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Exploring the resilience of industrial ecosystems

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A B S T R A C T

Industrial ecosystems improve eco-efficiency at the system level through optimizing material and energy flows, which however raises a concern for system resilience because efficiency, as traditionally conceived, not necessarily promotes resilience. By drawing on the concept of resilience in ecological systems and in supply chains, resilience in industrial ecosystems is specified on the basis of a system's ability to maintain eco-efficient material and energy flows under disruptions. Using a network model that captures supply, asset, and organizational dependencies and propagation of disruptions among firms, the resilience, and particularly resistance as an important dimension of resilience, of two real industrial ecosystems and generalized specifications are examined. The results show that an industrial ecosystem is less resistant and less resilient with high inter-firm dependency, preferentially organized physical exchanges, and under disruptions targeted at highly connected firms. An industrial ecosystem with more firms and exchanges is less resistant, but has more eco-efficient flows and potentials, and therefore is less likely to lose its function of eco-efficiency. Taking these determinants for resilience into consideration improves the adaptability of an industrial ecosystem, which helps increase its resilience.

1. Introduction

Industrial ecosystems have been discussed and studied for more than two decades. They are proposed as a desirable, more integrated and closed-loop approach for industrial production and consumption based on recycling, use of by-products, and life cycle consideration since Frosch and Gallopoulos's inspirational work (Frosch and Gallopoulos, 1989); they are used as the bases for analogies to identify valuable principles in ecological systems to assist in understanding and fostering the evolution of industrial systems (Graedel, 1996; Korhonen, 2001); and they are referred to in the context of regional, sectoral, or network based industrial systems featuring the interplay of producers, consumers and regulatory agencies, which exchange materials, energy and information with each other and the environment (Ruth and Davidsdottir, 2008, 2009).

An important standard and target for building and managing technologically feasible and economically attractive industrial ecosystems is eco-efficiency, which is approached through reducing material and energy throughput without influencing goods and services supplied, by optimizing current production lines – individually or together – and with their associated waste flows. However, concern has been expressed that eco-efficiency as a single target may erode an industrial system's resilience – its ability to sustain in a fluctuating market environment (Korhonen and Seager, 2008). Specific critics focus on the risk of interdependency and uncertainty raised by the increasingly optimized, complicated material and energy flows among firms in industrial ecosystems (Bansal and Mcknight, 2009; Gibbs, 2009; Schlarb, 2001; Sterr and Ott, 2004).

The concept of resilience has been used and developed in ecology, as a metaphor related to ecosystem sustainability, as a property of dynamic models, and even as a measurable quantity that can be assessed in field studies of social-ecological systems (Carpenter et al., 2001). Its ecological meaning has been extended to provide guidelines for design and management in supply chains (Christopher and Peck, 2004; Pettit et al., 2010) and in sustainable engineering systems (Fiksel, 2003).

Industrial ecosystems have been considered as complex adaptive self-organizing systems (Ehrenfeld, 2007; Kay, 2002), to which ecological models like food webs (Hardy and Graedel, 2002) and adaptive cycles (Ashton, 2009) have been applied quantitatively or

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metaphorically. Complementing previous research, we advance the concept of resilience for industrial ecosystems by drawing more intensively on the ecology and supply chain literature, demonstrate material and energy flows as a key to systems' transition and resilience, and explore factors that can influence resilience, and its different dimensions, by employing a network model of inter-firm dependency.

Such an effort may contribute to the industrial ecosystem literature in several ways. First, by demonstrating that industrial ecosystems may be more vulnerable than we expected, it suggests the need to improve resilience through increasing firm and system level adaptability to disruptions. Particularly, for planned and policy-supported industrial ecosystems, resilience should be an important dimension that is incorporated in the plans and policies. Second, it offers some insights that help improve industrial ecosystem resilience – mitigating inter-firm dependency, fostering more homogeneous industrial organization, taking care of the large, highly connected anchor firms, and broadening and increasing exchanges. Third, by advancing the concept and evaluating resilience as an important system property, it helps improve the understanding of industrial ecosystems.

2. Toward the concept of resilience in industrial ecosystems

This section introduces the concept of resilience as developed and used in ecology and the supply chain literature. Both strands of research then inform the application of the concept in understanding and analyzing the resilience of industrial ecosystems below.

2.1. *Resilience in ecological systems*

Resilience was introduced to the ecological literature by Holling (1973), defined as the ability of a system to absorb changes and still persist, and distinguished from stability – the ability of a system to return to an equilibrium state. Some other authors later defined resilience in a way more similar to the definition of stability by Holling, as the time required for a system to return to an equilibrium or steady-state after a perturbation (for example Pimm, 1984). Holling referred to such a return time definition as "engineering resilience", and to his own definition of systems' ability to absorb changes and persist as "ecological resilience" (Holling, 1996). The existence of alternative stable states that are subject to change triggered by exogenous factors (Beisner et al., 2003) suggests a more dynamic, comprehensive understanding of resilience based on Holling's, as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker et al., 2004).

Walker et al. (2004) specified resilience to encompass four aspects: latitude, resistance, precariousness, and panarchy. To deliver a more precise understanding of resilience, the authors drew on the concepts of "basins of attraction" and "stability landscapes" (Fig. 1) commonly used in dynamic systems analysis. The state variables that describe a system constitute the state space of the system. A basin of attraction is a region in the state space where the system tends to remain and move about or toward equilibrium, i.e. an attractor, in the basin. Therefore, "retain essentially the same function, structure, identify, and feedbacks" means that the system stays in the same basin of attraction. Latitude measures the extent to which a system can be changed before moving out of the basin of attraction, i.e. the width of the basin; precariousness measures how close the current state of the system is to the boundary of the basin; resistance measures the difficulty of changing the system, i.e. the depth, or more accurately the slope, of the basin. When there is more than one basin of attraction for a system, these basins, and the boundaries that separate the basins, form a stability landscape for the system. A stability landscape for a system at a particular scale, e.g. an industrial system, is subject to change because of exogenous factors at higher or lower scales, e.g. changes in institutions or individual preferences. The concept of panarchy, which was introduced by Gunderson and Holling (2002), captures such cross-scale interactions that influence a system's resilience by reshaping its stability landscape. With a main focus on ecosystems and the definition of resilience mainly capturing the physical aspects, Walker et al. (2004) proposed a complementary concept, adaptability, as the collective capacity of the human actors in the system to manage resilience by influencing one or more of the aspects of resilience.

A system transition between alternative basins of attraction is driven by some key variable of the system state. For example, lakes usually have two basins of attraction, or states, that are of interest: a clear-water or oligotrophic state, and a turbid-water or eutrophic state, for which the phosphorus flow is a critical moderator (Carpenter et al., 2001). Natural disruptions like rainstorms or earthquakes, and social changes like intensive use of fertilizer or stricter environmental regulations can all move a lake system from one state to another, but they only change the phosphorus flow directly, which in turn changes the state of a lake. The state of a lake can be simply represented by oxygen concentration (or biological oxygen demand, BOD), which is decided by phosphorus concentration, but also prevents a change in phosphorus concentration, and forms a feedback process. Therefore, a great change in phosphorus flow beyond a lake's resilience moves the lake to the alternative state, while a small change moves the lake within the basin.

2.2. *Resilience in supply chains*

The concept of resilience in the supply chain literature addresses the operational and financial performance in the interconnected,

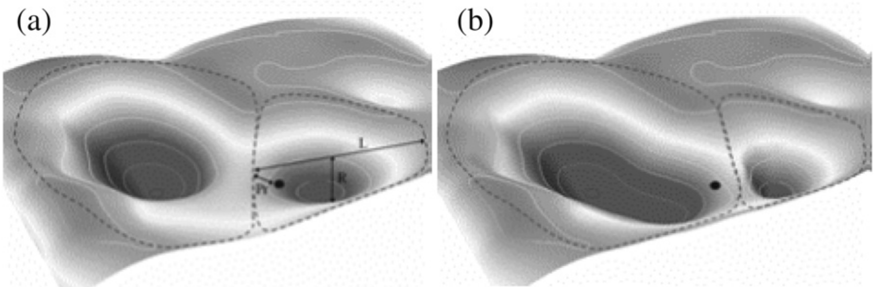

Fig. 1. Three-dimensional stability landscape with two basins of attraction. (a) The current state of the system portrayed by three aspects of resilience, latitude, precariousness, and resistance. (b) Without changing its state, the system moves to another basin of attraction, because of changes in the stability landscape. Source: Walker et al., 2004.