*Networking our way to better Ecosystem Service provision*

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*Linking the natural and social sciences with networks*

The Ecosystem Services (ES) concept is being used increasingly to attach values to natural systems and the multiple benefits they provide to human societies [1-4]. Ecosystem processes or functions only become ES if they are shown to have social and economic value (Box 1), thereby connecting research between the natural and social sciences. ES research is challenging because its multiple disciplines have very different traditions and vocabularies (*common-language challenge*) and span many organisational levels and temporal and spatial scales (*scale challenge*) that define the relevant interacting entities (*interaction challenge*). We propose a network-based approach to help unify and structure the ES field, by transcending disciplines.

ES is a rapidly developing field that requires clear, unified frameworks [5], but has been criticised on both philosophical and practical grounds [6]. Naeem et al. [7] have suggested that few Payments for Ecosystem Services (PES) studies “get the science right” due to poor interdisciplinary coordination and communication. Network-based approaches could help by providing a common language and tools that deal with complex systems of interacting nodes (see Glossary); these nodes could be the species within an ecosystem or individual humans within a socio-economic system. The approach also naturally identifies the organisational level and spatial and temporal scales of study through the appropriate definition of both the nodes and the relationships between nodes (links) within the network.

***Glossary***

**Degree**: The degree (or connectivity) of a node is the number of edges connected to it. In directed networks, each node has an in-degree and an out-degree that respectively count the number of incoming and outgoing edges.

**Link**: A link, or edge, connects two nodes in a network. Information transacted across a link can be undirected (the flow goes both ways) or directed (one way). In the case of energy pathways, directed links represent energy flux. In the case of mutualistic networks, a pair of directed links represents an interaction with mutual benefit, such as in the case of plant-pollination. For classical food webs, directed links go from the prey/resource to the predator/consumer.

**Networks of networks** or **Multi-networks**: combining individual networks through links between entities either in the same domain (e.g. pollinators and herbivores linked through shared plants) or in different domains, which is the proposal of this paper.

**Node**: A node, or vertex, represents an individual component of a network, for example a species in a species–species interaction network such as a food web or a plant–pollinator network.

**Nonlinear network dynamics**: Whether constructed using ecological, economic or social data, the phrase “More is different” can be fully applied to networks [46]. Networks, and their dynamical properties, are more than the sum of their interacting parts [47]. The progression of an epidemic depends crucially both on the average degree of potential infections and on the variance of degree. The impact on the spread of the disease of removing one node from the network (e.g. through vaccination) may be very different from that of removing another node with the same degree [48]. Thus, the clustering of nodes needs to be taken into account in order to predict epidemic dynamics [49]. Hence, infection epidemics are highly nonlinear [50], and it is impossible to model the dynamics of a node, relative to a given process, by isolating it from the network. All processes modelled within networks (such as contact/diffusion processes, trophic and competitive interactions between different types of agents, etc.) have these intrinsically nonlinear dynamics. The combination of this nonlinearity and the multitude of possible interactions, both direct and indirect (i.e. those mediated by a third element) can produce highly non-intuitive effects when networks are subjected to perturbation, such as the importance of indirect effects for the maintenance of food web complexity and biodiversity [51]. As a result, the dynamical properties of networks are not predictable through an additive, reductionist framework focused on the study on individual elements.

**Resilience**: In the strict mathematical sense, it is the rate at which a system returns to its original equilibrium following disturbances from it [52,53]. When applied to ecosystem functioning, it is the speed at which a given ecosystem returns to a state with a similar level of functioning. Another definition that is in common use is whether or not a system returns to its former equilibrium or to another one. This can be expanded to compare systems in terms of what range of disturbances a system can withstand before being shifted to the new equilibrium [54].

**Scale**: Scale defines both the organisational level and the spatial and temporal dimensions of ecosystems, particularly as these can change between disciplines as we shift from ecological to anthropogenic representation of the ecosystem. The description of nodes and links naturally leads to the scale under consideration. If we consider a node to be an individual population of a species, we immediately define an organisational level based upon the population. The links, measured as the frequency and flow of information between the nodes, define the basic spatial and temporal dimensions of the network. Hence, at the organisational level of individual populations, trophic links are relevant to foraging patterns and frequency of feeding.

A considerable body of literature has demonstrated the importance of networks as a structuring concept in ecology and the social sciences, and has illustrated startling commonalities in the properties of networks within and between disciplines [8]. These commonalities reveal networks might be used to bridge disparate disciplines, allowing the identification of the indirect effects and mechanisms prevalent in complex systems to be understood.

Despite huge potential, network-based approaches to biodiversity-derived ES (multi-network) studies, which consider economic, social and ecological networks together do not yet exist. This is because they are data rich and integrating networks across disciplines would very quickly become intractable. We therefore use examples of networks from these three disciplines, and elsewhere in science where multi-disciplinary network to support our line of reasoning. We are not advocating a crude one-size-fits-all approach here, in which a prescriptive definition of network nodes and links is shoehorned into all types of study [10], nor are we suggesting that economic, social and ecological data must always be integrated into a single multi-network. Rather, we advocate an adaptive and flexible network-based approach that will help solve the *common-language*, *scale* and *interaction challenges*, and in so doing will structure and make tractable the use of networks in ES.

Box 1. Close to here

*Networks as unifying tools in a multidisciplinary world*

Network methods are essential wherever interactions between multiple entities are important (Figure 1), resulting in complex, nonlinear dynamics (see Glossary). From the earliest work of Euler in 1735 on how to cross the “Seven Bridges of Königsberg” [11] to more recent problems of how node and link diversity determines stability and resilience to perturbations [19-21], networks have proved invaluable tools in disciplines from biology [16,17], maths, physics and engineering to social science [12-14], economics [15] and ecology [19-21]. Increasingly sophisticated methods and metrics [22] have driven great advances in understanding of the simplicity underpinning complex ecological systems, such as the pervasive role of body size in structuring food webs (e.g. [19,23,106,107]). Network thinking has been fundamental to our understanding of ecosystem functions, showing that not only biodiversity *per se*, but also the arrangement of trophic links governs ecosystem functions [24].

Figure 1. Close to here

Much of the network research, above, has not been limited to any one discipline, but springs from a merging of networks from different disciplines (e.g. [12,15] and Figure 1). There is a long history of promoting the use of networks across discipline boundaries [100], and considerable advances have been made across the divide between the social sciences, be this Economics or Social science, and ecology [101-104]. Our contention, which has been made elsewhere [101, 104], is that harnessing the benefits of these already established approaches to the explicitly multidisciplinary needs of ES research is the logical next step. The question is, how?

*The common-language challenge*

Scientists from different disciplines come to ES problems with specific vocabularies and analytical approaches. These may be effective for within-discipline communication, but they often hinder cooperation across disciplines [7,25]. Similar terminology may be used for different things, while the same meaning may be ascribed to different terms. Network science has a far stricter vocabulary, which comes with a common set of tools that can be applied to any network problem. Adopting this ‘language’ could greatly facilitate interdiscipline communication, specifically, while retaining discipline-specific language and approaches where appropriate. In a network, nodes (e.g., species, people, banks, etc.) are linked by informational flows (e.g., biomass flux, sentiment exchange, money, etc.) that can simply be treated as information to be analysed. It is in considering the complexity of these nodes and links that the value of network vocabulary really comes to the fore. Network metrics can be used to describe groupings, structural complexity, resilience and dynamics of information flow that map on to the (often less well-defined) terminology used in each discipline, such as “sustainability”, donating clarity and rigour.

Questions that require a common language to answer become particularly pertinent where human groupings impact ES. Whether due to genetic, social or economic relationships, the consequences of groups can be complex and interdisciplinary. In the case of cultural ecosystem services, such as the auction-based conservation of traditional quinoa varieties in the Andes [26] or governance of biodiversity in green areas in Stockholm [27], a network approach could help establish rules about optimum sizes of groups, leadership and maximising fairness in cultural resource use by stakeholders. The network approach might also explain unexpected, apparently emergent properties of the system, such as why some groupings of quinoa farmers were self-policing, reducing cheating and potentially allowing reductions in the overhead for monitoring payments for ES [26].

Understanding groupings, based on link complexity, is a staple of network analysis developed in engineering and social science, and is used increasingly in ecology. New metrics of substructure, such as the “Rich core” [28], are used to define groupings of important nodes. Originally developed in social science these metrics has been applied to ecological networks. Conversely, the “keystone species” concept of highly connected and influential nodes within a network was developed in ecology, and is now routinely examined in studies of social and engineering network performance [22,29,30]. Clearly, a transfer of network-based methods and language among disciplines is already underway, and could be extended to ES research.

*The scale challenge*

The definition of nodes and links within a network will determine the level of organisation, and the spatial and temporal scales over which it operates. Each of the different ES disciplines works at characteristic spatial and temporal scales, often due to logistical constraints. Ecological data are typically collected on organisms that operate at local spatial scales and over the short term, of up to a few years [31,32]. Social scientists work with individuals or populations of humans at larger spatial scales and over the medium-term, of annual to decadal timescales. Economists, meanwhile, work at scales up to the

global economy and often over much longer time periods. While a gross simplification (see [33] and [34]), these examples illustrate that although there is some scope for overlap, the scales at which the disciplines work often differ.

Methods and paradigms for coping with such scale disparity already exist within network research, and could be applied to ES (Figure 2). For instance, computer and data networks like the Internet can be treated as a complex of social, economic and electronic elements that exist in a series of architectural layers, each of which is discrete in terms of functionality and can be treated in isolation, but which also builds upon the layers below [35]. Thus, in the lowest layer, the engineering structure of the Internet is made up of individual computers as nodes physically linked together, electronically. At higher levels, these engineering nodes are aggregated based upon economic criteria of response time and information flow that may have little relation to their physical distance; the computers may even be in different countries (Figure 1A). Higher layers again add social network information based upon the relationships between users of the Internet that are again further abstractions of lower layers.

While it is possible to analyse any layer in isolation, the tools exist to analyse across layers and scales, allowing the consideration of system-wide properties [36], such as how the engineering, economic and social structure of the Internet can be managed to maximise information flow and resilience to disturbance and alterations in human behaviour [37]. These properties of the system resonate very strongly with the properties we would wish to predict for ES, and this paradigm of layering (Figure 2) in combination with multi-networks is what we propose as a way forward to solve the *interaction challenge*, while still facilitating discipline-specific (within-layer) research.

Figure 2. Close to here

*The interaction challenge*

For practical purposes, researchers have focused on a few groups or taxa that deliver simple ES. For instance, as providers of crop pollination, bees are often treated in this way. Such oversimplification, to a single ES, undermines the multivariate nature of ES research [1,6]. Pocock et al. [38] approached the question of interacting ecosystem functions using a network of species interactions in arable agriculture, linked by feeding interactions, pollination and seed dispersal [Figure 1B]. The different functions varied in their robustness, with pollinators being particularly fragile to loss of plant species, but there was no strong co-variation in function because the different interaction types were often in conflict. This network-based approach revealed there was no “Optimist’s Scenario” or ‘win-win’ management that benefited both biodiversity and multiple ecosystem functions (see [39,40] for other biodiversity-multifunctionality relationships).

The structure of the Pocock et al. network demonstrates clearly why this is (Figure 1B): consumer species interact with one another through the diverse plants in the agricultural system, the weeds. Herbivores may therefore profit by reducing the weeds at the expense of other groups. Thus, management to conserve any one biodiversity group or service may have by turns negative or positive impacts on other groups and services, both above- and below-ground [41, 105], because of trade-offs and indirect effects mediated though the weeds.

Figure 1 illustrates some benefits of an ES network approach. The critical points of interaction can be readily communicated to stakeholders and the public, even for complex networks. By embracing the complexities, especially of nonlinearity and indirect effects (see Glossary), network approaches can generate robust and valuable system simplifications, such as the clear rebuttal of the Optimist’s Scenario and the identification of the central role of weeds, while avoiding some of the *a priori* oversimplifications commonly found in ES research.

To fully develop a network approach to ES from the work of Pocock et al. [38], we need to return to the layering paradigm and reimagine their network as being the first layer of the agro-ecosystem description (Figure 2). Here, the consideration of the ecological network has identified the weeds as all-important and they become the core structural nodes of interaction with the higher-layer networks. In place of potentially considering all social, economic and ecological interactions linked to biodiversity-derived ES in farmland, ***now*** the analysis can be made tractable by considering only the ES derived from weed biodiversity. Decisions about applying herbicides that were primarily questions of cost-effectiveness in the past, might now also include consideration of ES and biodiversity explicitly. Social and economic values held by stakeholders for particular weed management strategies can thus be used to modify the combinations of ecological network properties that are acceptable. Explicit development of a network approach to understand the adoption of a novel agro-ecological management for ES is taking place in France (Case Study).

Case study. Close to here

*A network methodology for Ecosystem Service provision*

Networks are now a mainstream method of analysing and understanding complex systems. We advocate them as a powerful new approach to ES research that builds upon a discipline-independent vocabulary to provide a common framework for uniting the disciplines of social science, economics and ecology and to provide rigour via a consistent suite of tools.

Considering the multitude of interactions between nodes, which is at the heart of the ES network approach, can reveal simple explanations of the structure of the system: in the study of Pocock et al. [38] for instance, managing weeds was revealed as the key mechanism by which the balance of services provided by the agricultural ecosystem could be modified most effectively.

Arguably the greatest practical criticism of an ES network approach is that characterising all the interactions necessary to represent the complexity of natural ecosystems, alongside networks that sufficiently explore the nuances of human social and economic sentiment, could be prohibitively data-greedy. The utility of the approach, however, is that it does not always require full implementation but, rather, is adaptive and flexible (Box 2). At its simplest, the network vocabulary co-exists with discipline-specific terminology, but serves the purpose of promoting communication between the disciplines. At intermediate levels of implementation, networks already constructed within any one discipline may also be used to help identify the interactions that structure the system. Only at its most complex, would the approach integrate networks from ecology, economics and social science, tackling directly the networks of interaction that exist within and between each of these disciplines to deliver multiple ES.

Box 2. Close to here

The ability to adapt the approach to the question does not wholly avoid the challenge of it being data-greedy. A core element of the tractability of the approach is to represent the different disciplines as layers, starting from the ecological networks at the base, with social and economic networks overlain. The interactions within Layer 1 give rise to the core nodes that structure all subsequent layers. Whether these are weeds [38], carabids (Case study) or any other taxa, these nodes structure the social and economic networks that are built, their scale, the amount of data needed and, ultimately, the types of question about ES that can be posed. The ecological networks could therefore provide the natural-science context that is often identified as a weakness in ES [6,7,25].

Decision-making for ES requires that multiple stakeholders contribute via a feedback loop of advocacy that includes demonstration, consultation, learning, co-development and engagement [42,43]. Whether ecological, social or economic in nature, networks are explicitly graphical, are visually attractive and deliver complex information with often surprising clarity [Figure 1]. This is particularly true for lay audiences who may find “scientific” representations, such as 95% confidence limits on a chart, too abstract to understand. A tractable network approach could become an essential part of co-development including demonstration, consultation and engagement (e.g. [44]), as well as learning. It is not yet clear whether the decision-making for ES in many different ecosystems will have similar solutions, due to common ecological, social and economic conditions, because the field is still too embryonic to afford generalisations. At least, by adopting the common vocabulary and tools of a network approach, it becomes possible to consider and compare all biodiversity-derived ES, from any ecosystem, in the same manner. General patterns of response in different ecosystems could then be identified, as knowledge, and communicated to stakeholders. Whether treated as “rules-of-thumb” or as more formal learning, such knowledge could be applied to novel ecosystems and could greatly increase the rate and certainty of ES decision-making (see Outstanding Questions).

Ultimately, the aim of ES research is to develop more rational, evidence-based decision-making that can be used to manage combinations of ES simultaneously. “Bundles” of multiple, interlinked ES arise from complex patterns of interaction within and between network layers (Case Study). From the work done to date, it is becoming clearer that bundles of ES cannot be sought within the ecological layer alone, at least in agricultural networks. However, when social and economic sensibilities are included, such as those of farmers and the public, acceptable bundles of ES may be identifiable using tractable ES network approaches. These bundles will not all be ecologically positive, with some services increasing and others decreasing, but they will be more acceptable as a consequence of a nonlinearly complex and dynamic social and economic weighting. Moreover, they will likely produce novel combinations of ES that could provide innovative management solutions beyond the traditional ingrained expectations, which properly reflect the ‘bigger picture’ that using a network-based approach would bring.

**Outstanding Questions**

We can see two sorts of outstanding questions. The first relates to ES network methodology, and how this might be developed. The second concerns the potential new research questions that ES network approaches might open up.

***ES network methodology development***

**Scale overlap**: While network analysis methods can cope with changes in scale (see text and Glossary), it would still be far simpler to find common, overlapping scales for ES analysis across all disciplines. Changing scale implies potentially important impacts on the types of information we get out of network analyses (see [51]). Future research should identify both compatible scales of research between disciplines and what the consequences of such common scaling would be: what information is lost; how does this affect network dynamics; and is this information loss worth the greater simplification that ensues?

**Layering**: The layering of networks, from the ecological through to social and economic layers, is a key element of the network approach for ES. With hindsight, the engineering, social and economic layering used for electronic networks, which inspired the ES layering, would appear obvious, but this is not so with ES layering. There is an important research question of whether there exists a generalised layering, a common framework as it were, which would allow us to define *a priori* the layers that go into a network model of ES.

**Testing**: It seems to us that the possibility of doing the research necessary to examine the Scale overlap and Layering question, and more importantly to evaluate the utility of a network approach to ES is not too distant. For example, data probably exist across the different groups working on pollination or pest control to construct social and economic networks of stakeholder sentiment, which could be used with existing ecological networks to examine whether ES network approaches deliver the advantages expected from the decision-flow (Box 2).

***New research questions***

**Nonlinearity and indirect effects on ES**: Nonlinearity and indirect effects have marked effects on network performance. Within the ecological layer, this can include effects on food web stability and resilience [51]. How such ‘higher-level’ performance is affected by the addition of effects within and between the social and economic layers is as yet unclear. Whether this might lead to greater ES stability and resilience that might be promoted through PES schemes or show that most domains of possible management would reduce stability and resilience of ES delivery, is clearly important to understand.

**Socio-economic feedback on Biodiversity-Ecosystem Function (B-EF)**: A network approach to ES might be used to prioritize ecological and B-EF research. If we constrain part of the research in this area, through feedback from social and economic networks, which B-EF relationships become important and how do they vary under different scenarios of change.

**General predictors and rules-of-thumb**: Decision-making for ES would be greatly facilitated by the discovery of general, synthetic predictors or rules-of-thumb for the performance and behaviour of ES networks. Future research should consider whether synthetic predictors, such as ecological traits considered at the node- and network-level, have predictive value.

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BOXES

Box 1. What is the relationship between Ecosystem Services and ecosystem functions?

Box 2. Decision-flow for adopting a Network Approach to ES Groups of researchers who are open to using networks for ES presumably either have data already available or are trying to specify the data requirements for the study. We imagine that they have in mind how deeply they would want to work with ES, i.e. from simply facilitating inter-discipline communication all the way down to working with multi-networks. Given this, then working through the flow of text boxes, starting at Aim #1 below, would determine what would be required for their research question.

Case Study. Hypothetical network approach for the adoption landscape management to support multiple services delivered by carabids

FIGURES

Figure 1. Visualizations of networks from natural and social sciences and engineering. (A) Map of the Internet, as of January 15th 2005. The link is drawn between nodes representing two distinct server IP addresses with colour codes that denote the domain names of the server representing some combination of computer hardware, social use and country of location (dark blue ~ .net, .ca, .us; green ~ .com, .org; red ~ .mil, .gov, .edu; yellow ~ .jp, .cn, .tw, .au, .de; magenta ~ .uk, .it, .pl, .fr; gold ~ .br, .kr, .nl; and white ~ unknown). The length of each link indicates an economic metric such as the response time between the nodes. (used with permission of opte.org). (B) Species interaction networks at Norwood Farm, Somerset (revised from [38] and used with permission). Each species is represented by a node that is a filled circle and each trophic link is represented by a line. Weed plants are the green nodes in the centre, with crops in light green. Each type of consumer node has a unique colour and associated indicative species in illustration.

Figure 2. Illustration of the layering of the multi-networks we propose for ES, 1.-3., using the network of [38] as the inspiration for the ecological network in Layer 1 (see also Figure 1B).