Impact Network Analysis (INA) Evaluating the success of interventions

A framework for evaluating the effects of management information through linked socioeconomic and biophysical networks

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Abstract

The success of intervention projects in ecological systems depends not only on the quality of a management strategy, but also how that strategy plays out among decision makers. Impact network analysis (INA) is a framework for evaluating the likely regional success of interventions before, during, and after projects, for project implementers, policy makers, and funders. INA integrates across three key system components: (a) the quality of a management strategy and the quality of information about it, (b) the socioeconomic networks through which managers learn about the management strategy and decide whether to use it, and (c) the biophysical network that results from those decisions. A common example where INA can be useful is management of an invasive (or endangered) species or genotype. A management strategy to reduce (or increase) the probability of establishment of a species may or may not be adopted by each land manager in a region, depending on the quality of the management strategy and the information they have available about it. The resulting management landscape will determine whether the intervention project is successful, in terms of how much of the region the species can spread through and the resulting effects on the desired ecosystem services. INA can be applied in general to evaluate the success of immediate intervention strategies, and to contribute to fundamental understanding about what makes interventions successful.

Key words: adaptive management, agent-based models, complex adaptive systems, data science, decision making under uncertainty, ecosystem services, emerging pathogens, epidemics, intervention ecology, invasive species, meta-research, multilayer networks, non-indigenous species, One Health, operationalizing sustainability concepts, science of science, social capital, socio-environmental systems, translational science, value of information

Introduction

Interventions in ecological systems have the potential to fail due to lack of consideration of the system components that are limiting factors for what would otherwise be a successful management strategy. The success of interventions in ecological systems depends on both how effective the management methodologies are, and whether a critical mass of decision makers adopts the necessary types of management. Because of the complexity of most ecological systems, scenario analysis platforms are needed for evaluating the likelihood of intervention success before, during, and after implementation. Data limitations will always be a challenge, but uncertainty quantification methods can inform decisions about investments in interventions.

A common challenge across applied ecology, agricultural development, and public health programs is to integrate across socioeconomic and biophysical processes to understand how research products can change systems on the ground. Agricultural development often depends on technologies for managing the spread of pathogens and arthropod pests, and for supporting the spread of desirable crop genotypes. Public health is supported by technologies for communicating about and using methods such as vaccination to slow the spread of disease. Understanding how to optimize the effects of research and data collection typically requires integration across three general types of system components: (a) the type and quality of management information and other technologies, (b) socioeconomic networks that determine communication and influence about management technology use, such as networks of land managers or farmers, and (c) biophysical networks where decisions about use of technologies determine ecological outcomes, such as networks of pathogen invasion or networks of endangered species dispersal. Here, “impact networks” are defined as the linked socioeconomic and biophysical networks through which management may have a regional effect. This paper introduces a framework for scenario analysis, impact network analysis (INA), to integrate these three components, and thus to evaluate the likelihood of success for interventions.

The first component in this framework is an intervention technology, which might be, for example, a model describing a management effect on transmission probabilities, or another form of information about how to modify the system. Information can be considered in the broad sense, such as genetic information in the form of selection of appropriate genetic material for agriculture or for ecological restoration projects. These types of information will also have an associated uncertainty (Klerkx et al., 2010). Analyses of the ‘value of information’ have been incorporated in, for example, medical decision making at multiple scales (Bartell et al., 2000; Claxton and Sculpher, 2006; Tappenden et al., 2004), decision making by foraging animals (Freidin and Kacelnik, 2011; McNamara and Dall, 2010), management of species (Canessa et al., 2015; Tallis and Polasky, 2011; Wiles, 2004), and adaptive resource management (Williams et al., 2011). Even neurological processing of the value of information has been characterized (Behrens et al., 2007). As the reproducibility of science is critically evaluated in multiple disciplines, the quality of information is a focus (Ioannidis, 2005; Kenett and Shmueli, 2014; Leek and Peng, 2015). And even if information and technologies are of very high quality, their influence on system-level outcomes will be minimal if decision-makers are unaware of them or are not persuaded that they are a good investment of resources. Impact network analysis can be thought of as an evaluation of the regional value of information in landscapes.

The second component is the socioeconomic network, where nodes are key decision makers such as farmers, other land managers, or individuals managing their families' health, or farmers (Rebaudo and Dangles, 2011; Rebaudo and Dangles, 2013) – and potentially also include other agents such as scientists (Ekboir, 2003), extension agents, policy makers, consumers, and related institutions. Links between nodes may indicate the spread of ideas, influence, and/or money. Within businesses, networks for the spread of information may be designed to try to achieve economic goals (Allee, 2002). In many scenarios, networks of communication and influence form haphazardly. Individual decision-making about whether to adopt new technologies plays out in the context of the information available through individuals' networks (Garrett, 2012; Rogers, 2003). Agricultural management is often limited by lack of information (Parsa et al., 2014). Even if the current standard of information is available to most agents (nodes), the information may be of low quality, and heuristics for decision-making may or may not be well-developed (Ascough et al., 2008; Gigerenzer and Gaissmaier, 2011). The effects of decision-making by agents in the socioeconomic network, with or without full information about options, creates a "management landscape" that influences the success or failure of species in the biophysical network.

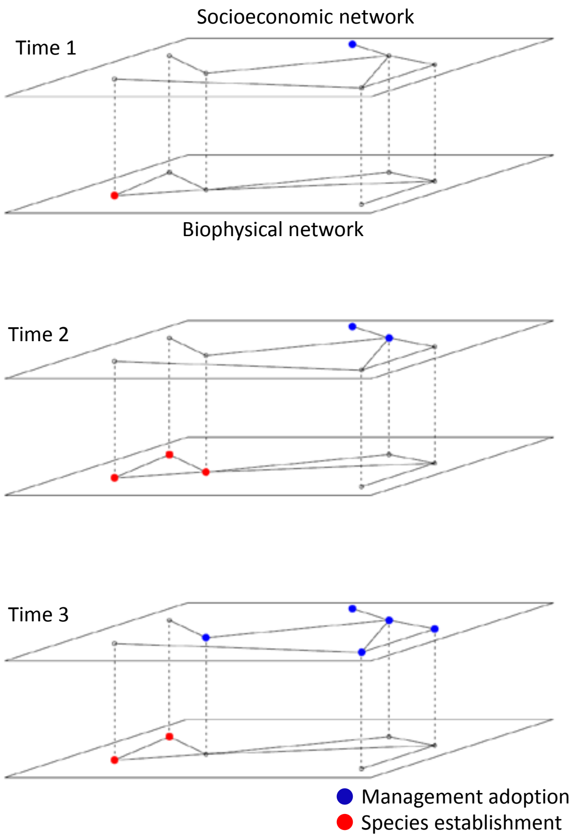

Figure 1. An impact network analysis can be applied to evaluate how likely an intervention is to be successful. A common type of intervention is an attempt at regional management of an invasive (or endangered) species. An intervention would often be based on an attempt to make effective management of the species more widespread. Adoption of the management may prevent or disrupt spread of an invasive species, as illustrated here. Links represent potential spread of information about the management option in the top layer, and potential spread of the species in the bottom layer. Links between layers indicate a manager in the top layer linked to a land unit in the bottom layer, where the managers' decisions will change the management landscape.

The third component is the biophysical network, where nodes indicate the entities or geographical locations where success or failure occurs. Nodes might be groups of people (as hosts to human pathogens), farms, or other land management units. Links between nodes indicate the potential for the spread of undesirable species or genotypes, such as antibiotic resistant human or agricultural pathogens (Epanchin-Niell et al., 2010; Margosian et al., 2009; Sutrave et al., 2012), or of desirable species or genotypes, such as endangered species or improved crop varieties. In some cases, the same type of biophysical network model may usefully be applied to related processes, such as the spread of pollutants, soil erosion, and provisioning of fresh water (Baron et al., 2002). Nodes in the biophysical network are linked to the corresponding decision-makers in the socioeconomic network layer, such that the probability of successful management at a biophysical node is modified by the corresponding decisions about management. Successful management also depends on the quality of information or other technologies that may be applied at a given biophysical node.

Combining these three components provides a systems perspective that can be used in scenario analyses to evaluate potential outcomes from research investments, before, during, or after projects begin. It can also be used to evaluate the likely degree of success of adaptation strategies to pulse (intermittant) or press (continual) system stressors, such as the introduction of a new pathogen or climate change, to evaluate system sustainability, resilience, or economic viability. Some of these system components have been considered together more or less explicitly in disease ecology (Funk et al., 2009; Funk et al., 2010; Garrett, 2012; Harwood et al., 2009; Manfredi and d'Onofrio, 2013; Sahneh et al., 2012) and natural resource management (Bodin and Prell, 2011; Epanchin-Niell and Hastings, 2010; Hernandez Nopsa et al., 2015; Mills et al., 2011; Rebaudo and Dangles, 2011). Combining the components also provides a new perspective on the science of science policy (Fealing et al., 2011) by directly evaluating interactions among agents engaged in developing scientific results and in implementing the new results.

The overall goal of impact network analysis is to provide a common framework that integrates across all these types of applications, to enhance opportunities for lessons learned across systems and scientific disciplines, and to create a general platform for analysis of sustainability, resilience, and economic viability. Applying network analyses, as compared to more aggregated models, allows consideration of the role of geographic and social structures on the likelihood of success of technological innovations. The specific objective of this paper is to introduce the impact network analysis framework for evaluating the degree of success of a project in intervention ecology, using an example of model structure for management of an invasive or endangered species.

Methods

The model presented here is a simpler version of the range of potential impact network analyses that could be considered. For example, this simple model addresses a single “unit” of management information that is generated by an agent such as a research team, while more elaborate models might address “big data” in the form of information that is generated throughout a network, as well as spread throughout that network. The simpler model is introduced here, for the most part using a standard format for describing agent-based models (Grimm et al., 2010).

Purpose

The purpose of this model is to understand the likelihood of success of an intervention in an ecological system, before the intervention and with iterative adjustments as more information about the system become available. It evaluates the outcomes of information and technology impacts on linked socioeconomic and biophysical networks. These system components tend to be studied separately in traditional disciplinary models, but the way they are integrated influences system sustainability. The broader goal is a new impact network modeling framework that can be applied across a broad range of system contexts and questions, providing research spill-over and cross-disciplinary lessons learned. The impact of information related to management of an invasive or endangered species is considered.

State variables and scales

The model describes the effects of a management strategy (information or other types of technologies), socioeconomic networks that influence management decision-making, and biophysical networks that influence species dispersal and establishment, in the case of the application to invasive or endangered species.

Ecological information or other technology, and the management effect size

The state variable describing information is the researchers' *estimate* of the management effect size, in terms of the percentage change in the probability of species establishment, with the goal of stopping invasive species establishment, or supporting endangered species establishment. (The *actual* effect size is a model parameter.)

The generation of an estimate is based on two parameters, the mean effect size and the standard error of the mean (which is implicitly a function of both variance in effect size and the experimental sampling effort). The estimated management effect size must be greater than a threshold value in order to trigger communication about the management.

Communication network

The nodes of the communication network, which determines how information (or other types of technology) may be propagated, are individual people or institutions (land managers, policy makers, information brokers, researchers). The link weights indicate the probability of sharing information between two nodes. The state of each node at a given time step is presence or absence of the information. The time step (temporal resolution) is related to logical time units for the linked ecological network, such as the generation time for the species being managed.

The probability of information sharing between a given pair of nodes is constant throughout a simulation, where sharing of information at a particular time step is determined based on that probability.

The higher-level measures of the status of the communication network include the number of nodes where information is present and the network properties associated with the communication network.

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Decision-making at a node

Whether or not land managers who have information about a new management technology will choose to use the new management is determined by factors such as the distribution of early and late adopters. In this model, each land manager node has associated with it both the information status described above and a decision status. If the information has not reached a land manager node, the decision will be ‘do not adopt’ by default. If the information has reached a land manager node, the decision may be ‘adopt’ or ‘do not adopt’.

Each land manager node has an assigned likelihood of adoption during a time step, where a given land manager node retains its probability of adoption throughout a simulation. Whether management is used is determined at each time step.

The higher-level measures of the status of the network of land managers will include the number of nodes where the outcome is ‘adoption’ and the network properties associated with those nodes.

Ecological network and establishment

The nodes of the ecological network are units of land managed by a particular land manager, such that the land manager node and the corresponding land node are connected. For the invasive or endangered species example, the links between land nodes indicate the probability of movement of the species between the pair of land nodes. Whether or not movement occurs is determined at each time step based on that probability. The probability of successful establishment at that land node is a function of whether or not management has been adopted. The state of each land node for the species movement case is ‘species established or ‘species not established'.

The higher-level measures of the status of the network of land units will include the number of nodes where the outcome is ‘species established'.

Process overview and scheduling

The processes in the model for an invasive or endangered species are as follows for a single realization, in discrete time.

1. An estimate of the management effect is generated once.
2. A round of communication occurs, such that some land manager nodes may change status from ‘absence of information’ to ‘presence of information’.
3. A round of decision making occurs, such that some land manager nodes may change status from ‘non-adoption’ to ‘adoption’, thus changing the management status of the corresponding land nodes.
4. A round of dispersal occurs, such that some land nodes may change status from ‘species absent’ to ‘species present’ because of movement.
5. For species presence to be maintained, the species must also become established, where the probability of establishment is conditional on whether the management is adopted at a

land node. Some land nodes where the species was previously established may change status from ‘species present’ to ‘species absent’ as a result of management.

6. Steps 2 through 5 are repeated for as many time steps as are being considered.

Design concepts

Emergence: System-level traits that “*emerge*” from individual traits include the spatial distributions and frequency distributions of (a) land manager nodes with information present, (b) land manager nodes with adoption (and corresponding land nodes with management), and (c) land nodes where the species is established.

Sensing: In this simple version of an impact network, land managers become aware of information only through their links to other people aware of the information. The threshold for the effect size estimate determines whether there is any communication about the management, and can completely restrict land managers’ ability to learn information. Adaptation and fitness-seeking are not modeled explicitly in this simple version, but are implicit in information sharing and decision-making about adoption.

Stochasticity: To understand the general effects, and the upper and lower percentiles of outcomes, network structures are generated anew for each simulation. The probability of movement of information and species is fixed for each pair of nodes within a single simulation, and whether or not movement occurs in each time step is determined independently based on this probability. The probability of establishment at a given node is modified by whether the management has been adopted at the corresponding manager node.

Collectives: Interactions among land managers are modeled by the network of communication.

Observation: At the end of step 5 (in the process overview above), the species is established in a set of land units for that time step. The status of information and adoption at each socioeconomic node, and species establishment in each biophysical (land) node, is collected for analysis.

Initialization

In the network of land managers, those who initially have the information about management are those conceptualized as having access to the information from researchers and/or information brokers such as journalists and extension agents. Each land manager has a probability of initially having this information in each simulation. A proportion of land nodes initially have the species present, and are randomly selected *along one edge of the map* or randomly in each simulation.

Input data

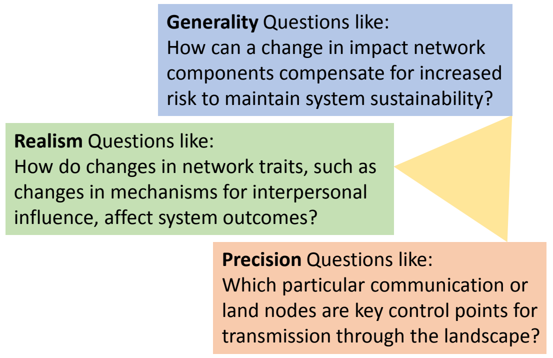
Input data are simulated in these examples, but could come from observed environmental variables. The environmental input in this simple version of an INA is defined in terms of environmental conduciveness to species establishment or persistence. For simplicity, underlying environmental conduciveness is considered to be the same at all nodes for a given time step, so that the probability of establishment is the same at each land unit node. Three types of scenarios are considered for conduciveness. In the ‘constant’ scenario, conduciveness does not change. In the ‘sustainability test’ scenario, conduciveness increases slowly and steadily over time. In the ‘resilience test’ scenario, conduciveness increases suddenly for a limited period of time.

Next steps

This introduction to INA will be updated with a more detailed example

Comments

When evaluating the likely success of interventions that are under immediate consideration, analyses will generally try to achieve the greatest level of precision possible given the data available. When considering the potential for different types of future interventions, or the theory of effective interventions, other priorities may be at least as important. There are often trade-offs in the ability of a model to achieve precision, realism, and generality (Gross, 2013; Levins, 1966). Other applications of impact network analysis could focus on developing general theories for the development of future intervention strategies (Fig. 2). Uncertainty quantification frameworks can incorporate multiple types of objectives in impact network analysis.



Generality Questions like:
How can a change in impact network components compensate for increased risk to maintain system sustainability?

Realism Questions like:
How do changes in network traits, such as changes in mechanisms for interpersonal influence, affect system outcomes?

Precision Questions like:
Which particular communication or land nodes are key control points for transmission through the landscape?

Figure 2. Three potential priorities in impact network analysis, and examples of the types of questions that might be asked in each context

Seed systems are an important example of multilayer networks in agriculture. Layers include the network of seed movement in formal and informal systems, the network of pathogen or pest movement through seed, and the network of information and influence related to integrated seed health strategies (Thomas-Sharma et al., 2016; Thomas-Sharma et al., 2017). Successful seed systems will optimize the maintenance and spread of desirable crop varieties (Labeyrie et al., 2016; Pautasso, 2015; Pautasso et al., 2013) while minimizing the spread of pathogens through seed or grain movement (Andersen et al., 2017; Buddenhagen et al., 2017; Hernandez Nopsa et al., 2015). Additional linked networks include the global network of crop breeders who exchange genetic material (Garrett et al., 2017).

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