Identifying Socio-Environmental System Solutions: A Causal Approach to Actionable Research Design

James Boyd
Director of Social Science & Policy, SESYNC
Senior Fellow, Resources for the Future

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THE NATIONAL SOCIO-ENVIRONMENTAL SYNTHESIS CENTER

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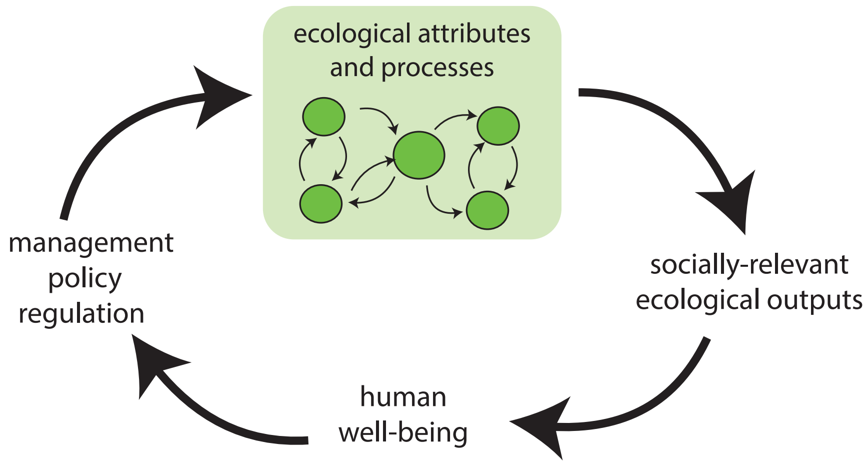

Solving socio-environmental (S-E) problems requires identifying social actions that can alter the S-E system to protect or enhance socially beneficial outcomes. These actions could be *policy interventions*, or they could be efforts targeting *changes in social behavior*. Identifying potential actions requires cross-disciplinary discussion and research planning to elucidate how the components of a S-E system are connected in relation to the desired outcome. To accomplish this goal, this document outlines a diagramming method that can guide a researcher's or research team's thinking about complex environmental systems and how their system of interest connects to policy, action, and social outcomes.

Who should be interested in this approach and why?

Researchers who have a desire to understand how social policies and behaviors can affect a S-E system, positively or negatively, will find this approach extremely useful. It applies to research where there is a desire to connect S-E system outcomes to well-being, economic, health, and other social outcomes. In other words, the approach can be useful to any individual or team interested in solutions-oriented S-E research. The approach applies to research exploring a S-E system with multiple interacting components and that involves, or is at least open to, input from multiple natural and social science disciplines.

What is the origin of the approach?

Although SESYNC teams and learning groups have used this approach, it is certainly not unique to the Center. It is based on the well-established method of *Causal Diagramming* (also called Directed Acyclic Graphs [DAGS]),[1] which has been used extensively in the interdisciplinary field of study called systems dynamics. It was designed as an analytical tool to help people understand complex systems, visualizing the key components of the system and the connections between them and how they relate to the state of the system.

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[1] Johannes Textor, "Robust causal inference using directed acyclic graphs: the R package 'dagitty'," *International Journal of Epidemiology* 45, no. 6 (December 2016): 1887–94, https://doi.org/10.1093/ije/dyw341.

STEP 1
Depicting the socio-environmental system

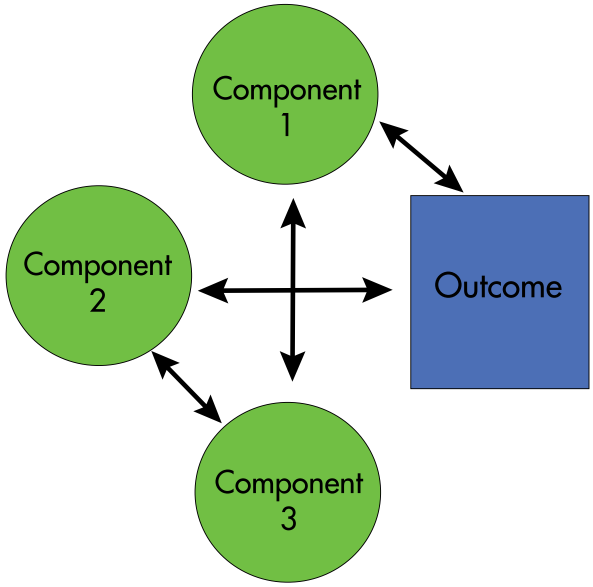
Researchers and research teams will identify:
1. The key biophysical and social components of their S-E system that interact to drive an outcome.
2. The relationships between the components.
3. The logical paths toward an outcome.

Important Considerations >>> Extensive discussion among researchers is required to reach consensus on the focal outcome, as well as which system components are most important to consider because disciplinary background, values, and experiences influence individual views.

Advanced Tip >>> The exact form of the relationships between components may be determined by theory or empirical findings. While relationships may be represented mathematically or statistically, for S-E systems, both qualitative and quantitative information are almost always used. Tools are available to help researchers translate qualitative information (e.g., narratives, beliefs) into semi-quantitative models to test ideas about potential futures.[2]

The first step in causal diagramming is to simply draw a node and arrow diagram that reflects the basic components and relationships of interest to your research (Figure 1). A generic version will look something like the following:

Figure 1. Node and arrow diagram



This diagram depicts a simple S-E system with only three interacting components (nodes) that drive a single outcome (another node). Any real S-E system, of course, can require teams consider many more components and outcomes (Figure 2). A recommendation, however, is to begin the diagramming with a central core of relationships known to be of interest to the team or individual and representing the minimal components believed essential to the system under study. However, the number of components and interactions (arrows) are likely to expand as you proceed through subsequent steps in the causal diagramming process. Biophysical processes (e.g., physical, chemical, or biotic) and social processes (e.g., economic, political, cultural)—can create causal relationships between nodes. The nature of these relationships may already be firmly established based on empirical work or theory—or the nature of the relationship may require further exploration and validation.

[2] Alison Singer et al., "Translating community narratives into semi-quantitative models to understand the dynamics of socio-environmental crises," *Environmental Modelling & Software* 97 (2017): 46–55, https://doi.org/10.1016/j.envsoft.2017.07.010.

Note also that the causal interactions depicted in the diagram can be, and in this case are, complex in that individual features do not independently affect the outcome but rather *interact* in their influence on the outcome. As described in SESYNC's introductory video tutorials to modeling S-E systems, "Building the Basics," this leads to what are called "emergent behaviors"—i.e., patterns, properties, or characteristics that emerge over time due to interactions, feedbacks, and resulting changes.

Figure 2. A SESYNC socio-environmental research team working on diagraming their S-E system.

Moving beyond identification of a socio-environmental system's core components requires considerable discussion among team members. Depiction of causal relationships is often initially based on hypotheses with a later goal of data-based verification.

STEP 2
Connecting the science of the system to concrete actions

<u>Researchers and research teams will identify</u>:
1. Points of social leverage that can affect S-E outcomes positively or negatively.
2. Variables that correspond to actions taken by institutions, communities, or households that affect the system positively or negatively.
3. Possible gaps in causal understanding (between the new action variables and core ecosystem features) that need to be addressed.

<u>Important Considerations</u> >>> Researchers should ensure the actions are relevant to tangible policy, management, or behavioral interventions.

<u>Advanced Tip</u> >>> S-E systems involve relationships that span spatial, temporal, and organizational scales. Team members must decide on the overall system boundary, which they determine based on the team's goals and data availability. Multi-scale systems are often viewed modularly as a set of subsystems, and there are upscaling and downscaling methods to connect these.[3]

The goal of this step is to identify features of your system that are "actionable." *By actionable, we mean system components that can be directly changed by social policies or behaviors*. In this exercise, direct change means specific, concrete alteration of a component/driver by a specific social actor or actors, such as a government agency, business, non-governmental organization (NGO), or household.

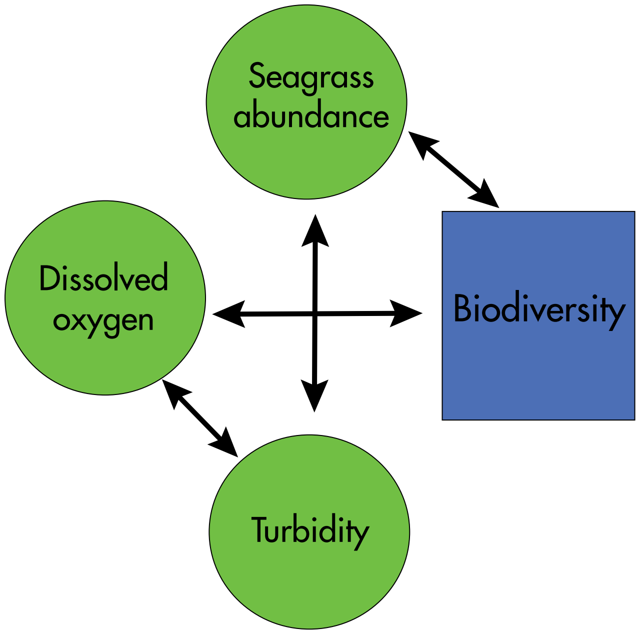
To some extent, the definition of an actionable component (action variable) is in the eye of the beholder. Theoretically, almost any biophysical feature can be altered via human agency. In practice, however, researchers should search for actions that they can address given the constraints of their research endeavor and that have relevance to tangible policy, management, or behavioral interventions. Note that researchers should take care to understand the constraints that policy makers and managers face. Some of the actions that researchers may want to see implemented may simply not be feasible. (e.g., The removal of impervious surfaces in watersheds may be impossible in urban regions even though it may solve an environmental problem.)

Consider the following, hypothetical example to illustrate the thought process. Imagine that you or your team depict a coastal seagrass system of interest as follows. In this system, seagrass abundance, water oxygen levels, and water clarity interact to affect the outcome of interest—biodiversity (Figure 3).

Are those three components action variables? By themselves, they are not. To explain why, note that they are not variables that can be concretely altered by a specific social actor or actors, such as a government agency, business, NGO, or household. Instead, we need to inquire

[3] Takuya Iwanaga et al., "Socio-technical scales in socio-environmental modeling: managing a system-of-systems modeling approach" *Environmental Modelling & Software* 135 (January 2021): 104885, https://doi.org/10.1016/j.envsoft.2020.104885.

Figure 3. Biophysical causal diagram, not solution oriented.



more deeply about what can be done *in practice* to affect oxygen concentrations, turbidity, and seagrass abundance.

For example, things like erosion-related runoff from agriculture, forest fires, and land development cause turbidity. A direct *action* to address one of these causes is installation or protection of vegetated coastal buffers. Accordingly, we could add an "action variable" (an additional node) to our system model. For instance, an action variable such as "area or miles of installed or protected vegetated buffer" would causally connect the turbidity feature to a concrete biophysical action that affects turbidity.

Including this as an additional node is beneficial in that it connects the science of the system to concrete actions, and thus helps identify practical solutions. Doing so, however, expands the scope of the system under study. In practice, this means that the researcher(s) must consider an additional causal relationship—that between vegetated buffers and turbidity.

Often, this expansion requires consideration of components and processes that operate on vastly different spatial and temporal scales and this complicates the search for clear causal relationships between actions and outcomes—as described in SESYNC's video tutorial and associated webcast on "Confronting Issues of Scale."

Similarly, for dissolved oxygen levels, we can think about the question of who or what can affect those levels. One answer is municipal water treatment facilities and the regulatory standards that govern nutrient concentration levels allowed in their effluents. Again, this consideration creates an additional action variable (nutrient discharges from water

As a general rule, the search for actionable features of the system both expands the system's complexity and requires additional causal gaps to be addressed.

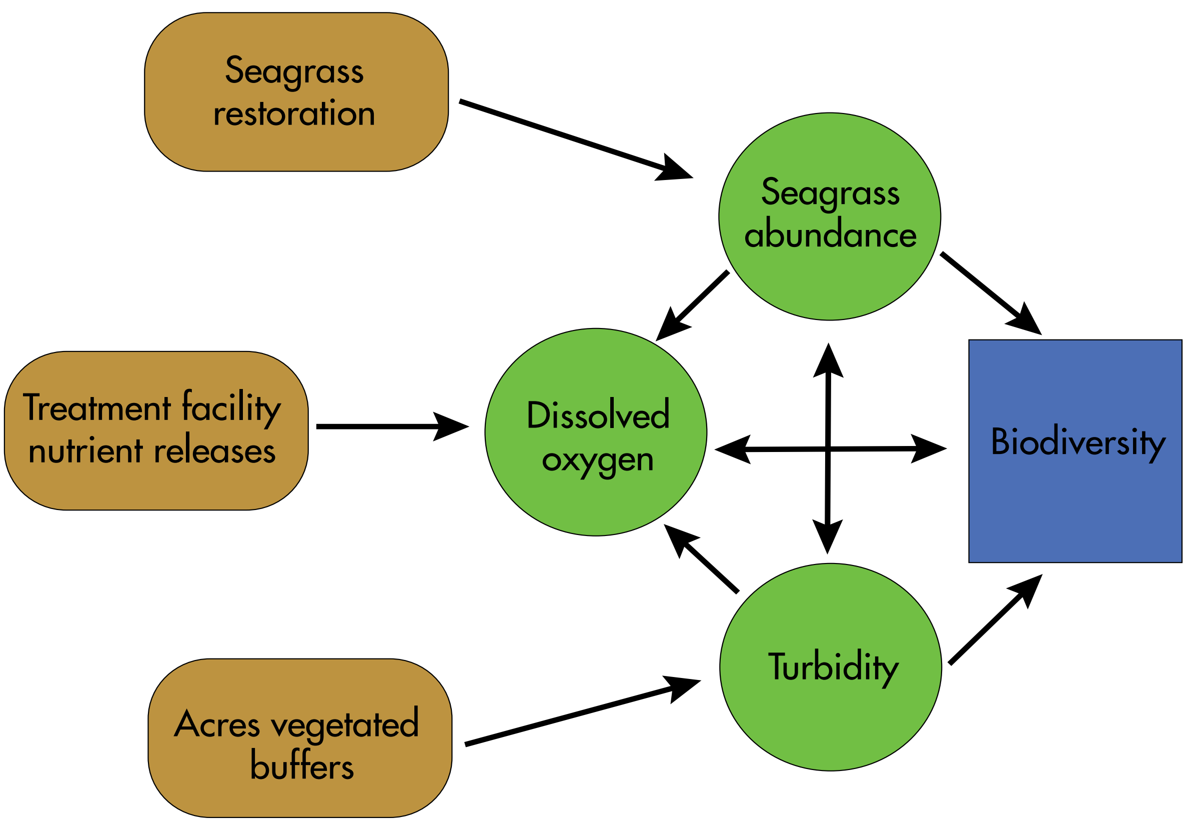
treatment facilities). That node is directly actionable but leads to expansion of the system being modeled and the need to causally relate nutrient releases to oxygen levels in coastal waters.

Seagrass abundance can be concretely managed by actions such as deliberate planting of new seagrass or prohibitions on boating in areas with seagrass beds. Corresponding action variables include acres of seagrass planted or acres of seagrass beds where boating and dredging are prohibited. Those action variables would then require analysis of how they lead to changes in abundance over time (e.g., because not all planted seagrass will survive or propagate).

Visually, this example and thought experiment leads to the following, new conceptual diagram (Figure 4). To be sure, the addition of action variables poses additional research questions to be addressed—in particular, the need to understand the causal relationships between the action variables (in brown) and the original core components (in green). But that additional work is necessary to evaluate the effects of social policies and behaviors on the system.

Researchers should ask themselves: Should all these additional nodes be included as part of the research activity? The answer depends on the time available, resources, skills, and ambitions of the research team. There is no one correct answer.

Figure 4. Solution oriented causal diagram; potential actions in brown.



STEP 3
Identifying and expressing the social relevance of outcomes

Researchers and research teams will identify:

1. Outcome variables that, even without subsequent social science analysis, communicate to social science research partners and non-research audiences what is socially important about the system being studied.
2. Possible gaps in causal understanding that need to be addressed i.e., between proxy outcomes and more publicly resonant outcomes.

Important Considerations >>> Researchers must distinguish between scientific variables that they commonly associate with outcomes vs. those outcome descriptors that are actually useful to or of interest to nonscientists.

Advanced Tip >>> Engaging interested nonscientists (e.g., stakeholders, decision makers) in the early phases of S-E research design helps ensure outcome metrics are relevant. Extensive scholarship on this has resulted in the availability of diverse methods and best-practice guidance tools for engaging non-scientists.[4,5,6]

Extensive research has shown that when actions (potential solutions) are proposed they are much more likely to be acted on if they result in outcomes the broader public views as desirable. Often, however, scientists express outcomes in ways poorly comprehended by non-scientists (however valid and important those terms are within the scientific community itself). It is essential that researchers communicate how the outcome will affect social well-being.[7]

Identifying socially relevant outcomes (i.e., outcomes understandable and viewed as directly meaningful by the public, stakeholders, and policymakers) facilitates communication with lay audiences and also helps interdisciplinary research teams create linkages between the natural and social aspects of their S-E system.

[4] Gabrielle Bammer, "Key issues in co-creation with stakeholders when research problems are complex," *Evidence & Policy: A Journal of Research, Debate and Practice* 15, no. 13 (August 2019): 423–35, https://doi.org/10.1332/174426419X15532579188099.

[5] Neal R. Haddaway et al., "A framework for stakeholder engagement during systematic reviews and maps in environmental management," *Environmental Evidence* 6, no. 11 (2017): 1–14, https://doi.org/10.1186/s13750-017-0089-8.

[6] Leah M.Sharpe, Matthew C. Harwella, and Chloe A. Jackson, "Integrated stakeholder prioritization criteria for environmental management," *Journal of Environmental Management* 282 (March 2021): 111719, https://doi.org/10.1016/j.jenvman.2020.111719.

[7] Baruch Fischhoff, "The sciences of science communication," *Proceedings of the National Academy of Sciences* 110, Supplement 3 (2013): 14031–2, https://www.pnas.org/cgi/doi/10.1073/pnas.1213273110.

The definition of outcomes that are "understandable" and "directly relevant" to lay audiences is not always clear cut—in part, because different audiences have different degrees of baseline knowledge. However, several rules of thumb can help identify outcome measures that are more likely to be poorly understood and those more likely to resonate with the general public.

First, one way to clarify what "directly matters" is to ask (of a lay audience) if the outcome matters to them as an *end in itself* versus as a means to that end. For example, consider outcomes like nitrogen concentrations in water, atmospheric greenhouse gas (GHG) concentrations, or biodiversity measures.

Does the broader public view these as directly desirable outcomes? The likely answer is no. Rather, these outcomes are better thought of as precursor, or proxy, variables that affect those things about which people really care.

Consider each in turn. Nitrogen levels may be a precursor variable for outcomes like fish abundance, water odor and clarity, and risk of waterborne illness. The latter are clearly socially relevant outcomes and more easily understood by lay audiences. Similarly, GHG concentration is a precursor variable, via climatic processes, to rainfall, temperatures, and fire and flood risks. Again, the latter better convey outcomes directly relevant to lay audiences. Biodiversity may be directly valued by some audiences (e.g., those who understand the word and care about the existence of diverse species or habitats in a region). But biodiversity may also be precursor variable—it may be an ecological prerequisite for abundance of shellfish, amphibians, and other commercially and recreationally valuable species in the marine food chain. Accordingly, crab and shad abundance (for example) may in some settings serve as more understandable outcomes related to biodiversity.

Ecosystem outcomes are likely to be good socially relevant outcomes when they relate to things that can be seen, smelled, heard, tasted, and touched, as opposed to outcomes we cannot experience directly.

The clarity, taste, and odor of water are more likely to directly matter than water quality attributes we cannot detect without scientific instrumentation, such as nutrient processing or even nitrogen, oxygen, and phosphorus concentrations.

Finally, scholarly indicators expressed in technical or scientific terms (jargon) are less

likely to serve as good linking outcomes. Often "technical" ecological measures—e.g., measures of biotic integrity, disturbance, hydrogeomorphic class, and trophic states—signify the need to subsequently translate the measure into outcomes more meaningful to nontechnical audiences and nearer to their experience and wellbeing.

Returning to our example system, the search for socially relevant outcomes leads to an additional expansion of nodes in our conceptual diagram. Because biodiversity may be causally related to the abundance of specific species—such as blue crabs, shad, and sturgeon—we can include their abundance as additional ecosystem features of interest. The result is a causal diagram that includes outcomes people really care about—crabs and fish (Figure 5, in light blue).

As in Step 2 of the diagramming process, Step 3 yields an expansion of the system, but in this case, it is an expansion of the outcome variables considered (the new socially relevant outcomes).

Again, with any expansion of the system, the research task is expanded. So, it is now necessary to explore, and perhaps quantify, the causal relationships between biodiversity (our original outcome measure, in dark blue) and crab, shad, and sturgeon abundance (in light blue). However, undertaking this additional effort is important if the social consequences of changes to the ecological system are to be expressed in ways that are meaningful and understandable to broader audiences.

In our discussion of action variables (Step 2), we noted that a given research effort could address many kinds of actions and action variables. Similarly, in this exercise (Step 3), researchers may be confronted with a wide variety of possible socially relevant outcomes associated with their system.

Again, the question of how many additional outcomes to explore depends on the time available, resources, skills, and ambition of the research team.

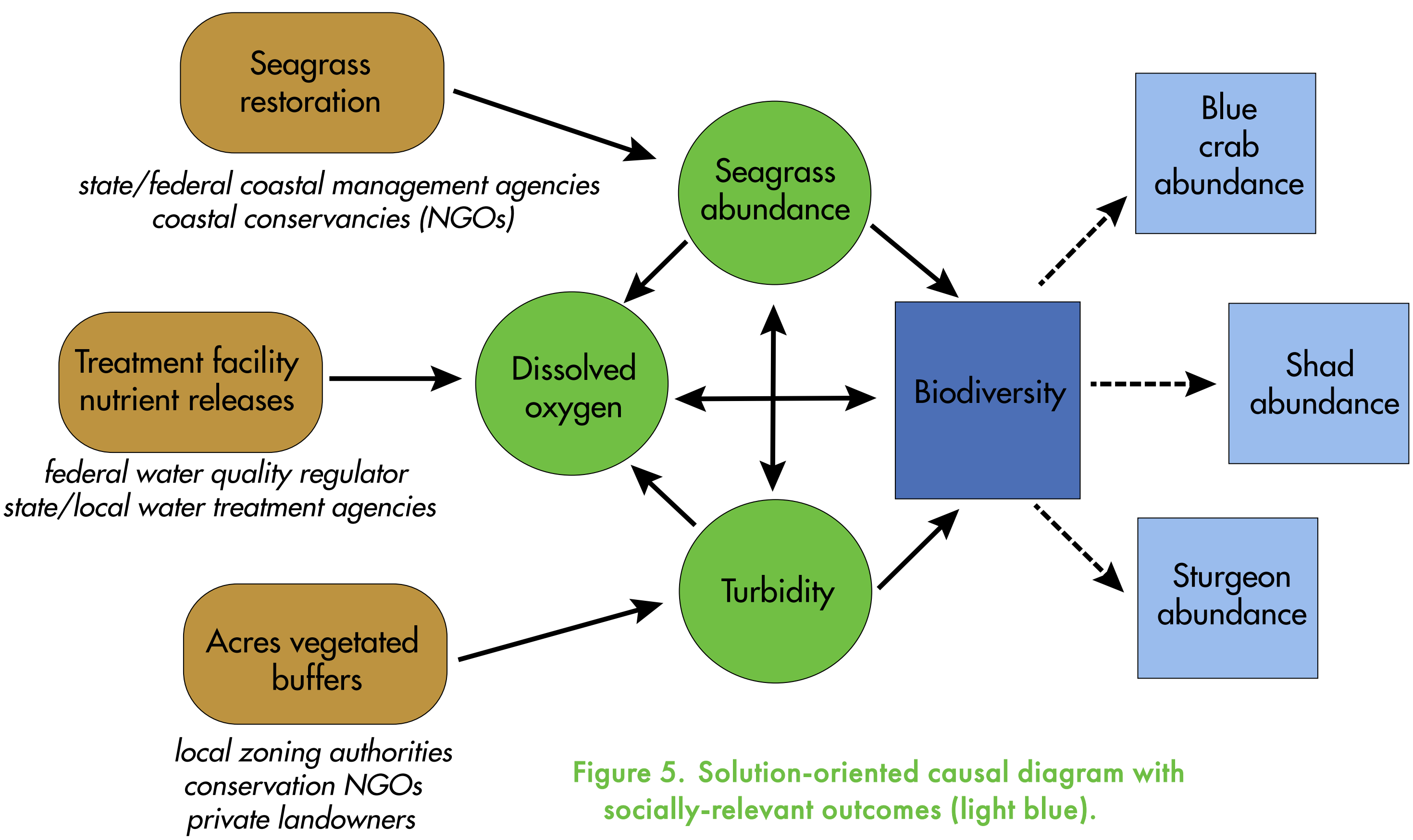


Figure 5. Solution-oriented causal diagram with socially-relevant outcomes (light blue).

STEP 4
Identifying responsible parties

Researchers and research teams will identify:

1. The institutions, organizations, or individuals who are responsible for implementing the proposed actions.
2. Stakeholders who can help them further tie their research to actionable outcomes.

Important Considerations >>> Groups or individuals who play a role in moving the action towards a desired outcome can be diverse—their values, perspectives, and expertise may vary and researchers must genuinely commit to engaging without bias.

Advanced Tip >>> Scholarship is more likely to influence outcomes when researchers engage with those who understand the decision context (such as administrative, government, or business practices); the mechanisms that can result in actions; and the current priorities of the responsible parties.[8]

Responsible parties can provide insights to action-oriented research by helping identify additional options (action variables), the costs of various options, and legal or regulatory drivers that can foster or impede taking action in the S-E system.

The goal of this step is to relate action variables and to link outcomes to specific institutions, social groups, or individuals. At a minimum, doing so helps researchers tell the story of how their ecological system of interest can be managed and by whom. Beyond that, this step can help identify research partners from the responsible parties and interested groups who can help identify additional action options, assess the costs of various actions, and highlight social conflicts associated with actions relevant to the search for real-world solutions. And stakeholders as researcher partners that are interested in public awareness or political deliberations, can help motivate and diffuse the research findings. In other words, using causal diagramming to identify the responsible parties can be extremely useful in tying the research activity to actionable outcomes.

Action variables often are the responsibility of specific governmental institutions or lie in those institutions' mission areas. What are those institutions and why do they matter? For example, in a forest ecosystem, a state or federal forest service agency may be responsible for choosing areas that can or can't be logged; areas where invasive species are targeted for removal; or where understory and other fire suppression activities take place. Such agencies will know about the costs of such activities, the laws and regulations that govern such options, and potential political and economic conflicts associated with the action variable options.

[8] Ruth A. O'Connor et al., "The role of environmental managers in knowledge co-production: Insights from two case studies," *Environmental Science & Policy* 116 (February 2021): 188–95, https://doi.org/10.1016/j.envsci.2020.12.001.

Often scholars outside of the field of policy do not know what is within the realm of possibility. For example, a research project may indicate a need to eliminate all fishing of an at-risk species, yet law guarantees tribal members' access to the fishery. Once aware of this, the research team may consider additional options.

Note that "social responsibility" should often be defined more broadly than "legal or governmental responsibility." Responsibility can be associated with individual and household behaviors that are entirely legal and unregulated but that contribute to ecosystem change—in either positive or negative ways. For example, commercial anglers are "responsible" for reduced fish stocks, home builders for removal of tree and other natural land cover, households for application of pesticides and fertilizer to their lawns, etc. Commercial and community behaviors can also be voluntary and positive, as when a company voluntarily chooses to conserve land or when a household voluntarily plants native species in their yard.

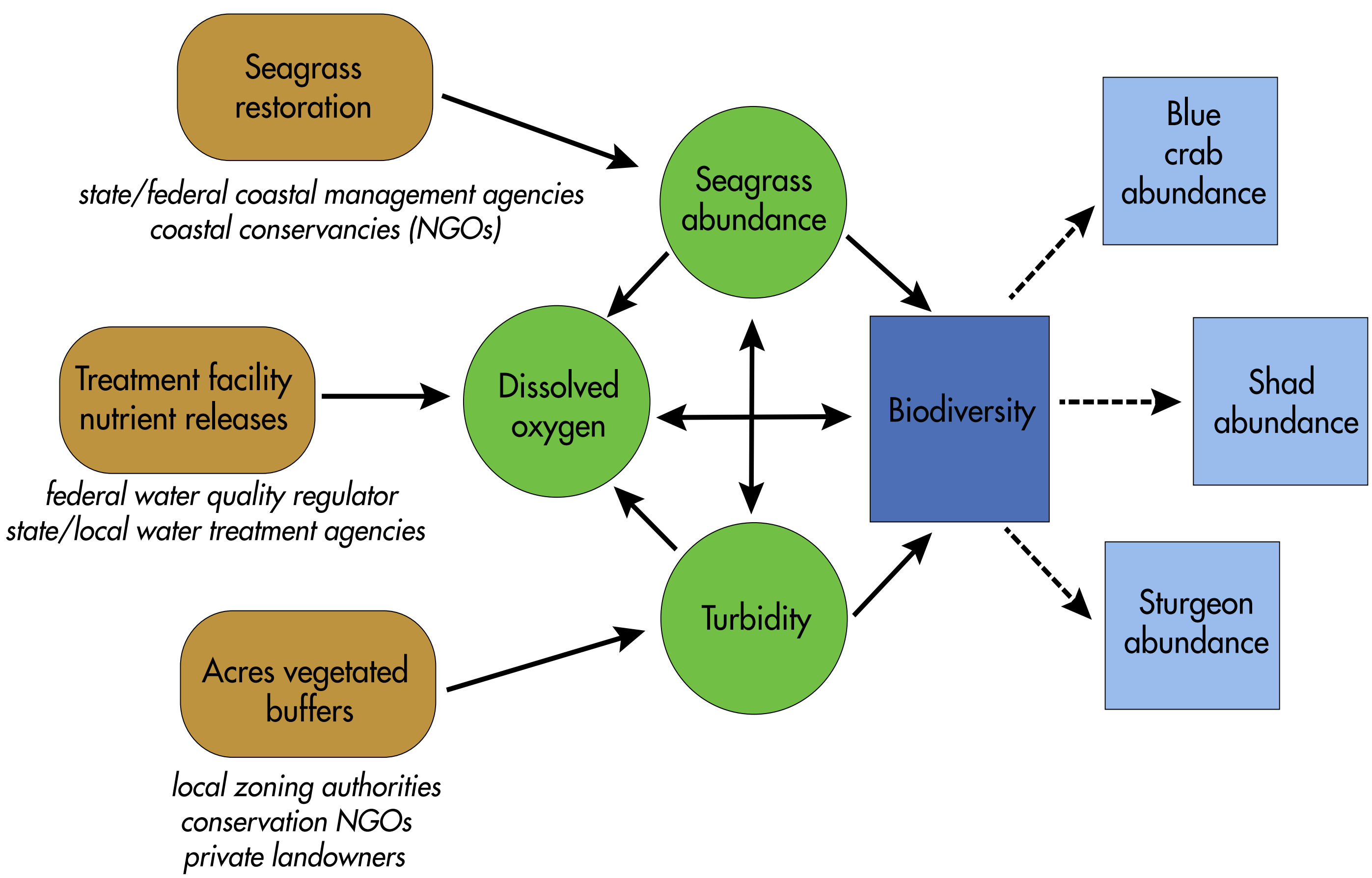
Understanding these forms of responsibility can also be very important to a research project in that it helps identify additional policy options geared toward public behavior change via, for example, social messaging, product labeling, development of new regulations to control the behavior, tax incentives, etc.

Regardless, the core recommendation is to explore the relationship between action variables and social leverage over those variables, whether that leverage comes via government, NGO, business, or household behaviors. Having done so, consider getting input to your research from those responsible parties.

Building on our example system diagram, the following visualization (Figure 6) depicts a set of candidate responsible institutions and relates them to specific action variables.

State and federal government agencies may have responsibility, programs, and funding for seagrass restoration, and NGOs may have their own missions and funding to support such restoration. Federal water-quality regulations govern standards for effluent releases to water, and local water-treatment agencies will have direct control over nutrient and other releases from their facilities. Additionally, coastal vegetation can be influenced by local zoning rules that may require preservation of water-abutting vegetation or by the behavior of individual landowners.

Figure 6. Causal diagram showing parties (text below brown boxes) responsible for actions.



STEP 5
Identifying parties interested in the outcome

Researchers and research teams will identify:

1. Individuals or groups that have some interest in the outcome but are not necessarily the responsible parties for taking actions—these may be "winners" or "losers" of the outcomes.
2. Why and how their research matters to the public.

Important Considerations >>> Researchers should expect that trade-offs will be required for actions to be implemented because of differences in opinion, legal/policy/political constraints, and economic or other costs.

Advanced Tip >>> There is extensive research on why the public supports certain policies while opposing others, and this points toward the importance of believing a policy is needed, fair, unintrusive, and that the policy will actually lead to the desired outcome.[9]

Setting aside those who are responsible for implementing actions, researchers should begin focusing on why the socially relevant outcomes matter to diverse stakeholders. There are typically people, institutions, or groups that have a real interest in the outcomes. These interests may be governmental (e.g., when an agency's decisions influence the responsibilities of another); commercial (e.g., a business that relies on the ecosystem outcome); or a community of households (whose health, property values, recreational opportunities, etc. depend on the outcome). Sometimes the outcomes that researchers identify may be undesirable to certain groups or organizations (e.g., citizen-action groups or NGOs). If so, it is beneficial to understand that these concerns may require trade-offs and compromises to find practical solutions.

To illustrate this idea, return to our linking outcomes from the coastal wetland example: blue crab, shad, and sturgeon abundance. Blue crab and shad abundance are important to both commercial interests (harvesters and the supply chains that sell to consumers) and recreational interests (households that fish for crabs and shad) (Figure 7). And all three may be important for state and local government agencies who have oversight over or responsibility for those populations to take into account. For example, in the United States, Atlantic sturgeon is a federally listed endangered species in such ecosystems and thus subject to protections by the National Marine Fisheries Service.

9 Robert A. Huber, Michael L. Wicki, and Thomas Bernauer, "Public support for environmental policy depends on beliefs concerning effectiveness, intrusiveness, and fairness," *Environmental Politics* 29, no. 4 (June 2019, https://doi.org/10.1080/09644016.2019.1629171.

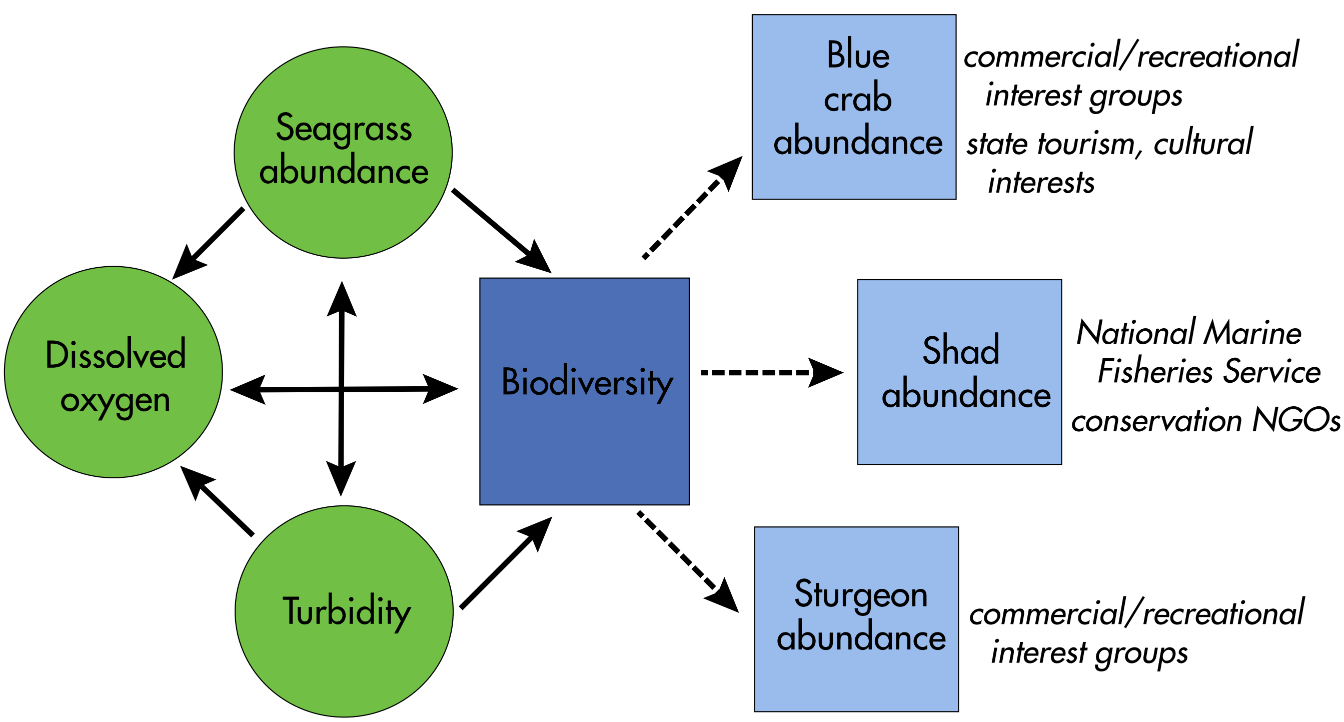
In addition, because blue crabs are a culturally iconic species in Maryland, a broader community interest in a species like that may represent an important social audience for research on such a system outcome.

Building on our example system diagram, the following visualization depicts a set of candidate stakeholders and responsible institutions and relates them to specific socially relevant outcome variables.

By identifying the connection of socially relevant outcomes to these kinds of interests, your research can:

- Better describe why the study of your system matters to lay audiences
- Identify additional points of institutional leverage to promote protective and restorative actions in the system (as when a government agency has responsibility for the outcome)
- Identify non-governmental audiences (e.g., household, NGO, or business community stakeholders) interested in your research and any policy recommendations emerging from it.

Figure 7. Causal diagram showing parties with interest in the socially-relevant outcomes.



CONCLUSION

All environmental problems are social problems; thus, research with the potential to change policy or behaviors requires a focus on when and why people care enough that they are motivated to act. This applies to research teams, their efforts to understand the biophysical and social processes underlying the problems, and who can actually influence change. The method outlined in this document—causal diagramming—is one of many ways to analyze a S-E system problem including the players that influence and are influenced by it, the system's status, or change.

In the corollary content, a few variations on the method are outlined to emphasize that the method is actually highly flexible. Hopefully, the steps laid out there and above can help researchers think through, expand, and bound their research objectives to connect S-E science to actionable interventions and their importance to social well-being.

COROLLARY CONTENT

The following examples illustrate the approach's flexibility, applicability to different types of S-E systems, and how different "starting points" can be used by researchers to build their causal analysis.

Example 1: Start with a Policy Action

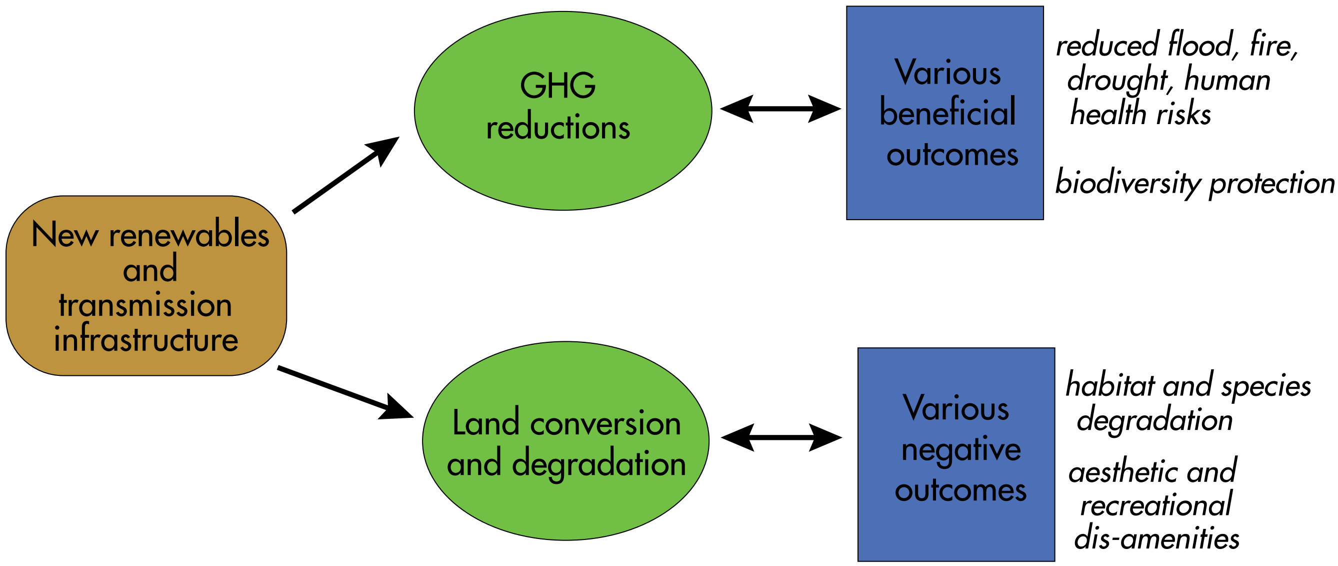
The first example uses a different entry point to the analysis—namely a policy action, rather than a depiction of an ecological system (which was our entry point in the earlier coastal seagrass example).

In this example, think of a research team exploring the S-E implications of expanded investment in and development of renewable energy facilities (an action). Renewable energy from solar arrays and hydropower requires a corresponding action: connection to regional and national power grids via construction of new transmissin lines and other grid infrastructure. Broadly ,then, these actions trigger changes in two systems: 1) the atmospheric climate system via renewables' ability to reduce non-renewable energy emissions (e.g., from coal and natural gas sources); and 2) terrestrial ecosystems impacted by the development of transmission infrastructure.

Thus, imagine that in Step 1 you or your team could depict the S-E system as in Figure 8.

The brown node, represents an action; the green nodes represent system components, and the blue nodes represent system outcomes. To be clear, in an actual research setting, the blue component nodes in this illustration should be depicted in much greater detail (e.g., what are the specific GHG reductions and when do they occur; what specific kinds of land are being converted; and how are those lands being degraded). Moreover, a variety of interactions within the climate and terrestrial components could be explored as they relate to specific socially relevant outcomes (e.g., the impact of land degradation on habitat, water quality, etc.).

Figure 8. Example of a causal diagram developed by starting with policy actions.



Note from this (hugely over-simplified) illustration, that a research team's point of entry can be an environmental action that then triggers inquiry into the S-E system components that action affects.

A second important point is that systems analysis can reveal that an environmental action triggers both positive and negative outcomes. In the earlier coastal wetlands example, this issue didn't arise because the focus was on a *single* outcome we wanted to enhance (biodiversity) and a set of universally positive knock-on outcomes for specific species. However, in general, the complexity of S-E systems means that a given action will trigger multiple changed outcomes, some of which may be negative. Trade-offs emerge in the renewable energy development example. For example, do the long-term biodiversity benefits of reduced GHGs offset the short-term disruption to habitats from construction of energy transmission infrastructure? How important are the negative aesthetic and recreational impacts of transmission development to communities?

The identification of pros and cons, winners and losers via S-E systems analysis should be embraced by S-E researchers interested in actionable solutions as it can trigger research on how those trade-offs can be minimized or overcome.

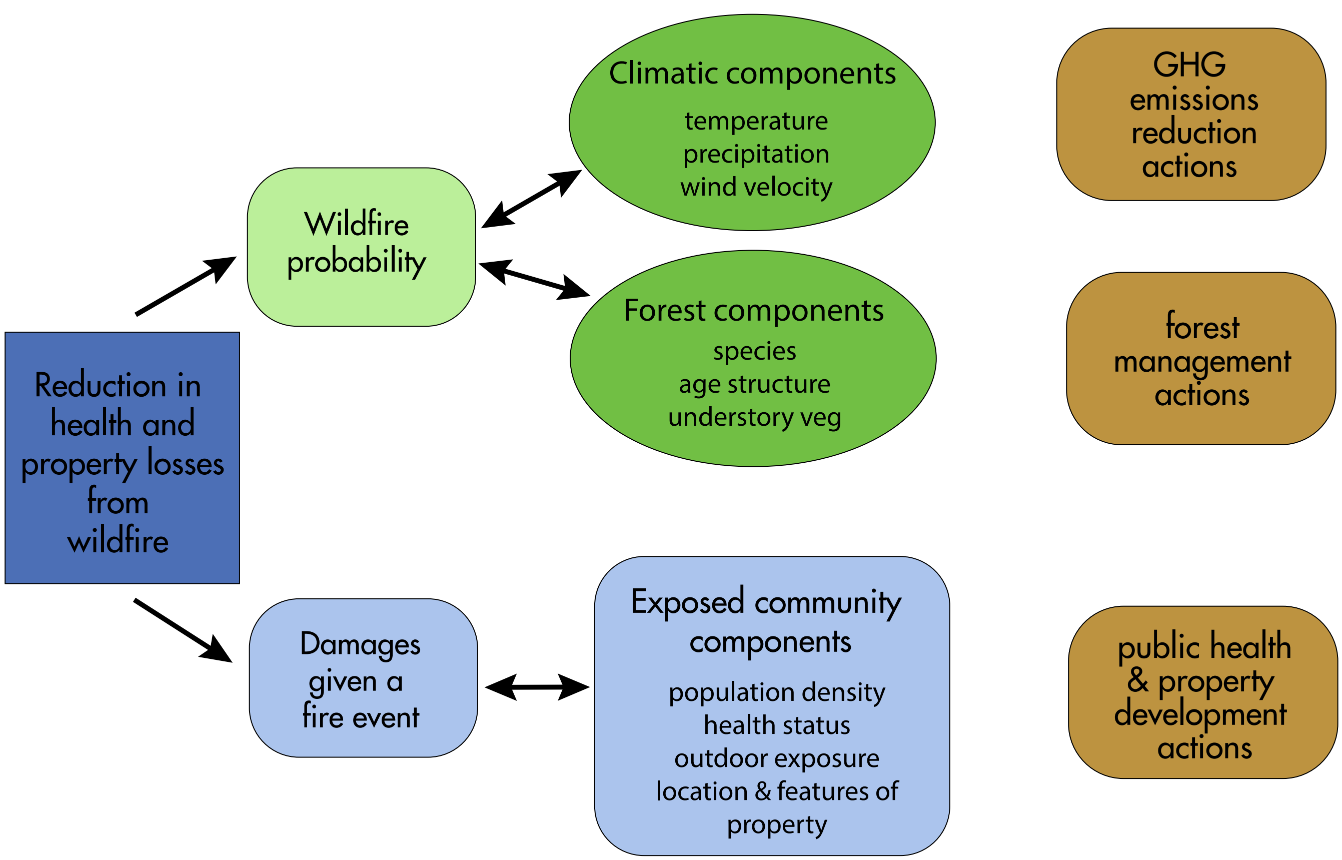
Example 2: Start with a Desired Socially Relevant Outcome

Another possible point of entry is a desired policy outcome dependent on change and actions taken within a S-E system.
In this example, consider a specific desired outcome—reducing the social costs of damage from wildfires—as the point of entry.

Broadly, there are two ways to reduce wildfire damages: (1) reduce the probability of wildfire and (2) limit the damage caused when a wildfire occurs.

Reducing the probability of wildfire involves altering climate components and/or forest components—each here represented as a single green node but containing within it multiple components. Interactions within and across these collections of components would be explored by a research team interested in how associated actions (in brown) could alter the climate and forest systems to achieve reductions in wildfire probability. For example, forest management agencies and private foresters could put in place fuel treatment requirements to reduce flammable understory vegetation, require planting of less flammable tree species, or invest in fire breaks and other risk-reducing planting and harvest practices. These actions would perturb forest components and interact with other forest and climate components to wildfire probability.

Figure 9. Causal diagram involving changes within the socio-environmental system.



A third set of components is also in play in this example, related to the "Exposed Community." These are social components of the system related to the people and property damaged in fire events. Damage arising from fire is closely tied to these components: where people live; how their homes are constructed; the value of those homes; the prevalence of lung issues and other health conditions in the exposed population; time spent outdoors in employment and recreation; and the presence of vulnerable municipal infrastructure (power, water, transportation) facilities.

These social components can be altered (improved to reduce damages) via their own set of actions. For example, building codes could require use of materials and techniques designed to reduce fire damage. Property owners could be required to invest in fire insurance that would incentivize and encourage good land development practice, such as setbacks from forested areas, or discourage development of property in fire-prone areas. Labor laws could be used to limit exposure of outdoor workers and provide easy access to health services during fire events.

This example, with its emphasis on community components, illustrates a final important point: that S-E systems analysis can involve complex interactions that are *social*, not just biophysical. Coastal wetlands, forests, and atmospheric climate interactions are clearly complex. But so are social, cultural, and economic systems. Ultimately, solutions to S-E problems require behavior change on the part of individuals, households, businesses, NGOs, or governments. But behavior is driven by a wide variety of factors: rules and regulations, social norms, money and market forces, property ownership, power and political dynamics, and cultural and kinship relationships. For some S-E research teams, their problem's social components may represent the key complexity to be analyzed in a search for S-E solutions.

! A word of caution

Researchers should ask themselves: Have I considered potential confounding factors and unintended consequences? That is, variables that can cause the same outcome but are not linked to the "treatment" of interest. Researchers should also recognize that implementing actions can and often do have social consequences—either positive or negative. For example, restoring or planting vegetated borders may provide new jobs in needed areas, but it could also limit access for recreation if these areas are protected. It could also result in higher taxes to cover the costs. Considering such possibilities is important because they may result in feedbacks that undermine the intended goals.

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ADDITIONAL RESOURCES

This article describes a process for developing causal chains that link management decisions to ecological responses and all the way to effects on human well-being. The authors propose a type of indicator that they call a biologically relevant indicator (BRI) that is an intermediary helping to link scientific measures and metrics to outcomes. Their BRIs identify what is valued and by whom, but stop short of valuation. The article provides several examples.

Olander, Lydia P., Robert J. Johnston, Heather Tallis, James Kagan, Lynn A. Maguire, Stephen Polasky, S., Dean Urban, James Boyd, Lisa Wainger, and Margaret Palmer. "Benefit relevant indicators: Ecosystem services measures that link ecological and social outcomes." *Ecological Indicators* 85 (February 2018): 1262–72. https://doi.org/10.1016/j.ecolind.2017.12.001.

This article describes a research method for tracing causal mechanisms used by many social scientists to make causal inferences. This approach, called process tracing, involves tracing causal mechanisms using in-depth case studies that provide within-case, mechanistic evidence of causal processes.

Beach, Derek. "Process-Tracing Methods in the Social Sciences." *Oxford Research Encyclopedias: Politics*. (January 2017). https://doi.org/10.1093/acrefore/9780190228637.013.176.

This article introduces the fundamental concept of systems thinking that is at the heart of understanding S-E systems. It describes essential features of S-E systems including why they belong to a class called complex adaptive systems and why this poses challenges for policy interventions to influence outcomes. This is fundamental reading for those new to S-E systems causal analysis.

Levin, Simon, Tasos Xepapadeas, Anne-Sophie Crépin, Jon Norberg, Aart De Zeeuw, Carl Folke, Terry Hughes, Kenneth Arrow, Scott Barrett, Gretchen Daily, Paul Ehrlich, Nils Kautsky, Karl-Göran Mäler, Steve Polasky, Max Troell, Jeffrey R. Vincent, and Brian Walker. "Social-ecological systems as complex adaptive systems: modeling and policy implications." *Environment and Development Economics* 18, no. 2 (2013): 111–32. https://doi.org/10.1111/conl.12156.

This reference provides a link to a browser-based environment for creating, editing, and analyzing causal diagrams. It also provides links to learning resources and tutorials.

Textor, J., B. van der Zander, M.S. Gilthorpe, M. Liśkiewicz, and G.T. Ellison. "Daggity – draw and analyze causal diagrams." 2016. Retrieved from: http://www.daggity.net/.

This article describes best practices to ensure that S-E modeling has an impact on decision making and policies. It provides specific examples (case studies) that have been highly effective. Among other things, it reviews requirements, including the human dimension and essential elements of the partnership between modelers and decision makers.

Will Meike, Gunnar Dressler, David Kreuer, Hans-Hermann Thulke, Adrienne Grêt-Regamey, Birgit Müller. "How to make socio-environmental modelling more useful to support policy and management?" *People and Nature* 3, no. 3 (2021): 560–72. https://doi.org/10.1002/pan3.10207.