Corridors assist with complex ecosystem management. Canada's Bow Valley Provincial Park is part of a wildlife corridor that attempts to balance local resource use and ecosystem health across borders.

REVIEW

Ecosystem management as a wicked problem

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Ecosystems are self-regulating systems that provide societies with food, water, timber, and other resources. As demands for resources increase, management decisions are replacing self-regulating properties. Counter to previous technical approaches that applied simple formulas to estimate sustainable yields of single species, current research recognizes the inherent complexity of ecosystems and the inability to foresee all consequences of interventions across different spatial, temporal, and administrative scales. Ecosystem management is thus more realistically seen as a "wicked problem" that has no clear-cut solution. Approaches for addressing such problems include multisector decision-making, institutions that enable management to span across administrative boundaries, adaptive management, markets that incorporate natural capital, and collaborative processes to engage diverse stakeholders and address inequalities. Ecosystem management must avoid two traps: falsely assuming a tame solution and inaction from overwhelming complexity. An incremental approach can help to avoid these traps.

People modify and manage ecosystems to provide food, energy, building materials, and other resources, as well as to filter water, control infectious diseases, decompose wastes, and connect with nature. Ecosystem managers who oversee the provision of these resources and services to society range from government administrators, policy-makers, and industry officials to farmers, fishers, and foragers. They collectively manage many types of ecosystems, including forests, grasslands, lakes, rivers, coastal areas, farms, protected areas, and cities. In this Review, we assess how views toward ecosystem management have changed over time and what approaches can guide ecosystem management in the changing ecological and socioeconomic realities of the 21st century.

U.S. Department of Agriculture Forest Service Chief F. Dale Robertson coined the term "ecosystem management" in 1992, describing an ecological approach to "blend the needs of people and environmental values in such a way that the National Forests and Grasslands represent diverse, healthy, productive and sustainable ecosystems" (*1*). Long before this formal definition, preindustrial traditional societies embraced many principles of ecosystem management. Indigenous and local knowledge evolved to suit local conditions, with social institutions based on ecological understanding of the local dynamics of the resource base (*2*, *3*). Two of many examples are the pre-Columbian Incan prohibition against harvesting guano, a valuable fertilizer, during bird nesting season (*4*) and the widespread existence of sacred groves that provide refuge for biodiversity (*5*).

For most of the industrialized age, extraction of maximum yields of fish, timber, and other resources was the prevalent paradigm. Science to manage forests emerged in Germany in the latter 18th century, with a single focus on timber production. This focus spread throughout the industrialized world—for example, to the United States, which managed national forests for efficient production of timber to support the growing housing industry after World War II (*6*). Similarly, managers used fisheries science to maximize catch on the basis of historical statistics of single species (*7*, *8*). The purpose of management was to achieve a theoretical sustained yield and efficiently manage only those species with commercial value. The approach was based on the concept that ecosystems exist in equilibrium and that once an ecosystem

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reaches a climax state, yields can be controlled and sustained indefinitely (*9*).

Ecological research in the 1970s and 1980s revealed, however, that ecosystems are not in a continual state of stable equilibrium. Rather, disturbances such as fire, wind, floods, and drought are integral to maintaining healthy ecosystems (*10*, *11*). This shift in thinking implied that managing ecosystems was more complex than extracting predetermined sustainable yields. Disturbances are necessary rather than harmful, viability of commercially relevant species depends on the whole ecosystem, and populations vary spatially and temporally. In short, ecosystems function as complex, dynamic systems with nonlinear responses to internal and external forces, feedbacks across space and time, thresholds, and inherent unpredictability (*12*).

Another fundamental shift from the maximum-yield paradigm came from the realization that human societies depend on ecosystems for well-being and services other than commodities. In 2005, the Millennium Ecosystem Assessment called attention to the multiple services provided by ecosystems, including provisioning (e.g., food), regulating (e.g., water filtration and decomposition of wastes), supporting (e.g., soil formation), and cultural services (e.g., recreation) (*13*). Ecosystems perform several functions simultaneously. A forest can sequester carbon from the atmosphere, provide habitat for biodiversity, constitute a sacred and recreational space, and produce timber.

Awareness of human behavior and social institutions as integral parts of ecosystems has also been growing. For example, the spread of infectious disease depends on human behaviors, such as contact with others, as well as population dynamics of disease vectors. These interactions give rise to complex dynamics (*14*). Moreover, in a globalized world, trade and exchanges between distant regions alter norms and rules of resource extraction in increasingly unpredictable ways (*15*).

The realization that ecosystems behave as complex systems, with humans as a component, has upended the notion that managers can predictably obtain resources from ecosystems by following simple formulas and exerting top-down control. Problems in ecosystem management, such as reducing mortality from infectious diseases (*14*) and improving water quality affected by non–point source pollutants (*16*), have proven to be much less tractable than once thought.

Table 1. Examples of wicked problems in ecosystem management.

Management problem	Example of management question	Reasons for wickedness
Control of infectious disease	Where and when will outbreaks and spread of infectious diseases occur? Will vaccinations and other control strategies be effective?	Nonlinear population dynamics of disease vectors and hosts; feedbacks between disease incidence and human behavior (*14*)
Non–point source pollution	Which sources (e.g., agricultural or urban runoff) and pollutants should managers target to improve water quality?	Complex causality from multiple pollution sources; long lag times in system response (*16*)
Fire management at urban-wildland interfaces	Should managers suppress fires?	Unintended consequences of increased fuel loads and fire severity (*66*)
Conservation of biodiversity	How much and where should places be protected from other sectors (e.g., mining, roads, fishing)? How to protect species with ranges outside protected areas? How to rectify inequities for local communities that lose access to resources?	Differences in values (*35*); mismatch in ecological and administrative boundaries (*42*); divergent objectives of stakeholders (*56*)

Complexity gives rise to wicked problems

Because ecosystems are inherently dynamic and largely unpredictable complex systems, ecosystem management is a "wicked problem" (*17*–*19*). The concept of wicked problems arose more than 30 years ago in response to the dominance of top-down, expert-driven technical and engineering solutions to thorny issues in public policy, such as poverty alleviation and unemployment in urban communities (*20*). Wicked problems are inherently resistant to clear definitions and easily identifiable, predefined solutions. In contrast, tame problems, such as building an engineered structure, are by definition solvable with technical solutions that apply equally in different places. Wicked problems have been described in many disciplines, including public health, political science, business management, urban and regional planning, and natural resource management.

Rittel and Webber (*19*) have defined 10 primary characteristics of wicked problems, including the elusiveness of a final resolution, no definitive test for a solution, and no generalizable solution that applies in all cases. Wicked problems are seemingly intractable and subject to multiple interpretations.

Heifetz (*21*) classified problems in terms of their wickedness. Type I problems are technical in nature and have clearly defined questions and mechanical, straightforward solutions (i.e., they are tame). Type II problems are clearly definable but have no clear-cut solution. Solutions to type II problems are only proposals that must be tested and refined on the basis of outcomes. Type III problems have neither clear-cut definitions nor technical solutions. Type III problems are the most wicked and require continual learning to formulate the problem and adaptively work toward solutions.

In ecosystem management, researchers have identified many types of wicked, non–type I problems (Table 1). Wicked problems arise from one or a combination of multiple dimensions (*20*): complexity and interdependency of components, which create feedbacks and nonlinear responses to management interventions; uncertainty of risks and unintended consequences; divergence in values and decision-making power of multiple stakeholders; and mismatches in spatial and temporal scales of ecological and administrative processes.

Tame, type I problems such as controlling point source pollution are amenable to technical solutions. Wicked, non–type I problems that involve inherently unpredictable complex ecological systems, compounded by human behavior and socioeconomic complexities, require incremental and adaptive approaches to continually reframe their definition and develop incremental solutions.

Increasing wickedness in the 21st century

Several realities of the 21st century make ecosystem management an increasingly wicked problem. For most of human history, ecosystems essentially functioned as self-regulating adaptive systems with self-organizing properties that evolved through long-term interactions between populations and their environments (*12*). Human societies benefited from these properties to obtain resources. In the 21st century, humans have increasingly used approaches that replace or supplement ecosystem functions—such as pesticides that replace the ecological function of natural predators of pest species and fertilizers that augment nutrient cycling, a fundamental role of ecosystems. These approaches often do not mimic the self-regulating properties of ecosystems. The mismatch gives rise to unintended consequences, such as the loss of natural predators of pest species and the accumulation of excess nutrients in waterways that receive runoff from fertilized fields. Such human management has helped unprecedented numbers of people to escape extreme poverty and undernourishment (*22*), but it often lacks the built-in feedback loops that lead to self-regulation.

Another reason for the increasing wickedness of ecosystem management is the separation in space between the production and consumption of resources. As a result of these "teleconnections," locations that experience the consequences of resource use are disassociated from those where demand originates. For example, tropical forests are cut down to enable export of feed and vegetable oils across continents (*23*). Decoupling decisions from local impacts reduces the likelihood of self-regulating feedbacks that would change management practices when negative impacts arise, such as political pressure to control local pollution.

Ostrom (*24*) famously identified eight design principles for successful management of common pool resources such as fisheries and forests. These principles are applicable when small groups have local control over decisions, information, and institutional arrangements and thus can change management practices. With teleconnections, possibilities for applying many of the Ostrom principles break down. For example, communities often no longer have opportunities to match rules governing the use of common resources to local needs and conditions, ensure that outside authorities respect the rule-making rights of community members, or access means for dispute resolution.

Third, concern about inequalities in access to ecosystem resources is becoming more common, particularly where subsistence communities that depend on local ecosystems for fishing, forest product collection, or grazing are negatively affected by conservation or land acquisitions. To address these concerns, ecosystem management approaches are becoming more inclusive—for example, by ensuring that protected area management involves collaborating with local communities (*25*). These shifts are welcome from human rights and equity perspectives, but they increase wickedness for ecosystem management by adding stakeholders with divergent views, norms, goals, power, and influence.

Systemic approaches to wicked problems

Many researchers have called for systemic approaches to ecosystem management to replace previous, equilibrium-based methods for extracting maximum yields (*26*–*28*). These approaches are detailed in the following sections and Table 2.

Multisector decision-making

Stated goals for management of landscapes and seascapes often aim to provide a single ecosystem service. For example, protection of forests in the Catskills aims to filter water for use by New York City (*29*), and scenic value was the justification for establishing Yellowstone, the first U.S. national park (*30*). In reality, landscapes and seascapes often provide multiple services simultaneously, including marketed services such as timber and fisheries and nonmarketed services such as flood protection, erosion control, and climate regulation through carbon storage. Management decisions can lead to trade-offs or synergies among ecosystem services (*31*). Advanced models allow evaluation of the trade-offs and synergies from different management scenarios to inform decision-making (*32*, *33*).

However, sector-wise administrative structures limit abilities to weigh outcomes of management decisions that affect sectors outside a given sector's mandate. For example, the decision to establish a protected area might lie within the jurisdiction of an environment ministry, but the repercussions for local people who would be excluded from using resources from a newly established protected area might lie outside the purview of that ministry. With "stovepiped" decision-making, opportunities to account for multiple ecosystem services affected by management decisions are limited. At a national or subnational scale, spatial planning to compare outcomes of land use scenarios for multiple ecosystem services can overcome sector-wise decision-making; an example is national-scale planning to determine where economically important oil palm plantations could be located with minimal carbon emissions in the highly forested country of Gabon (*34*). Multifunctional ecosystem management also requires multilevel governance systems that recognize the importance of state, community, and private ownership (*35*).

Table 2. Approaches to address ecosystem management as a wicked problem.

Approach	Problem to address	Examples of implementation	Obstacles
Multisector decision-making	Services from multifunctional landscapes and seascapes are not factored into decisions about single sectors	National-level spatial planning (*34*); multilevel governance (*35*)	"Stovepiped"administrative structures
Decision-making across administrative boundaries	Ecological processes transcend administrative boundaries	River basin commissions (*40*); large-scale corridor planning (*42*, *43*)	Managers lack incentives and authority to consider other jurisdictions
Adaptive management	Learn-by-doing when outcomes of decisions are uncertain because of complex system dynamics	Ecosystem restoration; fisheries management (*48*)	Inflexible bureaucracies; lack of monitoring
Incorporating natural capital and ecosystem services in markets	Externalities are not included in economic accounting systems	Payments for ecosystem services; certification; inclusive wealth accounting (*50*)	Difficulty in determining value of nonmarketed ecosystem services
Balancing ideologies and political realities of diverse stakeholders	Politics and different expectations of ecosystem management lead to logjams in decision-making	Collaborative planning (*67*)	Differences in ideology and values; political realities

Decision-making across administrative boundaries

Ecological processes encompass spatial scales that often transcend administrative boundaries. National and provincial boundaries can cut across watersheds, airsheds, and home ranges of mammals and birds. Consequently, ecosystem management in one country or province can affect ecosystem services in other jurisdictions. For example, winds transport polluted air from fires in Indonesia to downwind countries, with major public health consequences (*36*). Also, protected areas commonly do not encompass the full geographic extent of migration patterns, as is the case for grizzly bears in western North America (*37*) and endangered tigers in central India (*38*). Further, water impoundments can trap sediment upstream, leading to downstream loss of wetlands, as has occurred in the Mississippi delta (*39*).

In the absence of governance arrangements that span administrative boundaries, managers lack incentives, authority, and mechanisms for considering the consequences of their decisions beyond their own jurisdictions. Institutional mechanisms can address this mismatch in ecological and administrative boundaries; examples include the Mekong River Commission (*40*) and the Association of South East Asian Nations (ASEAN) Agreement on Transboundary Haze Pollution (*41*). Institutional mechanisms for landscape-scale connectivity for wildlife movement include the Yellowstone to Yukon corridor (*42*) and the Mesoamerican Biological Corridor (*43*).

Adaptive management

The essence of adaptive management is learning by doing and recognition of uncertain outcomes. Adaptive management requires an explicit consideration that the future may be unknowable and

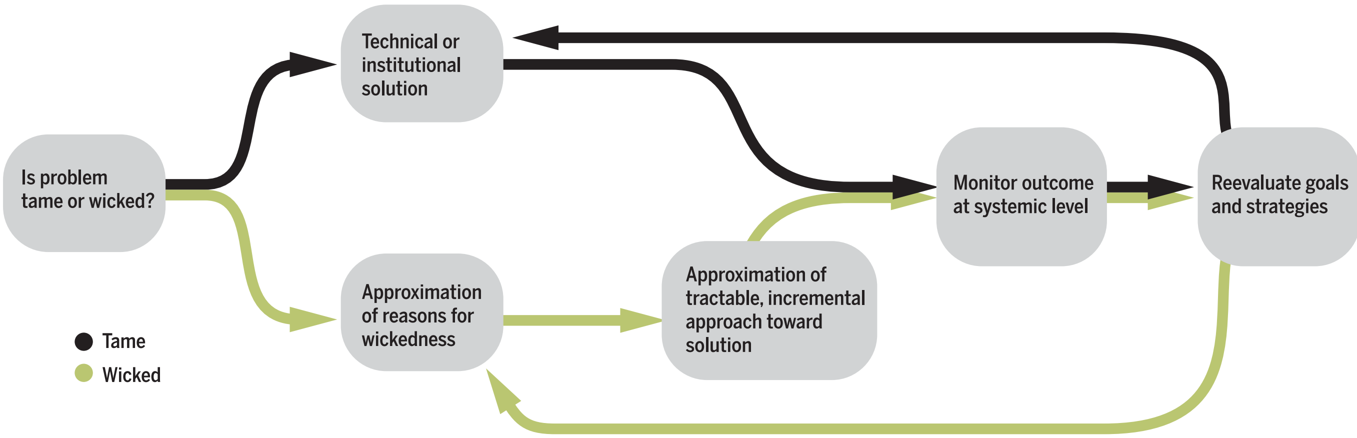

Fig. 1. Decision flowchart for wicked problems in ecosystem management. Such an approach can help to avoid trap A (falsely applying a technical, tame solution to a wicked problem) or trap B (inaction from overwhelming complexity).

predictions have limited reliability. Key features of adaptive management are monitoring, reassessing initial plans, redefining goals on the basis of new evidence, social learning, and collaborations (*44–46*). Planning needs to be geared toward flexible decision-making, with nimble management structures that are capable of swift changes (*47*). Examples include engagement of multiple stakeholders to determine water allocations in the congressionally mandated Florida Everglades ecosystem restoration program and management of salmon in the Columbia River basin in the northwestern United States (*48*).

Adaptive management to address wicked problems is intuitively appealing, but scientific and institutional barriers hamper implementation. Entrenched bureaucracies and social and legal limits of authorities constrain opportunities for flexible decision-making and the ability to change course once a policy is put into place. Ideally, active adaptive management would be conducted through controlled experiments to identify causes and effects among policies and outcomes, but such experiments are costly and time-consuming. Monitoring systems, which are essential for adaptive management, have suffered from lack of funding and leadership (*48*, *49*).

Incorporating natural capital and ecosystem services in markets

Economic systems reward short-term production and consumption of natural resources. Changes in nonmarketed ecosystem services (such as watershed protection) and natural capital (such as stocks of minerals, energy sources, and forests) are externalities that are not factored into traditional economic accounting systems. Consequently, markets do not provide incentives to value ecosystem services and natural capital (*50*).

Approaches to correct these market failures target different decision-makers. At a national level, tax policies and environmental regulations provide incentives or penalties to corporations and other natural resource users. Some countries have adopted programs to incentivize households and landowners to value natural capital. For example, China's reforestation program promotes conversion from croplands and barren lands to forests and grasslands. Costa Rica's national payment scheme for ecosystem services has reversed deforestation trends (*50*, *51*). The inclusive wealth index, although yet to be used in standard practice, incorporates the value of natural capital into national accounting systems to complement standard accounting systems that disregard natural capital (*52*).

> ***"Explicit recognition of the underlying reasons that a wicked problem occurs...could help identify incremental interventions that avoid either oversimplifying a problem or inaction from overwhelming complexity."***

At a regional level, payment for ecosystem services by the beneficiaries incentivizes the providers' use of natural resources. Such payments are most commonly applied in the case of upstream watershed protection to provide clean water to downstream users (e.g., New York City) (*29*). At an individual consumer level, product certifications and labels allow consumers to identify products that are produced in ways that conform to guidelines aimed at protecting natural capital and ecosystem services (*53*). Many corporations have incorporated the value of nature into their supply chains—for example, with no-deforestation pledges (*54*).

Market mechanisms have been criticized for exacerbation of inequities, particularly in places with unequal power relations and coercive redistribution of property rights (*55*). In addition, processes to assess effectiveness of these mechanisms and ensure that negative externalities are not displaced to other locations need to be consistently applied. Although a potentially powerful approach, the appropriateness of market mechanisms depends on the local socioeconomic and governance context.

Balancing ideological differences among stakeholders

The challenge of understanding the perspectives of diverse stakeholders contributes to the wickedness of ecosystem management. Ecosystem management decisions that may seem to be a simple matter of setting scientific limits on resource use frequently fail because of the political process of decision-making, differing values and norms, and power imbalances.

The history of protected areas to conserve nature, for example, is fraught with differences in ideologies and values among diverse stakeholders, including conservationists, extractive industries, and local communities (*56*). Conservationists historically have aimed to set aside lands and waters from human use, which caused conflicts with industries aiming to extract resources and with communities dependent on local resources for livelihoods. Managers have attempted to reconcile these goals through approaches such as mixed-use management, integrated conservation and development projects, community-based management, and eco-development. Such efforts have yet to resolve this wicked problem, although dialogs that recognize divergent aims are increasing. For example, continual engagement among policy-makers, communities, and researchers in East Africa aims to balance pastoral livelihoods with wildlife conservation (*57*).

A way forward

No two wicked problems are alike, and the above approaches apply differently depending on the problem and the ecological and socioeconomic contexts. Efforts to control infectious disease and non–point source pollution call for adaptive management because the population dynamics and complexities of human behavior are inherently

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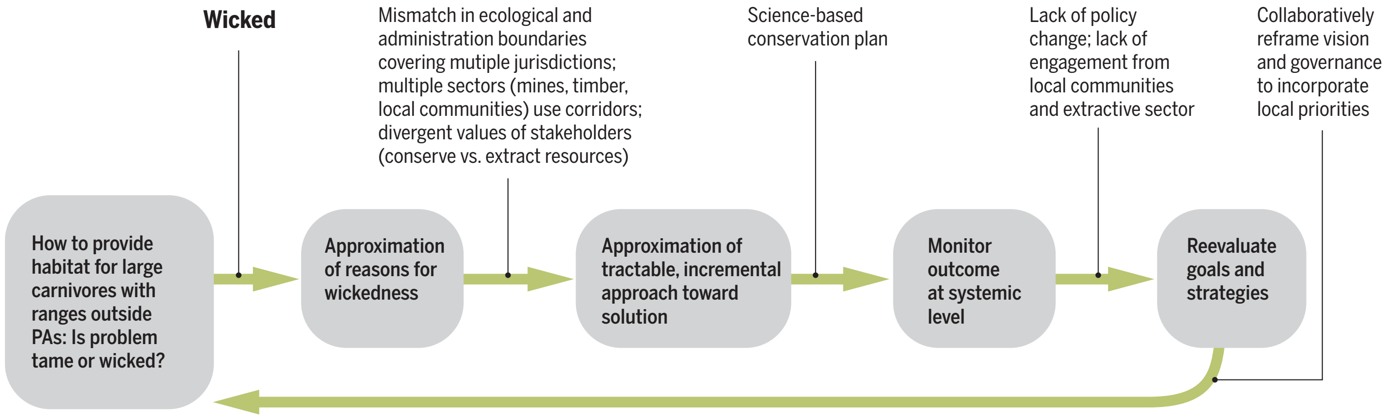

Fig. 2. Flowchart for managing an example wicked problem. This example illustrates the wicked problem of providing habitat for large carnivores outside protected areas (PAs) through efforts such as the Yellowstone to Yukon (Y2Y) Conservation Initiative (*42*).

nonlinear. A multijurisdiction planning approach is needed for conservation of migrating species. Each problem requires careful analysis to identify the main sources of wickedness and the approaches that might be appropriate for incremental solutions.

From a governance perspective, policy-makers can approach these problems in ecosystem management through mechanisms that promote institutional "fit" or "interplay." Institutional fit aligns institutions to spatial, temporal, and functional scales of different parts of an integrated system, such as river basin commissions that encompass multiple jurisdictions to cover a watershed (*58*). Institutional fit is challenged by the reality that an appropriate spatial fit for one problem, such as water, may lead to spatial misfits with other associated problems, such as wildlife movements (*59*). Conversely, policies can promote institutional interplay to include multiple institutions, each with their own legacies and cultures of operation, and accept the associated messiness (*60*). Institutional interplay, such as national-level land-use planning with multiple sectors, requires policies that shift institutional interactions biased toward dominance, separation, and merger toward negotiated agreements and systemic change (*61*). Both institutional fit and interplay are likely to be messy. Decisions about which approach is more effective and tractable depend on the context.

There is no single or best solution to wicked problems in ecosystem management. Two types of traps can curtail incremental, partial improvements. First, there is a risk of oversimplifying a problem and assuming that a technical solution will fix a wicked problem (trap A). For example, approaches to provide food security run this risk. In the 20th century, fertilizer, irrigation, and plant breeding vastly increased the amount of food production, reduced the cost of food, and alleviated famine. However, the explosive increase in production also had unintended consequences, including underpinning the current rise in obesity, reducing the nutritional content of cereals (*62*), creating inequities in access to food, and causing environmental problems such as soil degradation, fertilizer runoff, and greenhouse gas emissions. A continued sole focus on technical solutions to produce more food would overlook the myriad social, economic, and environmental dimensions of the problem.

Conversely, there is a risk of making a problem overly complex (trap B). Managers trained in technical problem-solving can be ill-equipped to confront complex social processes. The result can be inaction from the inability to identify an incremental, partial solution. The long-standing problem of balancing needs of local people with conservation in and around protected areas risks falling into a trap of inaction (*56*).

A middle ground between the two traps can be found by using the principles of adaptive management (Fig. 1). To complement an adaptive approach, analysis of a problem in ecosystem management, whether it is tame or wicked, and the primary reasons for the wickedness (if applicable) can help identify an initial, tractable institutional or technical intervention, whose outcome can be readily tracked. Analysis that considers divergent stakeholders and possible unintended consequences from the outset can help to avoid trap A. An initial experimental intervention, including monitoring and reassessment, helps to avoid trap B and find solutions appropriate for the context (*63*). Successive interventions are based on a more complete understanding of the problem, reasons for wickedness, and realistic institutional possibilities for interventions.

Efforts to protect habitat for species whose ranges transcend boundaries of protected areas, such as the decades-long Yellowstone to Yukon (Y2Y) Conservation Initiative in North America, are one illustration of how this process could work (Fig. 2). Y2Y was founded in the early 1990s to promote conservation of large carnivores over an area of 120 million hectares, encompassing three U.S. states, four Canadian provinces, and many jurisdictions of Canadian and U.S. land management agencies, Canadian First Nations territories, and U.S. Native American tribal lands. The contemporary history of the area includes agriculture and resource extraction. Initially, Y2Y was a loose network of conservation organizations and individuals that advocated land-use change conducive to large carnivore conservation through a science-driven plan. The initial effort encountered difficulties in implementing this vision because of conflicts over property rights and divergent values from those of local communities and industry. Y2Y then reshaped its vision to harmonize "the needs of people with those of nature" and adopted governance structures to enhance participation by local partners (*64*). The consortium has enabled wildlife crossings and protected status for land throughout the corridor (*65*). These governance strategies could evolve further, with the role of local partners moving from participation toward coproduction of governance strategies.

Explicit recognition of the underlying reasons that a wicked problem occurs in a particular geographic, institutional, and cultural setting could help identify incremental interventions that avoid either oversimplifying a problem or inaction from overwhelming complexity. Analyses of empirical case studies, identification of possible incremental solutions, and context-appropriate, tractable metrics to assess progress are all needed to address understudied wicked problems in ecosystem management.

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