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A framework to quantify the strength of ecological links between an environmental stressor and final ecosystem services

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Abstract

Anthropogenic stressors such as climate change, increased fire frequency, and pollution drive shifts in ecosystem function and resilience. Scientists generally rely on biological indicators of these stressors to signal that ecosystem conditions have been altered. However, these biological indicators are not always capable of being directly related to ecosystem components that provide benefits to humans and/or can be used to evaluate the cost-benefit of a change in health of the component (ecosystem services). Therefore, we developed the STEPS (**ST**ressor – **E**cological **P**roduction function – final ecosystem **S**ervices) Framework to link changes in a biological indicator of a stressor to final ecosystem services. The STEPS framework produces "chains" of ecological components that explore the breadth of impacts resulting from the change of a stressor. Chains are comprised of the biological indicator, the ecological production function (EPF; which uses ecological components to link the biological indicator to a final ecosystem service), and the user group who directly uses, appreciates, or values the component. The framework uses a qualitative score (High, Medium, Low) to describe the Strength of Science (SOS) for the relationship between each component in the EPF.

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We tested the STEPS Framework within a workshop setting using the exceedance of critical loads of air pollution as a model stressor and the Final Ecosystem Goods and Services Classification System (FEGS-CS) to describe final ecosystem services. We identified chains for four modes of ecological response to deposition: aquatic acidification, aquatic eutrophication, terrestrial acidification, and terrestrial eutrophication. The workshop participants identified 183 unique EPFs linking a change in a biological indicator to a FEGS; and when accounting for the multiple beneficiaries, we ended with 1104 chains. The SOS scores were effective in identifying chains with the highest confidence ranking as well as those where more research is needed. The STEPS framework could be adapted to any system in which a stressor is modifying a biological component. The results of the analysis can be used by the social science community to apply valuation measures to multiple or selected chains, providing a comprehensive analysis of the effects of anthropogenic stressors on measures of human well-being.

Keywords

Acidic Deposition; Air Quality; Critical Loads; Ecological Production Function (EPF); Eutrophication; Nitrogen & Sulfur Deposition; Science Policy

Introduction

Anthropogenic stressors such as land conversion (Suarez et al. 1998), above-background greenhouse gas emissions (IPCC 2014), and the release of pollutants into the air and water (Galloway et al. 2003), have impacted ecosystems in a variety of ways including: changing competitive dynamics of interspecies relationships (Fenn et al. 2003, Fisichelli et al. 2014), reducing available habitat (Barrows and Murphy-Mariscal 2012, Riordan and Rundel 2014), and altering fire frequency and intensity (Westerling et al. 2006, Westerling et al. 2011). Researchers often characterize the impacts of stressors by identifying and measuring biological indicators, organisms or biotic responses that are sensitive to the condition of the environment (Phillips 1977, Clarke 1993, Conti and Cecchetti 2001, Walther et al. 2002). Sensitive biota are not always directly used, appreciated, or valued by the public which complicates the process of determining the public welfare implications of changes to environmental stressors and associated changes in indicators. To facilitate the translation of biological indicators into measures meaningful to public welfare, we developed a framework that links changes in a biological indicator to changes in final ecosystem services (Boyd and Banzhaf 2007). Final ecosystem services are “the components of nature, directly enjoyed, consumed, or used to yield human well-being” and represent the last thing in the environment used by humans (Boyd and Banzhaf, 2007).They are distinct from the ecosystem processes and functions, (sometimes referred to as “intermediate” ecosystem services), such as carbon sequestration or nutrient cycling, which are important to human well-being but not *directly* observed or appreciated by humans.

Titled STEPS (**ST**ressor – **E**cological **P**roduction function – final ecosystem **S**ervices), this framework produces “chains” to evaluate the broad ecosystem and human impacts of a change due to a specific stressor. The STEPS Framework first identifies changes in ecosystem indicators resulting from a change in the stressor. These indicators are then

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connected, through cause-and-effect relationships that characterize the subsequent cascading ecosystem impacts, to changes to an ecological component that society values as a final ecosystem service. The output of the STEPS Framework is therefore a list of affected ecological endpoints, which are each linked to the specific categories of human beneficiaries who value them. From this list, measures of human well-being can be assigned to document the human welfare impact of a stressor change. This framework was developed to evaluate changes to ecological indicators from a single stressor, but can be expanded to incorporate multiple stressors that may be acting antagonistically or synergistically. In this paper, we describe the STEPS Framework and present a summary of a case-study application of this Framework developed within a workshop setting that linked the ecological impacts of nitrogen (N) and sulfur (S) pollutant emissions and deposition to changes in final ecosystem services using the Final Ecosystem Goods and Services Classification System (FEGS-CS) (Landers and Nahlik 2013). Extended analysis of the four modes of response to deposition: aquatic acidification (O'Dea et al. In Press), aquatic eutrophication (Rhodes et al. In Press), terrestrial acidification (Irvine et al. In Press), and terrestrial eutrophication (Clark et al. unpublished manuscript), are covered in the subsequent papers of this special section.

STEPS Framework

The STEPS Framework consists of three modules that feed into one another to classify how a stressor impacts the ecosystem components that humans use and appreciate -- the Stressor Module, the Ecological Production Function (EPF) Module, and the Final Ecosystem Services Module (Figure 1). The Stressor Module identifies how a change in environmental conditions affects specific biological indicators. For example, much research has been done identifying how human modification of the environment negatively impacts sensitive species, and these relationships can be used as the input into this Module of the STEPS Framework. The EPF Module is the core of the STEPS Framework as it identifies the series of cause-and-effect relationships that link each biological indicator of a stressor to ecological endpoints that are directly used, appreciated, or valued by humans. An EPF is an expression of the processes by which ecosystems produce ecosystem services (Bruins et al. 2016). The final module of the STEPS Framework is the Final Ecosystem Services Module which links the identified ecological endpoints with specific types of human groups who use or value the resource (e.g., beneficiary groups). If society's interaction with the environment is framed as one of supply (what the environment provides that humans use) and demand (how humans interact with the environment), the STEPS Framework delineates how stressors are impacting the supply side of the equation (i.e., how do changes in stressors impact the supply of final ecosystem services?). This top down approach identifies what is changing and how many different components of the ecosystem it will affect.

The output of the STEPS Framework is a list of final ecosystem services that change due to a stressor, which can be used to define the measures reflecting changes in human well-being (e.g.; water quality, board feet of timber supplied by a forest, health benefits of nature). The link between FEGS and beneficiary classes is important, because many groups will value a given resource differently. The framework enhances previous research that has described the economic impacts of stressors, such as acid rain and nitrogen deposition (Chestnut and Mills 2005, Sobota et al. 2015), by providing a more detailed breakdown of how a stressor changes the ecosystem and lists user groups who have a variety of interest in the effects. Developing these values of the impacts was outside the scope of this analysis and will require significant interaction among economists, social scientists, and ecologists.

In its current form, the STEPS Framework acts as a conceptual model for ecosystem relationships that occur with the change in a stressor. It allows for a component to affect two (or more) downstream components, but does not take into account feedbacks to upstream components. As relationships are defined and confirmed, the intensity of the response of one component on the other can be added to the model to better understand the direct impact. The long term developmental goal will be to use the defined relationships as an integrative model linking stressors and ecosystem components to understand tradeoffs based on management and policy decisions.

Stressor Module

The Stressor Module of the STEPS Framework describes the relationship between changes in a stressor and changes in a physical, chemical, or biological indicator that has downstream effects on human welfare. For example a physical change could be the change in the shape of a stream bank, a chemical change could be an increase in temperature or corrosivity of water, and a biological change could be an increase in dominance of an exotic grass species (Figure 1; red boxes). The confidence of the science literature detailing the response of the indicator to the stressor is recorded as the Strength of Science of the Stressor (SOS_S; Figure 1, blue circle). Impacts of a stressor are not always direct, and information regarding the impacts of the stressor on chemical or biological conditions which ultimately impact a biological indicator is not always available. Therefore, the Stressor Module combines known scientific knowledge of the response of an indicator to a measurable change in a stressor and classifies it as the SOS_S value. The SOS_S addresses varying levels of uncertainty in the understanding of the stressor –indicator relationship by adopting the system developed by Pardo et al. (2011) for critical loads of nitrogen deposition. The three levels include:

High – The relationship between a stressor and the change in an indicator is reliable indicating that the scientific literature confirms a detrimental response of the biological indicator to an observed change in a stressor. These can be based on gradient studies, field experiments, or observation in long-term studies. This is equivalent to symbol ## used in Pardo et al. (2011).

Medium – The relationship between a stressor and the change in an indicator is fairly reliable based on research in similar habitats or steady-state mass balance models and dynamic models are used to simulate ecosystem component responses to a changing stressor. These maintain inherent uncertainty due to biological complexity. This is equivalent to symbol # used in Pardo et al. (2011).

Low – The relationship between a stressor and the change in an indicator is based on expert judgment from field observations or transferring results from another geographic region, but not at the one in question. This is equivalent to symbol (#) used in Pardo et al. (2011).

Ecological Production Function Module

The biological indicator is generally the last component of the Stressor Module and the first component of the EPF Module. If no biological indicator is influenced to alter human welfare, the biological indicator step would be bypassed and the ecological production function would begin after the chemical or physical threshold has been surpassed. An EPF defines the ecological relationships that link the stressor to an ecological component that is directly used, appreciated, or valued by humans – a final ecosystem service. This stepwise, cause-and-effect function provides scientific backing to downstream ecosystem components so a direct relationship can be created for the change in an indicator relative to the change in a final ecosystem service (Figure 1; purple boxes). If a stressor directly impacts an ecological component that is a final ecosystem service, then no EPF is created. The variable length of EPFs within the EPF Module of the STEPS Framework is denoted by the purple box "Component n" in Figure 1.

Each link within the EPF is given a strength of science score based on the literature supporting the link between the two components in the EPF (SOS_E; Figure 1, yellow diamonds). As with the SOS_S, the SOS_E score is a confidence measure representing that there is data supporting one component influencing a second component; an ecological cause and effect (rubric for decision making is in Appendix S1).

High – Evidence for the relationship between components is based on multiple, strong lines of published scientific evidence. High quality research shows that the change in $Component_i$ is one of the main factors influencing the change in $Component_{i+1}$. Site specific studies can be applied locally with high confidence, while if the change is of the nature that it should not be influenced by environmental or site specific factors, a high SOS_E can be applied on a regional basis.

Medium – Evidence for the relationship is limited, inconsistent, or conflicting. The link between components may be tied to site specific factors and have limited transferability among sites (which should be noted).

Low – There is no published scientific evidence that shows a change in $Component_i$ leads to a change in $Component_{i+1}$. However, observations that a change in $Component_i$ resulted in a change in $Component_{i+1}$ have been made by experts in the field or based on unpublished data.

The attribution of scientific literature to the links is important so that chains can be defended when used to direct management and policy actions. If the available studies are of insufficient quality, consistency, or statistical power to permit a conclusion regarding the relationship between $Component_i$ and $Component_{i+1}$, and expert judgment does not support a link, the links should not be included in the assessment.

SOS_E scores are given values of High=1, Medium=0.67, and Low=0.33. The scores are combined using Equation 1 to characterize the strength of science for the ecological production function (SOS_{EPF}; Figure 1, orange circle) is:

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$$SOS_{EPF} = \frac{\sum SOS_E}{\text{EPF Length}} * \left(1 - \frac{1}{M - \text{EPF Length}}\right) \quad \text{Equation 1}$$

This equation reduces the overall confidence score of the EPF based on the number of components connecting the biological indicator to the ecological endpoint. The equation is meant to account for the likelihood that a single ecological component affects more than one subsequent component and is affected by more than one component that precedes it. As EPFs get longer, there is less confidence that there are not confounding factors impacting the identified components. The constant M is a diminution factor to reduce the SOS_{EPF} value as more ecological components are added. For the case study that follows, M is set to 8; therefore there can be up to 6 ecological components within an EPF for the SOS_{EPF} to have a positive value and at 7 components the SOS_{EPF} is zero. This intends to represents the length of the chain at which point the ecological endpoint is too far from the biological indicator to have any confidence in the relationship. This equation is used to rank the chains based on knowledge, not to suggest the relative impact of the ecosystem components on one another.

Final Ecosystem Services Module

The ecological endpoint of the EPF is then classified by Final Ecosystem Services Module. The intention of the STEPS Framework is to use a classification system that focuses on final (rather than intermediate) ecosystem services to create direct relationships to human well-being. A final ecosystem service is classified by the environmental component (the ecological endpoint; Figure 1, green box) and the user group interacting with the environmental component (Figure 1, blue boxes). This module acts as the handoff between the biological science and social science communities, where an analysis on the societal or economic value of the final ecosystem service and how to measure it will take place. Although other classification systems for ecosystem services exist, such the Millennium Ecosystem Assessment (MEA 2003), the National Ecosystem Services Classification System (USEPA 2015), and the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2013), we selected the FEGS-CS for STEPS in part because of its focus on final services.

During the development of EPFs, it is important to coordinate with social scientists for help distinguishing intermediate from final ecosystem services when determining the ecological endpoint. It is desirable to always have the ecological endpoint be the final ecosystem service, but it is sometimes necessary to link an intermediate step of the EPF to the Final Ecosystem Service in order to capture the full impact on human well-being. For example, increased fire intensity and frequency (the intermediate ecosystem service) has a direct effect on beneficiaries such as homeowners whose property is at risk if they live near affected areas. These fires also alter ecosystem function, such as reducing shrub habitat for sensitive species (Talluto and Suding 2008), which in turn impacts beneficiaries who value flora and fauna (the final ecosystem service).

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The advantage of using final ecosystem services are that they:

- can be associated with readily definable ecological production functions
- facilitate the identification of biophysical metrics and indicators
- count only direct interactions (uses) between a user (or beneficiary) and the ecosystem, thereby minimizing or avoiding double counting
- identify human beneficiaries and use, thus linking to human well-being; and
- facilitate direct communication and collaboration between natural and social scientists.

The entire set of links from the stressor to the user group is identified as a *chain* (Figure 1; red outline). The chain is the entirety of the discrete series of components identified within the STEPS Framework to highlight how a change due to a stressor impacts a user group. If an ecological endpoint is utilized by multiple beneficiaries, chains are replicated for each one. The number of chains produced for the change in a biological indicator helps to establish the breadth of impacts of that resource. The reason that is important to classify all user groups associated with the ecological endpoint is that most final ecosystem services represent limited resources (e.g., number of fish, number of trees, etc.). If usage rates of individual users can be determined, and if competing uses exist, tradeoffs can be calculated and it can be ensured that a resource is not counted twice in the valuation process. While in many of the examples provided, the end-users may be a small group lacking legal authority to challenge an impact, or have insufficient economic clout to be taken into consideration in valuation assessments, establishing many end-user beneficiaries provides a list of potential stakeholders of a decision; which is particularly useful to public land agencies.

The strength of science of the chain (SOS_C) represents the confidence in scientific data from the change in an indicator due to a stressor to the change in a final ecosystem service and is calculated using Equation 2.

$$SOS_C = \frac{SOS_S + \left(SOS_{EPF} * \text{EPF Length}\right)}{\text{EPF Length} + 1} \quad \text{Equation 2}$$

The equation averages the full weight of the SOS_S with the diminished value of each SOS_E based on the chain length. The SOS_S retains its full confidence because this is the basis of the analysis and the start of the measured change in the ecosystem. For those indicators that are also ecosystem services, the SOS_C score will be equal to the SOS_S value. The SOS_C value is intended to be the dominant metric used to evaluate the relationships within the STEPS Framework. Since the analysis is not measuring the relative response of one component on another the SOS_C is a measure of confidence that the relationships exist within published literature and can be used to defend decision making. When using the results to calculate trade-offs, analysis at a local scale will need to be completed to understand the intensity and the importance of each chain being debated.

Additionally, we identify the lowest SOS_E or SOS_S score within each chain and label it as the strength of science weakest link (SOS_{WL}). This is based on the idea that a chain is only as strong as its weakest link. While an argument can be made that there is no need to move past the weak link because the whole relationship can break down at this point, we believe that this value can be used alongside the SOS_C to help identify where an otherwise high impact chain may need more research. Both values are provided to enhance the use of the output depending on the user's interest.

Lastly, having a separate equation for the SOS_{EPF} will allow for additional analyses comparing the SOS_C with the SOS_{EPF}. Since the research that goes into how changes in the environment affect the initial biological indicator is different than research on measured downstream ecosystem responses, it may be beneficially to compare these two values to isolate areas of uncertainty in the cause of the initial change. This also allows for the synthesis of efforts where multiple stressors may be impacting the same EPFs.

Case-Study Application of Framework – Air Quality and Ecosystem Services Workshop

The functionality of the STEPS Framework was tested at a workshop bringing together scientists, resource managers, policy makers, and economists to explore the relationships between air quality and ecosystem services (Blett et al. 2016). The benefit of having this diverse group was to limit any particular participant from getting caught up in the details of their expertise and to try to understand where vocabulary overlapped and conflicted between disciplines. Economists and policymakers helped to guide the scientists towards final ecosystem services as scientists described the importance of their known ecoregion. Alongside having detailed understanding of local responses, resource managers were familiar with user groups of the natural areas that they manage. The boundary of inputs into the Stressor Module was set as biological responses to exceedances of N and S critical loads (in kg ha^{-1} yr^{-1}). The scope was limited and defined due to the large body of literature identifying biological impacts of deposition (Fenn et al. 2010, Pardo et al. 2011, Greaver et al. 2012). For the workshop, the Final Ecosystem Goods and Services Classification System (FEGS-CS) was used within the Final Ecosystem Services Module. FEGS-CS uses a standardized system to conceptually and theoretically link a product derived from a particular sector of the environment with a specific user or beneficiary (Landers et al. 2016).

Workshop attendees were split into groups to classify the ecological responses to exceedance of critical loads deposition based on the mode of response to deposition: aquatic acidification (O'Dea et al. In Press), aquatic eutrophication (Rhodes et al. In Press), terrestrial acidification (Irvine et al. In Press), and terrestrial eutrophication (Clark et al. unpublished manuscript). The specific objectives of the workshop were to test the STEPS Framework and explore its utility to: 1) develop relationships (chains) based on published literature to link the indicators of an environmental stressor with a final ecosystem service and its associated user group and 2) use these chains to identify an effective method to transfer ecological information into information useful to managers and policy makers.

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Critical loads of nitrogen deposition

The deposition of N and S can lead to the acidification and eutrophication of both aquatic and terrestrial systems, altering species compositions and ecosystem function (Fenn et al. 2011, Pardo et al. 2011). Global anthropogenic N additions (dominated by burning fossil fuels and fertilizer application) have more than doubled since the preindustrial era (Galloway et al. 2004), while S additions have been steadily declining since the Clean Air Act of 1970, but are still high enough to alter ecosystem function in the eastern United States (Driscoll et al. 2001, Greaver et al. 2012). Scientists have monitored ecosystem responses to deposition and have identified biological indicators sensitive to emissions (Nilsson and Grennfelt 1988, Fenn et al. 2011, Pardo et al. 2011). The deposition loading rate at which these biological indicators begin to change is known as the critical load. A critical load is defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge’’ (Nilsson and Grennfelt 1988). Critical loads vary among species and among ecosystems as physical, biological, and chemical environments determine how responsive species are to changes.

Nitrogen is often limited in terrestrial and aquatic systems, and when the limitation is overcome through inputs (eutrophication), responsive species’ populations can increase or decrease (Saros et al. 2003, Rao and Allen 2010, Jovan et al. 2012). This shift in community composition can alter competitive relationships, reduce food sources, and diminish habitat (Weiss 1999, Fenn et al. 2003). Sulfur and N deposition can also have acidifying impacts on terrestrial and aquatic ecosystems. Acidification lowers the pH of soil, leaching calcium ions (and other base cations, including deleterious heavy metals) while mobilizing aluminum ions (Greaver et al. 2012), which has negative growth effects on soil fauna and vegetation (Driscoll et al. 2001). N and S deposition can also result in decreased acid neutralizing capacity and pH in aquatic systems to levels where it degrades habitat quality and inhibits invertebrate and fish growth and development (Greaver et al. 2012).

Critical loads were obtained from the national database of critical loads for S and N (http://nadp.sws.uiuc.edu/committees/clad/db/), developed by the Critical Loads of Atmospheric Deposition Science Committee (CLAD) of the National Atmospheric Deposition Program (NADP). This database provides a thorough evaluation of both empirically derived and calculated critical loads for a variety of biological indicators.

Final Ecosystem Goods and Services Classification System

The FEGS-CS provides an interdisciplinary framework that allows for ecologists and other natural scientists to identify and measure affected ecological endpoints, and for economists and other social scientists to assess and measure the related ecosystem services. Final services are identified in FEGS-CS by connecting specific beneficiary groups with the endpoints they directly utilize, consume, or enjoy from the environment. To assist in defining the ecological endpoints, it divides the natural environment into 15 distinct environmental sub-classes (e.g., rivers and streams; and grasslands). To define the final ecosystem services provided by the endpoints, it identifies 38 specific human beneficiary categories, each of which represents a different type of human interest that drives active or

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passive consumption and/or appreciation of the endpoints (Appendix S2; e.g., foresters, anglers, artists). In short, FEGS are the functional intersection linking nature and people, or what is produced by the environment and what is valued by humans.

The use or appreciation by a beneficiary of an environmental component makes that component a FEGS. Remove the user, the environmental component, or the relationship between the user and that component, and there is no FEGS – as when one lists ecosystem-service "benefits" for which users are implied but not identified. In any classification system for potential FEGS, the potential of the user to use or appreciate a candidate ecosystem service must exist. This positions the FEGS to be properly valued by economists based on amount of change of the ecological components and the characteristics of beneficiary groups who value it. Therefore, when applied to a specific question, the list of FEGS must be compared to the resources that exist in a place and if there is proper access to said resources.

Applying the STEPS Framework

Each of the groups applied the STEPS Framework to their mode of response to deposition. The specifics of each analysis can be found in the papers within this special section, but are described in brief below. The Aquatic Acidification (AA) group started by identifying a single chemical criterion of the critical load (acid neutralizing capacity) to determine changes to biological indicators and then working backwards from the beneficiaries to determine which critical loads were impacting users (O'Dea et al. In Press). The Aquatic Eutrophication (AE) group used trophic levels to identify ecosystem responses to excess air pollution above critical load thresholds, so the results can be applied to any region, with each specific area replacing the trophic level with their local species (Rhodes et al. In Press). The Terrestrial Acidification (TA) group focused on two discrete biological indicator tree species (white ash, *Fraxinus americana* L., and balsam fir, *Abies balsamea* (L.) Mill) and fully developed their chains to identify all FEGS (Irvine et al. In Press). The Terrestrial Eutrophication (TE) group took a regional approach and focused many of their biological indicators and FEGS at a community level (Clark et al. unpublished manuscript). Each group developed a spreadsheet describing the chains linking ecological effects of air pollution on specific biological indicators to Final Ecosystem Goods and Services (Appendix S2).

Results

The application of the framework identified 47 biological indicators impacted by critical load exceedances and associated them with 84 ecological endpoints (Table 1). The average SOS_S value was 0.85 with 9 Low, 7 Medium, and 31 High ranked critical loads evaluated. There were 183 unique EPFs leading to the formation of 1104 chains linking a change in a biological indicator to a beneficiary (Data S1). Due to the differing focus of each group, the number of chains does not represent the relative impacts of air quality on each ecosystem. Since the STEPS Framework does not report on the intensity of the response, the current focus of interpretation should be on the breadth of beneficiary groups impacted by a change, and the scientific integrity of the relationships.

The EPFs developed by the groups ranged from one to six ecological components with an average length of 1.9 components. The ecological endpoints of the EPFs were tied to nine beneficiary classes and 25 beneficiary sub-classes from the FEGS-CS (Figure 2). The identified beneficiary classes ranked in descending order of number of chains were: Recreational, Non-use, Learning, Inspirational, Commercial / Industrial, Subsistence, Government-Municipal-Residential, Agricultural, and Humanity. The count of beneficiaries sub-classes was weighted heavily towards 7 groups that trended together; People Who Care (Existence) (139), People who care (Option/Bequest) (139), Experiencers and Viewers (137), Artists (123), Spiritual and Ceremonial Participants and Participants of Celebration (117), Educators and Students (112), Researchers (109; Figure 2). These chains made up 876 of the 1104 identified relationships (79%). The remaining beneficiary sub-classes, in descending order, were: Resource dependent businesses (45), Hunters (30), Timber, Fiber, and Ornamental Extractors (29), Residential Property Owners (21), Food subsisters (18), Anglers (15), Timber, Fiber, and Fur/Hide subsisters (15), All Humans (10), Food extractors (8), Traditional medicine subsisters (8), Boaters (6), Food pickers and gatherers (5), Livestock Grazers (5), Waders, swimmers, divers (4), Aquaculturist (3), Water subsisters (3), Municipal drinking water plant operators (2), Pharmaceutical and food supplement suppliers (1).

The seven beneficiary sub-classes that trended together are all non-consumptive users who may be members of a wide range of interest groups and generally cover all geographic areas. The size of the group (whether it consists of a native plant society members or wildlife organization, for example) will vary based on the type of ecological endpoints and the importance of it to local conservation or politics, but inclusion of these groups of non-consumptive users in the FEGS-CS system highlights the broad impact of stressors on the outputs of ecosystems that people value.

SOS_{EPF} scores ranged from 0 to 0.86 with an average score of 0.77. SOS_C scores ranged from 0.39 to 1 with an average score of 0.82. The SOS_{EPF} and SOS_C scores skewed towards high numbers based on the short average EPF length and the high SOS_S scores (Figure 3). This is probably partially due to the fact that most of the relationships were developed in a short period of time at the workshop where experts relied on their knowledge of known relationships within their study areas to define the ecosystem components. If this database is expanded to include a broader range of ecosystem interactions, the average SOS_E score will probably decrease as less studied ecological interactions are added. As is, the distribution chart allows for the easy identification of high-ranking relationships on which policy and management action can be based, as well as low ranking relationships where further research is needed (Figure 3).

The different methods used had the greatest impact on the SOS_{WL} metric. The AA (mean SOS_{WL}=0.91) and TA (mean SOS_{WL}=1.00) groups focused their analysis on a limited range of well-studied systems which lead to minimal weak links in the chains. This does not imply that all the knowledge has been accumulated on the impacts of AA or TA, but rather that the chains created are those that are highly backed by scientific studies. The TE (mean SOS_{WL}=0.67) and TA (mean SOS_{WL}=0.67) cast a wider net when looking at ecosystem impacts of critical loads leading to lower SOS_{WL} scores relative to the AA and TA analyses.

The presence of a Low SOS_E link in a chain implies that more scientific study is needed on the defined relationship.

Additionally, Figure 4 demonstrates the importance of taking the SOS_{WL} into account when evaluating the chains. Thirty-one of the 183 EPFs and 266 of the 1104 chains created at the workshop have an SOS_{WL} of Low. While the SOS_C equation differentiated among the chains, the range for the final score of a chain with a link rated as Low ranged from 0.68 to 0.39. These chains should be highly scrutinized before being used for policy decisions to ensure that the weak link is not scientifically limiting. This analysis also can highlight those chains, when tied to important beneficiaries that should be pulled out to identify future research directions.

The differences in the value and distribution SOS_C scores among groups highlight the difficulties in comparing systems that have missing ecosystem data. As with the discrepancy in the number of chains that each group produced, the differences in SOS_C scores do not represent a difference in the importance of each of the responses. The amount of research that has taken place in each of the modes of response, as well as the specificity to which each group focused their chains, impacted the outcomes.

Discussion

The STEPS Framework is a system to explore the links between indicators sensitive to a stressor, related final ecosystem services, and their user groups. The relationships among the components within an ecosystem, described by the collective EPFs, not only delineate how changes in biological indicators cascade through an ecosystem, but also provide a structure to which additional stressors can be added to understand the synergistic impacts of anthropogenic stressors on the natural world. The EPFs developed during the workshop represent the dominant, documented pathways of ecological response based on a change in selected biological indicators of atmospheric deposition. The use of the Final Ecosystem Goods and Services Classification System provided a functional structure to classify the ecological endpoints as final ecosystem services. The SOS scoring system helped to identify chains that should be more fully developed to support quantitative analysis, as well as highlight the chains where strong science currently exists. This analysis will help to develop communication strategies about what is already known about the broad effects of a stressor on human welfare.

Functionality of STEPS Framework

The flexibility of the STEPS framework was evident by the various relationships that the four groups developed in their chains. First, it was shown to be effective in both terrestrial and aquatic systems, and likely could be transferred easily to marine systems if the stressor impacted those areas. It can be used at a local scale, as shown by the Terrestrial Acidification group, to understand species levels responses and the broad impacts that a single species can have on a system. It can be used at a regional scale, as the Terrestrial Eutrophication demonstrated by linking changes at the community level to broader impacts. It can also be used in reverse, as the Aquatic Acidification group first identified FEGS for aquatic systems and then linked them back to known biological indicators.

The different ecosystems and taxonomic ranks analyzed highlight both a strength and a weakness of the framework. The number of chains that were produced in the short amount of time suggests that the STEPS Framework is a useful method to produce a reasonably comprehensive set of chains for the ecological responses to a stressor. The total number of identified chains, 1104, can be a little overwhelming when considering how this could be used to guide policy or a management action. This being a national assessment, the relevant chains to an area can quickly be sorted down to a functional level based on the presence of the proper habitat or species. The difference in scale adopted by each group shows the functionality of the framework for different types of questions; whether it is a regional or local analysis. In future uses of the STEPS Framework, it will be important to provide guidance at the outset as to the necessary regional and species level detail to make sure identified responses are comparable.

As EPFs are developed for additional stressors, ecosystems, or species, there will be the opportunity to identify points where synergistic and antagonistic relationships among stressors (and EPFs) may be occurring (Darling and Côté 2008). Identifying points at which multiple stressors are acting may highlight integral ecosystem component to further prioritize future management and policy decisions. As the number of defined EPFs grows, relevant biological indicators can be the database as an initial screening of broader impacts.

The biggest challenges when describing the ecosystem responses to a changing biological indicator are related to ecosystem complexity. The workshop attendees used their collective knowledge to describe known quantities of the ecosystem, but some relationships between ecological components have yet to be empirically studied. The responses described in EPFs have been measured in the literature, but the heterogeneity, connectivity, and history of a site can lead to changes in response (Cadenasso et al. 2006). Within systems, there may be built in aspects of species redundancy, or biological substitution that reduce the stressor effect on the ecosystem (Naeem 1998). Additional information on the importance and the intensity of the interaction between two ecosystem components will provide another layer of depth to evaluate chains (Brooker et al. 2005, Brooker and Kikividze 2008). The list of interactions identified within these papers represents the most obvious interactions. It is important to convey that expanding the responses is important and by no means does this represent the full breadth of the impacts of a stressor. The concept of multiple pathways impacting a single ecosystem service can be evaluated through joint valuation where, in the case of the STEPS Framework, multiple chains could be valued together where similar impacts occur (Farber et al. 2006, Sauer and Wossink 2012).

Tying results to Management and Policy

Understanding and characterizing the quality of science linking the change in a biological indicator to the change in a final ecosystem service can be useful in policy and management settings to rank and compare EPFs. Managers and policymakers may use this information to understand uncertainty imbedded in the chains, or select chains with strong scientific foundations for further assessment and subsequent valuation. Ecosystem management may take many directions based on the main users and agencies involved. Often, due to limits of time and personnel, active management of a resource is limited prior to exceeding an economic (or ecological) threshold where change is unacceptable (Ludwig et al. 2005). If the land management objectives are resource focused, the final ecosystem service can be targeted to track backwards to identify the thresholds which should not be exceeded in order to minimize impacts to ecosystems and their components. If a specific type of user is most important, beneficiary interests can be tied to multiple potential biological perturbations (e.g., anglers' concerns about both stream acidification and eutrophication) that can then be linked to management priorities. This framework is valuable for managers and policy makers in that it provides a methodology for identifying a comprehensive suite of cascading impacts to ecosystems once ecosystem impact thresholds are exceeded. It may also be used to identify efficiencies in mitigation of a stressor, such as choosing to manage a biological indicator (or response) that leads to a broad impact on final ecosystem services relative to another, that may be easier to manage, but has a narrower impact.

The chains can also be used to develop educational tools (e.g., land managers can use them to explain the importance of national park, national forest, and wilderness resources). An example is to translate the impacts of air pollution to a beneficiary-specific audience by using the ecological component that the group values and linking it back to the exceedance of a critical load via the EPFs. This provides an opportunity to connect with audiences who may not have seen the relevance of air pollution to their directed interests. Box 1 provides an example of how land managers may use the chains to tell simple stories, linking the impacts of a stressor (air quality in the desert) to things that people care about (loss of diversity and increased fire frequency). Three additional examples with high confidence in the chains have been expanded upon in Blett et al. (2016) to highlight the ways in which information from chains can be used to tell stories creating ties between air quality and its effects on parts of the ecosystem which end users care about and is expanded on in Irvine et al. (In Press).

Another potential use of this framework will be to help assess the policy relevance of scientific evidence. The Environmental Protection Agency Office of Air Quality Planning and Standards, which is responsible for reviewing and setting the National Ambient Air Quality Standards (NAAQS), first conducted a joint review of secondary standards for N and S oxides (NO_x and SO_x) in 2012 and identified many ecosystem services potentially affected by NO_x and SO_x. Those services were described, and where possible the magnitude of the total service provision was quantified. For example, the valuation of recreational fishing was estimated in a case study. The current air quality secondary standards review intends to expand and refine the use of ecosystem services following the same strategy. The STEPS framework will be considered as a potential tool for use in the risk assessment portion of the standards review, by identifying quantified relationships between deposition rates and ecological effects, and between ecological effects and Final Ecosystem Goods and Services.

Valuation of Final Ecosystem Services

One of the outputs of the STEPS Framework is a count of user groups who are potentially impacted by the change in the stressor. The number and diversity of users can be used to understand measures of human well-being that are impacted. Using the concept of supply and demand, the list of beneficiaries is, in essence, the *demand-side* classification of ecosystem services and can support decision making based on combination of market-based (e.g., price of a board foot of timber) and non-market (e.g., availability of clean drinking water, cognitive awareness) valuation of the identified final ecosystem services. Valuation, integrates the concepts of scarcity and beneficiary demand, thereby increasing the reliability and legitimacy of policy decisions (Farber et al. 2002, de Groot et al. 2010). It allows for trade-offs to be compared and debated when a decision leads to an unequal impacts on services among beneficiaries. Much research has been completed on integrated monetary and non-monetary valuation in decision making, but generally past efforts have been heavily weighted towards monetary valuation of resources to place a dollar value on ecosystem health and the preservation of ecosystem function (de Groot et al. 2012).Traditionally, when evaluating the users of ecosystem services, non-consumptive users who are negatively impacted can be overlooked due to the fact that they often exist in smaller groups. This analysis demonstrates that these non-consumptive users can be systematically identified and lumped into larger categories to highlight their collective value of these groups. Such as, users of US National Parks generated over $16.9 billion to gateway communities (which would be classified as resource dependent businesses in the FEGS-CS) through 307 million park visitors in 2015 alone (Cullinane Thomas and Koontz, 2016). Our analysis confirms that there are many beneficiaries who have non-consumptive demands for ecosystem services.

Efforts have been made to incorporate cultural and spiritual value of FEGS within the Recreation, Inspiration, and Education beneficiary classes (Chan et al. 2012, Daniel et al. 2012, Hernández-Morcillo et al. 2013). Additionally, there is improved awareness of the mental health benefits of natural systems (Shanahan et al. 2015, Soga and Gaston 2016). It is important for measures of human well-being to take these less tangible non-consumptive components into account when identifying total impact of a change in a final ecosystem service.

Conclusions and Next Steps

The STEPS Framework is a potentially effective method of linking biophysical responses of a stressor to ecological components that are used, appreciated, or valued by humans. This paper identifies and demonstrates potential links between an ecological component and a beneficiary. The benefit of using the FEGS-CS within the STEPS Framework is that it categorizes ecosystem services into discrete environmental and beneficiary categories for each identified ecological endpoint, and provides the structure to define metrics of the change in services. This output can then be processed through the socio-economic lens to determine the value of each relationship so that policy and management decisions can be made (Heal 2000). The transdisciplinary workshop environment including both social and natural scientists was an effective means of developing the relationships between a stressor and a FEGS because it encouraged ecologists to develop a better understanding of where within the system society draws the most value. The next step in a final ecosystem service assessment would be to evaluate the extent to which beneficiaries care about or understand the chains to identify where to focus efforts for the valuation step. It will also be important for ecologists to continue to provide their perspectives when working to identify the demand of potential user groups to ensure that the constraints of the ecological resource are accounted for. The focus of that analysis is on economic valuation; however, consideration should still be given to all facets of human well-being, including those that are difficult to monetize using standard economic methods.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Box 1: How a rain of fertilizer caused a reign of fire

Nitrogen deposition is like fertilizer raining down out of the sky. Just as the fertilizer that people put on their lawns causes them to be lush and grow quickly, atmospheric deposition of excess nitrogen can cause invasive grasses biomass to increase exponentially in natural areas, where they don't belong. In Joshua Tree National Park, a desert area in southern California, nitrogen deposition has caused non-native grasses to increase so much that they can now carry fire across some parts of the landscape. Park managers are now preparing for increased fire in the park, and it is unknown what will happen next, as large, intense fires have never been observed there since the establishment of Joshua Tree National Monument in 1936.

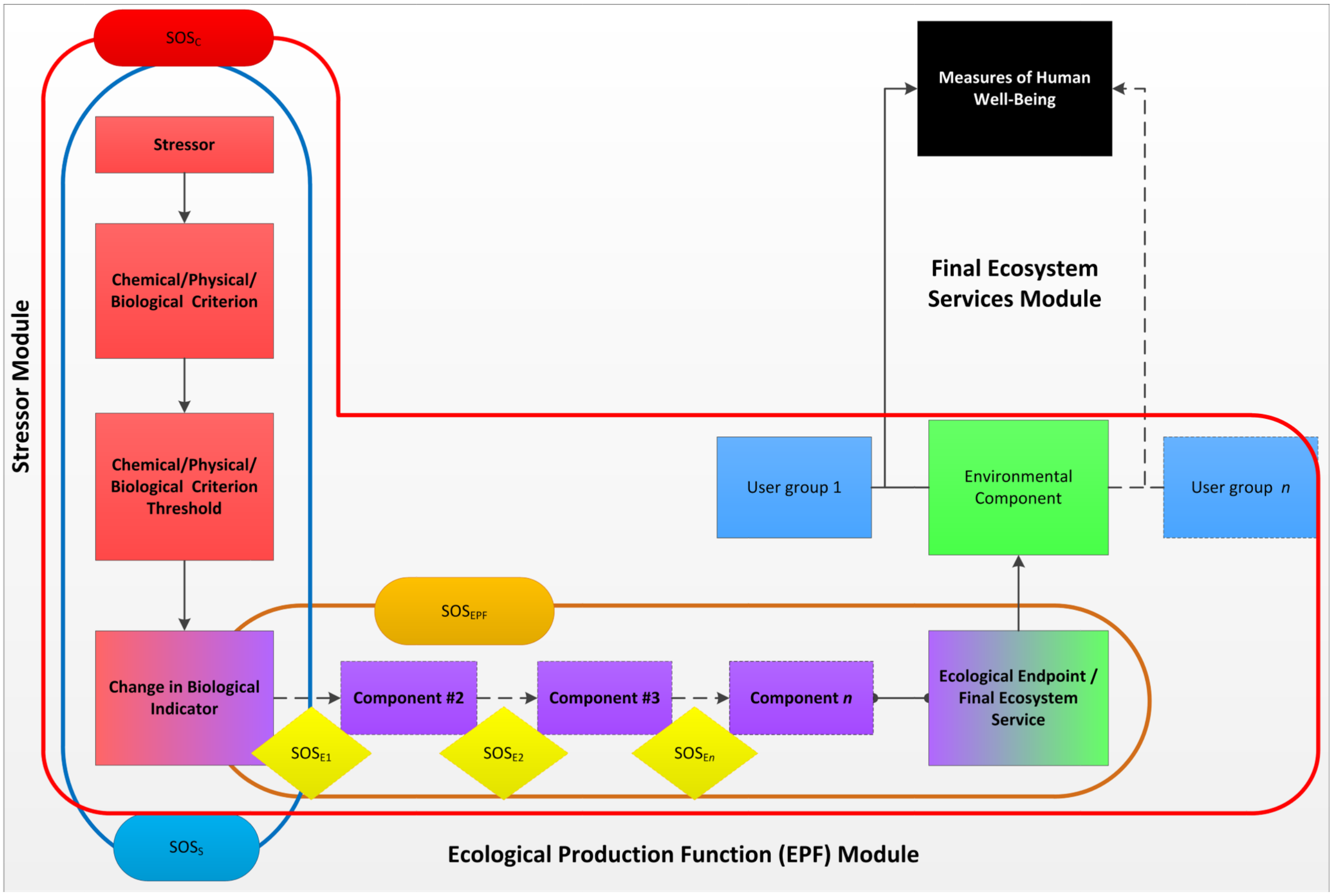

Figure 1.

A conceptual model of the STEPS Framework. The Stressor Module (red squares) consists of the chemical, environmental, and/or biological responses that are influenced by a stressor and lead to a change in the biological indicator. The SOS_S score represents the scientific integrity of the relationships within the module (blue line). The Ecological Production Function Module (purple squares) is the cascading ecosystem effects due to the change in the biological indicator. The EPF can have zero to n additional steps which is represented by the dotted lines connecting each component to the Ecological Endpoint. The yellow diamonds are the SOS_E score for the relationship between the two components. The orange circle represents the combination of all SOS_E scores in the SOS_{EPF} equation. The Ecological Endpoint feeds into the FEGS-CS Module which identifies a beneficiary class for each endpoint. A chain linking a change in biological indicator to a FEGS is represented by the red line. The FEGS-CS is funneled into the Measures of Human Well-being module that was outside the scope of this analysis.

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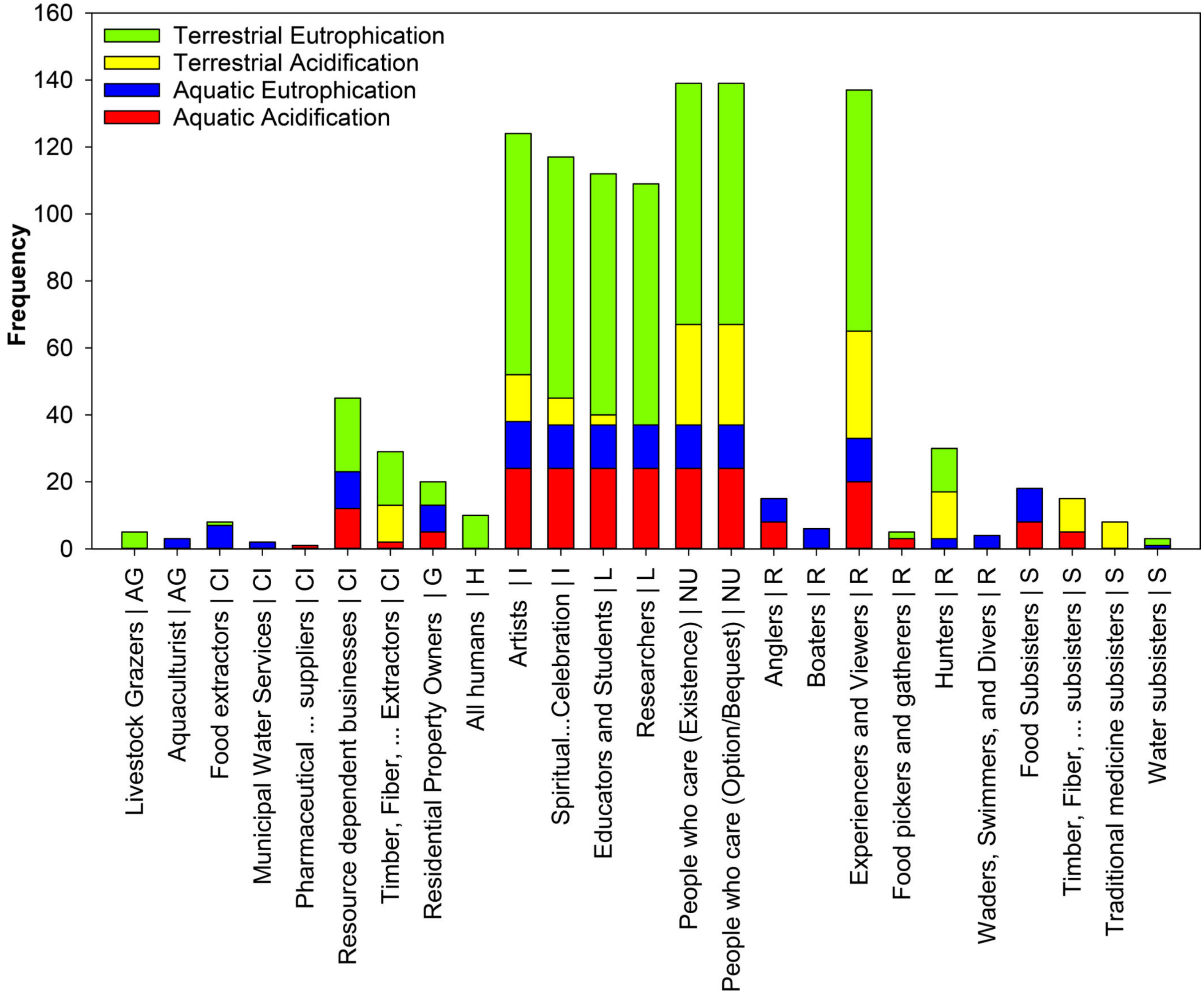

Figure 2.

Frequency of potential beneficiaries sub-classes impacted by the four modes of environmental response to atmospheric deposition. Sub-classes are grouped by their beneficiary class: Agricultural, CI-Commercial / Industrial, G-Government, Municipal, and Residential, H-Humanity, I-Inspirational, L-Learning, NU-Non-use, R-Recreational, S-Subsistence. Colors show how often each beneficiary was identified within each subsection.

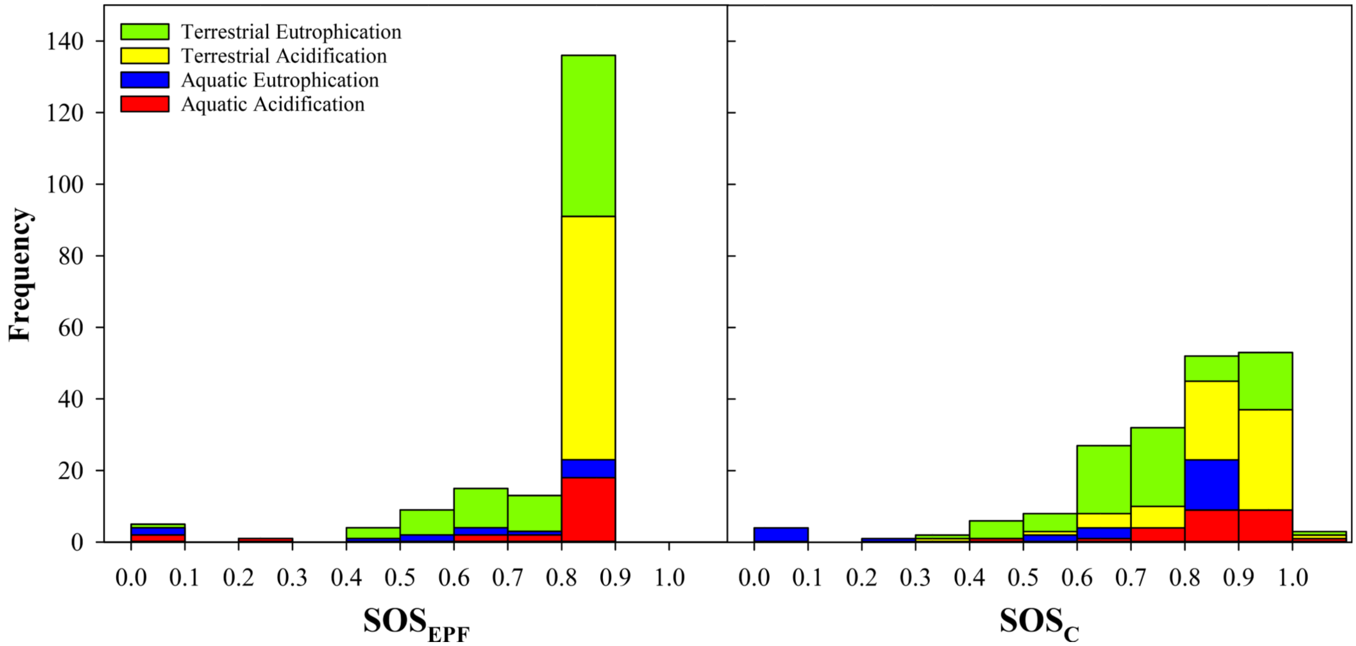

Figure 3.

Frequency distribution of SOS_{EPF} (left) show a high proportion of the EPFs have a high confidence. The variability in the SOS_S scores for the chains lead to the SOS_C (right) scores being distributed towards lower confidence values.

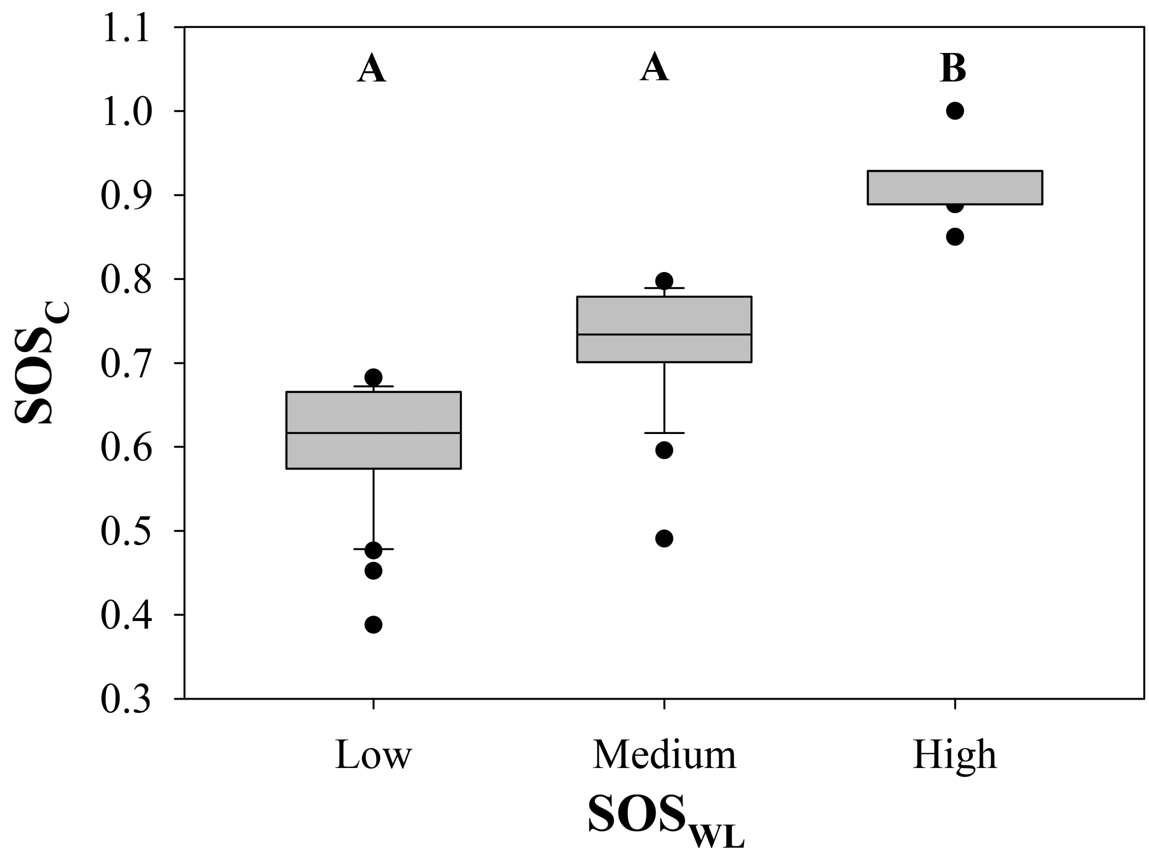

Figure 4.
Box plot of SOS_C scores relative to the weakest link in the chain indicate that the SOS_{WL} should be taken into consideration when comparing chains, as it does not always differentiate between chains with a weak link. Letters designate significant differences between groups (Dunn's Method).

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Table 1.

Summary statistics for each of the four modes of response to deposition. As each groups used different a different range of inputs to their chains, these values should not be directly compared as all potential outcomes for each mode of response. Counts of Change in biological indicators, Ecological endpoints, Beneficiary groups, Ecological Production Functions, Chains are provided for each group. SOS_{EPF}, SOS_C, and SOS_{WL} scores are the average strength of science of the literature based on unique EPFs.

Mode of Response	Change in biological indicators	Ecological endpoints	Beneficiary groups	Ecological Production Functions	Chains	Mean SOS_{EPF}	Mean SOS_C	Mean SOS_{WL}
Aquatic acidification	13	10	15	25	208	0.73	0.86	0.91
Aquatic eutrophication	4	13	17	13	154	0.61	0.77	0.67
Terrestrial acidification	8	16	10	68	160	0.85	0.91	1.00
Terrestrial eutrophication	22	44	16	77	582	0.75	0.74	0.67