A typology of timescale mismatches and behavioral interventions to diagnose and solve conservation problems

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Abstract

Ecological systems often operate on timescales significantly longer, or shorter, than the timescales typical of human decision-making, which causes substantial difficulty for conservation. For example, invasive species may move faster than humans can diagnose problems and initiate solutions. Climate systems may exhibit both long-term inertia and short-term fluctuations that obscure learning about the efficacy of adaptation and mitigation efforts. We adopted a management decision framework that distinguishes decision makers within public institutions from individual actors within the social system, calls attention to the ways that socio-ecological systems respond to decision makers' actions, and notes institutional learning that accrues from observing these responses. We used this framework, along with insights from challenging conservation problems, to create a typology that identifies problematic timescale mismatches and suggests solutions that involve modifying human perception and behavior at the individual level. The potential solutions are derived from the behavioral economics and psychology literature on temporal challenges in decision making. They include framing environmental decisions to enhance the salience of long-term consequences, using structured decision processes that make timescales of actions and consequences explicit, and structural solutions aimed at altering the consequences of short-sighted behavior. We demonstrate how our typology can be used to diagnose timescale mismatches and call for more research aimed at employing and validating the behavioral solutions identified.

Introduction: *The Timescales Challenge*

Mismatched timescales among the endogenous dynamics of the socio-ecological system and human decision making, action and learning are common features of conservation and environmental management failures (see case study examples in Fig. 1). Timescale challenges in socio-ecological systems have been discussed previously in diverse fields, including bioeconomics (Clark 2010), traditional environmental governance (Ostrom 1990), and most recently, panarchy theory (Gunderson 2001). In seminal work on panarchy theory, Holling (2001) described the complex scale interactions of nested socio-ecological systems, claiming that human foresight, communication, and technology can be used to overcome temporal and spatial mismatches (i.e., problems of fit) that generally lead to the collapse of otherwise healthy, adaptive complex systems (see also Cumming et al. (2006)). Folke et al. (2007) noted the pervasiveness of these challenges, again pointing to systems theory for understanding and adaptive management for solution. Guerrero et al. (2013) analyzed scale mismatches in the context of conservation planning, used a partial decision analytic structure to categorize mismatches, and pointed to social-network analysis as a solution. In short, there is a long-standing awareness of scale mismatches in socio-ecological systems, with several attempts to categorize temporal mismatches, and some broad advice and a few specific tools for resolving them.

In this paper, we expand on past work in three important ways. First, we cast temporal mismatches in socio-ecological systems in a decision analytical framework, recognizing that the problem of conservation interest is the nature of the actions taken by individuals within public decision-making institutions and the responses of individual actors within the social system. As a result, we suggest that solutions may be found in adjusting the timescales of human decision-making and action. Second, we describe where timescale mismatches occur within and between components of the public decision making process, and responses in the socio-ecological system, and we categorize the mismatches to reveal commonalities across cases that at first glance are quite different. Third, we identify tools from the behavioral sciences that recognize and correct for errors and idiosyncrasies in human judgment and decision-making related to time (see Fig. 2 for examples of the human tendency to engage in short-sighted thinking and behavior), associating them with domains of mismatches.

Our approach was both inductive and deductive in that we started by identifying common temporal mismatches across a range of case studies. We then developed the decision framework to deduce all possible pairs of temporal mismatches (i.e., 15 mismatches). These mismatches became our typology, which we applied to the case studies. We separately reviewed existing tools from the behavioral sciences and identified those that are most relevant to addressing issues of time in individual decision making. Then we used the case studies to test our ideas about how behavioral interventions might address conservation management difficulties. The result is a typology of troublesome timescale mismatches, derived from a decision analytic framework and observations of commonalities across case studies (including those in Fig. 1), and a suite of proven behavioral tools whose application to conservation can be validated through future research.

A Common Typology of Timescale Mismatches

We view conservation problems through the lens of public decision-making, focusing on five elements of a decision framework: the *objectives* considered by individual decision makers within a public institution, the *actions* taken by decision makers to achieve those objectives, the *social* and *ecological system* responses to the actions taken, and the *learning* mechanisms used by the decision maker to evaluate whether or not the actions had the intended effect (see Fig. 3). The driving force in this framework is a decision maker within a public decision-making institution, such as a governmental agency, that articulates management objectives and then compares potential management actions or policies while taking into account uncertainty about consequences and potential trade-offs across objectives. Once implemented, the actions have direct effects on the socio-ecological system. Individual actors within the social system, in turn, take actions that further affect the ecological system[1]. The decision maker has the opportunity to monitor the response of the socio-ecological system, and use the learning that accrues to (1) adjust actions or policies (single-loop learning), (2) update management objectives or consider new sets of actions (double-loop learning), or (3) change the existing institutional arrangement or governance structure itself (triple-loop learning) (Pahl-Wostl 2009).

Each element in the decision framework (see Fig. 3) has characteristic timescales. The *objectives* (O) considered by the decision makers have both implicit and explicit timescales, such as the timeframe over which ecological responses are evaluated to assess whether or not an objective has been achieved, and the discount rates, or present value of future benefits, assigned to assess ecological and social outcomes that occur at different points in time (Clark 2010). The temporal aspects of the *actions* (A) taken by the decision maker include the time it takes to begin implementation, the time over which the actions are implemented, and the interval(s) at which the actions can be adjusted. The *social system* (S) is composed of a variety of actors (e.g., individuals, groups, other institutions) who are affected by the decision maker's actions and who

[1] We choose to focus on individual actors within the social system, not groups (i.e., informal institutions) or other formal institutional actors within the social system who may respond to actions taken within a formal decision making framework. We recognize that individual actors within the social system are not solely influenced by formal policy and management actions, and that the impact of these actions may in fact be mediated by social or political context; however, this complexity within the social system is outside of the scope of this paper.

take action in response, based on their own sets of objectives and their assessments of the problem and the actions proposed. We choose to explicitly focus on individual actors within the social system (e.g., consumers, hunters, ranchers, homeowners, voters). Although these actors are influenced by a variety of forces within the social system, we focus on three time-based challenges: (1) individuals have their own timeframes for evaluation and their own discount rates that might differ from those of the decision maker; (2) the actions these individuals take have various lags and durations; and (3) the rate at which these individuals acquire and adapt to information varies. These are specific challenges that can influence the quality of the decisions that are made in response to formal action by the decision maker, and it is these challenges that might be amenable to time-scale focused behavioral solutions. The response of *ecological systems* (E) to management or policy interventions and to the actions of individual actors occurs on timescales driven by system dynamics[2]. These responses might be quite slow (e.g., recovery of top predator fish populations from overfishing), but in other cases, can be very fast (e.g., spread of invasive species or wildlife diseases). Institutional *learning* (L) from monitoring programs designed to reduce uncertainty about system states and dynamics has timescales related to the frequency of observation, background variability in the ecological system, the power to detect change over various spans of time, and the frequency of system perturbations.

Timescale mismatches within and among the decision elements described above are at the heart of the case studies described in Fig. 1. To lend structure to these mismatches, we offer the typology in Fig. 4, where 15 specific types of temporal mismatches are identified by two-letter acronyms representing the different components of the decision framework (e.g., AS, for actions taken by the decision maker that affect individual actors in the social system). The

[2] For a more detailed discussion of the dynamics within socio-ecological systems and a framework for identifying the factors driving change within coupled systems see work by Collins et al. (2010).

typology is intended to serve as a diagnostic tool to identify where problematic mismatches might occur for a particular conservation problem. The 15 types of mismatches can be grouped into 6 domains based on whether the conflicts occur within or between individual decision makers in the public institution, the individual actors in the social system, or the ecological system. Below we describe the six domains briefly.

Timescale mismatches within the decision-maker's domain

Six of the timescale mismatches are within the decision-maker's domain (Domain 1 in Fig. 4). For example, a forest management agency may need to manage timber extraction on annual scales while simultaneously maintaining biodiversity on decadal to century scales, representing a potential temporal conflict in short- versus long-term objectives (OO), immediate versus future actions (AA) and rates of learning across time (LL). Domain 1 mismatches also include mismatches between the decision-maker's objectives, actions and learning. For example, the long-term objective of maintaining ecosystem resilience in ocean fisheries might require drastic reductions in the harvest rate of fish that are socially, economically and politically unpalatable on short timescales (OA); understanding might arise too slowly to provide adequate feedback on achievement of objectives (OL); and the decision maker might have ineffective mechanisms in place for learning and adaptive management as is often the case in fisheries management (AL) (Mumby et al. 2007).

Timescale mismatches between the decision-maker's domain and individual actors in the social system

Three of the timescale mismatches occur between aspects of the decision-maker's domain and individual actors in the social system (Domain 2 in Fig. 4; OS, AS, LS). In many cases mismatches arise between decision makers acting on behalf of the public across generations and individuals acting with a narrower focus on the self (versus others) and on near-term consequences (see Fig. 2). For example, despite policies within the US Forest Service that support the use of fire as a management tool to promote long-term ecological health, reservations from multiple actors within the social system (e.g., short-term risk aversion among fire managers) can delay policy implementation (Wilson et al. 2011).

Timescale mismatches between the decision-maker's domain and ecosystem dynamics

Three of the mismatches occur between the decision-maker's domain and ecosystem dynamics (Domain 3 in Fig. 4). In the first case, the institutional objectives might be impossible to achieve in the desired timeframe, relative to the temporal response in the ecological system (OE), as demonstrated by the desire for an immediate end to cyanobacterial blooms in economically critical water bodies, despite decadal or even centuries-long retention of nutrients in sediments (Carpenter 2003). In other cases, the speed of ecological change may outstrip the ability of agencies to develop interventions (AE), as we have recently witnessed with the spread of white-nose syndrome in cave-dwelling bat populations in North America (Foley et al. 2011) or in the futile desire to measure the success of 3-year coral reef protection projects in systems where natural processes play out over decades (Bruno & Selig 2007). In other cases, important ecological changes may be difficult to detect against the backdrop of noise in the system (LE), as is the case with emerald ash borer where the invader's fast rate of spread relative to managers' ability to detect its presence in a location results in the spread outpacing the control (Herms & McCullough 2014).

Timescale mismatches within and between the social and ecological systems

The last three domains have to do with temporal mismatches within the social system (Domain 4 in Fig. 4, SS), between the social and ecological system (Domain 5, SE), or within the ecological system (Domain 6, EE). Domain 4 mismatches are those that occur within and among the objectives of individual actors in the social system, the rates at which they obtain new information, and the rates at which they act. This domain is similar in scope and complexity to Domain 1, but may be particularly amenable to behavioral solutions targeted at individuals acting within a social and political context. Domain 5 mismatches occur when individual actors operate on different timescales than the ecological system, either acting too quickly in response to short-term observations (e.g., misinterpreting short-term changes in the weather as indicative of longer-term climate patterns, leading to climate denial (Weber & Stern 2011)), or failing to perceive and respond to slower shifts in ecological conditions (e.g., failing to adjust agricultural practices in the Great Plains when a multi-year drought occurred after the unusually wet 1920s (Peters et al. 2014)). Domain 6 mismatches occur when different elements of the ecosystem respond to human action at different rates (Hastings 2010). One such example is the case of small predatory groupers that recover rapidly when fishing pressure is removed, compared to large predatory groupers that can take decades to recover, at which point they have a strong inhibitory effect on the abundance of smaller groupers (Mumby et al. 2011). Failure to account for the complexities of these temporal interactions can lead to mistaken predictions of the effects of conservation and management actions.

Solutions to Timescale Mismatches

Generally speaking, the tools that can be applied to address timescale issues are technological (engineering-based), cognitive (information-based), and structural (consequence-based) (Heberlein 2012; McKenzie-Mohr 2013). Technological solutions typically bypass the human behavior that is at the root of the problem, focusing instead on modifying ecological systems to suit human timescales. Such solutions are typically put into place when the ecological system is not responding quickly enough, or perhaps the system is changing too quickly, given individual objectives and needs (Domains 3 and 5). From a historical perspective, the development of agriculture (e.g., shifting vegetation toward higher-yielding annuals) can be interpreted as an attempt to solve a perceived problem using technological solutions. These manipulations have been successful in many respects, but failure to account for timescale alignment has also led to harmful consequences, such as the eutrophication occurring in water bodies around the globe as a result of large-scale modern agriculture (Carpenter 2003).

We think the most promising solutions to mismatched timescales can be found in modifying the behavior of individuals given that human behavior is at the root of most conservation problems (Schultz 2011). Cognitive tools change the way that information is processed and used in decision-making, while structural tools change the consequences of an action (in a positive or negative direction). The suite of cognitive and structural tools available has been presented in a variety of publications identifying how best to change behavior to achieve conservation goals (see Clayton et al. 2013; McKenzie-Mohr et al. 2011; Osbaldiston &

Schott 2011; Swim et al. 2011). Recommended approaches include, but are not limited to, appealing to existing environmental values (Stern 2000), triggering relevant social cues (Cialdini 2003), and making the intended behavior easy to perform (White & Simpson 2013). Here we will focus on recommendations that specifically aim to reduce errors in judgment related to how individuals perceive and value time (see Fig. 2). These tools have been tested across a variety of contexts including those related to the environment and conservation (Hardisty et al. 2012).

Cognitive Tools. Decades of research in the behavioral sciences indicate that an information deficit approach to changing behavior will be insufficient (Simon 1990). In some contexts, more knowledge can actually decrease support for a conservation effort by increasing the ability of individuals to counter-argue and defend a strongly held value or cultural identity (Kahan et al. 2012). To be effective, information aimed at changing the way an individual thinks about a problem, as a means to changing behavior, must be carefully *framed* (Chong & Druckman 2007). In the context of mismatched timescales, strategic framing can be used when it is difficult or impossible to change ecological timescales (e.g., fish reproductive cycles) or the tangible consequences (e.g., changing the price of fish). Specifically, framing can help increase alignment within the institution or social system (Domains 1 and 4), as well as bring institutional decision-makers into alignment with the timescales of socio-ecological systems (Domains 2 and 3) and individual actors into alignment with the timescales of ecological system (Domain 5). Generally, this involves changing the perceived value of costs and benefits over time in order to motivate action. Some potential framing tools to consider include:

1. *Magnitude*: People generally make more far-sighted decisions when considering larger magnitude costs and benefits (Thaler 1981). For example, reporting the total expected

number of ash trees to be killed by Emerald Ash Borer may be more effective at encouraging immediate reduction in firewood movement than annual statistics.

2. *Sequences*: People respond differently to single outcomes versus trends over time, preferring improving trends compared to declining even if the same set of average returns are presented (Loewenstein & Prelec 1993). For example, fishers may respond more positively to a fish restoration program in the present when the quotas are presented as an increasing allowable catch through time compared to a single total over that same period of time.
3. *Loss framing*: People make judgments with respect to a reference point (i.e., the present, the past, the future), and are generally more motivated by losses than by gains (Tversky & Kahneman 1991). As a result, presenting fire as a forest management tool to restore something previously healthy (i.e., recovering a loss) is more acceptable to stakeholders than describing it as a tool to achieve an improvement over the present (i.e., a gain) (Wilson et al. 2012).
4. *High-level goals*: People tend to construe more temporally distant events abstractly (i.e., focusing on "why" it happened or will happen) rather than concretely (i.e., focusing on "what" is happening). This typically leads to behavior more consistent with long-term values and goals (Trope & Liberman 2003). Therefore, if the goal is to encourage fishers to pursue long-term, abstract goals (e.g., sustainability) relative to short-term, concrete concerns (i.e., annual profit), one should focus their attention on the state of the fishery in 10 years, as opposed to the upcoming year.

A second set of cognitive tools comes from decision structuring and multi-criteria decision analysis, which inform decision making through a deliberate assessment of the tradeoffs across time (Gregory et al. 2012). To permit explicit consideration of intertemporal tradeoffs, the description of the decision context should include both the frequency with which management decisions might be revised and the timespan over which the consequences of management actions will be evaluated For example, management plans to restore old-growth characteristics in deciduous forests might be revised every 10 years, but the results of altered management will not be fully realized for decades or even centuries.

In order to choose among management options that impose costs and deliver benefits at different future times, the ways that different actors discount the future must be represented explicitly. For example, the heads of land management agencies may be most concerned about the near future, the timeframe most relevant to evaluating their own job performance, whereas members of environmental groups may be most focused on the long-term future, when the fate of endangered plant and animal species will become most evident. Some suggest using different time horizons and discount rates for financial versus ecological impacts (Rout & Walshe 2013) to account for empirical evidence that people discount financial costs and benefits at a more or less exponential rate, but non-financial costs and benefits at a more nearly hyperbolic rate (i.e., rapid discounting in the very short term and a much slower increase in discounting in the distant future). Such an approach would capture the timescales of both the land management agencies and the environmental groups in the same analytic model.

Structural tools. Although cognitive tools like strategic framing and decision analytic methods hold great promise at improving decision making by changing the way that individuals perceive and value time, structural tools (e.g., incentives) may be a more direct means of preventing short-sighted behavior (Clayton et al. 2013; Heberlein 2012; Schultz 2011). Such tools work by changing the social, political, or environmental context in which decisions are made, essentially altering the consequences of an action (Heberlein 2012; Thaler & Sunstein 2009). Structural tools can be used to increase alignment between the decision maker in an institution setting management policy and the individual actors in the system (Domain 2). They can also be useful to increase alignment within the institution or social system (Domains 1 and 4), or to reconcile mismatches between institutional decision makers or individual actors and the ecological system (Domains 3 and 5). Generally, this involves incentivizing individuals to match the timescale of the ecological system. Some relevant structural tools to consider include the following:

1. *Legal prohibitions:* Enacted when the "right" action is clear and the "wrong" action is so obviously harmful that it is outlawed. Many countries have laws (e.g., the Endangered Species Act in the United States) that directly, and in some cases indirectly prevent harm to a species in the short-term to achieve long-term objectives. Temporal aspects of conservation problems are sometimes acknowledged explicitly in these laws.
2. *Taxes and subsidies*: Used when an action is desirable but not deemed appropriate for legal prohibition. For example, government payments may be provided per acre to offset the short-term cost of taking land out of agricultural production to promote long-term wildlife habitat or protect water quality (Secchi et al. 2008).
3. *Temporal restructuring*: Used to better align timescales through the creation of new financial or legal contracts. Conservation easements, where landowners receive immediate tax breaks in return for restricting some uses of their property, have been successful in retaining undeveloped land in areas where development pressure is high.

Heirs to the property must continue the easement or repay the reduced taxes. Thus, individual actors receive immediate financial incentives to promote long-term conservation benefits, solving the timescale mismatch.

4. *Behavioral-economic nudges:* Used to guide people towards better choices that result in long-term benefits while not eliminating the freedom of choice in the present. These can include the framing tools discussed previously, as well as the following:
    a. *Pre-commitment*: People will more readily agree to a future commitment of time or money than an immediate contribution, due to discounting (see Fig. 2). The key is to ensure that commitments to future actions are binding (Thaler & Benartzi 2004). For example, a policy might encourage farmers to commit to adjusting their fertilizer application practices starting in 3 years (rather than immediately) to reduce impacts on water quality and aquatic species.
    b. *Defaults*: People are more likely to stick to a default than opt-in to an alternative option (Johnson & Goldstein 2003). Many US states have used check-off boxes on tax returns to raise money for programs like wildlife conservation. These typically require an "opt-in" by the taxpayer; changing the set-up so that the taxpayer needed to check a box to opt-out would be an example of making pro-conservation action the default.
    c. *Channel Factors*: People are more likely to act when it is easy and convenient to do the right thing (Leventhal et al. 1965). The tax check-off boxes mentioned above are an example of making it easy for people to "do the right thing".
    d. *Broad Bracketing*: People tend to make more rational choices when considering a large set of choices as opposed to choices considered in isolation (Read et al.

2000). If fire insurance on homes in the wildland-urban interface were offered on a 5- or 10-year basis, rather than annually, so that the premium reduction for "firewise" retrofits became substantial, homeowners might think about fire management decisions on a longer timescale and more readily undertake modifications to their houses and landscapes.

Together, cognitive and structural tools can be brought to bear on the different domains of timescale mismatches outlined earlier by targeting the temporally biased behavior of individuals within decision-making institutions and within the broader social system. In so doing, we can overcome some of the challenges identified in Fig. 2 that are the result of “boundedly rational” humans operating in a complex and temporally dynamic environment (Simon 1990). We expect that the tools might be used in combination, for example motivating individuals to increase invasive species control on their lands by highlighting the legacy they want to leave behind for their family and community, paired with technical assistance or subsidies that make the “right” choice easier. These are not mutually exclusive approaches, nor is our list of example tools within the categories exhaustive.

Synthesis & Prospectus

Here we have shown that poor alignment in timescales is a common thread helping to explain why many complex conservation challenges are difficult to solve. We identified a set of behavioral tools aimed at resolving timescale challenges in decision making, and suggested that many challenges in the management of coupled socio-ecological systems could be resolved if the right timescales issues were identified and appropriate behavioral solutions employed. These tools range from strategic framing and decision analytic approaches aimed at changing the way that individuals perceive and value time to a suite of tools aimed at altering the consequences of (often short-sighted) behavior.

Many of the tools described have been tested in environmental contexts, e.g., using large magnitude, broad bracket frames to increase the attractiveness of fuel-efficient vehicles (Camilleri & Larrick 2014) and applying decision aiding techniques to find a balance between long-term coastal ecosystem conservation and short-term coastal development under rising sea-levels (Mills et al. 2014). However, explicitly testing how these tools solve temporal mismatches within conservation contexts has received less attention. Wider testing of these solutions, along with long-term evaluation measures that assess not just behavioral changes but also associated changes in ecological systems, will provide further understanding of the advantages and limitations of our approach.

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Figure 1. Examples of timescale mismatches in conservation and environmental management

Figure 2. Behavioral science concepts useful for understanding how individuals perceive time

Figure 3. A decision framework for conservation and environmental management with adaptive feedback loops that can be used to modify actions, objectives, and governance structures determined by individual decision makers within public institutions (Pahl-Wostl 2009)

Figure 4. A typology of timescale mismatches, as delineated by the components of the decision framework presented in Fig. 3. The fifteen specific types of mismatches (e.g., within objectives of public decision-makers (OO), between decision-maker objectives and the response of individual actors within social systems (OS), etc.) fall into 6 domains represented by the circled numbers where 1 = mismatches within the public decision maker, 2 = mismatches between the public decision maker and the social system, 3 = mismatches between the public decision maker and the ecological system, 4 = mismatches within the social system, 5 = mismatches between the social and the ecological systems, and 6 = mismatches within the ecological system.

Cyanobacterial bloom in western Lake Erie, 2011 (Photo Credit: NOAA)

Cyanobacterial blooms in western Lake Erie decrease water quality leading to a myriad of ecological risks and an increase of toxic microcystins that pose a public health threat (Michalak 2013). Temporal lags between human actions across the landscape, responses in the downstream ecosystem, and feedback indicating how actions are influencing lake ecology are among the main factors hindering successful long-term management. Specifically, agricultural fertilizers are being applied at times and in ways that leave readily available nutrients on the surface of the field that are then flushed downstream through storm-pulsed runoff in the spring (Michalak 2013; Scavia et al. 2014). Learning about the consequences of when and how fertilizer is applied, and proposing changes in policy and management to reduce runoff, has been hindered by temporal complexity in the ecological system. Specifically, weather events interact with much slower ecological dynamics (the inter-annual to decadal build-up and removal of phosphorus stored in sediment), and decadal-scale climate shifts. In addition, short-term objectives of individual farmers and stakeholders regarding production often conflict with actions proposed to meet long-term social and institutional objectives related to water quality and the protection of ecosystem services.

Powerhouse Fire, Angeles National Forest, 2013 (Photo Credit: Maya Sugarman, KPCC)

Catastrophic wildfires in the western U.S. are attributed to an accumulation of fuels as a result of decades of fire suppression, and the recent expansion of residential development (Fountas & Blackmore 2005). Implementing the knowledge that these forests should burn periodically to achieve long-term goals related to forest health and public safety has been difficult due to public concerns about short-term impacts (e.g., smoke) (Daniel et al. 2007). Even with the political will to use fire as a management tool, it would take centuries to restore forests to their pre-suppression dynamics (Schoennagel & Nelson 2010). Meanwhile, current attempts at burning are occurring during a dry period, while decades of suppression coincided with a wet period within a long-term climate cycle, confounding understanding of the effects of fire management (Kitzberger et al. 2007). Forest fire regimes fluctuate on both shorter and longer timescales than institutional management policies, and the effects of suppression will linger for decades after policies change. Human perceptions about how "healthy" forests should look also linger long after new science emerges about forest dynamics. However, knowledge of long-term climate cycles is improving (Cook et al. 2004), providing a fuller context for the interpretation of short-term fire cycles.

The non-native emerald ash borer (Photo Credit: Leah Bauer, USDA Forest Service)

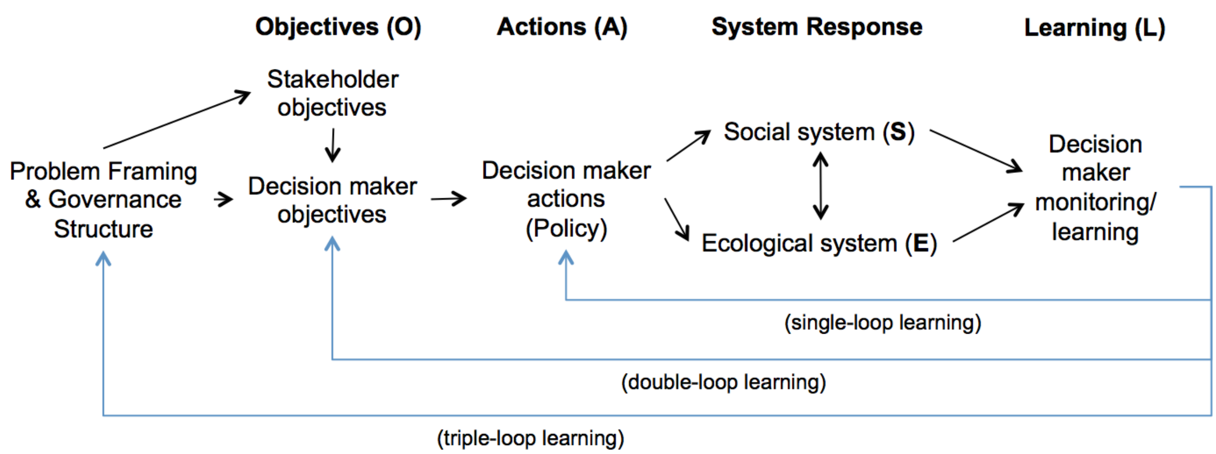
Emerald ash borer (EAB), a beetle introduced to the U.S. in the early 1990s, is causing widespread ash tree death as it spreads through the northeast (Herms & McCullough 2014). Likely introduced in wood packaging material from Asia, it continues to spread on its own and through the transport of nursery stock and firewood (Herms & McCullough 2014). Control is often hampered by mismatches in timescales both within and between the human and ecological systems. For example, the >10-year delay between arrival and detection of EAB, as well as ineffective detection and control technologies, prevented successful eradication or containment (Herms & McCullough 2014). While regulatory agencies were relatively quick in implementing quarantine policies to slow the spread following detection, compliance with quarantines has been slow and incomplete (Haack et al. 2010). The inability of humans to detect the sometimes cryptic initial spread of introduced pests, delays in developing and enacting effective control and detection techniques, and difficulty in changing human behavior to conform to regulations all exacerbate the negative impacts of invasives. Time lags that hinder learning and action are common features of invasive species problems, and strategies to reduce these lags could dramatically reduce negative impacts.

Humans are “boundedly rational”, making decisions with limited cognitive resources and using only part of the available information (Simon 1990). The field of behavioral science seeks to identify common limitations and shortcuts in human reasoning and to recommend solutions to these challenges. Some timescale-related heuristics and biases in human decision-making include:

- *Temporal discounting.* People generally devalue anything in the future. The farther in the future it is, the less people care about it. This is rational in some respects, but people’s choices often imply ridiculously high annual discount rates, such as 30% or even over 100% (Frederick et al. 2002). Furthermore, people put an irrationally large weight on “today” (so-called “present bias” or “hyperbolic discounting” (Laibson 1997)). This is problematic when considering environmental consequences that might not be realized until far into the future. For example, one reason many people do not act on climate change is because many of the most severe consequences are far in the future (Weber 2006).

- *Peak-end rule*. When evaluating a previous experience, people focus on the peak of the experience (the most positive or negative point) and the end (the most recent point) (Fredrickson & Kahneman 1993) (see also “primacy” and “recency” effects). This is problematic when evaluating cyclical or seasonal phenomena (such as lake eutrophication or forest fire frequency and severity), because people’s judgments of the severity of the problem will depend on where in the cycle they happen to be at that particular point in time.

- *Intertemporal commons dilemmas*. When consuming shared resources, people often put their own needs above those of the group due to a tendency to maximize personal benefit given the costs are shared (Van Lange et al. 2013; Wade-Benzoni 2002). This occurs over time as well, putting the needs of our current selves over those of our future selves and future generations. This is problematic for the management of common pool resources (e.g., fisheries, public lands, air), because without appropriate institutional norms or regulations in place individuals will often deplete the resource to exhaustion.


Objectives (O)
Actions (A)
System Response
Learning (L)
Stakeholder objectives
Problem Framing & Governance Structure
Decision maker objectives
Decision maker actions (Policy)
Social system (S)
Ecological system (E)
Decision maker monitoring/ learning
(single-loop learning)
(double-loop learning)
(triple-loop learning)

		Public'Decision'Maker			**System'Response**	
		Objectives(O)*	*Actions*(A)*	*Learning*(L)*	*Social*(S)*	*Ecological*(E)*
Public'	*Objectives*(O)*	OO	OA	OL 1	OS 2	OE 3
Decision'	*Actions*(A)*		AA	AL	AS	AE
Maker	*Learning*(L)*			LL	LS	LE
System'	*Social*(S)*				SS 4	SE 5
Response	*Ecological*(E)*					EE 6