How Not to Fall Off a Cliff, or, Using Tipping Points to Improve Environmental Management

Ryan P. Kelly,[1][*] Ashley L. Erickson,[2][*] and Lindley A. Mease[3][*]

Acknowledgements[4]

Three decades of study have revealed dozens of examples of natural systems crossing biophysical thresholds (or "tipping points") as a result of human-induced stressors, dramatically altering ecosystem function and services. Environmental management that avoids or reverses such tipping points could prevent severe social, economic, and environmental impacts. Here, we attempt to demonstrate the desirability of, and opportunities for, environmental management using thresholds under U.S. federal law. We find that conceptually, tipping points can and do guide some regulatory decisions. However, explicitly focusing a larger set of environmental rules on avoiding

---

[*] Each author contributed equally to this piece.

1. Assistant Professor, School of Marine and Environmental Affairs, College of the Environment, University of Washington; J.D., University of California, Berkeley, School of Law; Ph.D., Ecology, Evolution, and Environmental Biology, Columbia University. Email: rpkelly@uw.edu.

2. Policy and Education Manager, Center for Ocean Solutions, Stanford University; J.D., UNC School of Law. Email: ashleye1@stanford.edu.

3. Research Analyst, Center for Ocean Solutions, Stanford University; M.S., Earth Systems, Stanford University. Email: lamease@stanford.edu.

potential tipping points could yield greater policy efficiency and political benefits. We close by highlighting the value of cost-benefit analyses as a tool that may encourage threshold-based environmental management.

INTRODUCTION

Decades of ecology and environmental science have taught us much about the interactions between humans and their environments. In principle, this improved science makes its way into public policy in the form of environmental laws and regulations that in part govern these interactions. In practice, of course, the diffusion of new science into environmental law happens in fits and starts, driven by catastrophes (e.g., the Oil Pollution Act in

the wake of Exxon-Valdez[5]), economic pressure (e.g., the regulation of novel genetically modified organisms or nanotechnology), creeping scarcity (e.g., the Magnuson-Stevens Fishery Conservation and Management Act to mitigate fishery collapse), public health concerns (e.g., the Clean Air Act (CAA) in response to urban smog), or similar extrinsic forces that operate on an opportunistic basis. Ideally, the management of public resources is not merely opportunistic, but is also built upon evolving scientific consensus;[6] however, broad-scale philosophical shifts in science do not necessarily result in parallel legal updates.

One such philosophical shift has taken place over the past forty years in ecology, the field that underlies much of environmental law. Ecology is the study of what lives where, and of how the interactions among billions of constituent parts (individuals of different species) together form ecosystems.[7] The prevailing view until roughly the mid-1970s was that ecosystems were predictable outcomes of species that lived in a place and time, and that there would be a predictable succession as time moved on.[8] A classic example of such ecological succession is the pattern of settlement that can take place after a tree falls in a forest, creating a clearing that allows weedy, light-hungry species to invade, which in turn cede ground to species of larger stature, shading out the early invaders. Similar successions may take place after any large-scale disturbance such as a hurricane or volcanic explosion, with a parade of species marching (in order) toward a mature, stable equilibrium.[9] Essentially, we thought of the world as the sum of its parts, and that those parts would interact in the same, repeatable ways over time.

We were wrong. Interactions among billions of parts do not always result in the same outcomes.[10] Similar starting conditions can result in very different biological communities—for example, different levels of population diversity

---

5.   *Oil Pollution Act Overview*, EPA, http://www.epa.gov/OEM/content/lawsregs/opaover.htm (last updated Sept. 8, 2014) (providing background information).

6.   For example, managers could build a scientific consensus through "best available science" requirements or other mechanisms that encourage regulatory change with evolving science.

7.   Here we use a somewhat more colorful—though still faithful—definition of the discipline than do standard references. *Cf.* MERRIAM-WEBSTER'S COLLEGIATE DICTIONARY (11th ed. 2008), *available at* http://www.merriam-webster.com/dictionary/ecology (defining "ecology" as "the relationships between groups of living things and their environments"); OXFORD ENGLISH DICTIONARY, *available at* http://www.oed.com/view/Entry/59380?redirectedFrom=ecology#eid (last visited Oct. 20, 2014) (defining "ecology" as the "relationships between living organisms and their environment," and "the interrelationship between any system and its environment").

8.   *See* Lance H. Gunderson, *Ecological Resilience—In Theory and Application*, 31 ANN. REV. ECOLOGY & SYSTEMATICS 425, 428 (2000); Robert M. May, *Thresholds and Breakpoints in Ecosystems with a Multiplicity of Stable States*, 269 NATURE 471, 471 (1977).

9.   This orderly view of a dynamic planet allowed ecologists to form more general rules about species interactions over time, which helped ecology take its place as a formal discipline alongside the more established physical and life sciences.

10.   *See generally* Gunderson, *supra* note 8   (discussing this theory with relatively recent examples and terminology); May, *supra* note 8 (reviewing then-new literature on this phenomenon, in a seminal article).

arising under the same environmental settings.[11] And once established, these different outcomes can persist over time, a phenomenon known as "alternative stable states" within an ecosystem.[12]

By the mid-to-late 1970s, these revelations of the probabilistic nature of complex systems sat uneasily alongside the established view of predictable succession from one ecosystem state to another (e.g., from lake to swamp to meadow to primary forest to old-growth forest), suggesting nature worked in a less predictable manner than had been thought previously.[13] The switch from a deterministic, sum-of-their-parts view of ecosystems towards a view of ecosystems as unpredictable, dynamic, and highly complex marked an important change in how natural scientists came to view the world. This was a shift—in kind, if not in magnitude—akin to the difference between Newtonian and Einsteinian (i.e., modern) physics, in which the architecture of what we know about the world shifted substantially.

A prime example of the new ecological worldview was the observation that ecological components—from ecosystems to species to individuals—can exhibit drastic shifts between different ecological states. For example, a lake may switch from being blue in color (and hence, having a low nutrient content and limited plant growth, associated with high-quality drinking water)[14] to being green (high nutrient content and high growth, low-quality drinking water)[15] with only a slight increase in nutrient load[16]—a phenomenon known as an ecological threshold or "tipping point."[17] The subtle environmental stressors that might push an ecological component over such a tipping point are the focus of a great deal of research in the academic ecological literature, and could be of critical importance for federal environmental management.

---

11. *See generally* Benjamin Kerr et al., *Local Dispersal Promotes Biodiversity in a Real-Life Game of Rock-Paper-Scissors*, 418 NATURE 171 (2002) (showing different mixes of populations of bacteria arising from the same starting conditions, with the outcomes dependent upon the scale of bacterial dispersal).

12. Different initial conditions may also drive alternative stable states. *See generally* Jonathan M. Chase, *Experimental Evidence for Alternative Stable Equilibria in a Benthic Pond Food Web*, 6 ECOLOGY LETTERS 733 (2003) (demonstrating the existence of different stable mixes of species in a mesocosm, given different starting conditions).

13. *See, e.g.*, Joseph H. Connell & Ralph O. Slatyer, *Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization*, 111 AM. NATURALIST 1119, 1121 (1977) (diagramming the pathways of traditional succession and of less predictable, alternative stable states); *see also id.* at 1119 (discussing the history of the theory of succession).

14. *See Trophic State Index*, WIKIPEDIA, http://en.wikipedia.org/wiki/Trophic_state_index (last updated May 15, 2014) (providing a good overview of the trophic index and its use in ecology). Ecologists refer to low-nutrient waters as "oligotrophic." *Id.*

15. *See id.* High-nutrient waters are known as "eutrophic." *Id.*

16. *See infra* notes 39–43 and accompanying text.

17. We define an environmental threshold as a nonlinear change in ecosystem state, property, or phenomenon, where small changes in an environmental driver produce disproportionately large responses in the ecosystem. Note that the ecological literature also refers to these abrupt transitions between ecological states as "regime shifts." FOUNDATIONS OF ECOLOGICAL RESILIENCE xvi (Lance H. Gunderson et al. eds., 2009).

However, until now thresholds have received considerably less attention in the law, policy, and management spheres than in scientific circles.[18]

Before continuing, and to avoid confusion, we want to highlight the distinction between biophysical thresholds (i.e., ecological tipping points) and regulatory "thresholds." The latter is a phrase commonly used to denote a change in status that triggers a regulatory response. For example, if the economic effect of a proposed administrative rule exceeds a $100 million "threshold," it is deemed a "significant regulatory action" and the relevant government agency must conduct a cost-benefit analysis (CBA).[19] In this usage—which we avoid, and set off with quotation marks for emphasis—the regulatory "threshold" is simply a human-defined delineation between regulatory regimes (either a CBA is required or it is not), having no connection with the phenomenon of nonlinear change between alternative environmental states. In this Article, we focus on the importance of biophysical, environmental thresholds for management and policy, and the opportunities available to managers to align regulatory and ecological thresholds.[20]

Because both scientific insight and public attention have highlighted the importance of ecological thresholds, it is appropriate to evaluate how we might best apply this emerging science under existing environmental laws. This issue is particularly important because environmental statutes and their implementing regulations influence an enormous swath of natural resources—fresh water, air, forests, oceans, and many others—and rational management of those resources demands rules that accord with the best scientific approximation of the way the world works. Management to the contrary would be—and should be—difficult to justify. However, incorporating emerging science into an agency's existing

---

18. In part, this lack of attention is due to the inherently unpredictable nature of some ecosystem behaviors—if one can't understand or predict such behaviors, why bother to factor them into management? But as we discuss in the following pages, many important phenomena for environmental management are not inherently unpredictable, and recent work in theoretical ecology has pointed the way towards tools that may be able to predict tipping points before they happen. *See infra* note 45 and accompanying text. Such tools make this an especially relevant time to integrate improved ecological knowledge into the management sphere. Moreover, many relevant management scenarios involve closely analogous systems that can be models for determining when tipping points might occur elsewhere; for example, many temperate lakes may have similar dynamics, and the tipping point of one might inform the management of others.

19. *See* Exec. Order No. 12,866, 58 Fed. Reg. 51,735 (Sept. 30, 1993). A "significant regulatory action" triggers economic analysis requirements under Executive Order 12,866, section 3(f)(1)–(4). *Id.* Rules must also undergo economic analysis if they "adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or State, local, or tribal governments or communities." *Id.* § 3(f)(1); *see also* NAT'L CTR. FOR ENVTL. ECON., EPA, GUIDELINES FOR PREPARING ECONOMIC ANALYSES 2-2 (2010) [hereinafter GUIDELINES FOR PREPARING ECONOMIC ANALYSES], *available at* http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/guidelines.html.

20. Here we build on the discussion started by Malcolm L. Hunter Jr. et al. characterizing the "imperfect relationship between legal and ecological thresholds" and arguing that financial and social incentives for agencies "do more for the environment than meet legal minima." Malcolm L. Hunter Jr. et al., *Thresholds and the Mismatch Between Environmental Laws and Ecosystems*, 23 CONSERVATION BIOLOGY 1053, 1053–54 (2009). Note also that Hunter et al. do not clearly distinguish between regulatory "thresholds" and biophysical thresholds. *Id.*

environmental mandate is never straightforward, especially when accounting for pervasive environmental change and scientific uncertainty.[21] Uncertainties abound particularly with regard to environmental thresholds, and accordingly, we ask whether and how emerging scientific information about environmental tipping points can be made useful in practice, given existing laws and agency constraints.

For example, suppose a small city were weighing its sewage treatment and disposal options, and wanted to assess the consequences of dumping 100 gallons of minimally treated sewage into an adjacent lake. The lake would be at its least impacted state (all else being equal) with no sewage at all, and at its most impacted state when burdened with all of the city's sewage. Suppose further that some value (i.e., ecosystem service) attends the lake's condition, proportional to the degree of impact, such that a pristine lake is most valued for aesthetic, spiritual, and recreational purposes, as well as for its sewage-receiving capacity. The city is then left with a trade-off.

If one believes that 100 gallons of sewage will devalue the lake by $100, and that 200 gallons of sewage would similarly devalue the lake by $200, the city will decide on an appropriate course of action, given its resources and priorities.[22] It will weigh the costs and benefits of dumping versus transporting sewage elsewhere,[23] calculating the costs of dumping into the lake at a constant $1 per gallon. If, however, there is evidence for a threshold between sewage and impact,[24] the calculation changes drastically: some sewage has no effect and thus no discernable cost. But a slightly larger volume may shift the whole lake to a highly impacted state that may have prohibitive public health implications for swimming and drinking,[25] and accordingly high per-unit costs

---

21. *See* Dave Owen, *Probabilities, Planning Failures, and Environmental Law*, 84 TUL. L. REV. 265 (2009) (reviewing a swath of federal environmental laws and their struggle to incorporate scientific uncertainty and arguing for a more systematic and precautionary approach to accounting for such uncertainty in management); *see also* Dave Owen, *Law, Environmental Dynamism, Reliability: The Rise and Fall of CALFED*, 37 ENVTL. L. 1145 (2007) (discussing the challenges of managing unstable, unpredictable, and uncertain environmental systems within traditionally rigid legal and regulatory frameworks and how to adjust those systems to be more responsive).

22. The city will probably make its decision using an end-state target ("we want the lake to be *this* clean") or a dollar target ("we have *this* much money to spend on sewage"). In either case, the city will not base its decision on the relationship between sewage and environmental state because the city assumes that relationship to be constant along the whole range of parameter values. It is a linear relationship, and so it lacks obvious cost/benefit optima. By contrast, a nonlinear relationship provides natural optimization points.

23. For the sake of simplicity, we will assume that these are direct costs to the city, rather than externalized or indirect costs, among others.

24. For example, the evidence could show a change in the shape of the marginal cost curve for society from linear to nonlinear.

25. It is important to consider how we as a global society might move away from all-or-nothing management determinations, such as the commonly known shrimp-mangrove trade-off example in Southeast Asia. There, "[a]s in other areas of the world, perhaps the single largest impact of the rapid rise in intensive shrimp farming in Thailand is the destruction of mangrove wetlands." Forrest E. Dierberg & Woraphan Kiattisimkul, *Issues, Impacts, and Implications of Shrimp Aquaculture in Thailand*, 20 ENVTL. MGMT. 649, 651 (1996). In Latin America as well, mangrove destruction has historically been a direct consequence of intensive coastal shrimp farming. *See* Will Nixon, *Rainforest*

of pollution. A decision to limit sewage input to the amount before the threshold change in the lake occurs becomes considerably more attractive than adding a small amount more.

This observation—that environmental thresholds can significantly change environmental law and policy decisions—is the central theme of this Article. In a world where there is not a constant linear correspondence between pollutant and effect (or between cleanup and benefit), one might make very different environmental management decisions than are often made at present. Thresholds exist in the world in abundance, but we often do not govern as if this were the case, in part because those laws pre-date the scientific sea change during which the importance of nonlinear ecological change came to light.

The raft of environmental legislation in the 1960s and 70s faced a challenge still familiar today: recognizing environmental problems, and divining potential solutions, but having an incomplete mental model of the relationship between human activities and their effects on the air, water, land, and other aspects of the nonhuman environment on which humans depend. The result was a set of statutes that created target levels of human-generated pollution in at least three different ways, described below, reflecting different assumptions about the relationships between anthropogenic stressors (causes) and environmental impacts (effects).

The first two such models are *linearity* and indefinite *resilience*. Linearity is simply the idea that for each unit of pollutant, there is a consistent level of effect; this is the baseline case in the sewage example above where 100 gallons of sewage devalues the lake by $100.[26] Resilience—as we discuss below in Part I—is the idea that some amount of pollutant has no associated effect at all.[27] Professor Robin Kundis Craig has argued that, at least in the case of oil-drilling regulation:

Shrimp,   MOTHER   JONES,   March/April   1996,   *available   at* http://www.motherjones.com/politics/1996/03/rainforest-shrimp. Removing mangroves (along with their biodiversity, coastline stability, and other ecosystem services) is considered a small cost compared to the monetary gain to governments and local communities through employment and revenues in the shrimp farming industry. *See generally* Miriam Huitric et al., *Development and Government Policies of the Shrimp Farming Industry in Thailand in Relation to Mangrove Ecosystems*, 40 ECOLOGICAL ECON. 441 (2002). Nevertheless, there is good evidence that the net value of ecosystem services is at its maximum when mangroves and shrimp farming coexist. *See generally* Edward B. Barbier et al., *Coastal Ecosystem-Based Management with Nonlinear Ecological Functions and Values*, 319 SCIENCE 321, 321 (2008).

    26. U.S. environmental law frequently reflects an assumption of linearity, for example, by setting a constant per-ton penalty for air pollutant emissions in excess of a regulatory limit. *See, e.g.*, *Acid Rain Program*, EPA, http://www.epa.gov/airmarkets/progsregs/arp/basic.html (last updated July 25, 2012) (setting a penalty of $2000 per excess ton, plus an annual adjustment factor, under the CAA's Acid Rain Program).

    27. Or at least, no *net* effect. Definitions of "resilience" differ, with some focusing on a system's ability to recover after a perturbation (here, pollution), and others focusing on the system's ability to absorb the perturbation without changing in the first place. Carl Folke et al., *Regime Shifts, Resilience, and Biodiversity in Ecosystem Management*, 35 ANN. REV. ECOLOGY, EVOLUTION, & SYSTEMATICS 557, 558 (2004).

> The current law, policy, and remedy regime . . . effectively presumes that marine ecosystems have virtually unlimited . . . resilience with respect to oil spills[28] [and that] [a]s a practical matter in the law of natural resource management, the law tends to expect that ecosystems will be resilient . . . that is, the law assumes that ecosystems will generally successfully absorb any human-induced perturbations of the system.[29]

Technology-based standards, such as those in the CAA, arguably embrace the indefinite resilience model, setting pollution targets only on the basis of available pollution control technologies, independent of pollution effects on the environment of interest.[30] The implicit assumption is that the environment can absorb an amount of pollution that scales indefinitely alongside human technological advances, rather than the environment having an inherently limited capacity to absorb human pollution.

The third model of cause-and-environmental-effect is the threshold or tipping point model. Conceptually, tipping points can and do guide some regulatory decisions, as we will detail below in Part II, but explicitly focusing a larger set of environmental rules on likely tipping points could yield both management and policy efficiencies and political benefits. The efficiency argument is perhaps more intuitive: identifying environmental thresholds highlights opportunities for large returns on policy investments in pollution remediation or mitigation. But another substantial benefit of pollutant-effect thresholds is that they create obvious targets for purposes of management. Interested parties can argue indefinitely about the appropriate level at which to set a permissible pollutant load when there is a linear relationship between pollutant and effect because the "correct" limit will be a matter of preference for a particular level of outcome. With thresholds, by contrast, all parties should be able to agree that there are more and less dire consequences for a given amount of pollution at different points along the pollutant-effect curve. The existence of these different zones along the curve should lead to greater agreement about where to set permissible levels of pollutants, or conversely, the extent to which cleanup is necessary given the existing levels of pollution.[31]

---

28. Robin Kundis Craig, *Legal Remedies for Deep Marine Oil Spills and Long-Term Ecological Resilience: A Match Made in Hell*, 2011 BYU L. REV. 1863, 1888 (2011).

29. *Id.* at 1886. One might also argue that Professor Craig has a generous view of the theory underlying some natural resources management. After all, the line between assuming unlimited resilience and assuming humanity's actions have no impact whatsoever is vanishingly thin.

30. Hypothetically, these technology-based standards are set at a point where the economic costs of the technology are minimized and the societal benefits of abatement are maximized (the economically efficient point). However, in reality, the societal benefits of abatement (or the marginal costs of forgoing abatement) are not internalized and the technology-based standards merely reflect the market value of technological abatement, rather than the environmental and social impacts of pollution.

31. In a system with a clear tipping point, a permissible level of pollution may be efficient in terms of achieving desirable environmental outcomes. However, maintaining the system at that point may not be the most economically efficient action, depending on the technology and information available at the time.

This Article focuses on the implications of environmental thresholds for management under several primary U.S. federal environmental laws. We ask whether and how these existing legal structures allow for threshold-based management, and illustrate the ways in which such management can outperform traditional, threshold-blind decision making. After reviewing the science of environmental thresholds in Part I, we assess several major environmental statutes through a threshold lens, identifying opportunities for improved implementation using emerging science in Part II. Part III focuses in particular on CBAs as an incentive mechanism for implementing threshold-based management across a range of statutory schemes, before the Article concludes.

I. THE SCIENCE OF THRESHOLDS FOR LAWYERS

The math and vocabulary surrounding the science of thresholds can be daunting, but the core concept is straightforward: like the straw breaking the camel's back, sometimes a system[32] can take a substantial amount of stress until it reaches a breaking point. However, beyond this point, even a small amount of further strain will cause the system to undergo a significant change. Sometimes, but not always, this change is reversible in a similarly dramatic fashion.[33]

Many complex systems behave in similar ways—from lakes and bays to freeway traffic,[34] economies, and so on.[35] This kind of tipping point behavior is referred to as "nonlinear" in that the relationship between an input/stress and an outcome/response is described by a graph showing a curved (rather than straight) line (Figure 1). This simply means that the relation between input and outcome is not constant; rather, the outcome varies depending upon how much input the system has already experienced. The result is a nonlinear curve showing the relationship of outcomes to inputs as an elongated "s"—akin to the dose-response curves that we discuss below in Part II—with the middle part of the "s" describing the zone of transition between one state (intact camel, clear

---

32. Here and elsewhere, we use the word "system" as a flexible descriptor of a spatially coherent, integrated set of interactions among units of analysis. As a result, the camel and the straw form an analytical system, just as ecosystems do in a larger sense.

33. *See, e.g.*, Peter M. Groffman et al., *Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application?*, 9 ECOSYSTEMS 1, 9 (2006) (discussing reversibility).

34. *See generally* HANI S. MAHMASSANI ET AL., U.S. DEP'T OF TRANSP., INCORPORATING WEATHER IMPACTS IN TRAFFIC ESTIMATION AND PREDICTION SYSTEMS (2009), *available at* http://www.transportation.northwestern.edu/research/areas/networkmodelingplanning/IncorporatingWeatherImpacts.html (showing nonlinear traffic slowing in response to increased car density); Kara Maria Kockelman, *Modeling Traffic's Flow-Density Relation: Accommodation of Multiple Flow Regimes and Traveler Types*, 28 TRANSPORTATION 363, 365 (2001) (showing the same).

35. Malcolm Gladwell published a popular account of similar phenomena. *See* MALCOLM GLADWELL, THE TIPPING POINT (2000) (focusing on social thresholds rather than ecological ones).

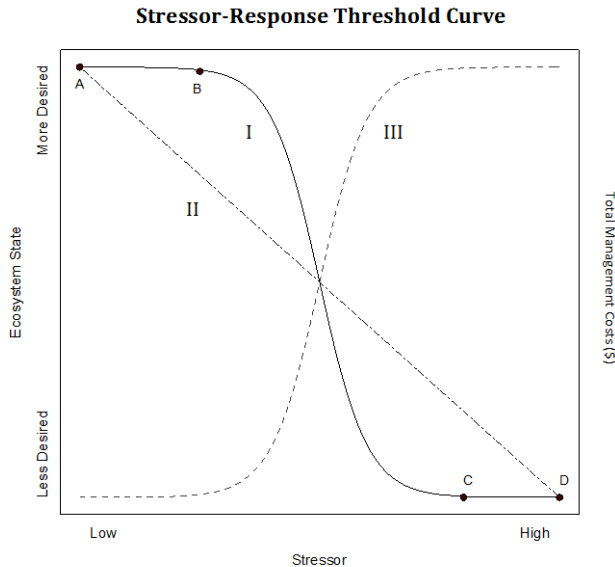lake, no algae, no traffic, etc.) and another (broken camel, green lake, lots of algae, gridlock, etc.).[36]

Stressor-Response Threshold Curve

Figure 1: Nonlinear (I, solid line) and linear (II, alternating dashes) curves describing a hypothetical relationship between ecosystem state (e.g., an estuary in an unimpaired state with clear water vs. an impaired state with algae-dominated, turbid water) and the intensity of an anthropogenic stressor (e.g., the amount of nutrient input to the estuary that may contribute to algal growth). In threshold cases, a small change in stressor intensity can drive a dramatic change in ecosystem state (e.g., from point "B" to "C" along the solid curve). The nonlinear curve that is the inverse of the relationship between ecosystem state and the intensity of the

---

36.   It seems that at least part of the explanation for these threshold dynamics is the complexity of the systems themselves. Where many interacting pieces create feedback loops (for example, one car changing lanes slows down others, which then may change lanes as a result), the system as a whole can change in unexpected and dramatic ways. A large body of math, engineering, and ecology has been dedicated to describing the behavior of these systems and to perhaps being able to forecast tipping points before they occur. *See, e.g.*, Stephen R. Carpenter & W. A. Brock, *Rising Variance: A Leading Indicator of Ecological Transition*, 9 ECOLOGY LETTERS 311 (2006) (studying indicators of impending regime shifts); Tim R. McClanahan et al., *Critical Thresholds and Tangible Targets for Ecosystem-Based Management of Coral Reef Fisheries*, 108 PROC. NAT'L ACAD. SCI. 17,230 (2011), *available at* http://www.pnas.org/content/108/41/17230.full (identifying management targets for coral reef fisheries after studying specific ecological thresholds); Marten Scheffer et al., *Anticipating Critical Transitions*, 338 SCIENCE 344 (2012). Note that authors in the ecological literature often portray thresholds as dependent on time, with time on the x-axis of a graph and some measure of the ecosystem state on the y-axis. It is true, of course, that time marches on and that ecosystems may change nonlinearly over time, but time does not itself drive the threshold. We have therefore focused on the drivers and responses of interest, rather than time, in our discussion.

ecosystem stressor (III, long dashes) represents the nonlinear increase in management costs that may result from a threshold change in the ecosystem. This cost curve assumes that management costs increase in step with environmental degradation. Cost is shown on the right-hand y-axis, with ecosystem state on the left-hand y-axis.

The idea of resilience is intimately tied to thresholds;[37] a system is resilient when it can absorb disturbances (here, inputs such as pollution) without crossing a threshold.[38] Hence, an ecosystem that can absorb a greater volume of pollution with comparatively little environmental effect is more resilient than one that is more easily pushed over a tipping point. What factors make ecosystems resilient is an area of active research in ecology, but for present purposes it is sufficient to say that while the degree of resilience varies across ecosystems, the existence of thresholds (rather than their precise quantification in any one case) is what drives our discussion of the implications of threshold-based management.

Tipping point dynamics create opportunities for efficiency and political compromise, as noted above, but also come with practical difficulties in a world in which we expect to know how much bang we will get for our policy buck. If we spend $1 billion to upgrade a sewage treatment plant, we expect to see a given amount of change in the quality of receiving waters. But in a threshold world—and it should be clear by now that this is the world in which we actually live—the return on that $1 billion investment depends strongly upon one's starting position, the shape of the curve that illustrates the waters' response to a change in pollution, and the costs of avoiding an ecosystem tipping point.

Tampa Bay is a classic example of such threshold change in the context of environmental policy. In the 1970s, the Bay experienced a large uptick in the growth of phytoplankton and macroalgae blooms associated with increases in land-based nitrogen runoff.[39] After absorbing increased nutrients from a variety of inland sources over a period of several decades, the Bay buckled under the pressure by the mid-1970s, when it exhibited a dramatic loss in seagrass in addition to marked increases in algal blooms, odor, and reduction in seabed-dwelling organisms.[40] In the opposite corner of the country, Lake Washington, which abuts the city of Seattle, experienced a similarly distinct decline in water

---

37. *See supra* notes 27–29 and accompanying text; *see also* Craig, *supra* note 28, at 1892–93 (arguing that the underlying assumption of U.S. policies is unlimited environmental resilience, rather than linear relationships between stressor and environmental response).

38. *See generally* FOUNDATIONS OF ECOLOGICAL RESILIENCE, *supra* note 17; Folke et al., *supra* note 27, at 558; *Resilience*, RESILIENCE ALLIANCE, http://www.resalliance.org/index.php/resilience (last visited Apr. 12, 2014).

39. Holly Greening & Anthony Janicki, *Toward Reversal of Eutrophic Conditions in a Subtropical Estuary: Water Quality and Seagrass Response to Nitrogen Loading Reductions in Tampa Bay, Florida, USA*, 38 ENVTL. MGMT. 163, 166 (2006).

40. *Id.*

quality in the 1960s as sewage inputs increased incrementally.[41] In both Tampa Bay and Lake Washington, the straw that broke the proverbial camel's back was a relatively small increase in nutrient pollution into a body of water that had already seen plenty. Both cases proved reversible, as small reductions in pollution subsequently resulted in stark decreases in algae and attendant rise in water oxygen levels[42]—indicators of the ecosystem states residents preferred.[43]

A.   *Prospective and Retrospective Management*

The examples of Tampa Bay and Lake Washington help to distinguish tipping point behavior from the expectation of a linear environmental response to pollution (in which case a small increase in pollution yields a predictably small increase in effect) or a resilient response (in which case a small increase in pollution yields little net effect). They also frame the distinction between prospective and retrospective management[44]: pollution reductions in Tampa Bay and Lake Washington only happened after each crossed an ecosystem threshold, and so the two are examples of retrospective management. Had agencies predicted the threshold in each case and reduced pollution in order to avoid it, these would have been examples of prospective management.

How to predict tipping points before reaching them is, of course, a critical scientific question. Emerging research in quantitative and theoretical ecology suggests that predicting tipping points—and hence, prospective management— is possible by closely observing the system of interest over time.[45] Prediction might also be possible by mathematical modeling, or by comparing one ecosystem under management (say, a rangeland, forest, bay, or lake) to other similar systems elsewhere that have already reached documented tipping points. Nevertheless, currently the only definitive means of detecting a threshold is to go over one,[46] and as a consequence most resource management systems remain reactionary, responding to environmental stressors when they

---

41.   W. Thomas Edmondson, *Phosphorus, Nitrogen, and Algae in Lake Washington after Diversion of Sewage*, 169 SCIENCE 690, 690 (1970).

42.   *See, e.g.*, *id.*

43.   *See* 1957 Wash. Sess. Laws 804 (creating public mechanisms to alleviate sewage pollution, among other ills associated with urban growth, in Washington). Seattle voters subsequently used this mechanism to authorize wastewater treatment to alleviate pollution in Lake Washington, demonstrating a public preference for an earlier ecosystem state. *See id.*; *The Birth of Metro*, KING COUNTY, http://www.kingcounty.gov/environment/wtd/About/History/BirthOfMetro.aspx (last visited Oct. 20, 2014).

44.   *See* Adam Babich, *Too Much Science in Environmental Law*, 28 COLUM. J. ENVTL. L. 119, 174–75 (2003) (discussing, indirectly, the differences between prospective and retrospective regulation under the Environmental Protection Agency's (EPA) jurisdiction).

45.   *See generally* Vasilis Dakos et al., *Robustness of Variance and Autocorrelation as Indicators of Critical Slowing Down*, 93 ECOLOGY 264 (2012) (studying indicators of imminent critical transitions); Marten Scheffer et al., *Early-Warning Signals for Critical Transitions*, 461 NATURE 53 (2009) (noting that "the existence of generic early-warning signals . . . may indicate for a wide class of systems if a critical threshold is approaching").

46.   Marten Scheffer & Stephen R. Carpenter, *Catastrophic Regime Shifts in Ecosystems: Linking Theory to Observation*, 18 TRENDS ECOLOGY & EVOLUTION 648, 648 (2003).

become noticeable rather than actively seeking them out before they cause problems.

Prospective management of environmental thresholds, then, is an information- and resource-intensive proposition that entails unavoidable uncertainty. Moreover, while avoiding harm (rather than experiencing harm and then trying to reverse or mitigate it) is both smart and efficient, it is likely to be an underwhelming public justification for policy action. Humans systematically undervalue harm avoided,[47] particularly where future harm is to some degree speculative. As a consequence, retrospective management is standard operating procedure and is likely to continue.

Where ecosystem thresholds are reversible, retrospective management offers valuable public incentive to remediate the loss of ecosystem services suffered through recent environmental harm. Examples abound, from Tampa Bay and Lake Washington, to watershed restoration to improve degraded water quality.[48] We therefore view both prospective and retrospective management as important tools; while efficiency demands that agencies strive for prospective measures, retrospective management retains practical and political advantages.

B.   *Applying Threshold-Based Management in the Real World*

A drawback of the metaphor of the straw and the camel's back is that it is too simple to be directly relevant to ecosystem management: the presence of a clear stressor (the straw) and its immediate impact (the broken camel) are what makes the metaphor a useful heuristic, but also what limits the analogy. In the real world of ecosystems, the camel's back may safely exist in any number of configurations (rather than simply broken versus not) and may bear an ever-changing mixture of goods (not simply straw) on its back in ways that might become unbalanced or untenable. That is, the ecosystem of interest (say, Puget Sound) has fuzzy boundaries, billions of interacting parts, and constantly changing elements. We understand neither the camel nor the straw fully, yet we must make the most informed decisions we can, given what we do know.

---

47.   *See, e.g.*, Michael D. Mehta, *Risk Assessment and Sustainable Development: Towards a Concept of Sustainable Risk*, 8 RISK 137, 145 (1997) ("Although environmental quality has always been a public good, the 'harm avoided' aspects of environmental protection defies traditional market-based valuation. This has not prevented governments from insisting upon such valuations nonetheless."). The tendency to undervalue the harms avoided may be due to a large and uncertain discount rate for future benefits forgone, but it may also be that humans discount future harm avoided disproportionately even relative to future benefits obtained.

48.   Graciela Chichilnisky & Geoffrey Heal, *Economic Returns from the Biosphere*, 391 NATURE 629, 629 (1998). Note that retrospective harm remediation is standard in environmental management, even where harm is linearly related to the degree of pollution and no threshold is present. One recent example is the public response to a chemical spill in the drinking water of West Virginia towns in 2014. Trip Gabriel, *Thousands Without Water after Spill in West Virginia*, N.Y. TIMES (Jan. 10, 2014), http://www.nytimes.com/2014/01/11/us/west-virginia-chemical-spill.html (describing the spill and the response to it, which included comprehensive river and municipal water cleanup, as well as bottled water delivery to over 300,000 people).

What we do know is that multiple stressors can influence ecosystems in several different ways—additive, synergistic, or antagonistic[49]—and that particular combinations of stressors can cause unexpected changes. We know that ecosystems may exist in multiple states given the same external conditions,[50] and that the transition from one state to another may differ from the path back to the first ("hysteresis").[51] Finally, we know the world is full of these thresholds and that environmental management is more likely to meet its goals if that management adjusts human behaviors by addressing such thresholds explicitly.[52]

This Article is not an attempt to surmount the difficulties of quantitative ecology, but rather it is an effort to demonstrate the desirability of, and opportunities for, the use of thresholds in environmental management under U.S. federal law. While thresholds create an expectation of zones of little return on investment (between points A and B and C and D in Figure 1), they also create great opportunity in the central threshold region of the curve in which large gains (or losses) can be had for relatively little change in a stressor (e.g., pollution). Hence, the incentives that thresholds create are wholly different from the incentives of a linear world. Below, we explore the way in which existing U.S. environmental laws interact with their underlying areas of regulatory interest through the lens of ecological thresholds.

II. OPPORTUNITIES FOR ENVIRONMENTAL THRESHOLD MANAGEMENT UNDER U.S. LAW

The relationship between human activities and environmental thresholds goes to the crux of many key federal environmental laws—for example, maximum sustainable yield (MSY) in the Magnuson-Stevens Act, jeopardy under the Endangered Species Act (ESA), a finding of significant impact under the National Environmental Policy Act (NEPA), and health and safety targets under the Clean Water Act (CWA) and the CAA. We assess these applications below, noting that environmental law is often about drawing lines—how much is too much?—and the existence of known ecological (or in some cases, human health) thresholds can greatly simplify this task. Indeed, as we noted in Part I and will elaborate on in Parts II and III, it can be more difficult to draw arbitrary regulatory lines where no ecological threshold exists (also known as a regulatory "threshold"). This in itself is a strong argument that, where

---

49. *See* Caitlin M. Crain et al., *Interactive and Cumulative Effects of Multiple Human Stressors in Marine Systems*, 11 ECOLOGY LETTERS 1304, 1306 (2008).

50. *See, e.g.*, Beatrix E. Beisner, *Alternative Stable States*, NATURE EDUC. KNOWLEDGE PROJECT (2012), http://www.nature.com/scitable/knowledge/library/alternative-stable-states-78274277.

51. *Id.*

52. *See* Ryan P. Kelly et al., *Embracing Thresholds for Better Environmental Management*, 370 PHIL. TRANSACTIONS ROYAL SOC'Y B: BIOLOGICAL SCIENCES 1 (2015) (reviewing fifty-one case studies of prospective and retrospective management examples in systems with demonstrated threshold relationships and finding that more explicit use of thresholds is strongly associated with better environmental outcomes).

thresholds do exist in the context of natural resources and environmental policy, threshold-based management regimes are desirable.

A.   Human-Focused Laws and Environment-Focused Laws

The primary purpose of most environmental laws is to preserve the human health, safety, and welfare that may be threatened by declines in air and water quality, a buildup in toxic materials, or exhaustion of common-pool resources. However, a few laws—for example, the ESA—expressly aim to protect specific species and resources from extinction at the hands of humans. These two sets of laws have different prospects for integrating emerging threshold science into agency decision making, and we group our discussion of them accordingly below. We begin with a discussion of those laws that focus on preserving human health, and use their emphasis on available human health based thresholds (e.g., the CAA and the CWA) as a springboard for discussing threshold-based management more generally, including specific opportunities to incorporate ecologically based thresholds into management structures that are historically focused on protecting human health. We also provide several examples of U.S. federal environmental laws that already demonstrate some form of species-specific threshold-based management. We conclude with a discussion of NEPA to consider how ecological thresholds can be used to manage tipping points on the scale of an entire ecosystem.

B.   Risk- and Technology-Based Targets and Best Available Science Requirements

A primary difference between classes of regulation is that some regulatory targets are based on acceptable levels of risk to human or environmental health, whereas others are technology based.[53] The examples we highlight below include the risk-based National Ambient Air Quality Standards (NAAQS) of the CAA and the technology-based National Pollutant Discharge Elimination System (NPDES) of the CWA.

Risk-based regulations provide better opportunities for matching ecological thresholds with regulatory targets, given that risk-based requirements are grounded in information about the affected ecosystem, rather than the state of human technology.[54] Accordingly, statutory Best Available Science (BAS) requirements[55] are one of the most prominent regulatory

---

53.   The CWA relies on technology-based standards. For example, for adopting or revising effluent limitation guidelines for point source pollution, the Act requires regulations to "identify, in terms of amounts of constituents and chemical, physical, and biological characteristics of pollutants, the degree of effluent reduction attainable through the application of the *best practicable control technology* currently available . . . ." 33 U.S.C. § 1314(b)(1)(A) (2012) (emphasis added).

54.   *See* Babich, *supra* note 44, at 125–30. As discussed in more detail in Part III, CBAs also militate in favor of risk-based analyses where feasible. *Id.*

55.   BAS requirements are procedural requirements that should apply to both risk-based and technology-based regulatory regimes, since they more finely calibrate the appropriate level of concern for environmental outcomes. However, if risk-based regulation is effectively the same as effect-based

mechanisms by which agencies may be required to incorporate new information about the world into their decision-making processes—whether applied to risk- or technology-based standards.[56] Courts also seldom second-guess an agency's choice of science, and no matter the court's deference, the basic understanding remains that only those agency actions that are arbitrary and capricious will be overturned.[57] BAS requirements can therefore influence which evidence an agency considers in making a decision, and so are particularly relevant in the threshold-based management context.[58] Where an

---

regulation, BAS folds in on itself somewhat since the BAS procedural requirement determines both the effect and what might be done about it.

56.   Many environmental laws have explicit BAS requirements, including the ESA, the Marine Mammal Protection Act (MMPA), and the Magnuson-Stevens Act. The ESA requires a determination of whether a species should be listed as endangered or threatened "solely on the basis of the *best scientific and commercial data available*." 16 U.S.C. § 1533(b)(1)(A) (2012) (emphasis added). Under the MMPA:

> The Secretary, on the basis of the *best scientific evidence available* . . . shall prescribe such regulations with respect to the taking and importing of animals from each species of marine mammal . . . as he deems necessary and appropriate to insure that such taking will not be to the disadvantage of those species and population stocks . . . .

16 U.S.C. § 1373(a) (emphasis added). The Magnuson-Stevens Act's requirement, implemented through the National Standard 2 on Scientific Information, requires that "[c]onservation and management measures shall be based upon the *best scientific information available*." *See* 16 U.S.C. § 1851(a)(2) (emphasis added); 50 C.F.R. § 600.315(a) (2014) (national standard).

57.   5 U.S.C. § 706(2)(A) (2012). Courts may assert their judicial review along a continuum with the "super deference" principle on the most forgiving end. Emily Hammond Meazell, *Super Deference, the Science Obsession, and Judicial Review as Translation of Agency Service*, 109 MICH. L. REV. 733, 772 (2011). The Supreme Court first set forth the "super deference" principle, stating that "a reviewing court must remember that the [agency] is making predictions within its special area of expertise, at the frontiers of science. When examining this kind of scientific determination, as opposed to simple findings of fact, a reviewing court must generally be at its *most deferential*." Balt. Gas & Elec. Co. v. Natural Res. Def. Council, Inc., 462 U.S. 87, 103 (1983) (emphasis added). The Court's finding in *Chevron* is next on the continuum, where the Court stated that it has "long recognized that considerable weight should be accorded to an executive department's construction of a statutory scheme it is entrusted to administer, and the principle of deference to administrative interpretations." Chevron U.S.A., Inc. v. Natural Res. Def. Council, Inc., 467 U.S. 837, 844 (1984). Alternatively, *State Farm*'s "hard look" is arguably the most hands-on approach to judicial review. Motor Vehicle Mfrs. Ass'n v. State Farm Mut. Auto. Ins. Co., 463 U.S. 29, 43 (1983) (citing Burlington Truck Lines v. United States, 371 U.S. 156, 168 (1962), in holding that arbitrary and capricious review requires that "the agency [] examine the relevant data and articulate a satisfactory explanation for its action including a 'rational connection between the facts found and the choice made'"); *id.* (citing Bowman Transp. Inc. v. Arkansas-Best Freight Sys., 419 U.S. 281, 285 (1974), in holding that courts must "'consider whether the [agency's] decision was based on a consideration of the relevant factors and whether there has been a clear error of judgment'"); *see also* Citizens to Pres. Overton Park, Inc. v. Volpe, 401 U.S. 402, 416 (1971); Matthew C. Stephenson, *A Costly Signaling Theory of "Hard Look" Judicial Review*, 58 ADMIN. L. REV. 753, 758 (2006).

58.   Alternatively, if staff do not incorporate the BAS on thresholds into decision making, even management measures with the best intentions can be wholly ineffective. In the Southeast, for example, researchers have identified a threshold relationship between drought, snails, and mass die-offs of salt marshes. Brian R. Silliman et al., *Drought, Snails, and Large-Scale Die-Off of Southern U.S. Salt Marshes*, 310 SCIENCE 1803, 1803 (2005). This research predicted "unprecedented" salt marsh die-offs at least six years prior to publication, and identified drought, coupled with snail grazing pressure, as the primary driver of extreme die-off events. *Id.* However, even today there is no evidence that managers in

agency's statutory mandate does not require it to incorporate evolving environmental science, we may see continued regulatory target setting without regard to thresholds, risking disruptive tipping points as a result.

C.   Statutory Opportunities for Threshold-Based Environmental Management

1. Human Health Related Laws as Models of Threshold-Based Targets

Of the two categories of laws described above, the landmark CWA and CAA fall into the first, more human health focused category, effectively asking how much is too much for the human body. A little benzene is bad for people, but is it so bad we need to regulate it? Furthermore, how much is "a little"? How much particulate matter are we prepared to accept in our skies and in our lungs?[59]

Where human health is the goal, a dose-response curve can greatly inform a decision about setting the target amount to a point at which the level of "too much" has been reached. These curves are generally the sigmoidal "s" curve described above in Part I (Figure 1): humans can take a little arsenic with no effect, but taking a little more will kill most people. On a population scale, x grams of arsenic will kill 0 percent of the population, but x+10g will kill 50 percent of the population, and so on. The precise amount at which we choose to set the legal limit for arsenic in drinking water can and should take into account this dose-response curve, with the regulatory target itself reflecting the value of human lives and other critical social parameters. So to a significant extent, we already use threshold-based management in environmental law, especially regarding human health tolerances.

a. The Clean Air Act

The CAA is one such human health based law that provides examples of both threshold-based and non-threshold-based control rules. Within the CAA,

---

the Southeast are incorporating these threshold-based interactions between snails, drought, and saltmarsh die-off into their management decisions surrounding wetland recovery or loss prevention. Telephone Interview with Brian R. Silliman, Silliman Lab, Marine Ecology & Conservation, Duke Marine Lab (Feb. 20, 2013).

   59.   Moreover, what's the acceptable cost of avoiding such pollution?

NAAQS and Hazardous Air Pollutants (HAPs) trigger, in theory,[60] prospective management tools to avoid certain human health thresholds.[61]

As to NAAQS, there are two general human health based thresholds built into the CAA's criteria pollutant standards. The initial trigger for regulation is whether a pollutant causes or contributes to air pollution that *may reasonably be anticipated to endanger public health or welfare*.[62] The human health threshold is therefore associated with a corresponding pollutant level (also known as a dose-response curve) where pollution is sufficient to cause "identifiable" or measurable adverse human health effects. Since the CAA's inception, the Environmental Protection Agency (EPA) has listed six such pollutants (known as criteria pollutants),[63] each of which is regulated with human health based limits ("primary standards"). However, the Act also allows EPA to set secondary standards to protect a broader concept of human welfare.[64] Given the interdependence of human welfare and ecosystem

---

60. In reality, however, across the United States, many air pollution levels have long surpassed their regulatory limits, and in response, the Act has triggered more retrospective measures. For example, the CAA requires the governor of each state to submit a list of all areas that do "not meet (or that contribute[] to ambient air quality in a nearby area that does not meet) the national primary and secondary ambient air quality standard . . . ." 42 U.S.C. § 7407(d)(1)(A)(i) (2012). Should a state fail to meet these standards, the CAA requires the state to develop a nonattainment plan that dictates the technology control measures available to bring the state into compliance. *Id.* § 7502(c). While retrospective, these requirements may allow state managers to identify the quantitative human health thresholds necessary to gain attainment status—an opportunity for retrospective threshold-based management.

61. The CAA envisions that scientists will rely solely on science to dictate the "requisite" standard, sometimes based on quantitative human health thresholds, to set the allowable levels of air pollutants. *See* 42 U.S.C. §§ 7408(a)(2), 7409(b)(1). However, in many cases scientists do not have adequate information on pollutant levels and their effects on humans to select a solely science-based standard. *See, e.g.*, Joseph M. Feller, *Non-Threshold Pollutants and Air Quality Standards*, 24 ENVTL. L. 821, 865 (1994). In reality, pollutant standards are set amidst considerable scientific uncertainty. *See, e.g.*, *id.* at 824 (citing MARC K. LANDY ET AL., THE EPA: ASKING THE WRONG QUESTIONS 55–56 (1990)); Dave Owen, *Probabilities, Planning Failures, and Environmental Law*, 84 TUL. L. REV. 265, 280–82 (2009). Value judgments or public policy considerations are always necessary to determine how much is "too much." (For example, how many asthma attacks in one year is too many? How many premature deaths are acceptable?) *See, e.g.*, Susannah Landes Weaver, *Setting Air Quality Standards: Science and the Crisis of Accountability*, 22 TUL. ENVTL. L.J. 379, 381 (2009).

62. 42 U.S.C. § 7408 (emphasis added). The EPA is not allowed to consider the economic or technological feasibility for controlling these criteria pollutants when determining whether they should be listed. *Id.*; *see also* Lead Indus. Ass'n v. EPA, 647 F.2d 1130, 1150 (D.C. Cir. 1980).

63. The pollutants are: sulfur dioxide (SO_2); particulate matter (PM); nitrogen oxide (NO); carbon monoxide (CO); ozone (O_3); and lead (Pb). *National Ambient Air Quality Standards (NAAQS)*, EPA, http://www.epa.gov/air/criteria.html (last updated Dec. 14, 2012).

64. Secondary standards are designed to protect public welfare from "known or anticipated adverse effects" under the CAA. 42 U.S.C. § 7409(b)(2). In 2008, the EPA established secondary NAAQS for SO_2 and NO_x to address the potential impacts of acidifying deposition on terrestrial systems, but acknowledged that there was insufficient scientific evidence to set standards protective of aquatic systems. EPA, DRAFT SCOPE AND METHODS PLAN FOR RISK/EXPOSURE ASSESSMENT: SECONDARY NAAQS REVIEW FOR OXIDES OF NITROGEN AND OXIDES OF SULFUR 6 (2008), *available at* http://www.epa.gov/ttn/naaqs/standards/no2so2sec/data/20080305_draft_scope.pdf. In 2011, the EPA determined that NO_x and SO_2 deposition contribute to the acidification of aquatic ecosystems, and called for further research to inform more protective secondary NAAQS. EPA, POLICY ASSESSMENT FOR THE REVIEW OF THE SECONDARY NATIONAL AMBIENT AIR QUALITY STANDARDS FOR OXIDES OF NITROGEN

services, these welfare-based secondary standards are an opportunity for EPA to set air pollution targets that reflect ecological (and not merely human health) thresholds.[65] Secondary standards require agencies to account for effects on the environment, including climate, wildlife, soils, water, and vegetation.[66]

Whether primary or secondary, NAAQS are risk-based measurements of the ambient air quality—not technology-based limits for specific emissions.[67] Hence, it is not surprising that these standards are candidates for threshold-based management. Primary pollutant standards also have a second feature consistent with managing to avoid a harmful threshold: they must be set with "an adequate margin of safety."[68] This margin of safety is a crucial component of proactive threshold-based management, particularly when the exact risk the pollutant poses to humans is unknown.[69] Buffers around regulatory targets (of which the "adequate margin of safety" is one) build the possibility of prospective management into the NAAQS.

Apart from managing ambient levels of criteria pollutants, the CAA also directly regulates categories of stationary sources that emit criteria pollutants.[70] Unlike their risk-based counterparts, technology-based standards, such as Best Achievable Control Technology[71] and Maximum Achievable Control

---

AND   OXIDES   OF   SULFUR   ES-1   (2011),   *available   at* http://www.epa.gov/ttn/naaqs/standards/no2so2sec/data/20110114pamain.pdf. At present, EPA has initiated a five-year pilot program to evaluate the contribution of SO_2 and NO_x deposition to regional, aquatic ecosystem acidification. *See* Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Sulfur, 77 Fed. Reg. 20,218, 20,264–65 (Apr. 3, 2012) (to be codified at 40 C.F.R. pt. 50). A detailed list of both the primary and secondary standards for the six criteria pollutants can be found at http://www.epa.gov/air/criteria.html.

    65.   One such example is the emission of greenhouse gases, which affects both human health and the environment through warming the global climate.

    66.   The public welfare category is much broader than public health, and includes effects on "soils, water, crops, vegetation, man-made materials, animals, wildlife, weather, visibility, and climate, damage to and deterioration of property, and hazards to transportation, as well as effects on economic values and on personal comfort and well-being." 42 U.S.C. § 7602(h).

    67.   For example, the NAAQS for CO may not exceed more than nine parts per million during an eight-hour period or thirty-five parts per million during a one-hour period more than once per year. National Primary Ambient Air Quality Standards for Carbon Monoxide, 40 C.F.R. § 50.8 (2014). These numbers are based on known risk levels associated with human exposure to CO, not on the best technology to effectively remove CO from the ambient air.

    68.   *See* 42 U.S.C. § 7409(b)(1).

    69.   THE CLEAN AIR ACT HANDBOOK 16 (Robert J. Martineau & David P. Novello eds., 2d ed. 2004) ("The administrator sets primary NAAQS not only to prevent pollution levels that have been demonstrated to be harmful, but also to prevent lower pollutant levels that she finds pose an unacceptable risk of harm, even if that risk is not precisely identified as to nature or degree. In selecting a margin of safety the EPA has considered such factors as the nature and severity of health effects involved, the size of sensitive population(s) at risk, and the kind and degree of the uncertainties that must be addressed." (citation omitted)).

    70.   42 U.S.C. § 7411(a)(3).

    71.   Best Achievable Control Technology is selected on a case-by-case basis and requires that the agency base emissions limitations "on the maximum degree of reduction of each pollutant subject to regulation." 42 U.S.C. §§ 7475(a)(4), 7479(3).

Technology,[72] control emissions directly from a source. As discussed above, agencies have a less defined pathway to incorporate threshold-based management into such technology-based standards because such targets are not grounded in a pollutant's human or ecosystem impacts.

Nevertheless, even the Act's technology-based standards provide an opportunity for threshold-based management. HAPs, which are regulated using technology-based requirements, do have known, quantifiable human health thresholds. The CAA distinguishes between threshold and nonthreshold HAPs, stating "[w]ith respect to pollutants for which a health threshold has been established" the EPA "may consider such threshold level, with an ample margin of safety, when establishing emission standards."[73] So here, the EPA has jurisdiction to infuse technology-based standards with a quantitative understanding of a human health threshold coupled with an "ample margin of safety."[74]

b. The Clean Water Act

Under the CWA, agencies set environmental standards based both on human health and on environmental thresholds,[75] but as in the case of the CAA, the CWA offers further opportunity for embedding threshold-based science into state and federal water quality criteria and standards. Like its clean air counterpart, the CWA has both technology-based and effects-based elements.

The Act's primary mechanism is the technology-based NPDES program for point source pollution, in which individual polluters are subject to permitting requirements.[76] Effects-based Water Quality Standards (WQS) exist alongside—and subsidiary to—the NPDES program, aimed largely at

---

72. The CAA regulates HAPs using Maximum Achievable Control Technology. 42 U.S.C. § 7412(d)(2). Maximum Achievable Control Technology requires that the highest degree of achievable technology be applied to sources emitting HAPs. *Id.*

73. *Id.* § 7412(d)(4).

74. *Id.* Of course, some HAPs are not safe at any level; their human health threshold for emissions is zero. In these cases, it is arguably more difficult to regulate pollutants that do not have a threshold than those that do. However, even if the EPA regulates a HAP with an established human health threshold, HAP standards are organized by source categories, where groups of different emitter types are regulated as one, allowing different sources to pollute different amounts. *See Pollutants and Sources*, EPA, http://www.epa.gov/airtoxics/pollsour.html (last updated Sept. 18, 2013). This arrangement is not conducive to threshold-based management, which does not distinguish between what source is polluting when and how much, but instead focuses on how much in total is being polluted, and whether that pollution may cause a system or species to cross a threshold.

75. The Act aims to restore or maintain water quality to a level that is suitable for aquatic life as well as humans—known colloquially as the "fishable and swimmable" standard. Thus, the CWA is guided by both human and nonhuman goals. *See, e.g.*, *Clean Water Act (CWA)*, EPA, http://www.epa.gov/agriculture/lcwa.html (last visited Apr. 7, 2014) (stating that the CWA's national goal is that waters be "fishable, swimmable"); Paul Greenberg, *The Clean Water Act at 40: There's Still Much Left to Do*, YALE ENV'T 360 (May 21, 2012), http://e360.yale.edu/feature/the_clean_water_act_at_40_theres_still_much_left_to_do/2532/ ("[The CWA's] essential demand [was] that all waterways in the United States be 'fishable and swimmable' by 1985.").

76. 33 U.S.C. § 1342 (2012).

maintaining a baseline level of ambient water quality. These work as follows: states designate the types of human uses each of its water bodies supports[77] and then set narrative or numeric criteria that must be met to maintain those uses.[78] The EPA provides states with guidance on the minimum requirements for such criteria through the WQS Handbook,[79] and classifies criteria for aquatic life protection and human health protection.[80]

The WQS, NPDES, and Total Maximum Daily Load (TMDL) programs are all inextricably linked. The technology-based NPDES program is the first stop on a state's pathway to meeting the CWA's "fishable and swimmable" goal. If, however, a water body is still considered impaired even after all point sources are permitted (i.e., where technology-based requirements are insufficient to safeguard those uses), the Act requires that the state undertake a TMDL analysis—essentially a budget of all pollution sources—for such impaired water bodies.[81]

When setting recommended Human Health Ambient Water Quality Criteria, the EPA distinguishes between noncarcinogenic and carcinogenic pollutants.[82] Noncarcinogenic pollutants are expected to have human health threshold concentrations (below which no adverse health effects occur), while carcinogens are assumed to have no safe concentration (i.e., there is no known human health based threshold).[83] Because the EPA determines the criteria for carcinogens based on the incremental risk of cancer per increase in exposure,[84] water quality criteria for carcinogenic toxicants were not traditionally determined based on thresholds for human health.

---

77.   40 C.F.R. § 131.10 (2014).

78.   40 C.F.R. § 131.11. For example, the states must classify each water body for any combination of protection and propagation of fish, shellfish, wildlife, recreation, agriculture, industry, or navigation. EPA, WATER QUALITY STANDARDS HANDBOOK § 2.1 (2d ed. 1994) [hereinafter WATER QUALITY STANDARDS HANDBOOK].

79.   *See* WATER QUALITY STANDARDS HANDBOOK, *supra* note 78, § 3.1.

80.   *Id.*

81.   The TMDL program, therefore, serves as a backstop for when the NPDES permitting scheme fails to achieve its intended targets. A TMDL identifies the maximum amount of a given pollutant that can be emitted to a water body before exceeding its WQS for that pollutant. *What is a TMDL?*, EPA, http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/overviewoftmdl.cfm (last updated Sept. 11, 2013). Once this threshold is determined, a state must develop a plan to bring the water body into compliance with its WQS, requiring modifications to its NPDES permitting scheme. *See id.*

82.   EPA, METHODOLOGY FOR DERIVING AMBIENT WATER QUALITY CRITERIA FOR THE PROTECTION OF HUMAN HEALTH ch. 3 (2000) [hereinafter METHODOLOGY FOR DERIVING AMBIENT WATER QUALITY CRITERIA], *available at* http://water.epa.gov/scitech/swguidance/standards/upload/2005_05_06_criteria_humanhealth_method_complete.pdf.

83.   EPA, QUALITY CRITERIA FOR WATER app. B (1986) [hereinafter GOLD BOOK]. As with the CAA, some water-based toxicants have carcinogenic effects requiring a maximum protection level of zero consumption, and no scientific basis exists to determine a "safe" level of carcinogen consumption above zero. *Id.*

84.   WATER QUALITY STANDARDS HANDBOOK, *supra* note 78, § 3.1.3.

However, the EPA is shifting towards a more threshold-based decision-making framework within the WQS program.[85] State regulators may use different equations set forth in the recommended Human Health Ambient Water Quality Criteria depending on whether the toxicant is considered to have a linear or nonlinear and carcinogenic or noncarcinogenic effect on human health.[86]

Meeting the CWA's "fishable" goal is another opportunity for EPA to go beyond the human health requirements and foci of the CWA. EPA recommends two separate criteria to protect against acute (short-term) and chronic (long-term) effects to aquatic life.[87] Current Aquatic Life Criteria guidelines recommend pollutant concentrations remain below ecological thresholds, where "unacceptable effect[s]" do not occur to aquatic organisms.[88] Therefore, although it is not required, states can incorporate ecologically based thresholds into the EPA's recommended Aquatic Life Criteria to meet the CWA's "fishable" goal.[89]

State water quality criteria developed pursuant to the EPA's WQS come in a variety of forms, including narrative, numeric, biological, nutrient, sediment, and wildlife.[90] Implementing narrative criteria can lead to the development of numeric criteria. For example, Florida recently adopted numeric *interpretations* of their narrative criteria[91] for lakes and streams, and in some cases they incorporated known ecological thresholds into those numeric criteria. To set numeric nutrient criteria for streams, for example, Florida used the EPA's "most comprehensive and scientifically defensible approach . . . to establish criteria to protect against dependably measured adverse biological responses."[92] The EPA's "dose-response approach" helped them set regulatory

---

85. The EPA is "seeing a shift from the traditional approach of viewing quantitative risk assessment for carcinogens as a linear process and noncancer assessments as nonlinear. Increasingly, the determination of whether to use a linear or a nonlinear approach for deriving human health [ambient water quality criteria] is based on the mode of action for an effect more than whether the effect of interest is cancer or not." *Water Quality Standards Academy*, EPA, http://water.epa.gov/learn/training/standardsacademy/health_page6.cfm (last updated Mar. 6, 2012).

86. METHODOLOGY FOR DERIVING AMBIENT WATER QUALITY CRITERIA, *supra* note 82, at 1-9 to 1-10.

87. CHARLES E. STEPHEN ET AL., EPA, GUIDELINES FOR DERIVING NUMERICAL NATIONAL WATER QUALITY CRITERIA FOR THE PROTECTION OF AQUATIC ORGANISMS AND THEIR USES 2 (2010), *available at* http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/85guidelines.pdf.

88. *Id.* at 1. However, the guidelines state "that this is a threshold of unacceptable effect, not a threshold of adverse effect. Some adverse effect, possibly even a small reduction in the survival, growth, or reproduction of a commercially or recreationally important species, will probably occur at, and possibly even below, the threshold." *Id.* at 4.

89. *Id.* at 1–2.

90. WATER QUALITY STANDARDS HANDBOOK, *supra* note 78, § 3.5.

91. Florida's narrative criteria stated "in no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in natural populations of aquatic flora or fauna." FLA. ADMIN. CODE ANN. r. 62-302.530 (2014).

92. FLA. DEP'T OF ENVTL. PROT., FLORIDA NUMERIC NUTRIENT CRITERIA: HISTORY AND STATUS 3 (n.d.), *available at* http://www.dep.state.fl.us/water/wqssp/nutrients/docs/fl-nnc-summary-100109.pdf.

targets based on numeric chlorophyll-*a* thresholds to protect both human and aquatic life uses in Florida's lakes.[93]

Such threshold-based targets are not entirely new. The Tahoe Regional Planning Agency (TRPA)[94] has designated, monitored, and regulated environmental thresholds in Lake Tahoe since 1982.[95] The TRPA has ecosystem threshold-based standards for nine different categories, including air, water, soil, fisheries, vegetation, recreation, and noise.[96] Within water quality, the TRPA sets various numeric threshold standards for deep waters, nearshore waters, tributaries, surface waters, groundwater, and other lakes.[97] For example, the nitrogen-loading threshold standard for the nearshore waters of Lake Tahoe is to reduce dissolved inorganic nitrogen loading from all sources by 25 percent of the annual average load between 1973 to 1981.[98]

The above examples show how the CWA can and does currently allow threshold-based management decisions based on known ecological or human health thresholds, perhaps providing replicable examples for future management. However, as with the CAA, additional opportunities remain to focus on ecosystem (and not merely human health) goals. Although the CWA does not require that regulatory targets be based on ecological thresholds, the Act does require the EPA to use "the latest scientific knowledge"[99] in setting regulatory targets and to revise these targets every five years.[100] Moreover, the Act's requirement that it do this without "consideration of social and economic impacts or the technological feasibility of not exceeding the chemical concentration values in ambient water"[101] further enables state and federal threshold-based water quality management decisions.

2. Laws Focusing on Single-Species Management as Models for Threshold-Based Management

One might think of the CWA and the CAA as the umbrella protectors of air and water, but protectors with policy goals that focus largely on protecting human health. By contrast, other key environmental laws like the ESA, the Marine Mammal Protection Act (MMPA), and the Magnuson-Stevens Act each

---

93. *Id.* at 1, 9.

94. The TRPA was established under a bistate compact between Nevada and California, and ratified by the U.S. Congress in 1969. *About TRPA*, Tahoe Regional Plan. Agency, http://www.trpa.org/about-trpa/ (last visited Apr. 7, 2014).

95. TRPA, Lake Tahoe Water Quality Management Plan 32–33 (2013), *available at* http://www.trpa.org/wp-content/uploads/Final-U.S.-EPA-Adopted-Lake-Tahoe-208-WQMP_2013.06.19.pdf.

96. TRPA, 2011 Threshold Evaluation 1-5 (2012), *available at* http://www.trpa.org/regional-plan/threshold-evaluation.

97. *Id.* at 4-1.

98. *Id.* at 4-6.

99. 33 U.S.C. § 1314(a)(1) (2012).

100. *Id.* § 1314(a)(9)(B).

101. *Introduction: EPA Role in Developing Aquatic Life Criteria*, EPA, http://water.epa.gov/learn/training/standardsacademy/aquatic_page2.cfm (last updated Mar. 6, 2012).

focus on managing particular named species. Because they are grounded in the nonlinear way single species' populations grow, these laws provide detailed examples of existing ecological threshold-based environmental management.

Every species—whether fish, whales, or endangered sand flies—has a population growth rate that depends strongly on the existing size of the population.[102] When a population (for the sake of illustration, say, the northern spotted owl) is small, there are few adults to produce young, and hence there is a low overall rate of population growth. As the population gets larger, the number of reproducing adults increases, and so growth accelerates as an ever-greater number of young are born. However, the resources necessary to support the species—food, water, etc., and in the case of the northern spotted owl, the available acreage of a particular old-growth forest habitat—are limited, and do not permit population growth to continue accelerating indefinitely. As a result, net population growth slows as the species reaches its environmental limits (its "carrying capacity"), as competition and mortality increase, and the number of individuals in the population begins to stabilize.[103]

This pattern of population expansion—which is known in ecology as logistic growth—therefore contains an explicit growth threshold.[104] When the population size is less than about one-half of its environmental carrying capacity, growth is accelerating; when the population size is greater than one-half its carrying capacity, growth is slowing.[105] The result is that growth in living species inherently follows threshold patterns.

The logistic growth threshold is at the heart of species-specific wildlife management in federal environmental law. For example, under the Magnuson-Stevens Act, fisheries conservation and management measures "shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry."[106] To meet these objectives, fishery management councils estimate the MSY, or MSY proxy, for each managed stock to determine the optimum yield for the fishery and avoid overfishing.[107] Although the Act specifies several additional parameters that

---

102.   For details on the dynamics of natural populations, including the logistic growth pattern described in the main text, see, for example, MICHAEL BEGON ET AL., ECOLOGY: INDIVIDUALS, POPULATIONS, AND COMMUNITIES 246–47 (3d ed. 1996).

103.   *Id.* at 224.

104.   *See id.* at 246–47.

105.   *See id.* at 223–24, 238.

106.   16 U.S.C. § 1851(a)(1)–(2) (2012).

107.   *Id.* § 1802(33)–(34). MSY is "the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological, environmental conditions and fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets." 50 C.F.R. § 600.310(e)(1)(i)(A) (2014). In theory, MSY and its associated reference points represent a straightforward example of environmental threshold-based management. In reality, where data are scarce or unavailable, MSY may be estimated by other means. Note also that, because the decline of a particular species' fishery is assumed to be reversible, MSY can be used for either prospective or retrospective threshold-based management: over-exploited stocks can be allowed to rebuild, and the threshold provides a guide for setting targets for the harvesting of species that have yet to experience a population crash due to overexploitation.

influence stock assessment and allowable catch—including optimal yield, total allowable catch, and overfishing limit[108]—the MSY estimate contributes to how the councils set each of these reference points.[109] And although each fishery management council has the latitude to use different models to estimate MSY depending upon available data,[110] these models are inevitably density-dependent, reflecting the reproduction threshold seen in the logistic curve.[111] The MMPA requires similar single-species assessments, again implicitly based upon the logistic growth curve.[112]

ESA implementation often makes use of the same property of biological population growth—the threshold characteristic of the logistic growth curve—to guard against extinction for selected species. Unlike the Magnuson-Stevens Act and the MMPA, the ESA is not explicitly threshold-based, but rather becomes so as implementation demands analyses of population viability and likelihood of recovery.[113] These modeling exercises depend upon the same

---

108.   50 C.F.R. § 600.310.

109.   For example, optimum yield is calculated as MSY "reduced by any relevant economic, social, or ecological factor; and, in the case of an overfished fishery, that provides for rebuilding to a level consistent with producing the MSY in such fishery." *Id.* § 600.310(e)(3)(i)(A). Total allowable catch is an annual numerical catch level set below the overfishing level to ensure that overfishing does not occur, and some fishery management plans consider optimum yield and annual catch limits to be numerically equivalent. *Id.* § 600.310(f)(2)(iv); *see, e.g.*, S. Atlantic Fishery Mgmt. Council, Comprehensive Annual Catch Limit (ACL) Amendment for the South Atlantic Region 173 (2011), *available at* http://safmc.net/Library/pdf/Comp%20ACL%20Am%20101411%20FINAL.pdf.

110.   Even within a council, different stocks are likely to merit their own models. *See, e.g.*, *Coastal Pelagic Species: Stock Assessment and Fishery Evaluation (SAFE) Documents*, Pac. Fishery Mgmt. Council, http://www.pcouncil.org/coastal-pelagic-species/stock-assessment-and-fishery-evaluation-safe-documents/ (last updated Aug. 21, 2014) (providing stock assessment documents for managed stocks in the Pacific council, each of which provides details on its own mathematical stock assessment model).

111.   This is true especially for data-rich fisheries; data-poor fisheries use a proxy for MSY.

112.   The MMPA terminology differs from that of the Magnuson-Stevens Act. Rather than defining MSY for each marine mammal species, the MMPA uses a quantity called an Optimal Sustainable Population, defined as "a population size which falls within a range from the population level of a given species or stock which is the largest supportable within the ecosystem to the population level that results in maximum net productivity." 50 C.F.R. § 216.3. "Maximum net productivity is the greatest net annual increment in population numbers or biomass resulting from additions to the population due to reproduction and/or growth less losses due to natural mortality." *Id.*

113.   Threshold dynamics of biological populations enter into ESA implementation in a few ways. The first is the listing decision itself, under section 4 of the Act, where the U.S. Fish and Wildlife Service and the National Marine Fisheries Service can designate animal and plant species as "endangered" or "threatened." 16 U.S.C. § 1533(a)(1). This is an opportunity for prospective threshold-based management, in which the agencies consider species' likelihoods of extinction, which is closely tied to population viability and in turn, to population size. Mark S. Boyce, *Population Viability Analysis*, 23 Ann. Rev. Ecological Sys. 481, 493 (1992). Consequently, agencies or consulting scientists commonly conduct population viability analyses, although these are not statutorily required. Population Viability Analysis 8–9 (Steven R. Beissinger & Dale R. McCullough eds., 2002). Once a species is listed, section 7 of the Act requires a second set of threshold-relevant decisions that prohibit federal agencies from acting in a way that would jeopardize the continued existence or recovery of a threatened or endangered species. 16 U.S.C. § 1536(a)(2); 50 C.F.R. § 402.02. The section 7 jeopardy analysis is designed to identify government actions that will most likely push endangered species beyond their tipping point or population viability threshold. 50 C.F.R. § 402.02. One might view section 7 analyses as incorporating both prospective and retrospective threshold-based management, given that

density-dependent logistic growth curves as MSY calculations do, where the threshold of interest is the population size below which the existence or recovery of the species would be in jeopardy.

At least in principle, then, much of federal biological management is already threshold management. Given the underlying reproductive dynamics of the resource at hand (a living species), threshold management is the means by which we aim to catch as many fish as we can without seriously diminishing next year's crop of recruits, or by which we determine the imperiled species that require special protection. In the context of the Magnuson-Stevens Act, threshold management strikes a long-term economically efficient balance between production and exploitation,[114] while in the context of the ESA and MMPA, population thresholds help agencies craft nonarbitrary management and conservation strategies.

Hence, laws aimed at single-species management generally must incorporate a threshold management regime because biological production is inherently susceptible to productivity thresholds. Consequently, Magnuson-Stevens, the ESA, and the MMPA are distinct examples of this kind of single-species, threshold-based target setting. Like rules grounded in human health thresholds, rules tied to population thresholds demonstrate the desirability of linking environmental decision making to the underlying dynamics of the species or service under management.

One well-reasoned criticism of these laws is that single-species management is a radically oversimplified approach to environmental policy, and is by nature inadequate to accomplish larger sustainability goals.[115] Indeed, ecosystem-based management has been a goal of federal natural resources management since at least the Clinton administration,[116] although progress towards—and even metrics for—this goal have proved elusive. The shortcomings of single-species management aside, we use single-species

---

the consultations must assess the likelihood that an action will adversely affect the *recovery* of the listed species; by contrast, the section 4 listing decision only analyzes the likelihood of future extinction. *See id.* ("Jeopardize the continued existence of means to engage in an action that reasonably would be expected, directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of a listed species in the wild . . . .").

114.   There are many, many criticisms of MSY and its drawbacks for ecosystems and species. *See generally* Sidney Holt, *Maximum Sustainable Yield: The Worst Idea in Fisheries Management*, BREACHING BLUE (Oct. 3, 2011), http://breachingtheblue.com/2011/10/03/maximum-sustainable-yield-the-worst-idea-in-fisheries-management (describing the history, benefits, pitfalls, and challenges of MSY). *See also* CARMEL FINLEY, ALL THE FISH IN THE SEA: MAXIMUM SUSTAINABLE YIELD AND THE FAILURE OF FISHERIES MANAGEMENT (2011); P.A. Larkin, *An Epitaph for the Concept of Maximum Sustainable Yield*, 106 TRANSACTIONS AM. FISHERIES SOC'Y 1 (1977). Our purpose here is to illustrate an example of existing threshold-based management in the United States, not to endorse MSY or single-species management.

115.   *See, e.g.*, J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean Up the Environment by Making a Mess of Environmental Law*, 34 HOUS. L. REV. 933, 968–72 (1997).

116.   *See, e.g.*, National Forest System Land and Resource Management Planning, 65 Fed. Reg. 67,568 (Nov. 9, 2000) (to be codified at 36 C.F.R. pts. 217, 219) (embracing principles of ecosystem-based management).

growth or exploitation targets as examples of rational, threshold-based management that hold important lessons for larger, ecosystem-based goals. In the following section, we discuss NEPA as a mechanism by which government entities might begin to apply principles of threshold-based management to whole ecosystems, the human elements of those ecosystems included.

3. NEPA as a Vehicle for Ecosystem-Level Threshold-Based Management Decisions

If science can equip managers with indicators of pending ecosystem-level thresholds, those managers could select large-scale management targets to avoid harmful tipping points. Such ecosystem-based thresholds could support a shift in business-as-usual decision making on a species-by-species or pollutant-by-pollutant basis to regulatory decisions based instead on a broader, more contextualized understanding of the water bodies, airsheds, and species of an entire system. Within the scientific community, researchers are beginning to use ecosystem indicators as a way to link single-species thresholds and ecosystem thresholds,[117] suggesting that the science underlying threshold-based ecosystem management is becoming increasingly tractable.

Unlike the previously described laws, NEPA is a largely procedural statute that aims to increase transparency in governmental decision making rather than to reach any particular human health, species protection, or ecosystem conservation goals. Although NEPA's broader policy goal is to conserve, respect, and preserve the environment, the statute only requires that the government create, share, and consider relevant environmental information.[118] Despite its weak substantive role, NEPA's procedural requirements provide several opportunities to link management decisions to quantitative ecological thresholds. When taken together, these components can be used to encourage more integrative environmental analyses that are more faithfully grounded in the underlying science of ecosystem-level ecology.

Agencies may—and should want to[119]—incorporate scientific knowledge on thresholds when undertaking Environmental Assessments (EAs) and Environmental Impact Statements (EISs) under NEPA. The EA process is used to determine whether a proposed "major Federal action[] [is] significantly affecting the quality of the human environment."[120] Any action that is

---

117. *See generally* Jessi Kershner et al., *Selecting Indicator Portfolios for Marine Species and Food Webs: A Puget Sound Case Study*, 6 PLOS ONE 1 (2011), *available at* http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0025248; Jameal F. Samhouri et al., *Identifying Thresholds for Ecosystem-Based Management*, 5 PLOS ONE 1, 3 (2010), *available at* http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0008907 (noting that "[a] consensus among indicators that a [] threshold has or has not been breached can in turn inform management decisions").

118. 42 U.S.C. §§ 4331–4332 (2012). As a result, NEPA does not require a specific environmental outcome, it only requires a specific decision-making process. Calvert Cliffs' Coordinating Comm. v. U.S. Atomic Energy Comm'n, 449 F.2d 1109, 1115 (D.C. Cir. 1971).

119. See discussion on incentives for threshold-based decision making in Part II.D, *infra*.

120. 42 U.S.C. § 4332(c).

considered "significant"[121] triggers the EIS process,[122] and we suggest that a measurable increase in the risk of crossing an ecosystem-level threshold is the quintessential example of a "significant" impact.[123] The EIS process "forms the scientific and analytic basis for compar[ing]" proposed project alternatives,[124] and is a good fit for institutionalized threshold-based decision making: projects that could contribute to a threshold change in an ecosystem deserve the substantial public scrutiny[125] that an EIS provides. Such scrutiny could lead to a change in the project, or a mitigation plan to reduce the risk of the threshold being crossed.[126]

The core idea behind threshold-based management is that a slight change in one stressor can have a drastic, nonlinear change in a system. Knowing whether and when certain stressors will cause (or have caused) such drastic changes is critical to environmental protection and human well-being. Both the EA and EIS phases of NEPA require an analysis of cumulative impacts[127] to determine whether the total effect of action is significant, even if the project's individual impact is slight.[128] Improving our scientific knowledge of cumulative impacts is critical to understanding threshold interactions, because

---

121.   The EA process identifies a "significant" threshold or target beyond which the project is deemed to have a significant impact. 40 C.F.R. §§ 1508.9, 1508.13, 1508.27 (2014).

122.   40 C.F.R. § 1501.4. We assume that any change in an ecosystem would significantly affect the *human* environment, which is the focus of NEPA. *See* 42 U.S.C. § 4332(C).

123.   The EA is essentially an analysis of the term "significantly." *See* 40 C.F.R. § 1508.27. And although the definition itself is circular—its statutory definition includes the word "significant"—the agency's goal for the process is to determine the "severity of [the] impact" of the action. *Id.* Species-specific thresholds, air or water pollution thresholds, or thresholds that tip an entire ecosystem may all be included in this analysis—making an agency's determination of "significance" a key candidate for an increased presence of threshold-based analysis in agency decision making. Indeed, an agency or project proponent failing to incorporate the existing scientific understanding (including any available knowledge about quantitative ecological thresholds) about the underlying ecological system is arguably behaving arbitrarily, particularly when conducting cumulative impact analyses and determining significance.

124.   40 C.F.R. § 1502.16.

125.   Agencies are required to submit draft EISs for public comment. *Id.* § 1503.1.

126.   *See id.* § 1505.3 (requiring that an agency implement any monitoring and mitigation efforts if they were part of the final agency decision). Unlike the California Environmental Quality Act and some other state environmental policy acts, NEPA does not have a mandatory mitigation requirement. *Id.*; CAL. PUB. RES. CODE § 21157.7 (West 2014). An agency may voluntarily create a mitigation plan based upon threshold science, but it is not statutorily required to do so.

127.   Cumulative impacts requirements are also found in other federal statutes, including the ESA's consultation process within its jeopardy provisions. The ESA defines cumulative effects differently than NEPA, as "those effects of future State or private activities, not involving Federal activities, that are reasonably certain to occur within the action area of the Federal action subject to consultation." 50 C.F.R. § 402.02 (2014).

128.   40 C.F.R. § 1508.27(b)(7) (requiring the agency to consider "[w]hether the action is related to other actions with individually insignificant but cumulatively significant impacts"); *see also* Erin E. Prahler et al., *It All Adds Up: Enhancing Ocean Health by Improving Cumulative Impacts Analyses in Environmental Review Documents*, 33 STAN. ENVTL. L.J. 351 (2014), *available at* https://journals.law.stanford.edu/stanford-environmental-law-journal-elj/print/volume-33/it-all-adds-enhancing-ocean-health-improving-cumulative-impacts-analyses (describing the what, when, and how of cumulative impacts analyses under NEPA and the California Environmental Quality Act and highlighting statutory challenges and recommendations for improving such assessments).

cumulative effects of multiple stressors can be synergistic.[129] When these synergistic interactions are either unknown or unacknowledged, a managed system may be in danger of crossing an ecosystem threshold due to the combined effects of many small insults. Where managers evaluate project-by-project EAs and EISs within a regional context that tallies cumulative impacts of human activities on the system of interest, agencies may have a better chance of avoiding looming tipping points.

D. Cost-Benefit Analyses Create Incentives to Link Agency Decisions to Underlying Environmental Thresholds

The foregoing discussion of the primary federal environmental laws offers examples of threshold-based decision making, and many opportunities for better integrating the science of thresholds into future management decisions. However, even accepting that threshold-based management is both desirable and feasible under our existing federal statutory structures, agencies still need incentives to act on the available scientific information—especially in light of ever-dwindling governmental resources and significant judicial deference to agency decisions. CBA requirements provide both motivation and a mechanism for agencies to do so.

A CBA is an assessment of the economic viability of an action or a set of alternative actions.[130] These ubiquitous analyses provide a ready-made tool to incorporate emerging science on environmental thresholds into agency decisions. In the case where costs parallel environmental degradation and both are nonlinear, an assessment of various management alternatives will reveal nonlinear economic benefits of action or inaction. In such a case, choosing the least-cost alternative will likely favor proactive management to avoid the ecological threshold, thus linking economic and environmental thresholds.

The federal government conducts CBAs under a variety of circumstances to assess the overall economic impact of proposed changes in statutes and regulations.[131] Such analyses take the following general form: 1) specify the social-cost problem, 2) identify policy alternatives, 3) determine foreseeable impacts, 4) assign values to those impacts, 5) discount future costs and benefits,

---

129.   *See* Caitlin M. Crain et al., *Interactive and Cumulative Effects of Multiple Human Stressors in Marine Systems*, 11 ECOLOGY LETTERS 1304, 1304–05 (2008); MEGAN E. MACH ET AL., CUMULATIVE EFFECTS IN MARINE ECOSYSTEMS: SCIENTIFIC PERSPECTIVES ON ITS CHALLENGES AND SOLUTIONS 8 (2014),   *available*   *at* http://www.centerforoceansolutions.org/sites/default/files/ScientificPerspectivesOnCumulativeEffectsIn MarineEcosystems_forDigitalUpload_0.pdf. Some known stressors interact in such a way that their cumulative effect is the sum of its parts (1+1=2) or in some cases less than the sum of its parts (1+1=1). However, many stressors interact in synergistic ways where the cumulative effect is *greater* than the sum of its parts (1+1=4).

130.   *See generally* NICK HANLEY & CLIVE L. SPASH, COST-BENEFIT ANALYSIS AND THE ENVIRONMENT (1993).

131.   *See* Exec. Order No. 12,866, 58 Fed. Reg. 51,735, §§ 3(f), 6(a)(3)(B)–(C) (Sept. 30, 1993).

and 6) compare the net benefits and costs of all alternatives.[132] Major value-laden decisions at each of these six steps significantly influence—and may determine—the outcome of the analysis, driving policy decisions in turn.[133]

Particular statutes and regulations may require,[134] allow,[135] or prohibit[136] CBA.[137] In addition, Executive Order 12,866[138]—issued by President Bill Clinton—requires all federal agencies to conduct CBAs for "significant regulatory actions,"[139] basing its assessment of costs, benefits, and alternatives on the "best reasonably obtainable scientific, technical, economic, and other

---

132. *See* Daniel H. Cole, *Law, Politics, and Cost-Benefit Analysis*, 64 ALA. L. REV. 55, 59 (2012). *See generally* Mathew D. Adler & Eric A. Posner, *Rethinking Cost-Benefit Analysis*, 109 YALE L.J. 165 (1999) (arguing for a more realistic and nuanced use of CBA).

133. For example, varying discount rates can lead to significant variation in assessment outcomes, with discount rates chosen based on the normative valuation of present over future well-being. MARK HARRISON, AUSTL. GOV'T PRODUCTIVITY COMM'N, VALUING THE FUTURE: THE SOCIAL DISCOUNT RATE IN COST-BENEFIT ANALYSIS IX (2010), *available at* http://www.pc.gov.au/__data/assets/pdf_file/0012/96699/cost-benefit-discount.pdf ("The choice of discount rate can make a significant difference to whether the present value of a project is positive, and to the relative desirability of alternative projects . . . ."); *see also* CASS SUNSTEIN, FREE MARKETS AND SOCIAL JUSTICE 129 (1997) ("[A] common complaint is that CBA is biased against the benefits of regulation, since these tend to be 'soft variables' that are not easily quantified."). Adequately assessing the costs and benefits of anything can be exceedingly challenging and data intensive. David M. Driesen, *Capping Carbon*, 40 ENVTL. L. 1, 24–25 (2010) ("CBA combines the complexity of technology-based cap setting with the complexity of effects-based cap setting, and then adds some additional difficult and controversial elements." (citing David M. Driesen, *Getting Our Priorities Straight: One Strand of the Regulatory Reform Debate*, 31 Envtl. L. Rep. (Envtl. Law Inst.) 10,003 (2001))).

134. *See, e.g.*, 33 U.S.C. § 1314(b)(1)(B) (2012) (noting that the CWA requires EPA to consider "[f]actors relating to the assessment of best practicable control technology currently available . . . [and] include consideration of the total cost of application of technology in relation to the effluent reduction benefits to be achieved"); 42 U.S.C. § 4332(B) (2012) (providing that NEPA requires the federal government to "identify and develop methods and procedures . . . which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations").

135. *See, e.g.*, 16 U.S.C. § 1533(b)(2) (2012) (stating that under the ESA an agency may "designate a critical habitat . . . after taking into consideration the economic impact, the impact on national security, and any other relevant impact . . . ."); Entergy Corp. v. Riverkeeper, Inc., 556 U.S. 208, 219–20, 226 (2009) (holding that the Best Available Technology Standard in the CWA was ambiguous and that the EPA could conduct a CBA while setting 33 U.S.C. § 1326(b) regulations).

136. *See, e.g.*, 16 U.S.C. § 1533(b)(1)(A) (providing that a species must be listed under the ESA "*solely* on the basis of the best scientific and commercial data available" (emphasis added)); 42 U.S.C. § 7409(b)(1) (noting that the CAA requires EPA to set NAAQS for criteria pollutants that "are requisite to protect the public health").

137. *See, e.g.*, *Entergy Corp.*, 556 U.S. at 217–26 (analyzing different sections of the CWA in order to determine the appropriate standard for EPA to use when promulgating 33 U.S.C. § 1326(b) regulations).

138. Executive Order 12,291, issued by President Ronald Reagan in 1981, required agencies to weigh the potential costs and benefits to society of a regulation. *See* Exec. Order No. 12,291, 46 Fed. Reg. 13,193 (Feb. 17, 1981). Executive Order 12,866, issued by President Clinton in 1993, provided new requirements for assessing the costs and benefits of regulatory action. *See* Exec. Order No. 12,866, 58 Fed. Reg. 51,735 (Sept. 30, 1993). Executive Order 13,563, issued by President Barack Obama in 2011, supplemented and reaffirmed President Clinton's Executive Order 12,866. *See* Exec. Order No. 13,563, 76 Fed. Reg. 3821 (Jan. 18, 2011).

139. Exec. Order No. 12,866, 58 Fed. Reg. 51,735 (Sept. 30, 1993). Among other criteria, a "significant regulatory action" is "any regulatory action that is likely to result in a rule that may. . . [h]ave an annual effect on the economy of $100 million or more." *Id.*

information."[140] The executive order expanded and normalized the use of CBA in federal rulemaking,[141] creating the internal administrative structure agencies use to promulgate regulations.[142]

Agencies may have an independent duty to conduct CBAs under the Unfunded Mandate Reform Act.[143] The statute requires federal agencies to conduct CBAs for all federal regulations that affect the economy by more than $100 million or that require state or local governments to act without providing the state or local government with funding where the regulation exceeds $100 million.[144] The Act also requires agencies to choose the most cost-effective alternative that accomplishes the regulatory purpose or to provide an explanation for choosing a different option.[145]

Conversely, particular statutes may prohibit agencies from conducting a CBA.[146] Statutory language that prohibits agencies from considering costs triggers a prohibition on CBAs.[147] Where there is conflict between statutes—as in the case of a listing decision under the ESA that would trigger the Unfunded

---

140.   *Id.* § 1(b)(6).

141.   *Id.* Executive Order 12,866 specified a mandatory centralized regulatory review process for CBAs. Agencies must obtain approval from the Office of Information and Regulatory Affairs before publishing new rules. *See* Helen G. Boutrous, *Regulatory Review in the Obama Administration: Cost Benefit Analysis for Everyone*, 62 ADMIN. L. REV. 243, 248 (2010).

142.   *See* Boutrous, *supra* note 141, at 248. We characterize legal challenges to the use of a CBA as falling within two main categories: challenges to "balance" and challenges to methodology. "Balance" refers to how the agency treats the cost analysis versus the benefit analysis; methodology refers to the specific models and discount rates the agency chooses to use. A CBA is "balanced" if, for every identified regulatory effect, the agency considers both the costs and the benefits of that effect. *See, e.g.*, Sierra Club v. Sigler, 695 F.2d 957, 976 (5th Cir. 1983) (discussing an asymmetrical cost analysis and a CBA with major deficiencies). This approach does not require the agency to value the costs and benefits of an effect equally, but it does require the agency to fairly monetize costs and benefits. *E.g.*, Ctr. for Biological Diversity v. Nat'l Highway Traffic Safety Admin., 538 F.3d 1172, 1201–02 (9th Cir. 2008) (finding that the agency was unreasonable by not monetizing uncertain benefits from carbon dioxide reductions given that the agency had monetized other uncertain benefits). Agencies are also required to use the same methods for valuing costs and benefits. *E.g.*, Corrosion Proof Fittings v. EPA, 947 F.2d 1201, 1218 (5th Cir. 1991). As with other administrative actions, courts use an "arbitrary and capricious" standard to review CBAs. *E.g.*, N. Cal. Power Agency v. Fed. Energy Regulatory Comm'n, 37 F.3d 1517, 1522 (D.C. Cir. 1994). Agencies must reasonably balance CBAs in order for them to survive judicial scrutiny. *E.g.*, Calvert Cliffs' Coordinating Comm. v. U.S. Atomic Energy Comm'n, 449 F.2d 1109, 1115 (D.C. Cir. 1971) (stating that pursuant to NEPA, reviewing courts "probably" cannot hold a CBA invalid "unless it be shown that the actual balance of costs and benefits that was struck was arbitrary or clearly gave insufficient weight to environmental values"). Agencies also must employ reasonable methodologies when conducting CBAs. *E.g.*, Natural Res. Def. Council v. Herrington, 768 F.2d 1355, 1391 (D.C. Cir. 1985). Courts will find a CBA's methodology inadequate only if the agency fails to provide a rational justification for choosing the methodology. *E.g.*, *Ctr. for Biological Diversity*, 538 F.3d at 1204. Potential claims against CBA methodologies include challenges to the present discount rate, the valuation method, and the time scale. *E.g.*, *Herrington*, 768 F.2d at 1404, 1410, 1412–13. Courts generally defer to agencies, not requiring that the agency choose the *best* method, only that the agency choose a reasonable method. *Id.* at 1383.

143.   2 U.S.C. § 1501 (2012).

144.   *Id.* § 1532.

145.   *Id.* § 1535.

146.   *See, e.g.*, Tenn. Valley Auth. v. Hill, 437 U.S. 153, 185 (1978) (holding that the ESA prohibits agencies from considering costs when deciding to issue a section 7 jeopardy finding).

147.   *Id.*

Mandate Reform Act—agencies may be required to conduct a CBA,[148] but are statutorily prohibited from considering the CBA in the rulemaking procedure.[149]

Where environmental thresholds exist, CBA is likely to push agencies toward threshold-based management because different policy actions are economically efficient at different points along the spectrum of ecosystem impacts. Given adequate information, such analyses would allow an agency to maximize benefit, minimize cost, and closely match economic decisions to environmental impacts on the ground. Moreover, CBA may serve as a simple translation device for natural scientists to communicate the complexity of ecological thresholds to decision makers in a digestible manner.[150] In Part III, we offer a practical example of CBA motivating threshold, rather than linear, management of a hypothetical estuary environment.

III. Cost-Benefit Analysis Provides a Mechanism for Explicit Threshold Management

Federal agencies often must evaluate the costs of a proposed action on the environment and balance these against the action's economic benefits. Where the cost-benefit relationship is linear for each action alternative, there is no obvious policy choice—each unit of cost will yield a consistent amount of benefit, and the agency must decide among alternatives on the basis of noneconomic information.[151]

Conversely, where a nonlinear relationship exists between the costs and benefits of action alternatives, CBA provides an economic basis on which an agency may base its decision.[152] For example, the agency may select the action

---

148. 2 U.S.C. § 1532; Exec. Order No. 12,866, 58 Fed. Reg. 51,735 (Sept. 30, 1993).

149. Exec. Order No. 12,866, 58 Fed. Reg. 51,735, § 1 ("[I]n choosing among alternative regulatory approaches, agencies should select those approaches that maximize net benefits . . . , unless a statute requires another regulatory approach."); *see also* Cole, *supra* note 132, at 72 ("[A]lthough the EPA is statutorily barred from considering costs in setting NAAQS, the agency nevertheless prepares CBAs in setting or revising those standards because it is legally obligated to do so by a different statute and an executive order.").

150. CBAs may serve as a framework for understanding nonlinear changes in ecosystem services across their ecological, social, economic, and legal dimensions. *See* Kristin Carden et al., *Ecosystem Service Tradeoff Analysis: Quantifying the Cost of a Legal Regime*, 4 Ariz. J. Envtl. L. & Pol'y 39, 59–60 (2013).

151. In such a case, comparative CBA would not provide any extra useful information to the agency. For example, an agency could then base the decision solely on how much they were willing to spend, or solely on how much environmental protection they wanted, because the relationship between the costs and benefits would be constant. *See generally* Sarah E. Lester et al., *Evaluating Tradeoffs Among Ecosystem Services to Inform Marine Spatial Planning*, 38 Marine Pol'y 80 (2013) (discussing costs and benefits of ecosystem service trade-offs in a marine context).

152. Note that nonlinear cost curves drive the economies of scale beloved by industries worldwide: the per-unit cost of the millionth automobile produced is far smaller than the per-unit cost of the first automobile produced. Hence, the company will make different cost-benefit calculations at different points along this (nonlinear) production curve.

alternative that is most cost-effective[153] or the proposal with the greatest net social benefits.[154] Where an ecological threshold is measurable and closely tied to the economic value of an ecosystem, the costs and benefits of management actions will similarly follow a threshold curve (see Figure 2).[155] Here, a CBA can reveal information about the linked social-ecological system to provide agencies with a dual incentive to implement threshold-based management: both carrot and stick. The carrot is a management action that accounts for a more cost-effective economic threshold; the stick is a regulatory requirement to conduct a CBA under certain statutes.[156]

The use of insecticides in U.S. soybean aphid management provides an instructive example of CBA informing management decision making where economic and ecological thresholds are closely linked. In 2011, the United States grew over three billion bushels of soybeans.[157] Much of the U.S. soybean crop is plagued by soybean aphids, which reduce soybean yield.[158] In the last decade, an emerging scientific consensus has identified an economic threshold beyond which the application of pesticides to reduce aphid numbers becomes cost-effective.[159] The economic threshold occurs when the number of aphids on an individual soybean plant reaches about 273.[160] This threshold is a direct result of the nonlinear population growth of aphids on soybean plants.[161] The economic threshold considers the additional elements of pesticide and soybean prices.[162] The soybean market price determines the net benefit of preventing crop loss and the costs of pesticide management are the financial costs associated with crop loss prevention.[163]

153.   *See* Joshua Farley, *The Role of Prices in Conserving Critical Natural Capital*, 22 CONSERVATION BIOLOGY 1399, 1400 (2008).

154.   *See* GUIDELINES FOR PREPARING ECONOMIC ANALYSES, *supra* note 19 ("Conceptually, net social benefits will be maximized if regulation is set such that emissions are reduced up to the point where the benefit of abating one more unit of pollution (i.e. marginal social benefit) is equal to the cost of abating an additional unit (i.e. marginal abatement cost)."); Farley, *supra* note 153, at 1401–02.

155.   *See* Farley, *supra* note 153, at 1406.

156.   *See, e.g.*, 33 U.S.C. § 1314(b)(1)(B) (2012); 42 U.S.C. § 4332(B) (2012).

157.   *Major Crops Grown in the United States*, EPA, http://www.epa.gov/oecaagct/ag101/cropmajor.html (last visited Apr. 11, 2013).

158.   *Soybean Aphid*, PURDUE U., http://extension.entm.purdue.edu/fieldcropsipm/insects/soybean-aphid.php (last visited Oct. 15, 2014).

159.   Soybean aphid management since the aphid's arrival in 2000 has caused a 130-fold increase in insecticide applications in the United States in less than a decade. *See* Erin W. Hodgson et al., *Assessment of Iowa Soybean Growers for Insect Pest Management Practices*, 50 J. EXTENSION, no. 4, Aug. 2012, *available at* http://www.joe.org/joe/2012august/rb6.php.

160.   David W. Ragsdale et al., *Economic Threshold for Soybean Aphid (Hemiptera: Aphididae)*, 100 J. ECON. ENTOMOLOGY SOC'Y AM. 1258, 1265–66 (2007).

161.   *See id.* at 1258–59, 1265–66.

162.   *See id.* at 1259.

163.   Email from Scott Swinton, Professor, Mich. State Univ., to Lindley Mease (Feb. 7, 2013) (on file with author). Economic models demonstrate that farmers should apply a pest control input when the market value of soybean yield lost to aphid herbivory, multiplied by the amount that value can be reduced by the pest control action, is greater than or equal to the unit cost of the pest control input. *See* Larry P. Pedigo et al., *Economic Injury Levels in Theory and Practice*, 31 ANN. REV. ENTOMOLOGY 341, 346 (1986).

The soybean-aphid example demonstrates the value of CBA that links changes in ecology with threshold changes in economic value. Examples such as this are relatively common within industries where market values are easily observed (e.g., dollar value of crop loss). However, examples remain rare in the context of the management of ecosystem services, which often have large nonmarket values and low market values.

The five theoretical scenarios that follow illustrate how CBA may be used to maximize benefits and evaluate costs of approaching or crossing an ecological threshold. Four scenarios take the four points along the stressor-response curve (Figure 1) as their starting points; we also compare these to an alternative scenario where no such nonlinear curve exists.

A. Hypothetical Management Scenario in a Coastal Estuary

An influx of nutrients from terrestrial runoff (most often sourced from human sewage or agricultural runoff[164]) can alter the chemical composition of coastal marine ecosystems. Nearshore waters that are nitrogen-limited[165] experience significant biological productivity associated with this influx of nitrogen-rich runoff.[166] This productivity creates a frenzy of algal growth and death, with subsequent sedimentation and microbial decomposition of algae. Decomposition consumes oxygen and, in turn, leads to local hypoxia.[167] This process is often referred to as eutrophication, and threshold behavior between nutrient input and eutrophied waters has been well documented.[168]

Eutrophication imposes a number of social costs, diminishing the ecosystem services[169] coastal waters naturally provide, including reduced production of raw materials,[170] increased harmful algal blooms that affect benthic populations, and changes in water transparency.[171] The benefits of uncompromised coastal systems, unperturbed by eutrophication, include

---

164. *See* David Whitall et al., *Assessment of Eutrophication in Estuaries: Pressure-State-Response and Nitrogen Source Apportionment*, 40 ENVTL. MGMT. 678, 678 (2007).

165. Nitrogen limitation describes a scenario in which nitrogen compounds are in short supply in an environment, relative to other nutrients critical for the growth of plants. Accordingly, adding nitrogen to a nitrogen-limited system relieves this bottleneck, resulting in additional plant growth.

166. *See* Whitall et al., *supra* note 164, at 678–79.

167. *See* James E. Cloern, *Our Evolving Conceptual Model of the Coastal Eutrophication Problem*, 210 MARINE ECOLOGY PROGRESS SERIES 223, 226 (2001). Hypoxia is the deprivation of adequate oxygen supply.

168. *See, e.g.*, Carpenter & Brock, *supra* note 36, at 312.

169. Ecosystem services are the natural resources and processes from which humans benefit. There are four primary types of ecosystem services: provisioning (production of food and water), regulating (climate control), cultural (spiritual and recreational benefits), and supporting (nutrient cycling). *See* Robert Costanza et al., *The Value of the World's Ecosystem Services and Natural Capital*, 387 NATURE 253, 254 (1997); Charles H. Peterson & Jane Lubchenco, *Marine Ecosystem Services*, *in* NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS 177, 182 (Gretchen C. Daily ed., 1997).

170. *See* Edward B. Barbier et al., *The Value of Estuarine and Coastal Ecosystem Services*, 81 ECOLOGICAL MONOGRAPHS 169, 174 (2011).

171. *See* Cloern, *supra* note 167, at 236; Whitall et al., *supra* note 164, at 679–81.

nursery habitat for fish and invertebrates,[172] waste treatment, recreation, and wildlife habitat.[173] In California, the eutrophication of coastal estuaries has compromised a number of designated uses[174] of the habitat, such as fishing, industrial service supply, navigation, fish migration, water recreation, protection of endangered species, estuarine habitat, and shellfish harvesting.[175] The degradation of these uses has spurred California's State Water Resources Control Board to propose a program in which nutrient thresholds are quantified, targets are set, and eutrophication is avoided.[176] If the costs and benefits of this program were to be enumerated at different points along the "threshold curve" (see Figure 1), the resulting CBA would demonstrate the value of management action at each transition point (see Figure 2).[177]

For the following hypothetical scenario, we use ecosystem services— selected from California's (actual) identified designated uses—as a starting point to evaluate how a threshold-based CBA may demonstrate the cost-effectiveness of various management options. In our hypothetical, a state agency has jurisdictional authority over an estuary with three dominant designated uses: 1) industrial service supply (a power plant), 2) noncontact water recreation (kayaking), and 3) wildlife habitat (waterfowl). A new strawberry farm, which is irrigation- and fertilizer-intensive, recently bought land abutting the estuary's shoreline, and its activities will lead to a significant increase in nitrogen inputs.[178] The agency is evaluating (a) the costs of nutrient treatment or removal to mitigate the impact of potential eutrophication events as a result of increased nitrogen,[179] and (b) the costs of managing the impacts

---

172.   *See* Barbier et al., *supra* note 170, at 171; Michael W. Beck et al., *The Identification, Conservation, and Management of Estuarine and Marine Nurseries for Fish and Invertebrates*, 51 BIOSCIENCE 633, 635 (2001).

173.   *See* Costanza et al., *supra* note 169, at 254.

174.   Under the CWA, WQS are pollution limits based on the designated uses of any particular water body. 33 U.S.C. § 1311(c)(2)(C) (2012); 40 C.F.R. § 131.6 (2014). For a description of estuarine designated uses in California, see MARTHA SUTULA ET AL., TECHNICAL APPROACH TO DEVELOP NUTRIENT NUMERIC ENDPOINTS FOR CALIFORNIA ESTUARIES 2-3 to 2-6 (2007), *available at* http://www.waterboards.ca.gov/sandiego/water_issues/programs/tmdls/docs/Loma_Alta_TMDL/Techni cal_Approach_to_Develop_Numeric_Targets_Endpoints_for_California_Estuaries.pdf (prepared for EPA Region 9).

175.   SUTULA ET AL., *supra* note 174, at 2-1 to 2-4.

176.   *Proposed Policy for Nutrients for Inland Surface Waters of the State of California*, ST. WATER RESOURCES CONTROL BOARD, www.swrcb.ca.gov/plans_policies/nutrients.shtml (last updated July 9, 2014).

177.   These scenarios are predicated on three principal assumptions. First, the costs to the ecosystem of prior existing uses of the estuary and incoming nutrient inputs have marginal impacts on the ecosystem (by degrading water quality, for example) and have marginal benefits to society (through agricultural production, for example). Second, the input of nitrogen is the primary human activity impacting the ecosystem and influencing the cost-benefit balance of ecosystem functioning and human use. Third, the societal benefits of the designated uses are equal to each other.

178.   For a review of agricultural nonpoint source pollution of nitrogen and phosphorus to coastal water bodies, see Stephen R. Carpenter et al., *Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen*, 8 ECOLOGICAL APPLICATIONS 559 (1998).

179.   Reducing phosphorus and nitrogen via tertiary wastewater treatment can be extremely expensive, but can reduce nutrient inputs significantly. For example, a secondary sewage treatment plant

of potential eutrophication on the designated uses of the estuary.[180] These costs are compared with (a) the monetary benefits of the ecosystem services gleaned from the estuary's designated uses, and (b) the monetary benefit of the strawberry farm's production to society.[181] There are five scenarios: four that take each point along the stressor-response curve (see Figure 1, points A, B, C, and D) as a starting point and one that begins at point A and assumes system linearity to point D for comparison. Each scenario is subject to a 3 percent annual discount over three years to account for the public's preference of current consumption over future consumption.[182]

Each designated use experiences a different degree of environmental impact from the same change in nutrient input, based on that use's sensitivity to nutrient pollution. Increased nitrogen runoff does not effect the coastal power plant, which uses estuarine waters for cooling. However, the waterfowl habitat is sensitive to a change in water quality, and recreational kayaking would be indirectly impacted by impaired water quality if eutrophication was visible and wildlife was threatened.[183]

For this heuristic model, we valued each of the three beneficial uses as having a maximum monetary benefit of $10. The benefit of nutrient pollution (or the value of the strawberry farm to society) and the cost of reducing nutrients within the estuary were also valued at $10. We valued management action and beneficial uses consistently in order to simplify the model. The

---

in the United States usually produces effluent with nitrogen concentrations of 19 gNm^{-3} while a tertiary plant will discharge only 3 gNm^{-3}. If all the treatment plants along the Hudson River were converted to tertiary plants, nitrogen (N) loading would be reduced from 23,000 tons N y^{-1} to 3.7 tons N y^{-1}. The costs of such a conversion would be the difference between $0.28 per cubic meter treated for secondary plants and $0.37 per cubic meter treated for tertiary plants. Robert W. Howarth et al., *Wastewater and Watershed Influences on Primary Productivity and Oxygen Dynamics in the Lower Hudson River Estuary*, in THE HUDSON RIVER ESTUARY 136 (Jeffrey S. Levinton & John R. Waldman eds., 2006).

180. The costs of managing an impaired water body as compared to an unimpaired water body may include increased restoration, monitoring, regulatory enforcement, scientific analysis, and public education costs. These costs will increase in step with the degree of degradation exhibited by the water body, in this case nonlinearly. The high costs of such restoration have been documented in a number of systems, including rangelands and climate-sensitive ecosystems. *E.g.*, Suzanne J. Milton et al., *Economic Incentives for Restoring Natural Capital in Southern African Rangelands*, 1 FRONTIERS ECOLOGY & ENV'T 247, 248–50 (2003); Palmer et al., *supra*, at 87–88.

181. We attempt to standardize the costs and benefits of designated uses, nutrient pollution, and management costs across the model for simplification. However, we acknowledge that in reality these designated uses will have varying costs and benefits relative to each other. Moreover, the CBA will be strongly influenced by the relative societal valuations of these designated uses. (For example, society could economically value coastal power plants much higher than recreational use of an estuary.) For the purposes of our analysis, we attempted to value uses equally to reflect the tangible and intangible benefits of each and to ensure that we were not biasing our model towards a particular designated use.

182. The benefit of a management decision to the public's welfare is equal to the public's willingness to pay to obtain these benefits. The costs of the management decision are equal to the opportunity cost of using resources for management instead of for some other social benefit. As summarized by the EPA, the purpose of discounting is to reflect observed preferences for current consumption over future consumption. *8.3 Discounting Benefits and Costs*, EPA, http://www.epa.gov/ttnecas1/econdata/Rmanual2/8.3.html (last updated June 22, 2007).

183. Waterfowl habitat is sensitive to development, erosion, and sedimentation, but is particularly impacted by changes in water quality. SUTULA ET AL., *supra* note 174, at 2-2.

threshold reflects a decrease in the societal value of beneficial uses from $8 (in a slightly degraded habitat at Point "B" on the stressor-response curve) to $2 (in a significantly degraded habitat at Point "C" on the stressor-response curve). A full table of the costs and benefits across three years and the five scenarios can be found in Appendix A.

Figure 2 shows the results of the model exercise given the parameters above, demonstrating the cost-efficacy and net benefits of permitting the strawberry farm and managing nitrogen pollution in the four different scenarios and in the alternative, no-threshold, scenario.[184]

There is a nonlinear relationship between nutrients (the stressor) and phytoplankton abundance (ecosystem exists in either a clear, unimpaired stable state or a turbid, impaired stable state), which is reflected in the relationship between the steady increase in nutrient inputs and the nonlinear increase in costs to the ecosystem from water quality impacts. Economic values will change significantly for slight alterations in an ecological component where there is an ecological threshold present.[185] In our scenarios, the costs of management increase nonlinearly, in response to the nonlinear degradation of water quality in the estuary. Per-unit costs of removing nitrogen[186] or treating nutrient-enriched inputs[187] are constant, but have a larger return on investment if implemented prospectively and near the threshold. In this hypothetical, avoiding an ecological threshold minimizes management costs and avoids compromising the human uses of an ecosystem.

---

184.   These costs and benefits are imaginary and created to reflect the relative costs or benefits of management action or inaction in a threshold-based ecosystem.

185.   Additionally, it is important to note that CBAs have limited utility where the ecosystem component in question is nonsubstitutable. In the presence of scarcity, nonsubstitutability (where nothing can fill the same demand as the resource), and inelastic demand (where demand does not change in response to changes in price) economic analyses become impractical. In such a case, although price is bounded by available income, CBA is of limited applicability. Scarcity provides a useful decision-support tool, as the value of the resource dramatically increases when the threshold is in proximity. However, we argue here that when ecosystem services are elastic and can be assigned value, CBAs may be useful for highlighting cost-effective management actions to avoid ecosystem thresholds. Stephen C. Farber et al., *Economic and Ecological Concepts for Valuing Ecosystem Services*, 41 ECOLOGICAL ECON. 375, 384 (2002); Farley, *supra* note 153, at 141. Furthermore, CBAs are often required by law, as discussed in the main text.

186.   Nitrogen may be removed from water bodies in a number of ways, including filtration—which may be the most cost-effective—by shoreline vegetation and constructed wetlands. *See* Carpenter et al., *supra* note 178, at 565.

187.   Treatment could include such methods as constructing artificial wetlands that filter municipal, industrial, and agricultural wastewater as it enters estuarine systems. Fengliang Zhao et al., *Nutrient Removal Efficiency and Biomass Production of Different Bioenergy Plants in Hypereutrophic Water*, 42 BIOMASS & BIOENERGY 212, 212–13 (2012).
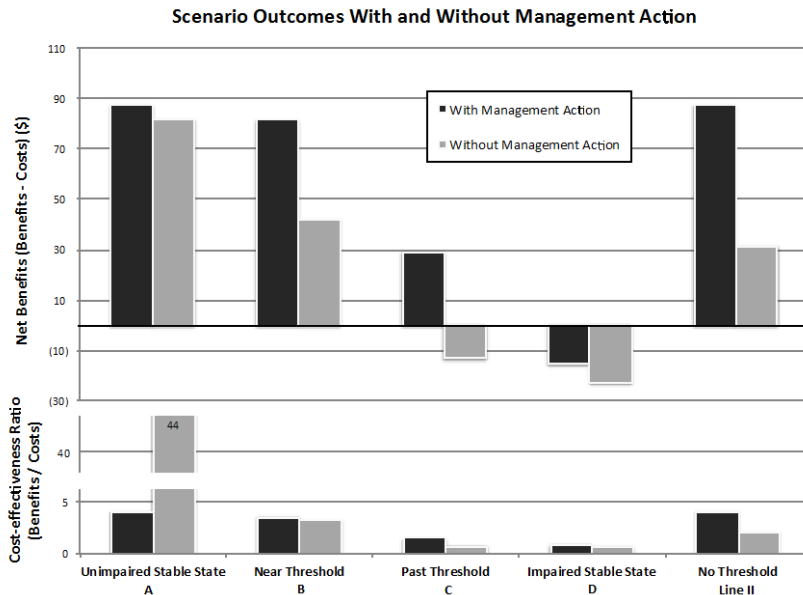
Figure 2: The net benefits (benefits – costs) and cost-benefit ratio of each of the five scenarios ((1) unimpaired stable state, (2) near threshold, (3) past threshold, (4) impaired stable state, and (5) no threshold (linear alternative)) with management action (black) or without management action (grey). Labels A, B, C, and D on the x-axis correspond with points in Figure 1 bearing the same labels.

B. *Cost-Benefit Analyses in Hypothetical Management Scenarios*

In the first scenario, the estuary is relatively unperturbed from prior and existing uses of the estuary and its watershed; it maintains key functions and is less vulnerable to ecosystem-level change as a result of human stressors. The strawberry farm is emitting nitrogen at a rate that is unlikely to degrade water quality significantly.[188] In this scenario, the estuary is in an unimpaired state ("Point A" on the stressor-response curve).[189] Management action is less cost-effective than no management action because the costs of reducing nutrients exceed the minimal loss of ecosystem services (see Figure 2).

---

188.   This analysis does not include the potential cumulative impacts of nutrient pollution over time on various estuarine ecosystem services or as compounded with other impacts of human activities on the estuary.

189.   The Southern California Coastal Water Research Project evaluated twenty-seven Southern California estuary segments and ranked them according to three indices of water quality and eutrophication: macroalgal abundance, phytoplankton biomass, and dissolved oxygen. KAREN MCLAUGHLIN ET AL., 8 SOUTHERN CALIFORNIA BIGHT 2008 REGIONAL MONITORING PROGRAM: ESTUARINE   EUTROPHICATION   31   (2012),   *available*   *at* ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/711_B08EE.pdf.   Batiquitos Lagoon is an example of an estuary that meets these indicators and is within a relatively unimpaired stable state. *See id.*

In the second scenario, the estuary is near its water quality threshold—"near threshold" ("Point B" on the stressor-response curve). Prior agricultural development in the area has led to heightened concentrations of estuarine nutrients. The agency has determined the nitrogen threshold in this estuary based on previous eutrophication events and analogous estuarine systems that have undergone threshold shifts.[190] The additional increase in the stressor, nitrogen input, from the new strawberry farm will push the estuary's nutrient load over the nitrogen threshold and lead to a dramatic decline in water quality as a result of eutrophication. Here, management action to reduce nutrient loading (i.e., nutrient treatment or removal) yields net benefits—in terms of harm avoided and ecosystem service benefits gained—as compared with no management action (Figure 2); the absence of action leads to the greatest, most immediate loss of benefits, as compared with the other scenarios.

In the third scenario, the estuary has significantly impaired designated uses due to prior human activities, and the estuary is eutrophic—"past threshold" ("Point C" on the stressor-response curve). However, the estuary remains near the threshold and a small reduction in nitrogen input may eliminate future eutrophication events if nutrient loading is maintained at levels associated with the impaired estuarine stable state.[191] In this scenario, management action will lead to the greatest, most immediate return on investment as ecosystem services from designated uses are restored and estuarine water quality improves.[192]

In the fourth scenario, the estuary is heavily loaded with nutrients and is in a eutrophic, "impaired stable state" ("Point D" on the stressor-response curve).[193] It would take substantial reductions in nutrient loading to reverse eutrophication. Wildlife habitat is significantly degraded, and though kayaking continues, the business is hard hit by the compromised aesthetic and loss of wildlife habitat. In this scenario, management action remains cost-effective because the costs of unfettered pollution outweigh the management costs of

---

190.   These methods, including existing literature, expert opinion, and monitoring data, are currently being used to identify "nutrient numeric endpoints" in California estuaries by the California State Water Resources Control Board. *See* SUTULA ET AL., *supra* note 174, at iv–v. Nutrient numeric endpoints will establish nutrient targets based on thresholds of impairment for biological indicators of eutrophication. *See id.*

191.   Management action is only cost-effective if the eutrophication of the estuary is reversible by lowering the nutrient load. Although estuarine eutrophication often can be reversed, many threshold changes are not reversible, particularly as a result of resource managers controlling a single ecosystem variable. (For example, threatened species have a number of stressors driving them to their extinction threshold.) If "recovery curves" do not match the stressor-response curve, the value of maintaining an ecosystem at Point B increases exponentially as the costs to recover the ecosystem (in any capacity) increase exponentially in turn. *See* Joshua Farley, *Ecosystem Services: The Economics Debate*, 1 ECOSYSTEM SERVICES 40, 42 (2012).

192.   The slope between Point C and Point B is the steepest, and management action to move the system towards Point B will, thus, lead to an increase in benefits.

193.   The Santa Clara River is an example of an impaired estuary from the Southern California Coastal Water Research Project. *See* MCLAUGHLIN ET AL., *supra* note 189, at 31.

achieving an increase in ecosystem services and mitigating the costs of managing further harmful impacts on ecosystem services.

In the alternative scenario, no threshold exists and the change in ecosystem degradation is linear. Management action is cost-effective at each decision point, but there is no obvious point at which management action is most cost-effective along the curve. Costs and benefits accrue incrementally as the ecosystem degrades and any action to reduce nutrients will reflect stakeholder preferences rather than a critical transition in one or more ecosystem variables.[194]

This heuristic CBA illustrates the value of matching the underlying science of thresholds to management decisions, maximizing ecosystem services while minimizing management costs. In each of the four scenarios above, proximity to the threshold has a large impact on costs and benefits. Theoretically, humans will reap the greatest net benefits from management near the ecological threshold, where the ecosystem remains productive, yet management costs remain low. The cost-benefit ratio of management action is highest for society in scenario 1 (Figure 2), where the management agency has no management costs and ecosystem services are maximized.[195] If the estuary already has moderate concentrations of nitrogen that push it within proximity of its nitrogen threshold, management action still yields net benefits—when ecosystem services from designated uses are not yet compromised and the costs of managing compromised ecosystem services are minimal. The cost-efficacy of management action declines once the ecological threshold is crossed, as marginal management effort yields fewer marginal benefits in a nonlinear ecosystem. This simplified analysis demonstrates one potential advantage of proactively managing a threshold-based system.

These scenarios also reveal a number of important caveats for CBA, both in the abstract and as applied to ecological thresholds. First, in reality, many ecological thresholds are irreversible,[196] creating a more drastic cost-benefit difference between scenarios 1 and 2, before the threshold change, and 3 and 4, after the threshold has been crossed. Irreversible change dramatically increases the value of management action to avoid the loss of an ecosystem.

---

194. When there is a linear relationship between the values of multiple ecosystem services, decision makers must seek societal preferences to determine which service to favor in management decision making. *See* J.B. RUHL ET AL., THE LAW AND POLICY OF ECOSYSTEM SERVICES 284 (2007) (citing MILLENNIUM ECOSYSTEM ASSESSMENT, ECOSYSTEMS AND HUMAN WELL-BEING: SYNTHESIS 93–94 (2005), *available at* http://www.millenniumassessment.org/documents/document.356.aspx.pdf).

195. In reality, a management decision never perfectly balances the interests of all stakeholders. The parties involved in this hypothetical scenario—the power plant operators, the strawberry farmers, the kayaking guides—have varying degrees of decision making or political power, incentive to influence decision making, and regulatory requirements. Distinct valuations of the ecosystem among these parties makes it challenging to identify management actions that maximize ecosystem services to society overall (even presuming that maximizing societal value is the goal in our hypothetical).

196. For a discussion of the economics of irreversibility, see Charles Perrings & William Brock, *Irreversibility in Economics*, 1 ANN. REV. RESOURCE ECON. 219 (2009). For a discussion of irreversibility in ecology, see Stephen R. Carpenter et al., *Management of Eutrophication for Lakes Subject to Potentially Irreversible Change*, 9 ECOLOGICAL APPLICATIONS 751 (1999).

Second, CBAs are only useful to the extent that the drivers of ecological thresholds are well understood scientifically. Resource managers must have accurate information on (a) the ecological threshold of concern and how various stressors may move the system within proximity of the threshold, (b) the relative costs and benefits gained from the ecosystem services in their jurisdiction, and (c) the cost of taking action to mitigate the stressor. Establishing or estimating these parameters is likely to be difficult and/or expensive in many real-world management contexts.

Third, as has been widely discussed, assigning monetary value to particular ecosystem services can be problematic. Monetary designations are highly dependent upon author-chosen valuations, which can be manipulated by individual stakeholder preferences or financial incentives. Moreover, there is a tendency to undervalue nonmarket costs and benefits and overstate ecological use values. For example, the cost or benefit of noncontact recreation can be determined via willingness-to-pay or willingness-to-accept research.[197] However, the value of less tangible services (e.g., the taste of a strawberry, exercise within and aesthetic appreciation of an estuary, sense of place among adjacent farmers) or indirect services (e.g., wildlife health, water filtration, estuarine carbon dioxide sequestration, electricity) are more difficult or impossible to quantify.[198] One tool that may be used to mitigate these difficulties when qualitative data of ecosystem services are attainable is ecosystem service trade-off analysis.[199]

---

197. *See* Costanza et al., *supra* note 169, at 255; Farber et al., *supra* note 185, at 378.

198. Debra Satz et al., *The Challenges of Incorporating Cultural Ecosystem Services into Environmental Assessment*, 42 AMBIO 675, 679 (2013). In addition, CBAs do not typically consider the distribution of costs and benefits. Farley, *supra* note 153, at 1401 ("Cost-benefit analysis typically ignores questions of distribution—who gets what."). They serve as useful decision-making tools, but not as a method to determine appropriate compensation to aggrieved parties, which may include ecological components. As the estuarine case study illustrates, regulatory decisions may be normative choices based on preferred designated uses or services.

199. Ecosystem service trade-off analysis is nested between ecological and economic theory, and can be used to examine, relatively simply, the real and perceived trade-offs among ecosystem services. *See* Carden et al., *supra* note 150, at 46; Sarah E. Lester et al., Ecosystem Service Trade-Off Analysis 6 (2010) (unpublished manuscript) (on file with author Lindley A. Mease). This method for weighing management decision making around multiple ecosystem services can be an effective strategy for evaluating the trade-offs between multiple market and nonmarket values. Similar to a CBA, an ecosystem service trade-off analysis quantifies various ecosystem services in order to guide decision makers in taking efficient action that maximizes societal benefit. *See also* Stephen R. Carpenter et al., *Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment*, 106 PROC. NAT'L ACAD. SCI. 1305, 1305 (2009). It may also serve as a conceptual framework for incorporating societal judgments about a particular ecosystem where threshold dynamics are unknown. More specifically, ecosystem service trade-off analysis establishes the efficiency frontier along which various ecosystem services fall. This frontier allows decision makers to evaluate where one service may be substituted for another or, when services rendered do fall on the frontier, where an additional service could be protected or used to improve overall efficiency. *See* Carden et al., *supra* note 150, at 63 ("Exactly which point along the [efficiency] curve represents the 'best' point (i.e., the 'best' tradeoff among ecosystem services) is a societal value judgment.").

CONCLUSION

Environmental management is an ongoing struggle limited by political and economic incentives, data, and the fundamentally imperfect link between human decisions and environmental response. Nevertheless, the pervasive impact of an ever-increasing human population on the natural resources on which that population depends means that responsible environmental management will continue to be an ever-more-critical priority for the indefinite future. Responsible management, in turn, requires that humans (and their governments) tie their decisions to some underlying environmental reality. And as the scientific approximation of that reality improves, it is incumbent upon rational decision makers to revisit the assumptions on which they base their decisions, grounding decisions in reality to the maximum extent possible.

The predominant view of ecology—that is, the way the nonhuman world works—has transformed significantly since most federal environmental laws came into being. If indeed this newer view of ecology is a closer match to the underlying environmental reality, we must manage our environmental resources to reflect this improved understanding.

It seems likely that many ecosystem processes have a threshold response to stressors (such as pollution, overexploitation, etc.): a lake or estuary can absorb nutrient pollution up to a point, after which the whole system shifts to a different and less desirable state. This is a profound idea. Thresholds make attractive and rational targets for environmental regulation. They are obvious points of agreement, illustrating points of no return (or points of greatly increased effect) in a world of otherwise slippery slopes. Perhaps most importantly, dose-response curves lead us away from the seductive but erroneous idea that there exists a constant, linear relationship between cause and effect in human-ecosystem interactions.[200] Rules that apply human health or single-species thresholds are perhaps models for applying evolving science surrounding ecosystem thresholds in management decisions, allowing managers to align regulatory targets with larger-scale ecological thresholds.

However, even where sufficient science is available to base regulatory targets on known or suspected thresholds, agencies require the political or economic incentive to do so. We believe the incentives for threshold-based management are threefold. First, where thresholds exist, explicitly basing regulatory targets on them appears to yield better outcomes.[201] Second, CBAs

---

200.   As described in Part I, in ecosystems, rather than in humans, dose-response curves can be more complicated, because we often lack significant information about ecosystem responses to single stressors. Multiple stressors are even more challenging. Our ability to measure and understand stress-response relationships within an ecosystem will continue to mark the limits of our ability to account for the large variety of stressor interactions within a single system, and how those multiple interactions may interact.

201.   *See* Kelly, *supra* note 52.

that incorporate system nonlinearities may help decision makers better identify management actions that are both economically and ecologically rational. Finally, even where CBAs are not done, threshold-based management is likely to minimize political conflict by presenting an obvious endpoint for environmental regulatory provisions.

Several primary U.S. environmental laws reveal examples of existing threshold-based management targets as well as various opportunities for agencies to better align regulatory targets with emerging science. As scientific information about environmental tipping points continues to accumulate, it falls to the legal, policy, and management communities to make this science useful in practice.

Location on Threshold Curve	Designated Uses	Tons of Nitrogen Input	Total Costs of Reducing Nutrients	Total costs of managing impacts to Designated Use Year 1	Total costs of managing impacts to Designated Use Year 2	Total costs of managing impacts to Designated Use Year 3	Discounted Costs w Action	Total costs of managing impacts to Designated Use Year 1 w/o Action	Total costs of managing impacts to Designated Use Year 2 w/o Action	Total costs of managing impacts to Designated Use Year 3 w/o Action	Discounted Costs w/o Action	Benefits to Farm of Using Nitrogen per year	Value of ecosystem services Year 1	Value of ecosystem services Year 2	Value of ecosystem services Year 3	Total Discounted Benefits w Action	Value of ecosystem services Year 1 w/o Action	Value of ecosystem services Year 2 w/o Action	Value of ecosystem services Year 3 w/o Action	Total Discounted Benefits w/o Action	Ratio of Benefit to Cost w Action	Ratio of Benefit to Cost w/o Action	Net Benefits w Action	Net Benefits w/o Action
Stable state	Industrial Service Supply			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Noncontact Water Recreation			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Wildlife Habitat			$0.0	$0.0	$0.0		$0.0	$0.0	$2.0			$10.0	$10.0	$10.0		$10.0	$10.0	$8.0					
	Total	1	$10.0	$0.0	$0.0	$0.0	$28.6	$0.0	$0.0	$2.0	$1.9	$10.0	$30.0	$30.0	$30.0	$115.86	$30.0	$30.0	$28.0	$83.8	4.06	44.00	$87.29	$81.90
Near threshold	Industrial Service Supply			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Noncontact Water Recreation			$0.0	$0.0	$0.0		$0.0	$0.0	$8.0			$10.0	$10.0	$10.0		$10.0	$6.0	$2.0					
	Wildlife Habitat			$2.0	$2.0	$0.0		$2.0	$2.0	$8.0			$8.0	$10.0	$10.0		$8.0	$5.0	$2.0					
	Total	1	$10.0	$2.0	$2.0	$0.0	$32.4	$1.0	$2.0	$16.0	$18.1	$10.0	$28.0	$30.0	$30.0	$113.96	$28.0	$21.0	$14.0	$60.0	3.52	3.32	$81.58	$41.90
Past threshold	Industrial Service Supply			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Noncontact Water Recreation			$8.0	$8.0	$0.0		$8.0	$8.0	$10.0			$2.0	$6.0	$10.0		$2.0	$2.0	$2.0					
	Wildlife Habitat			$8.0	$8.0	$2.0		$8.0	$8.0	$10.0			$2.0	$5.0	$8.0		$2.0	$0.0	$0.0					
	Total	1	$10.0	$16.0	$16.0	$2.0	$61.0	$16.0	$16.0	$20.0	$49.5	$10.0	$14.0	$21.0	$28.0	$90.15	$14.0	$12.0	$12.0	$36.2	1.48	0.73	$29.20	($13.33)
Impaired stable state	Industrial Service Supply			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Noncontact Water Recreation			$10.0	$10.0	$8.0		$10.0	$10.0	$10.0			$2.0	$2.0	$2.0		$2.0	$2.0	$2.0					
	Wildlife Habitat			$10.0	$10.0	$8.0		$10.0	$10.0	$10.0			$0.0	$0.0	$2.0		$0.0	$0.0	$0.0					
	Total	1	$10.0	$20.0	$20.0	$16.0	$81.9	$20.0	$20.0	$20.0	$57.1	$10.0	$12.0	$12.0	$14.0	$66.34	$12.0	$12.0	$12.0	$34.3	0.81	0.60	($15.56)	($22.86)
No threshold	Industrial Service Supply			$0.0	$0.0	$0.0		$0.0	$0.0	$0.0			$10.0	$10.0	$10.0		$10.0	$10.0	$10.0					
	Noncontact Water Recreation			$0.0	$0.0	$0.0		$0.0	$5.0	$10.0			$10.0	$10.0	$10.0		$10.0	$6.0	$2.0					
	Wildlife Habitat			$0.0	$0.0	$0.0		$0.0	$5.0	$10.0			$10.0	$10.0	$10.0		$10.0	$5.0	$0.0					
	Total	1	$10.0	$0.0	$0.0	$0.0	$28.6	$0.0	$10.0	$20.0	$28.6	$10.0	$30.0	$30.0	$30.0	$115.86	$30.0	$21.0	$12.0	$60.0	4.06	2.10	$87.29	$31.43