the agricultural landscape.

2.1. Landscape metrics

Landscape metrics have been previously applied to study urbanization and land use and land cover change (Huang et al., 2009; Luck and Wu, 2002; Seto and Fragkias, 2005; Weng, 2007; Yu and Ng, 2007). In order to analyze agricultural landscape change of the study area due to changes of land use and land cover, the officially published land use and land cover maps of 1971 and 2006 were collected for analysis. This study selected several landscape metrics and use FRAGSTATS version 4.2 (McGarigal et al., 2012) to calculate landscape metrics to assess the fragmentation of farmland (Table 1). Change of agricultural lands directly affects crop production, therefore provisioning ecosystem services can be reflected through the percentages of farmland (PLAND). From the perspective of configuration of agricultural landscape, the larger farm size (Mean Patch Size) and more regular shape (SHAPE) will be buffered from disturbances, making the practice farming more efficient. When a landscape is fragmented due to land use change, patch number increases and the size of patch becomes smaller, creating more edges (Botequilha-Leitão et al., 2006). There by using these metrics we can assess the degree of farmland fragmentation that has taken place in each township and across the entire region over the thirty-five year period of the study.

2.2. Emergy synthesis

Emergy synthesis is a concept and method of ecological energetic analysis that uses a common energy unit to measure the input flows of natural and economic resource to evaluate the contribution of natural environment to the economic system (Odum, 1996). The emergy synthesis has been applied as a tool for environmental policy by synthesizing different resources on the basis of the dynamic interaction between ecological and economic systems. Emergy indices have been used to assess the sustainability of the economic use of resources by quantifying both environmental and economic resource flows in emergy terms and then analyzing how resource flows from natural environment and economic system match. The theories of ecological energetics and energy hierarchy embedded in the emergy concept can also explain the spatial hierarchy of a landscape. The sustainability of a landscape must rely on the ability to balance the inflows and outflows of energy between different components and its ability of maximizing energy inflows (Lee et al., 2013). Emergy synthesis has been used to evaluate different food production methods for assessing the sustainability of agricultural systems (Rótolo et al., 2015; Franzese et al., 2013; Zucaro et al., 2013; Lefroy and Rydberg, 2003; Rydberg and Jansen, 2002; Ulgiati et al., 1994; Ulgiati and Brown, 1998). Such studies have also been applied at different spatial scales ranging from a single farm to regional or national agricultural systems.

Using Odum's energy circuit language, Fig. 3 shows an aggregated flow diagram of an agricultural system to present the different resource inflows and they are interacted to produce yields. The emergy synthesis of the agricultural system can be started by multiplying the energy content or mass of each flow by its transformity. The emergy flows are normalized both for area (1 ha) and time (1 year) and the values of transformities are mostly referred to literatures and are relative to the 9.44E + 24 seJ/year baseline (Odum, 1996):

$$\text{Emergy (seJ)} = \text{energy (J)} \times \text{solar transformity (seJ/J)} \qquad (1)$$

Emergy indices for evaluating system performance can be calculated by aggregating emergy values of resource flows. The definition and explanation of the aggregated emergy flows and emergy indices used in this paper are summarized and described as follows:

Renewable emergy flows (R): The emergy of energy flows from the biosphere are more or less reoccurring constantly (e.g. sun, wind, rain, etc.), and that ultimately drive the biogeochemical processes of the ecosystem. The value of R for the study system is by derived selecting the largest flow from renewable sources (sun, wind, rain, etc.) to avoid double counting.

Non-renewable flows (N): The total emergy of material and energy flows such as minerals, soils, and ground water for irrigation from within the study system that are depleted at rates far exceed the rates they were produced.