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Ecological network analysis of an industrial symbiosis system: A case study of the Shandong Lubei eco-industrial park

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ABSTRACT

China's Shandong Lubei eco-industrial park was approved for construction in 2003, just after the first national eco-industrial demonstration parks were confirmed by China's State Environmental Protection Administration in 2002. It has therefore been recognized around the world as a successful example of an industrial symbiosis system. The park's success results from the harmonious and coordinated relationships among its members. Analyzing the ecological characteristics of these relationships and identifying the resulting advantages provide a basis for improving the park's efficiency and examining other parks. In this paper, we analyzed the flows of sulfur in the Lubei park (as an example of typical flows) using ecological network analysis to describe this industrial symbiosis system. The integrated analysis of the utility resulting from direct and indirect exchanges of byproducts and wastes can reflect the ecological relationships among members within the system. Based on these ecological relationships, members can be divided into producers, primary consumers, and secondary consumers; the integral flow weight for each level of the hierarchy can then be compared to reveal the system's overall ecological structure. By examining the exchanges of resources within the system, we can describe the ecological connotations of the symbiosis and how these ecological relationships influence the overall development and resource flows within the system.

1. Introduction

The Shandong Lubei eco-industrial park has been developing rapidly and stably since it was approved for construction in 2003 (Chen et al., 2010). It is currently the biggest base for China's ammonium phosphate, sulfuric acid, and cement joint-production plants (Shandong Lubei Enterprise Group General Company, 2013). The park leads the development of Chinese eco-industrial parks, and its ecological and economic benefits have been increasing significantly. These good results arise from the stable and harmonious relationships among members of the park. Therefore, important insights can be gained by examining the flows of byproducts and wastes among the members of the park in terms of an ecological analogy that describes the connotations behind these relationships and their strengths or weaknesses. The theoryof interspecies relationships that was developed for use with ecological systems can also effectively explain the relationships based on exchanges of resources that arise among the members of a socioeconomic system, and can be used to analyze the nature of the ecological relationships between any two members that result from their interaction. This form of analysis will therefore reveal ways to improve the park's functioning and guide the development of other eco-industrial parks.

An eco-industrial park is a typical example of an industrial symbiosis (Côté and Cohen-Rosenthal, 1998). Industrial symbiosis is a subset of industrial ecology (Roberts, 2004) in which traditionally separate industries act collectively to obtain a mutual competitive advantage through their physical exchanges of materials, energy, water, and byproducts (Chertow, 2000). For the cooperating industries, resource availability can be increased through reusing and recycling the byproducts and wastes of other industries, thereby providing economic and environmental benefits for all members of the park, as well as for society (Chertow, 2007; Geng et al., 2010; Park et al., 2008; Mirata, 2004).

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The Kalundborg eco-industrial park provided a proof that this concept works in practice, and provided an impetus for the development of industrial symbiosis systems around the world (Ehrenfeld and Gertler, 1997; Jacobsen, 2006). In this park, exchanges of industrial byproducts or wastes among plants arose via spontaneous communication among the members (Desrochers, 2001, 2004; Kaiser, 1999). Once the benefits of this approach became apparent, industries in other countries began to wonder whether they might achieve similar success, and some countries explicitly set out to create their own eco-industrial parks. The industrial symbioses in the United States were sponsored by federal government through the President's Council for Sustainable Development (Gibbs and Deutz, 2007). Japan aimed to establish innovative recycling activities in cities and based them on its existing "eco-town" program (van Berkel et al., 2009; Zhu and Côté, 2004). In South Korea, an eco-industrial park project was initiated under the leadership of the Korea National Cleaner Production Center (Behera et al., 2012). Once parks were developed, researchers began to compare industrial symbioses from different countries (Gibbs and Deutz, 2007; Heeres et al., 2004).

Material-flow analysis was introduced to assess the resource flows among the individual facilities in an industrial symbiosis (Sendra et al., 2007). This approach reveals consumption of resources, the characteristics of production activities and waste discharge, and the resource-utilization efficiency in a given system (Goto et al., 2005; Sendra et al., 2007). Shi et al. (2010) analyzed how material-flow analysis could be used to conduct research on the resource metabolism of eco-industrial parks, and proposed an analytical model (EIP-MFA) to evaluate the potential for increasing resource utilization efficiency within a park. Another approach, substance-flow analysis, concentrates on the stocks and flows of a single substance or of several closely related substances. It has been used to assess industrial systems (Tian et al., 2013), including studies of the flows of carbon (Tian et al., 2013; Wu, 2010; Zhang et al., 2013), sulfur (Tian et al., 2012), nitrogen (Wu, 2010), and phosphorus (Wu, 2010). To further analyze the inherent relationships between material flows and economic flows, and to account for the interactions among the plants in an eco-industrial park, input–output analysis has been a useful tool because it explicitly addresses the economic aspects of the relationships (Dong et al., 2013; Liang and Zhang, 2013). It has been widely used to account for resources such as water (Hite and Laurent, 1971), for energy (Casler and Wilbur, 1984), and for natural resources (Wright, 1975). In industrial symbiosis systems, researchers have combined insights from systems ecology with economic input–output models to develop hybrid physical input and monetary output models that are capable of assessing the resource utilization processes in an industrial symbiosis (Dong et al., 2013).

Although input–output analysis can quantify the flows among facilities, it cannot identify the ecological relationships represented by these flows. Scholars have therefore attempted to define the relationships among the members of a network both qualitatively and quantitatively. Liwarska-Bizukojc et al. (2009) stated that by analogy to a natural system, the relationships among members in an eco-industrial park can be divided into positive, negative, and neutral. However, they only determined the relationships qualitatively. In order to further analyze these relationships, utility analysis, a tool from ecological network analysis, can provide the information quantitatively and describe the integrated ecological relationships among the system's members (Patten, 1991, 1992). This approach can account for both the direct utility among pairs of members and the indirect utility that are implied in the direct flows. These integrated relationships therefore provide a more complete description of the exchanges among members (Fath, 2007). Because ecological network analysis has advantages in evaluating the ecological relationships and providing a systematic overall view of the structure and function of a system (Fath and Patten, 1999), it has been widely applied to studying natural systems such as bays (Baird et al., 2009; Christian and Luczkovich, 1999), estuaries (Christian et al., 2009; Whipple et al., 2007), saline ponds (Dame and Christian, 2008), near-shore bodies of water such as straits (Jordán et al., 2009), and wetlands (Heymans et al., 2002). It has also been used to study human systems such as cities (Li et al., 2012; Zhang et al., 2009, 2014a,b), industries (Bailey et al., 2004a,b; Chen, 2003), fisheries (Pauly et al., 1998; Walters et al., 1997), energy (Zhao, 2006), and utilization of water resources (Bodini and Bondavalli, 2002; Li et al., 2009). However, there have been few studies that used ecological network analysis to study the relationships among members in an industrial symbiosis system (Chen, 2003; Lu et al., 2012).

Among these few studies, Chen (2003) used ecological network analysis to evaluate the paths, the lengths of these paths, and the flows within these paths between any two nodes in a system. He used this approach to discuss the relationships among members of the Lubei park based on the specific flows of sulfur. By combining these flows with a metric that represented the weight of each node, he divided the nodes into three levels based on their status in the system. He recognized that not all of the members are equal: some contribute more than the others, some contribute less, and others have an intermediate contribution. Although Chen's analysis did not discuss the nature of the relationships between pairs of members, the approach could be used to identify the control or dependence relationships among members at different levels in the overall hierarchy. Lu et al. (2012) analyzed the relationships between pairs of members for the Beijing International Business Park using ecological network analysis. By combining the nature of the relationships with data on the flows among members of the park, they determined the direct and integral ecological relationships (including mutualism, competition, competition, or neutrality) among the park's six members. However, they only shallowly discussed the ecological connotations of these relationships and the benefits gained by the members of the park through these relationships.

In the present study, our goal was to build on the insights provided by these previous studies by solving some of their problems. To do so, we chose a park with strong reuse and recycling characteristics, the Shandong Lubei eco-industrial park, and analyzed the flows of all forms of a single representative element (sulfur) that is an important resource in most of the system's production chains. We used ecological network analysis to describe the ecological relationships within the park based on these flows, the benefits provided by the relationships among the park's members, and how these flows influence the relationships within the system. First, we analyzed the direct and indirect utility between any two members to identify the resulting ecological relationships and their ecological connotation. Next, we used these relationships to divide the members into a hierarchy with three levels: producer, primary consumer, and secondary consumer. Based on the integral flow weight of each member, we summed these weights for each level in the hierarchy, and compared the total weight of each level to obtain insights into the system's ecological structure. Finally, we analyzed the links between the ecological relationships and the reuse or recycling characteristics of the network, and discuss how the different ecological relationships influence the overall development and flows of resources through the system.

The results of our analysis reveal the strengths and weaknesses of the Lubei park's industrial symbiosis, thereby providing a basis for seeking improvements in the park's efficiency and in the benefits obtained by members. The results also reveal how the tools provided by ecological network analysis can be applied to the field of industrial symbiosis.