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Modeling ecological two-sidedness for complex ecosystems

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ABSTRACT

Complex ecosystems consist of social, economic, and natural subsystems that are relatively stable and symmetrical in undisturbed situations. However, external or internal disturbances may result in both positive and negative effects (referred to as "two-sided effects") on the structure and functions of any complex ecosystems. Such two-sided effects are likely to arise following the re-combination or re-regulation of the flows of matter, energy and information among these three subsystems. How to evaluate the consequences of disturbance events with such two-sided effects is challenging, requiring a new methodology. Here we describe an approach for calculating net benefit to systems where new events have such two-sided effects, and suggest how to maximize potential benefits. In this system, we termed the positive disturbance attribute comprehensive profit (*CP*), which includes social, economic, and natural profits, while the negative disturbance attribute is termed comprehensive cost (*CC*). To link and quantify profits and costs, we proposed an "index of ecological two-sidedness" as the Ratio of *CC* to *CP* (i.e., $R_{CC/CP}$), whose values can be combined using some modern mathematical methodologies, where the $R_{CC/CP}$ index matrix, $W_{CC/CP}$, is defined as the index optimization matrix of *CC* divided by the index optimization matrix of *CP*. Theoretically, the lower the value of $R_{CC/CP}$, the more stable the post-disturbance complex ecosystem is. This methodology of studying ecological two-sidedness may be useful to policy makers and ecologists in ecological management, restoration, planning, and design.

1. Introduction

Ecosystems, consisting of plants, animals, microorganisms and their interactions with the abiotic environments are generally divided into natural and man-made systems. However, every ecosystem is subject to internal or external disturbances, either natural or anthropogenic in origin, biotic or abiotic in nature, to name but a few of the largest categories. Disturbance is thus an important process in the ecological succession of any ecosystem (Johnson and Miyanishi, 2007; Spieles, 2010).

The relationships between disturbances and ecosystems are readily visible. For instance, natural disasters have made terrestrial ecosystems more fragile (Attiwill, 1994; Ajith and Cui, 2010); global warming has had an impact on aquatic and terrestrial ecosystems (Lejeusne et al., 2010); people have created and managed agroecosystems (Lin et al., 2011); and pollutant emissions/discharges resulting from human activities have threatened natural and urban ecosystems (Ramalho and Hobbs, 2012). To a large extent, these disturbances determine the stability of their attendant ecosystems.

Ecosystems are complex (Li, 2000), being composed of social, economic and natural subsystems, which are often called the "social-economic-natural" complex ecosystems (hereafter referred to as the "complex ecosystem"). The three subsystems, each with its own properties, not only have respective differences in structure, functions and evolutionary laws, but also interact with and are constrained by each other (Ma and Wang, 1984; Holling, 2001).

Under disturbance, ecosystems may become more complex (Frelich, 2002; Spieles, 2010). For instance, with the anthropogenic input of chemical pesticides into agroecosystems, all aspects of the complex ecosystem are affected compared to the undisturbed ones

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under natural conditions. Consequently, the social subsystem has been affected both positively (e.g., the enhanced prosperity of the chemical enterprise) and negatively (e.g., the food safety issues). Similarly, the economic subsystem has also been altered. For example, farmer income increases due to improved crop yield, but inputs or costs also increase). Finally, the natural subsystem has also been affected, since pests are largely killed (positive impact) but so are natural enemies (negative impact). Feedback among subsystems then follows, with change in the social subsystem influencing the economic and natural subsystems through increased social concern over the safety of food produced using pesticides, leading scientists to seek substitutes for chemical controls, including biological control, at the expense of crop yield. Meanwhile, changes in the economic subsystem limit the social and natural subsystems as, to maximize their profit, farmers increase their use of chemical pesticides against crop pests to benefit chemical enterprises and harm natural enemies. Often, modification of the natural subsystem has a restrictive effect on the economic and social subsystems. For example, the gradual extinction of natural enemies in crop fields stemming from extensive use of chemical pesticides has resulted in a less-resilient agroecosystem more susceptible to insect pest damage, making growers less likely to adopt the use of biological control techniques over chemical control) (Wan et al., 2005, 2008). Disturbance creates complexity in ecosystems, altering both their structure and functions in ways that are both caused by change and that affect change.

Ecosystems begin with complexity (Pimm, 1984), and post-disturbance ecosystems retain this complexity, to which the two-sided effects that arise from many subsystem changes are added. Both pre- and post-disturbance complex ecosystems consist of the three subsystems described above, and the structures and functions of these subsystems in a post-disturbance ecosystem are all reshaped to some extent. Disturbances may be due to single or multiple factors, and may be direct or indirect in nature, acting locally or regionally. But no matter which type of disturbance is considered, all disturbances enter the ecosystem as information, material or energy flow, which subsequently produces profitable or unprofitable effects on the ecosystem, and these effects play out among the subsystems (Wan et al., 2009; Jiang and Wan, 2009). For instance, an increasing number of cars in the planetary ecosystem facilitates transportation, but the subsequent increasing carbon dioxide emissions lead to global warming (Spalding, 2010). Prairie and forest fires temporarily pollute the air but can also improve biological productivity (Farina, 1998). Anthropogenic grazing can alter grassland structure and destroy grass-seed adaptability (Hobbs, 1991), but effective management can enhance species diversity and meadow productivity (Hopkins and Wainwright, 1989). Installation of sun-powered insecticidal lamps in agricultural fields kills pest insects and decreases the need for chemical pesticides, but harms natural enemies and increases production input costs. Thus, the two-sidedness of ecosystem disturbance can be found everywhere.

Since two-sidedness is an intrinsic attribute of disturbed ecosystems, there is a need to conduct qualitative and quantitative analyses of these two conflicting characteristics. Wan et al. (2009, 2013a,b) defined the beneficial effect of disturbance on an ecosystem as comprehensive profit (*CP*), labeling the beneficial effect on social, economic and natural subsystems as social, economic and natural profits, respectively. Meanwhile, the adverse effect of disturbance was defined as comprehensive cost (*CC*), composed of social, economic and natural costs. Wan et al. (2009, 2013b) and Jiang and Wan (2009), taking chemical pesticide pollution control as an example, constructed an indicator system that weighed the positive and negative effects of the disturbance on the three subsystems. This paper systematically develops the theoretical framework for the concept of ecological two-sidedness and establishes the eco-index, $R_{CC/CP}$, for measuring the consequences of such two-sided events to ecosystems.

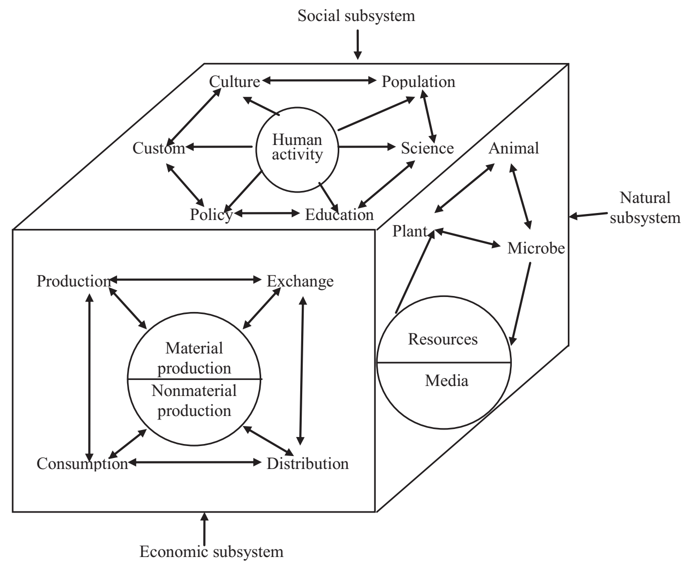

Fig. 1. Sketch illustration of complex ecosystem (simulated from Ma and Wang, 1984).

2. Theoretical framework

2.1. Complex ecosystems

Complex ecosystems are composed of social, economic and natural subsystems (Holling, 2001; Brown et al., 2002), which can be considered as the systems' prime components (Ma and Wang, 1984; Wan et al., 2009; Jiang and Wan, 2009). Each subsystem not only has its own structure, functions and developmental rules, but also influences and restricts the others (Fig. 1).

2.2. Study framework of ecological two-sidedness

Disturbances have specific impacts on social system as the social organizations and human interrelationships are disturbed, which is indicated by the fact that population, policy and social structure, culture, science and technology, education and traditional customs are reshaped, and that the individual actions among people driven by their social relationships are reversed (Parsons, 1951).

Disturbances have specific impacts on economic system as a number of interrelated economic elements are disturbed, which is expressed by the evidence that the living entities composed of interactive economic elements in a production system at all stages of production, exchange, distribution and consumption are reshaped (Nishimura, 1983; Tyszka and Sokołowska, 1992).

The impacts of disturbances on a natural system are also specific, as the forces of nature rather than human activities are reshaped, and the interrelations and interactions among organisms as well as between organisms and environment are disturbed, changing the dynamic equilibrium of material exchange and energy conversion (Kohut, 2003; An, 2012).

While complex ecosystems are relatively stable, the three subsystems experience dynamic exchanges after disturbance. Disturbance factors may be single or multiple, transient or sustained, above- or below-ground, involve living organisms or inanimate matter, be direct or indirect, natural or anthropogenic, internal or external, and biological or abiotic. This illustrates the two-sided nature of ecosystem disturbances.