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Perspective

An Immune System Perspective on Ecosystem Management

Marco A. Janssen

Vrije Universiteit

ABSTRACT

A new perspective for studying the complex interactions between human activities and ecosystems is proposed. It is argued that biological immune systems share a number of similarities with ecological economic systems in terms of function. These similarities include the system's ability to recognize harmful invasions, design measures to control and destroy these invasions, and remember successful response strategies. Studying both the similarities and the differences between immune systems and ecological economic systems can provide new insights on ecosystem management.

KEY WORDS: adaptive systems, artificial immune systems, biological invasions, ecological economic systems, ecosystem management, immune systems, institutions, models.

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INTRODUCTION

The public is becoming increasingly aware of the degree to which human action is simplifying and degrading the Earth's ecosystems (Vitousek et al. 1997). However, there is little understanding of the features of human institutions, defined as the formal and informal constraints that regulate human behavior, that produce sustainable ecological economic systems. Some examples of sustainable ecological economic systems can be found in the relationships between some traditional societies and their environment (Berkes and Folke 1998). Researchers are trying to discover what kinds of institutions enabled some of these traditional societies to sustainably co-evolve with ecosystems. Specifically, we need to know how such institutions detect problems, generate solutions, and remember successful strategies.

Empirical work has shown that successful ecosystem management depends largely on the allocation of property rights, the dynamics of ecosystems, and ecological knowledge (Berkes and Folke 1998, Ostrom et al. 1999). These insights are based on anecdotal evidence as well as laboratory experiments involving small groups. Although a large amount of empirical information is available, no transparent models of the functioning of institutions exist. Game theory has been used to study the interactions between various parties, but this approach is static: it is not able to detect new problems or design new responses to unexpected novel problems. The lack of a powerful model of such institutions may be attributed to the fact that there is no effective way to translate institutional dynamics into formal models. In this paper, I argue that analyzing regional ecological economic systems from the perspective of an immune system may provide such a framework.

The aim of this paper is to begin a discussion of ecosystem management from precisely that perspective. To do this, I outline the basic properties of the immune system before examining the properties that ecological economic systems and immune systems share. I then discuss the models of an immune system that could be used to study institutions, followed by a description of how this approach could serve to evaluate the severity of biological invasions. I also examine the limitations of the immune system perspective and conclude with suggestions on how to implement this approach.

THE IMMUNE SYSTEM

The immune system protects the body against harmful microbiological invasions by recognizing and destroying harmful cells or molecules. In addition, it is able to remember previously successful strategies for overcoming harmful invaders. Below is a brief sketch of how the immune system functions. It is based mainly on Hofmeyr (2001), who provides a clear description of the immune system from the perspective of systems dynamics.

An immune system contains a large number of interacting cells and molecules that detect and eliminate infectious agents (pathogens). It is a distributed system without central control. The surfaces of immune system cells are covered with various receptors, some of which chemically bind to pathogens and some of which bind to other immune system cells or molecules. An activated receptor produces local signals of recognition that mediate the immune response. Most immune system cells circulate around the body via the blood and lymph systems, forming a dynamic system of distributed detection and response. The detection and elimination of pathogens are a consequence of trillions of cells interacting through simple, localized rules. As a result, the immune system is very resilient when it comes to the failure of individual components and to attacks on the immune system itself.

Because it is healthier for the body not to initiate an immune response to harmless invaders, detection focuses on the identification of harmful "nonself" pathogens. Once harmful pathogens have been detected, the immune system is able to eliminate them in different ways. The problem is choosing the right response (i.e., the right cell to respond) for that particular pathogen.

The immune system is adaptive, because it adjusts the distribution of different kinds of proteins in response to its recognition of specific classes of pathogens; it also retains a memory of successful strategies that helps speed up future responses to those and similar pathogens. This adaptation occurs during the first response to a new pathogen. Because this initial response is slow, the organism will experience an infection, but the immune system retains a memory of the kind of pathogen that caused the infection. If the body is infected again by the same kind of pathogen, the response of the immune system is faster, because it remembers its earlier response to this pathogen.

The memory of the immune system stems from the fact that it is unable to contain a sufficient diversity of proteins to respond to all possible pathogens. The immune system contains about 10^6 different proteins, whereas there are potentially 10^{16} different foreign pathogens to be recognized (Hofmeyr 2001). Therefore, the immune system needs to contain enough diversity to respond to new kinds of pathogens. One of the main mechanisms for producing the required diversity is a pseudo-random process involving the recombination of DNA. Furthermore, the memory function of the immune system must be powerful enough to allow it to respond rapidly to pathogens that invade frequently. The immune system, therefore, balances the costs and benefits of innovation and memory.

COMPARISON BETWEEN IMMUNE SYSTEMS AND ECOLOGICAL ECONOMIC SYSTEMS

Ecological economic systems and immune systems share a variety of features. In this section, I compare these two kinds of systems in terms of the immune system concepts of pathogens, detection, response, memory, and maintenance.

Pathogens

Immune systems protect the body from harmful pathogens. Pathogens include a large set of microorganisms, such as bacteria, parasites, viruses, and fungi, that constantly invade and harm the body. These pathogens are the source of many diseases. Rapid recognition and elimination of harmful pathogens is therefore required to sustain the health of the organism.

Ecological economic systems are also subject to constant invasions. Some of these benefit society, whereas others lead to severe costs. Examples of such invasions are:

1) human invasions, e.g., by migrants, refugees, colonists, and soldiers;

2) technological invasions, e.g., by genetically modified organisms (GMOs), cars, and computers;

3) cultural invasions, e.g., by religion, communism, capitalism, and "fast food";

4) biological invasions, e.g., by harmful or beneficial organisms, as explained below.

Harmful biological invasions are the result of the uncontrolled spread of pests (e.g., fire ants in the southern United States), weeds (e.g., zebra mussels in the Great Lakes), or diseases (e.g., by the malaria mosquito in tropical areas). On the other hand, the deliberate introduction of certain plants (e.g., potatoes in Europe) and animals (e.g., sheep in Australia), mainly in the practice of agriculture, has had important benefits for society.

The amount of harm that will be caused by invasions of the ecological economic system cannot always be predicted in advance. The same is true for the pathogens that threaten the body, but the immune system is usually able to recognize the most harmful invasions before they damage the organism irreparably. Societies are not always as effective as immune systems at detection, but some similarities can be observed.

Detection

The detection of pathogens focuses on the identification of harmful nonself pathogens. The immune system has evolved in such a way that false negatives (nondetected nonself pathogens) and false positives (pathogens corresponding to self but recognized as nonself) are rare. Local recognition of a harmful pathogen occurs when the number of bounded receptors on the surface of a cell exceeds a certain threshold.

Detection of harmful invasions in an ecological economic system depends on knowledge of the system and the monitoring of particular indicators. Within ecosystem management, there are far too many uncertainties about how the system functions to be able to clearly identify harmful activities. For example, GMOs are currently accepted in various countries where it is believed that they will not have harmful effects on the ecological economic system. On the other hand, nuclear power plants in several countries are being closed because their nuclear energy production is regarded as a harmful human activity. Sometimes harmful activities are not recognized immediately. For example, the detection of the Antarctic ozone gap came at a relatively late stage because observations of low ozone concentrations were not recorded in automated satellite measurements. Because of these imperfect indicators, detection of the problem was delayed.

Our knowledge of the way nature functions is still incomplete; thus we need experiments and active learning processes to collect data on harmful nonself activities. This will be discussed in more detail in the latter part of this section. However, let us first consider what happens when a harmful invasion is detected.

Response

When a harmful pathogen is detected by the immune system, chemical signals trigger a response. The immune system has a variety of alternative responses because different pathogens require different methods of elimination.

Analogously, in ecological economic systems, once the harmful impacts of human activities have been detected, people begin to organize a response. These responses are shaped by the institutional structures of the ecological economic system. They can range from informal, uncoordinated actions to the development of new formal institutions. For example, responses to the spread of fire ants in the southern United States ranged from the extermination of domestic infestations by individual householders, through changes in land use practices, to federally sponsored research and control efforts (Garry Peterson, *personal communication*).

The immune system is adaptive because it is able to learn and adapt to new kinds of pathogens. In a similar way, humans can learn and adapt to novel challenges. A key element in the adaptivity of systems is the role and function of memory.

Memory

The immune system is able to remember successful responses in the following way. When the immune system encounters a novel pathogen, it may take several weeks to eliminate the infection. During this period, the immune system is learning to recognize the new type of pathogen, which it accomplishes by replicating cells that are capable of this. If the pathogen invades the body again, the response is more rapid and effective.

However, this depends on the response being remembered. The immune system has only a limited capacity for remembering successful responses. When the body has not been infected by a pathogen for some time, the memory of that pathogen can be lost. The immune response to malaria provides a good example of this mechanism. Any individual who lives in an area where malaria is endemic will either die from, or develop an immunity to, the disease. However, if an immune person leaves the malaria-infected area for an extended period, the immunity will be lost.

Likewise, the memory of socioeconomic responses is embodied in society's institutions. This can take the form of formal constraints, such as laws and constitutions, or informal constraints, such as taboos, rituals, and religions. Memories are maintained by universities and museums, in traditional stories and songs, by religion, and via many other processes. How knowledge is passed on is one of the main concerns of research into the institutions of ecosystem management. Berkes and Folke (1998) present a large number of case studies that describe how traditional societies have successfully managed ecosystems over long periods. Traditional systems rely on the accumulation of knowledge over many generations, and knowledge is transmitted culturally by taboos, religions, rituals, and the like. These systems are able to integrate long-term knowledge into their daily practices. For example, traditional fishery systems are characterized by rules and practices that limit *how* people fish, rather than attempting to regulate *how much* fish should be caught (Holling et al. 1998). Traditional management relies on learning by doing and corrects management practices on the basis of feedback from the ecosystem.

As in immune systems, institutional memory needs to be kept up to date. Successful resource management systems include institutions that encourage learning and social experimentation. Such experiments are necessary for learning, and learning is necessary to cope with social and ecological changes.

Losing memory causes problems. This brings us to the final comparison of this section: how do ecological economic systems maintain their effectiveness?

Maintaining the immune system

The functioning of an organism's immune system depends on the condition of the organism. For example, when the organism is exhausted or malnourished, its immune system is less effective. This is because more energy is required for recovery and maintenance of the organism, and, as a consequence, less energy is available for immune system functions. An organism must remain in good condition to maintain the functionality of its immune system. Resilience, i.e., the ability of a system to persist despite disturbance, provides a system analog of condition. A system with more resilience is able to cope with disturbances that would destroy a less resilient ecosystem. How do ecological economic systems maintain resilience? Do they have to go to the gym?

The resilience of ecological economic systems is strongly influenced by how they are managed. Instead of considering ecosystems in such a dynamic context, most resource practitioners have a mechanistic image of the functioning of ecosystems (Holling et al. 1998). Management policies are based mainly on assumptions of smoothly changing and reversible systems, and aim to improve the efficiency of resource exploitation and control by reducing variability. This kind of strategy can be described as an "engineering" type of management. Engineering policies are often successful in the short term, but reduce the system's resilience over the long term, leaving the resource vulnerable to surprises. Reducing the variability of a system can make it more sensitive to disturbances.

Often, small disturbances that increase the heterogeneity of a system are necessary to maintain or improve its resilience. For example, pastoralists on Australian rangelands limit the occurrence of fire, because fires reduce the grass biomass and therefore also diminish short-term income from wool production. However, fire is an efficient way to restrict the development of woody shrubs. Shrub germination depends on rainfall, which is highly variable in these areas. After woody shrubs have reached a certain age, it is no longer possible to remove them by fire; the result is areas with high shrub densities that cannot be used to feed livestock for several decades.

Traditional management systems and adaptive management are the opposite of an engineering type of management. They both rely on local feedback and learning and on the progressive accumulation of knowledge. Adaptive management stimulates systematic experimentation designed to gain a better understanding of ecosystem dynamics. It acknowledges the unpredictability of ecological economic systems and focuses on social and institutional learning by means of workshops with stakeholders and scientists (Holling 1978, Walters 1986). Traditional management practices are also based on learning by doing, but without systematic experiments. Ecological knowledge in traditional societies is stored in cultural capital by means of social mechanisms.

Viewing ecological economic systems from the perspective of the immune system reveals interesting parallels. Recent work on artificial immune systems suggests ways in which models of immune systems could be used to model ecological economic systems.

ARTIFICIAL IMMUNE SYSTEMS

Natural immune systems are often used as an example of a complex adaptive system (Holland 1995), because they consist of interacting components that are able to adapt to a changing environment. Immune systems can be studied using mathematical models and computer simulations, which recently led to the creation of a new field of computer science called "artificial immune systems" (Dasgupta 1999). From this perspective, the immune system is a compelling example of an adaptive information processing system that may provide new insights into the development of artificial systems exhibiting properties such as robustness, adaptivity, and autonomity (Hofmeyr and Forrest 2000).

Artificial immune systems can absorb new information, recall previously learned information, and perform pattern recognition in a highly decentralized fashion (Tarakanov and Dasgupta 2000). Applications have been developed for information security, vaccine design, fault detection, data mining, robotics, etc. (Dasgupta 1999). Nevertheless, there is currently no clear mathematical basis for artificial immune systems (Tarakanov and Dasgupta 2000). Hybrid and heuristic algorithms based on ideas from genetic algorithms, cellular automata, artificial neural networks, and other agent-based methods from computer science form the foundation of artificial immune systems.

One of the first successful applications of artificial immune systems was in the field of computer security. Since the first computer virus spread on a computer network in October 1987, more than 10,000 viruses have emerged, making them a serious global problem (Kephart et al. 1997). There are three classes of computer viruses: file infectors, boot-sector viruses, and macro-viruses. Macro-viruses have caused many problems since they first spread via the Internet and are not dependent on the operating system. The ILOVEYOU virus, for example, infected computers all over the world within 24 h in the spring of 2000 thanks to the widespread use of Microsoft Outlook.

Within the field of computer security, biological metaphors are used to fight computer viruses (Kephart et al. 1997). One of these applications is the development of a computer immune system in which PCs are connected by a network to a central computer that analyzes viruses. Each PC runs a local monitoring program that detects suspicious files. Any suspect file is sent to the central computer, which performs a number of checks to determine whether it contains a virus that has previously been detected. If this is not the case, the file is tested in a digital petri dish by executing, writing to, copying, and otherwise manipulating it to assess its impact on the system. These tests also identify the program code of the virus. Once the characteristics of the virus are known, a script is formulated to remove the virus from the files. This script is sent back to the database of known viruses, which can be installed and updated on the PC. Such a computer immune system has been implemented by IBM and is able to produce effective responses to an infected sample within 5 min (White et al. 2000).

Artificial immune systems can also be useful tools for simulating complex interactions between people and nature. The next two sections cover applications of this type.

MODELING INSTITUTIONS

Analysis from an immune system perspective might help to solve one of the problems of ecological economic systems: the dynamics of institutions. Currently, there is no widely accepted concept that describes these dynamics. The main advantage of formal models is that they provide a means of linking the large number of case studies of institutions and common property regimes with laboratory studies on human behavior. Case studies try to identify relevant social mechanisms that explain the observed performance of ecosystem management. However, unlike controlled experiments, case studies can provide no more than pieces of a complex puzzle, with only a limited theoretical understanding of the processes behind the interactions between people and nature. Controlled experiments involving people can be performed in the laboratory, but they are restricted in time and space. It is therefore highly desirable to complement case studies and laboratory experiments with computer models, which can be used to carry out consistent experiments within virtual ecological economic systems and to perform systematic tests to explain observed behavior in both the laboratory and the field. Used in this way, computer models can bridge the gap between case studies and laboratory experiments.

Holling (1995) and Ostrom (1999) argue that new tools from the field of complex adaptive systems can help simulate realistic interactions between people and nature. Lansing (1999) is one of the few researchers who has used distributed systems to explain institutions, in this case the traditional irrigation system in Bali, where cooperation with local neighbors has led to a global cropping and irrigation pattern that maximizes yield. This study also describes the role of water temples in regulating this irrigation pattern.

Artificial immune systems can provide tools that mimic distributed ecological economic systems. When it is possible to simulate the dynamic interactions between human activities and ecosystems, the immune system approach can be used to assess alternative management regimes. Such an application is becoming increasingly important, because human activities are rapidly changing ecosystems on different scales. Whereas traditional societies have been able to develop management practices via a learning-by-doing approach, this is often no longer an option. Computer models based on insights from immune systems can provide a laboratory setting for testing possible futures in a systematic way. The repeated use of these models to test various assumptions can provide insights into robust management strategies.

BIOLOGICAL INVASIONS

One possible application of the immune system concept to ecological management is in understanding the response of ecological economic systems to biological invasions. An immune system perspective might provide new ideas on how to regulate and control biological invasions, which are becoming more of a problem as the globalization of human activities continues to reduce the biogeographical barriers that historically kept geographically separate flora and fauna apart (Williamson 1996). This change has dramatically accelerated the movement of plants, animals, invertebrates, and microbes. For example, over the last 500 yr, more than 30,000 foreign species have been introduced into the United States. Some of these species were imported deliberately (e. g., valuable crops such as wheat, rice, domestic cattle, and poultry), but many of them are unwelcome because they are harmful to ecosystems, causing crop damage and human and animal diseases (e.g., AIDS, livestock and crop pests). The impact of invading species in the United States has been estimated at U.S.$138 billion a year (Pimentel et al. 2000).

The issue of biological invasions seems to fit well into the immune system metaphor. Harmful invasions of diseases, weeds, and animals are not unlike the invasion of pathogens in terms of their consequences for the functioning of ecosystems. The main problem is how to detect harmful invasions at an early stage and put a stop to them. The management of biological invasions has to balance the costs of monitoring the introduction of alien species against the costs of harmful invasions. Just as the immune system cannot respond immediately to every new pathogen invading the body, it is impossible for researchers to investigate the harmfulness of every new species entering a certain area.

However, a system for monitoring biological invasions might be developed using the model of the computer immune system. Such a system would compare information on known harmful invasions with data on monitored alien species and changes in ecosystems. When the impact of a suspicious species is not known, controlled field and laboratory experiments could be carried out to help determine whether the alien species is a danger to the ecosystem. If an invading species is found to be harmful, it should be eliminated from the area in the same way that the body's immune system destroys invading pathogens. Unfortunately, the history of invading species shows that it is often impossible to eliminate them entirely. In that case, it may be possible to restrict the spread of the population using pesticides, mechanical methods, or biological control. The main problem of invading species is the *timely* recognition of the potential harm they can do, and an immune system perspective may provide insights and management tools in this area. However, the success of such control measures will also depend on the initial resilience of the ecosystem.

LIMITATIONS

The previous sections have emphasized possible similarities between immune systems and ecological economic systems. However, it is not unreasonable to question whether these similarities are strong enough to apply artificial immune systems in the ways suggested above. Where does the analogy between ecological economic systems and immune systems stop? How do ecological economic systems and immune systems differ? Answers to these questions may in themselves provide insights into the dynamics of institutions.

One of the central differences between ecological economic systems and the immune system is that the agents of the latter are cells and molecules, whereas the agents of the former are human beings and institutions. Another difference is that immune systems are reactive, whereas social economic systems are also proactive in terms of planning and anticipating the future state of the system. Moreover, in contrast to immune systems, psychological factors and mental models of reality influence the behavior of agents. Human beings can ponder their actions, experience doubts, or deliberately imitate the behavior of other people, whereas the behavior of cells is simply a direct response to chemical signals. Granted, this is only a difference of scale, because human beings are composed of cells and react indirectly to chemical signals, although the behavioral complexity of people is obviously far beyond that of cells.

These differences between people and molecules mean that an immune system model of ecological economic systems can only partly explain their dynamics, because the ability to anticipate the future using mental models changes human behavior. For example, people may modify their behavior in response to extreme weather events that may be related to climate change. However, it is unclear whether these extreme events are actually related to human activities. The design of response strategies is based on mental models of the (climate) system and the extrapolation of human activities into the far future. It is not always possible to detect harmful activities, but the anticipation of possible future states of the system produces a response as a precaution against the possibility of harm.

Another difference is the fact that harmful human activities sometimes continue even after they are detected. There is no automatic defense mechanism. Deforestation of tropical forests continues even though we know that it may have catastrophic consequences for future generations. This is an example of a social dilemma. Unlike humans, cells have no moral sense; they do not have ulterior motives or a desire for power. As a result, without effective institutions to sustain interactions between individuals and between people and nature, societies trigger their own collapse.

CONCLUSION

Ecological economic systems can be viewed as distributed systems in which organisms (humans, animals, plants) respond to local changes. Traditional ecosystem management, which has proven to be successful over long time periods, has developed mechanisms to detect anomalies, generate effective responses, and remember successful strategies. These characteristics of successful ecosystem management make them similar to biological immune systems.

This paper has examined a number of similarities and differences between ecological economic systems and immune systems. Despite the differences, there are enough similarities to suggest that an immune system perspective could provide a useful approach for studying how institutions evolve to develop responses to changes in ecological systems. Potential applications are the understanding of traditional ecosystem management, the design of new sustainable institutions for our fast-changing ecological economic systems, and the management of biological invasions.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a comment, follow this link. To read comments already accepted, follow this link.

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Address of Correspondent:
Marco A. Janssen
Department of Spatial Economics
Vrije Universiteit
De Boelelaan 1105
1081 HV Amsterdam, The Netherlands
Phone: +31 20 4446092
Fax: +31 20 4446004
m.janssen@econ.vu.nl
