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# Sequential Climate Change Policy

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Focus Article

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Successfully managing global climate change will require a process of sequential, or iterative, decision-making, whereby policies and other decisions are revised repeatedly over multiple decades in response to changes in scientific knowledge, technological capabilities, or other conditions. Sequential decisions are required by the combined presence of long lags and uncertainty in climate and energy systems. Climate decision studies have most often examined simple cases of sequential decisions, with two decision points at fixed times and initial uncertainties that are resolved at the second decision point. Studies using this formulation initially suggested that increasing uncertainty favors stronger immediate action, while the prospect of future learning favors weaker immediate action, but subsequent work with more general formulations showed that the direction of either effect is indeterminate, depending on multiple elements of model structure and parameter values. Current issues in sequential climate decision-making include assessing responses to potential slow learning or negative learning, and examining the implications of various mechanisms by which current decision-makers may seek to influence future decisions by altering the choice sets, knowledge states, marginal costs and benefits, or default procedural requirements faced by future decision-makers.  *WIREs Clim Change* 2011 2 744–756 DOI: 10.1002/wcc.128

## INTRODUCTION

Responding to global climate change is a problem of sequential, or iterative, decision-making. This means that decisions—by policy-makers, investors, and others—probably will be, and rational decisions must be, made and revised repeatedly over time in response to new knowledge, accumulated experience, or changed conditions. The changes to which future decisions will respond may come from new scientific knowledge about climate change and associated impacts and risks. Alternatively, they may be related to changes in technologies or other capabilities for response, with their associated performance, costs, and risks. There may also be changes in societal goals, priorities, or other factors. Sequential decision-making is required both for mitigation decisions to limit anthropogenic emissions and other drivers of climate change and for adaptation decisions to limit the harms from climate changes that cannot be avoided. If geoengineering interventions to alter the climate's response to increases in greenhouse gases are considered, these will also require sequential decision-making over time. The time horizon over which sequential decision-making continues may range from several decades to several centuries—either until human societies have transitioned to a state in which they impose no further net climate forcing or until, for whatever reason, global climate change has ceased to be a matter of concern. The Intergovernmental Panel on Climate Change (IPCC) recognized the need for sequential decision-making in the synthesis of the Fourth Assessment Report,[1] stating that 'Responding to climate change involves an sequential risk management process that includes both adaptation and mitigation . . .' (p. 64).

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## SEQUENTIAL CLIMATE CHANGE DECISIONS: BASIC CHARACTERISTICS

Why must climate decision-making be sequential? In practical terms, it is because today's decision-makers care about both present and future consequences, but lack the ability either to create a complete intertemporal response to climate change in a single stroke or to identify what such a complete response should be. In addition to whatever political and institutional constraints they face, today's decision-makers also lack this ability due to two structural characteristics of the climate issue that establish the need for sequential decisions in analytic terms: inertia and uncertainty. Long lags and inertia are present at several points in the climate and energy systems. Current mitigation actions affect emissions slowly, as new investments, innovations, or behavioral changes spread through the economy and society. In turn, changes in the flow of emissions only slowly modify the accumulated stock of atmospheric greenhouse gas concentrations. Furthermore, changes in concentrations exert only a slow influence on climate, due to inertia in the climate system arising mainly from the large heat capacity of the oceans. Given these lags, even extreme immediate actions to influence emission trends may take decades to produce a discernible climate response.

The climate and energy systems also exhibit large and persistent uncertainties. Although scientific research has established the reality, human cause, and future continuation of climate change essentially beyond doubt, there remain large quantitative uncertainties in projecting the rate, magnitude, and specific consequences of future change. Quantitative uncertainties also pervade projections of the feasibility and cost of alternative responses,[2–4] which strongly affect what responses are preferred. If climate change and its effects were known to lie near the lowest, least destructive end of the present uncertainty range or if responses to limit climate change were known to be highly costly and disruptive, smaller and later responses would be favored; if climate change damages were known to lie near the highest, most dangerous end of the uncertainty range or if responses were known to be cheap and easy, stronger and earlier efforts would be favored.

It is the presence of both inertia and uncertainty that makes sequential decision-making necessary. This can be illustrated by considering the counterfactual situations with only one of these characteristics present. With inertia but no uncertainty, an optimal trajectory of responses over time could be identified immediately. These responses would be tuned to the climate system's lags and inertia to push just the right amount at the right time. But while specific actions would vary over time, they would do so in line with a plan that could be fully specified today, and thus decision-making would not have to be truly sequential. On the other hand, with uncertainty but no inertia, optimal responses at each time could be determined based on observed conditions, knowledge, and uncertainties at that time. Any climate change or impacts occurring would be fully addressed in real time, and no action to address future changes would be warranted. But the presence of both inertia and uncertainty makes either of these simplified approaches to decision-making infeasible. Because of inertia, efforts to manage future risks must begin in advance. Because of uncertainty, these efforts must be based on uncertain projections of their effects. They are thus subject to error, so the trajectory of decisions must be adjusted over time in response to new information about risks and capabilities, costs, and benefits. Moreover, given that the need for future adjustments and knowledge to inform them is evident today, part of the task for current decisions is to establish conditions to support these future adjustments and to do research that aims to provide the knowledge to inform them.

This article discusses the implications of the sequential character of climate decisions and reviews the analyses of climate change decisions that have examined these, with particular focus on what they mean for near-term decisions. In particular, this article discusses and reviews the following: (1) why the most widely used climate decision models have been unable to examine the implications of sequential decisions, (2) the main results of studies that have focused on sequential decisions, (3) current work in two areas where achieving more decision-relevant insights requires further advances in modeling and analysis of sequential decisions, and (4) specific decisions and issues faced by current decision-makers that could be informed by a more sophisticated treatment of sequential decisions, whether via formal modeling or other methods of inquiry.

## TREATMENT OF UNCERTAINTY AND INTERTEMPORAL CHOICE IN CLIMATE CHANGE ANALYSES

The most widely used tools for analysis of climate change decisions have been integrated assessment models (IAMs), which combine representations of the economy and energy system that produce greenhouse gas emissions with representations of resultant radiative forcing, climate change, and impacts. Building on energy modeling approaches initially developed in the 1970s, IAMs saw a surge of activity in the 1990s coincident with the first serious policy attention to climate change. Major reviews of IAMs include Weyant et al.,[5] Parson and Fisher-Vanden,[6] Rotmans and Dowlatabadi,[7] and Kelly and Kolstad.[8]

IAMs take various approaches to representing climate decision-making, but most presume optimal climate policy-making by a unitary agent. The optimization can represent a single global decision-maker or separate decisions for each of the several major world regions and can use various specific formulations, including minimizing the cost of meeting specified energy service demands or maximizing the social utility of consumption. Climate change damages may enter the optimization through effects on utility or productivity. The optimization is typically conducted at discrete decision points, over a time horizon of 100–300 years.

With a few exceptions discussed below, most IAM studies have not allowed significant treatment of sequential climate decisions due to restrictive representations of both intertemporal decision-making and uncertainty. Intertemporal decisions in IAMs have been represented by two extreme approaches. In the first, optimization at each decision point is done separately, or 'myopically', based on conditions at that time. These conditions may include constraints, such as the current capital stock, that are the legacy of prior decisions. But the myopic optimization takes no account of future conditions or consequences except by proxy via current rates of return on investment. In the second approach, based on the Ramsey framework of optimal economic growth modeling, a single intertemporal optimization is performed for the entire time horizon, which specifies decisions at every point within the horizon. Neither of these approaches allows meaningful treatment of sequential decision-making under uncertainty, however. Myopic, period-by-period decisions make no attempt to advance future benefits, so future decisions are not adjustments to new information, but merely new static decisions made in response to new, current conditions. Intertemporal optimization, on the other hand, specifies the entire time path of decisions jointly, and so allows no possibility for mid-course learning, reassessing, and changing decisions. In fact, excluding such mid-course adjustments is one of the conditions that defines an optimal intertemporal decision path.

The ability to examine sequential decisions has also been constrained by the treatment of uncertainty in most IAM studies. Uncertainty analysis in IAMs is becoming more sophisticated, moving beyond point estimates and sensitivity analysis toward studies that propagate exogenous probability distributions of input parameters through to model outputs or that integrate observations to constrain distributions of model parameters.[9–13] Regardless of what form is used to represent uncertain characteristics or knowledge about them, however, if these do not change over time they cannot represent the learning that is central to sequential decision-making. A few studies have adopted alternative methods to study intertemporal climate decisions, including both optimal-control and formal feedback-control methods,[14–16] but treatments of these methods to date have also allowed only limited examination of sequential decision-making under uncertainty.

To date, model studies that have constructed future emission scenarios to represent either low-cost pursuit of environmental goals or optimal balancing of mitigation and impacts have adopted these simplified treatments of intertemporal decisions and uncertainty.[17–19] There are good justifications for adopting these simplifications in climate decision modeling. Introducing multiple decision stages in complex nonlinear optimization problems with multiple uncertainties being resolved over time poses large computational burdens. Moreover, representing sequential decision structures requires choosing specific structures for the evolution of information about uncertainties over time and the intertemporal structure of decisions from a complex set of possibilities, raising the risk that any particular choice may appear arbitrary. Still, these studies and the emission scenarios generated from them cannot represent sequential decision-making, because uncertainties are not revealed over time and because the specification of decision-making either takes no account of future effects or fixes a complete trajectory of responses with a single decision.

## REPRESENTING SEQUENTIAL DECISIONS IN ANALYSES OF CLIMATE CHANGE DECISION-MAKING

For an analysis of climate change decisions to allow investigation of sequential decisions, it must satisfy three conditions. First, there must be more than one decision point, separated in time. One-time specification of all decisions over the relevant time horizon—whether this reflects full intertemporal optimization or a granting of authority to the first-period decision-maker to fix all future responses—allows no opportunity to act on what may be learned over time, and so is not consistent with a sequential approach. Second, uncertainties and decision-makers' knowledge about them must change over time. Without such change there can be no learning, thus no reason to adjust a decision relative to prior plans nor any benefit in the ability to make such future adjustments. Third, decision-makers must care about the future—a condition that is required for a sequential approach, but not unique to it. Otherwise, preferred choices at each decision point can be identified solely on the basis of decisions of conditions at that time. While these three conditions are necessary for an analysis to examine sequential decision-making, they do not exhaust the issues that can be examined within a sequential framework, as the following section on 'challenges for further analysis' will discuss.

Studies of climate decision-making that meet these conditions and thus are relevant to sequential decisions have specified the intertemporal structure of the decision problem and the development of knowledge and uncertainty over time in various ways and have addressed several distinct but related questions. In addition to using the simplest possible specification of the decision-maker (a single unitary actor) and choice set (either a binary choice or one quantitative choice of mitigation stringency at each choice point), most have specified the simplest possible time structure of decisions that is compatible with a sequential approach: two decision points, with information available at various points relative to these. Initial studies examined the effect of information becoming available either before or after the first decision, comparing the 'act-then-learn' (ATL) sequence in which the initial choice must be made under uncertainty, with the 'learn-then-act' (LTA) sequence in which uncertainty is resolved before this choice. Distinguishing these two sequences allows study of hedging strategies and the value of information. In comparing the two sequences, LTA always has a better expected outcome (or strictly speaking, no worse), because it allows the best choice to be made given the true state of the world. The difference in value between the two sequences is the value of the information provided, while the best choice available under ATL identifies how best to hedge against the uncertainty before it is resolved.

Using many different models and formulations, these studies showed that when initial climate decisions must be made under uncertainty, the best choices lie between those that would be optimal under the various possible resolutions of the uncertainty. For example, if under one resolution the best near-term choice is little or no early mitigation, while under another it is aggressive early mitigation, the preferred choice under uncertainty hedges between these alternatives with moderate near-term mitigation. After uncertainty is resolved, preferred decisions diverge depending on the particular outcome revealed, converging toward the respective optimal choices given each resolution. These studies also provided quantitative estimates of the value of earlier resolution of these uncertainties.[20–22] When the timing of information or the extent to which the prior uncertainties were resolved by the new information were varied, earlier and more complete resolution of uncertainties increased the value of information, as expected.[21,23]

A different design for a two-period hedging analysis was presented by Hammitt et al.,[24] who treated the future choice of a global warming limit (along with climate sensitivity) as a first-period uncertainty, rather than having the model calculate the preferred limit based on specified benefits and costs. They examined what values of the later revealed uncertainties made it best to start with strong action under uncertainty and found, in line with intuition, that stronger early action was preferred in cases where it was later learned that climate sensitivity was high and the desired warming target was low.

The question most often posed in these two-period analyses has been the effect of uncertainty and future learning on the preferred or optimal choice for immediate action. In examining these questions, studies have sought to apply to climate change insights drawn from prior theory on investment under uncertainty. When the consequences of an investment decision are uncertain but the uncertainty is expected to be resolved in the future, there is a value to delaying the decision to acquire more information, because the decision can then respond optimally to what is learned. This additional value from learning and the ability to delay decisions was formalized in the concepts of option and quasi-option value. It is closely linked to the irreversibility of decisions, because it is in the ability to avoid regret from an initial *irreversible* decision that is later found to be wrong that the option to delay the decision acquires value.[25–28]

The concepts of irreversible decisions, uncertainty, and learning are clearly applicable to climate decisions. To avoid confusion, however, it is important to specify precisely the conditions of the comparison by which uncertainty or learning is varied, especially to avoid confounding these with changes in aggregate costs or benefits of action. For example, in considering the effect of increasing uncertainty on preferred near-term climate action, many assessments suggest that the distribution of climate impacts is positively skewed, combining a high probability of moderate damages with a long right tail of potential extreme impacts. If uncertainty is introduced to an analysis by adding such an extreme possibility or increasing its probability, this shifts the distribution of outcomes and the mean toward greater damages. Absent offsetting changes, this shift will favor stronger action to avoid climate change, but this is at least partly due to the overall shift toward worse outcomes, as opposed to an effect of increasing uncertainty.

  

Examining the effect of uncertainty requires introducing it as mean-preserving spreads in climate damages or other uncertain parameters. Similarly, examining the effect of learning requires comparing situations that are the same except for the presence or absence of learning. In a two-period analysis, this means comparing the situation in which a given uncertainty is resolved before the second decision point to that in which the second decision must be made under the same uncertainties as the first.

Initial studies of these comparisons found results in line with those drawn from the investment literature: more uncertainty favors stronger near-term emission cuts, while future learning partly offsets this effect, favoring weaker near-term cuts.[23,29] The intuition for these results is that with either convex climate damages or risk aversion, increasing uncertainty in damages increases near-term mitigation to reduce the contribution of high-damage outcomes. At the same time, learning acts against this effect and favors less immediate action, so future actions can be optimally tuned to the true state of the world.

Subsequent studies have shown, however, that neither of these results is fully general. For example, in contrast to investment decisions—in which the investment is irreversible, but the decision not to invest can be reversed—irreversibilities in climate decisions can go in both directions: commitment to irreversible climate damages resulting from too little mitigation and sunk costs from investment in too much mitigation. Under these conditions, the objective function does not exhibit the strict convexity needed to give a unidirectional result. Consequently, the effects of both uncertainty and learning can go in either direction, depending on the details of which curvature and which irreversibility dominate.[30–32]

Several authors have demonstrated this potential for both uncertainty and learning to make the preferred near-term action either stricter or weaker (including the possibility that the effects of uncertainty and learning go in the same direction) and have explored how these effects vary with parameters in particular model formulations. For example, Summers and Zeckhauser[33] examined the effect of a mean-preserving increase in climate-damage uncertainty on the fraction of total two-period cuts made immediately. Webster[34] and Lange and Treich[35] both compared optimal immediate cuts under 'learning' and 'no-learning' scenarios using simple dynamic programming models, while Webster[34] repeated the comparison using the Integrated Global System Model. These studies found that the direction of uncertainty and learning depended on multiple aspects of model structure, including specification of the objective function, the identity and distributions of uncertain quantities, and on parameter values defining the curvature of the mitigation and damage cost functions. It is important to note, however, that all multi-period analyses, even those in which the effect of future learning reduces preferred near-term action, still show that some immediate action is warranted, particularly in studies using IAMs with realistic characterization of mitigation costs and climate damages. For example, Yohe et al.[36] found that an immediate carbon price of about $10 per ton was robust to a wide range of uncertainties, while Harvey[37] found that only the most extreme favorable resolution of uncertainties in climate sensitivity and the threshold for dangerous warming avoided the need for strong near-term reductions.

## CHALLENGES FOR FURTHER ANALYSES

These analyses have offered significant insights, but all make substantial simplifications to the factors affecting actual climate decisions. Of these, the two that are potentially most important, and which therefore provide the richest ground for further analysis, are the treatment of uncertainty and learning, and the treatment of linkages between decisions made at different times and constraints operating on these. These are both areas of active current work.

### Characterizing Uncertainty and Learning

Current analyses use simplified treatments of uncertainties and learning, with regard to what uncertainties are considered and how knowledge about these uncertainties is presumed to advance over time. Regarding what uncertainties are considered, most studies use probability distributions of specified model parameters such as coefficients and exponents in mitigation cost and climate damage functions. Uncertainty over alternative models or causal structures is not represented, except for a few cases that subsume these into parameter variation, e.g., by letting the distribution for a coefficient include the value zero, thereby turning off the relevant model process. In addition, a few studies have presented probability distributions for a goal or preferred action that will be known in the future, thereby abstracting from all the uncertainties in mitigation costs, climate impacts, and preferences that would determine such a goal. Regarding progress of knowledge, most studies presume autonomous resolution of parameter uncertainties over time, not requiring any expenditure or exploratory decisions to achieve this. The presumed future resolution is usually total, occurring at a fixed, known time, while some studies vary the timing or degree of resolution to examine the resultant diminution in the value of information.

There are several directions in which representation of uncertainties and learning could advance to provide more useful representation of sequential decisions to inform policy and decision-making. First, despite some efforts and progress, the connection between abstract uncertainty as represented in climate decision models and the uncertainty that characterizes current scientific, technical, and economic understanding of climate change remains weak. Scientific assessments such as the IPCC are increasingly attempting to report uncertainties quantitatively, e.g., by linking the use of textual terms such as 'likely' to specified probability ranges. Still, the mapping of such statements about current scientific understanding onto parameters in climate decision models is in most cases highly indirect and not obvious.

The two points of closest approach between these two descriptions of uncertainty are global climate sensitivity—the global mean temperature response to a doubling preindustrial atmospheric $CO_2$—and the probability of specified extreme events such as collapse of a major ice sheet. Even here, however, the connections remain underdeveloped. IPCC assessments have gradually moved from simply reporting a range for climate sensitivity to providing a qualitative description of a right-skewed distribution, plus reports of model ensemble results as collections of separate scenarios. However, these assessments have never stated a full probability distribution. Many subsequent analyses using diverse methods have developed full probability distributions, but the distributions so produced have varied widely, reflecting the diverse judgments of the individual researchers producing them. Attempts to quantify damage uncertainties remain similarly few and *ad hoc*.[38] Consequently, attempts to connect formal analysis of uncertainty in climate decision models with uncertainty as represented by current collective judgments of scientific experts remain largely conjectural.

Further work is also needed in representing how knowledge advances. Most current studies have assumed learning occurs exogenously with time, does not depend on near-term decisions, and has no cost. In Kolstad's terms,[23] learning is 'autonomous', in contrast to 'purchased' learning (acquired through costly research and development) and 'active' learning (generated by near-term investments, policies, or decisions other than just spending money, including 'learning by doing' from cumulative investment). But the actual advance of knowledge may be more limited and its mechanisms more complex than has been assumed. Learning might not be predominantly autonomous, but might instead reflect a blend of all three mechanisms. Moreover, the relative importance of the different mechanisms may differ for different types of uncertainties: e.g., it may differ between scientific uncertainties about climate change risks and technological or economic uncertainties that influence costs of mitigation and adaptation responses.

Incorporating either purchased or active learning into sequential decision studies requires broadening the choice set at each point beyond current period mitigation effort, to include some form of research effort or investment in technology. Studies that have incorporated these mechanisms into representations of technological change have found that these strongly influence estimates of future mitigation costs.[39–43] These have shown that gaining potentially valuable knowledge warrants investing in research, but the cost of acquiring the knowledge, which is itself uncertain, must be included in value-of-information calculations. Moreover, if specific near-term actions contribute to decision-relevant learning through 'learning by doing' or similar 'purchased learning' mechanisms, those actions are favored at the margin by the expected value of the information they provide. But while alternative models of learning have divergent implications for near-term action, the relative importance of different learning processes in resolving key decision-relevant uncertainties remains weakly understood. The specific implications for near-term climate action, beyond general guidance to invest in knowledge, thus remain unclear.

Another possibility requiring further exploration is that key scientific uncertainties related to climate change risks may not decrease as fast or easily as has been assumed. Several mechanisms have been proposed that might obscure or delay learning. For example, because uncertainty in climate sensitivity comes mainly from the uncertain strengths of various feedbacks that affect sensitivity nonlinearly, even large declines in feedback uncertainties will bring much smaller declines in sensitivity uncertainty.[44] Moreover, studies of uncertainty and learning have routinely assumed well-behaved distributions with thin tails, when the tails of distributions of important climate change risks may actually be fat, lending greatly increased (but unknown) probability to the extreme outcomes that dominate concern about climate change. Fat-tailed distributions would imply greatly increased value to learning about the risk of extreme outcomes, yet their structure also imposes strict limits on the ability to achieve such learning.[45–47]

  

In addition, because climate exhibits variability over years and decades and because the processes of observation, calculation, and analysis that lead to learning are themselves subject to random variation, the process of learning is itself subject to various errors. Rather than learning about specified uncertainties proceeding monotonically toward tighter distributions and closer correspondence with reality, what looks like learning can sometimes produce increasing errors. Examples of such 'negative learning' have been identified retrospectively in other contexts, including projections of ozone loss, stability of the West Antarctic Ice Sheet, and population and energy dynamics.[48] Negative learning can arise from variability in natural processes subject to observation, use of incorrect models, or other processes, and can persist for years or decades, calling into question proposals for short-term adaptation of decisions based on new observations that are presumed to be reliable.[8] Finally, climate change assessment and decisions may be subject to 'unknown unknowns', i.e., factors omitted from previous analyses because their existence or importance was not recognized. Acknowledging the possibility of these provides an alternative way to describe instances of negative learning, as well as the many instances where quantitative uncertainty in specified parameters has not decreased over time as expected.

What are the implications of these ongoing studies for near-term decisions? Since they call into question strong assumptions of decisive near-term resolution of uncertainties, their principal implication is that near-term decisions should avoid relying on such assumptions. Instead, they suggest two alternative directions, both for near-term decisions and for analyses that seek to inform them. First, they suggest that one contribution of analysis can be clarifying what future observations or other information is likely to be most useful to inform future decisions. Current analysis can seek to identify how preferred future choices would depend on changed information about currently recognized uncertainties—thereby advancing current understanding of what future decision-makers are most likely to want to know—and what current research or monitoring is most likely to improve prospects for timely (and correct) learning on these key points.

Second, these studies suggest the value of developing decision strategies that are robust to major uncertainties. Various studies have suggested that robust strategies can be identified that yield acceptable outcomes under a wide range of assumed resolution of uncertainties about climate sensitivity, impacts, and costs of mitigation, while best-estimate strategies based on specific values of uncertainties can fail badly when their assumptions are wrong.[49,50] Most approaches to robust strategies, however, involve adapting choices over time in response to new information. They consequently depend on the availability of sufficiently informative observations to shape beneficial adaptations and on the ability and willingness of future decision-makers to act on these, consistent with long-term goals. Such strategies are thus vulnerable to 'unknown unknowns' and other negative learning processes. When there is judged to be a significant risk of these, which has not been mitigated by reasonable efforts to identify more potential risk processes and improve monitoring and analysis, the design of robust strategies should seek to limit their vulnerability to these processes through their choice of what observations are used as the basis for future adaptation, made with what frequency and with what form of corroboration. The risk of these processes also suggests more general advice, to recognize that analyses and decisions are always subject to unanticipated errors and that uncertainty bounds should be drawn wider than appears necessary, to embrace the paradox of 'expecting to be surprised'.

## Characterizing the Structure of Intertemporal Choice and Constraint

While the choice set available to real climate decision-makers can be quite rich in the range of interactions potentially present among choices at different times, studies of sequential decision-making have so far used a highly simplified structure for intertemporal decisions. Decisions, usually a single dimension of mitigation stringency, are made by a single unitary actor at two fixed time points. The earlier decision only affects the later one by changing the marginal costs and benefits of alternative second-period choices. Of the various simplifications in this representation, representing just two decision points is probably the least serious. Generalizations to multiple decision points at fixed times or to continuously variable choices are clearly feasible, but are unlikely to generate starkly different results from the two-period frameworks so long as they retain the same structural elements, i.e., that decisions are not linked across time and that decision-makers expect more knowledge to be available at future decision points.

More promising directions for further study would involve representing specific linkages and interactions between choices at different times, through which today's decisions can influence future decision opportunities, constraints, payoffs, or knowledge, or interactions among these at different future times. Representing such interactions will typically require broadening the set of choices considered at each time, and may also require moving from a single-actor to a multi-actor perspective. Moreover, the diversity and subtlety of such potential choices and linkages among them are challenging to model. Yet, these interactions may be high priorities for analysis, because they may represent the strongest opportunities today's decisions have to influence the complete time path of responses to climate change.

Current decisions can influence future decisions in several ways, some inadvertent or unrecognized today and others, to varying degrees, evident and thus potentially intentional. Today's decision-makers can seek to expand or contract the set of future options available, change the incentives of future actors by changing the costs or benefits of their choices, or change the expected state of knowledge in which future decisions will be made. More concretely, today's decision-makers can articulate long-term goals or strategies, create policies, laws, or programs with various provisions for longevity or future reconsideration built into them, establish institutions or procedures that seek to bias future choices in some particular way (including devices such as endowments, trusts, or constitutional provisions that are intentionally difficult to change), or conduct research, development, or new investments that will leave an accumulated stock of physical capital, technology, or knowledge to future decision-makers.

Certain constraints or biases may operate on future decisions, which can be represented as various forms of path dependence or socioeconomic inertia.[51] Even if today's decision-makers cannot influence these processes, if they have some knowledge of how the processes operate there can be implications for preferred action today. For example, Webster[52] modeled several forms of path dependency that may restrict the flexibility of future policy adjustment. Consistent with other studies of hedging and irreversibility, path dependency of policy that limits future adjustments in a particular direction tends to favor initial movements in that direction as a hedge. For example, obstacles to future strengthening of action tend to favor stronger action today. If today's actors perceive that they have a time-limited window of opportunity for action that is unlikely to recur, they should do more today than if future opportunities for action are unconstrained. More broadly, Webster's analysis argued for the plausibility of such constraints, and thus against blithely assuming radical future policy shifts will be easy as a justification for weak action today.

Webster's analysis concerned the effect on today's decisions of future decision structures that today's decision-makers can perceive but not influence. It is also possible that today's decision-makers may be able to influence future decision opportunities. For example, today's actors may have some control over the persistence of their decisions. Private investors may respond to climate change with various mixes of shorter- and longer-lived investments, while policy-makers may specify various durations for treaty review, legislative reauthorization, assessment processes, or program funding. These decisions under uncertainty are analytically parallel to many financial decisions that have been thoroughly analyzed, in which today's actors choose between shorter- and longer-term investments or obligations (e.g., investing in a 1-year or 10-year CD or borrowing on an adjustable-rate mortgage or a 30-year fixed).

Today's actors may also enact policies that explicitly attempt to influence future choices. Merely stating default trajectories for some policy measures (e.g., a trajectory of emissions or emission prices over time), or stating requirements or targets for distant-future dates may exert rhetorical influence, and thus some degree of real influence over future decisions, even where future decision-makers have formal authority to modify any expenditure, regulation, or law enacted today. Other decisions, such as procedural requirements for future decision-makers to revisit issues or act on certain findings, establishing institutions, or creating constitutional or quasi-constitutional obligations with associated rights of action, may exert stronger influence on future decisions, even if their specific future effects may be hard to control or anticipate.

To the extent that much influence on future decisions comes from the inherited structure of the economy, technology, and capital stock, today's decisions can also exert future influence by changing these inherited stocks and thereby the marginal costs and benefits of future actions. In this respect, today's decision-makers may choose to depart from the apparent intertemporal optimal decision trajectory to exert control over future decision-makers. Examples might include investing in energy sector capital that reduces the marginal cost of future mitigation or front-loading the costs of building future capacity for low-cost response, whether mitigation or adaptation. Today's decisions regarding alternative policy mechanisms can also influence future decisions by creating constituencies with foreseeable interests in the future trajectory of the policy. Examples might include policies that create long-lived classes of assets, such as emission allowances, whose holders will have an interest in defending the future value of their assets by resisting attempts to weaken the emissions constraint that gives them value.[53,54]

In contrast to intertemporal analyses that assume either a single decision-maker over time or full cooperation between current and future actors in managing climate change, many aspects of intertemporal decision-making can be represented as strategic interactions between current and future actors. These interactions are necessarily one-way, because current and future actors cannot bargain with each other, and future actors have no way to influence current actors but must simply act in the situation that is left to them. Yet current actors' choices may be influenced in various ways by their expectations of what future actors are likely to do, or value, in two ways. Current actors might want to ensure that climate change is adequately managed over time but not trust future actors to do their part. In this case, current decision-makers might attempt to influence future choices by making investments today that lower future marginal costs, generally by making more effort and incurring more cost today than would otherwise be preferred.[55] Alternatively, current actors might assume future decision-makers will act responsibly, but seek to avoid costs themselves by pushing more of the burden onto the future, in effect giving them the 'last clear chance' to avoid serious harms.[33] These interactions are closely related to the intertemporal structure of preferences, both in how today's actors value effects at various future times and in what today's actors assume about future actors' valuations of effects over time. Today's actors' preferred choices can depend strongly on what they assume about future actors' evaluation of climate change risks and willingness to bear costs to limit climate change. These assumptions are related to the evolution over time in trade-offs between environmental damages and monetary costs, and also to future actors' expectation of how these trade-offs will vary further in the future and their trade-offs between themselves and others still further in the future. These potential interactions can have high stakes for current decisions, but have been little examined.

In addition to strategic interactions between present and future actors, a sequential decision perspective can also influence strategic interactions among current actors, e.g., among policy-makers in different nations negotiating over their respective efforts to manage climate change today. These negotiations take place under uncertainty about costs and benefits, on which various actors' assessments may diverge, as well as uncertainty about others' actions, now and in the future. In this setting, several studies using simple stylized models have suggested that introducing sequential decisions with the prospect of future learning can obstruct cooperative action. Consequently, availability of information can reduce collective welfare, making the value of the information negative—a result that is impossible in the single-actor case.[32]

Related to these strategic interactions, today's actors also have opportunities to influence future decisions by designing policies that distribute the control over future adjustment among different actors. Tradable permit systems provide an illustration, especially when permits are long lived, conferring a right to emit one unit any time the holder chooses over an extended period, rather than in a specified year. Such policies delegate substantial control over the intertemporal profile of emissions and their prices to actors operating in private markets. Such delegation can have risk-reducing benefits. For example, Webster et al.[56] calculated that international emissions trading carried substantial hedge value. But such approaches can also subject future adjustments to risks of short-term price volatility and market manipulation, thereby increasing adjustment costs and weakening required incentives for long-term investment and development of emission-reducing technologies. In contrast, policies such as short-duration emission permits, emission taxes, or conventional regulations keep control over the path of future adjustments in government hands, whether legislators or regulatory agencies. The choice of policy mechanisms is thus partly a choice of which actors are trusted to make future decisions consistent with effective long-term management of climate change. Current analyses have little to say on this choice, because they mostly examine ideal, maximally efficient policies, sometimes modified by specific limitations such as some regions delaying accession to global regimes or specified forms of path dependence limiting future adjustment. In contrast, the choice among policy mechanisms strongly implicates judgments of how much and in what ways future decisions by particular actors are likely to depart from the ideal. In principle, such departures can be incorporated into formal analyses by introducing additional uncertainties about the design, implementation, and effectiveness of policies or other decisions, but this has not yet been done.

## INFORMING CURRENT DECISIONS THROUGH A SEQUENTIAL PERSPECTIVE

Just as today's decision-makers cannot specify a complete trajectory of future climate change responses, today's analyses cannot inform such a complete future trajectory. The reason to study climate decisions, whether through formal models, scenario exercises, political and institutional analyses, or other means, is to inform current decisions. Examining the sequential character of future climate decisions is not an abstract or impractical exercise, however, because this sequential character affects preferred choices today in many ways. Analyses of sequential decisions have provided several broad insights into preferred near-term choices. For example, they have demonstrated that some level of action is preferred now under a wide range of assumptions about uncertain quantities and processes; that delay in actions to limit emissions can put many potentially desirable future trajectories out of reach; and that there is value in near-term steps to advance knowledge and take actions likely to be informative. But the debate has been less useful for informing near-term policy choices than it might have. In part, this has reflected the appropriation of analytic discussions into broader political debates over the advisability of early action, with resultant loss of precision.

Making analyses of sequential decisions more useful will require taking more account of the specific responsibilities, authority, resources, and interests of particular decision-makers. Extending lines of current work sketched in the previous section, analyses could provide additional insights into several high-priority questions of concern to current policy-makers. For example, studies are needed to help inform the appropriate balance of effort between policies promoting research and development and regulatory policies implementing immediate incentives or requirements to reduce emissions. The preferred balance will depend on the mix of alternative causal processes influencing the advance of scientific knowledge and technological capability. Studies are also needed to inform the design of strategies to promote research, development, and demonstration of low-emitting and non-emitting technologies. These choices depend in part on the structure of uncertainties presumed to be most important to future decision-makers, including information that will be most valuable in informing their decisions, and current investments and initiatives that can most effectively increase the probability of that information being available when it is needed. Studies are needed to inform decisions regarding the duration of current commitments. For private investors, this means identifying preferred portfolios of short- versus long-lived investments under specified climate-related uncertainties they face, including climate policy. For policy-makers, it means identifying analogous portfolios of durations of regulations, laws, and expenditure programs under specified uncertainties including the response to policies by private actors and markets.

Current policy-makers face decisions regarding various matters of institutional design that are likely to strongly influence the long-term policy response. For example, in conjunction with setting the duration of initial programs and commitments, current actors can also establish the structure and frequency of future policy adjustments—at least as an initial default—by specifying what dimensions of policy are considered for revision, how frequently, with what lead-times or other constraints on future changes, and subject to what procedural requirements such as required findings or inputs from expert assessments. These decisions should be informed by consideration of the balance between the costs of changing policies too frequently or with too little notice, thereby raising adjustment costs and potentially weakening incentives for long-term research and investments and the cost of changing policies too infrequently or slowly, thereby increasing the divergence from ideal policies over time. Analyses using alternative representations of the structure of relevant costs and uncertainties can contribute to informing these decisions.

Current policy-makers also face decisions regarding the broad allocation of authority and constraint between themselves and future actors, and design of specific institutions and processes to implement this division of authority. Designing adaptive systems for sequential decision-making requires asking what future conditions should be considered in making future adjustments, and thus what should be monitored and how future decisions should respond to alternative results of the monitoring. This holds for private decision-makers and policy-makers at both national and international levels. While there are unavoidable elements of speculation involved in making these decisions, the decisions do have to be made. Taking decisions beyond speculation requires analyses of alternative specific adaptive strategy designs to examine their performance under realistic alternative specifications of uncertainties, advancing knowledge, and the interests and capabilities of future decision-makers. At the same time, it is necessary to increase the robustness of such strategies to various specifications of delayed learning, negative learning, and inconsistent or suboptimal decision-making.

A sequential perspective is valuable for informing multiple types of climate-related decisions, public and private, because this structure has major implications for what near-term choices are preferred. Many aspects of current climate decisions involve subtle matters of institutional design, allocation of authority between governmental and expert bodies, current and future actors, or construction of politically feasible policies. These aspects pose severe challenges for formal modeling and analysis. Still, there are many opportunities to enrich current analytic approaches, including exploratory and illustrative analyses of uncertainties such as these, to usefully inform current climate decisions in light of the large-scale structure of sequential decision-making.

## REFERENCES


1. Intergovernmental Panel on Climate Change. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC; 2007.
2. Intergovernmental Panel on Climate Change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, eds. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC; 2007.
3. National Research Council, Panel on Limiting the Magnitude of Future Climate Change. *Limiting the Magnitude of Future Climate Change*. Washington, DC: National Academy Press; 2010.
4. National Research Council, Panel on Advancing the Science of Climate Change. *Advancing the Science of Climate Change*. Washington, DC: National Academy Press; 2010.
5. Weyant J, Davidson O, Dowlatabadi H, Edmonds J, Grubb M, Parson EA, Richels R, Rotmans J, Shukla P, Tol RSJ, et al. Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce J, Lee H, Haites E, eds. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Chapter 10. Cambridge: IPCC/Cambridge University Press; 1996, 367–396.
6. Parson EA, Fisher-Vanden K. Integrated assessment models of global climate change. *Annu Rev Energy Environ* 1997, 22:589–628.
7. Rotmans J, Dowlatabadi H. Integrated assessment of climate change: evaluation of models and other methods. In: Malone S, Rayner E, eds. *Human Choice and Climate Change*. Vol 3. Columbus OH: Battelle Press; 1997.
8. Kelly DL, Kolstad CD. Integrated assessment models for climate change control. In: Folmer H, Tietenberg T, eds. *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*. Cheltenham: Edward Elgar; 1999.
9. Hope C. A fast and simple model of global warming from greenhouse gas emissions. *Research Papers in Management Studies 1992–1993*. Cambridge: Judge Institute in Management Studies; 1992.
10. Dowlatabadi H, Morgan MG. Integrated assessment of climate change. *Science* 1993, 259:1813.
11. Webster MD, Forest C, Reilly J, Baliker M, Kicklighter D, Mayer M, Prinn R, Sarofim M, Sokolof A, Stone P, et al. Uncertainty analysis of climate change and policy response. *Clim Change* 2003, 61:295–320.
12. Keller K, Bolker BM, Bradford DF. Uncertain climate thresholds and optimal economic growth. *J Environ Econ Manage* 2004, 48:723–741.
13. Smith SJ, Edmonds JA. The economic implications of carbon cycle uncertainty. *Tellus B Chem Phys Meteorol* 2006, 58:586–590. doi:10.1111/j.1600-0889.2006.00217.x.
14. Caetano MAL, Gherardi D, Ribeiro G, Yoneyama T. Reduction of $CO_2$ emissions by optimally tracking a pre-defined target. *Ecol Model* 2009, 220:2536–2542.
15. Jarvis A, Young P, Leedal D, Chotai A. A robust sequential $CO_2$ emissions strategy based on optimal control for atmospheric $CO_2$ concentrations. *Clim Change* 2008, 86:357–373.
16. Jarvis A, Leedal D, Taylor C, Young P. Stabilizing global mean surface temperature: a feedback control perspective. *Environ Model Softw* 2009, 24:665–674.
17. Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R. Scenarios of greenhouse gas emissions and atmospheric concentrations. *Synthesis and Assessment Product 2.1 Sub-Report 2.1A*. U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC: Department of Energy, Office of Biological & Environmental Research; 2007.
18. Nordhaus WD. *A Question of Balance: Weighing the Options on Global Warming Policies*. New Haven, CT: Yale University Press; 2008.
19. Richels RG, Rutherford TF, Blanford GJ, Clarke L. Managing the transition to climate stabilization. *Clim Policy* 2007, 7:409–428.
20. Manne AS, Richels RG. *Buying Greenhouse Insurance: The Economic Costs of $CO_2$ Emission Limits*. Cambridge, MA: MIT Press; 1992.
21. Manne AS. Hedging strategies for global carbon dioxide abatement: a summary of poll results—EMF 14 subgroup—analysis for decisions under uncertainty. Nakicenovic N, Nordhaus WD, Richels R, Toth FL, eds. *Climate Change: Integrating Science, Economics, and Policy*, IIASA CP-96-1. Austria: IIASA; 1996, 207–228.


  

22. Yohe G. Exercises in hedging against extreme consequences of global change and the expected value of information. *Glob Environ Change* 1996, 6:87–101.
23. Kolstad CD. Looking vs. leaping: the timing of $CO_2$ control in the fact of uncertainty and learning. In: Kaya Y, Nakicenovic N, Nordhaus WD, Toth FL, eds. *Costs, Impacts, and Benefits of $CO_2$ Mitigation*, IIASA CP-93-2. Austria: IIASA; 1993, 63–82.
24. Hammitt JK, Lempert RJ, Schlesinger ME. A sequential-decision strategy for abating climate change. *Nature* 1992, 357:315–318.
25. Arrow KJ, Fisher AC. Environmental preservation, uncertainty, and irreversibility. *Q J Econ* 1974, 88: 312–319.
26. Dixit AK, Pindyck RS. *Investment Under Uncertainty*. Princeton, NJ: Princeton University Press; 1994.
27. Henry C. Investment decisions under uncertainty: the irreversibility effect. *Am Econ Rev* 1974, 64: 1006–1012.
28. Epstein LG. Decision-making and the temporal resolution of uncertainty. *Int Econ Rev* 1980, 21:269–283.
29. Nordhaus WD. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press; 1994.
30. Ulph A, Ulph D. Global warming, irreversibility, and learning. *Econ J* 1997, 107:636–650.
31. Pindyck RS. Irreversibilities and the timing of environmental policy. *Resour Energy Econ* 2000, 22: 233–259.
32. Kolstad CD, Ulph A. Learning and international environmental agreements. *Clim Change* 2008, 89:125–141.
33. Summers L, Zeckhauser RJ. Policymaking for posterity. *J Risk Uncertain* 2008, 37:115–140.
34. Webster MD. The curious role of learning in climate policy: should we wait for more data? *Energy J* 2002, 23:97–119.
35. Lange A, Treich N. Uncertainty, learning and ambiguity in economic models on climate policy: some classical results and new directions. *Clim Change* 2008, 89:7–21.
36. Yohe G, Andronova N, Schlesinger M. To hedge or not against an uncertain climate future? *Science* 2004, 306:416–417.
37. Harvey LDD. Uncertainties in global warming science and near-term emission policies. *Clim Policy* 2006, 6:573–584.
38. Mastrandrea MD, Schneider SH. Probabilistic integrated assessment of ‘‘dangerous’’ climate change. *Science* 2004, 304:571–575.
39. Goulder L, Schneider S. Induced technological change and the attractiveness of $CO_2$ abatement policies. *Resour Energy Econ* 1999, 21:211–253.
40. Goulder L, Mathai K. Optimal $CO_2$ abatement in the presence of induced technological change. *J Environ Econ Manage* 2000, 39:1–38.
41. Edenhofer O, Lessman K, Kemfert C, Grubb M, Kohler J. Induced technological change: exploring its implications for the economics of atmospheric stabilization. Synthesis report from the innovation modeling comparison project. *Energy J* 2006, 27(Special Issue 1):1–51.
42. Weyant J, Olavson T. Issues in modeling induced technological change in energy, environmental, and climate policy. *Environ Model Assess* 1999, 4:67–85.
43. Jaffe AB, Newell RG, Stavins RA. Technology policy for energy and the environment. In: Jaffe AB, Lerner J, Stern S, eds. *Innovation Policy and the Economy*, Vol 4. Cambridge, MA: National Bureau of Economic Research; 2004, 35–68 (chapter 2).
44. Roe GH, Baker MB. Why is climate sensitivity so unpredictable? *Science* 2007, 318:629–632.
45. Weitzman ML. On modeling and interpreting the economics of catastrophic climate change. *Rev Econ Stat* 2009, 91:1–19.
46. Weitzman ML. Reactions to the Nordhaus Critique, March 17, 2009, www.economics.harvard.edu/faculty/weitzman/files/ReactionsCritique.pdf. (Accessed July 3, 2010).
47. Nordhaus WD. An analysis of the dismal theorem. *Cowles Foundation Discussion Paper No. 1686*. New Haven, CT: Yale University; 2009.
48. Oppenheimer M, O’Neill BC, Webster M. Negative learning. *Clim Change* 2008, 89:155–172.
49. Lempert RJ, Schlesinger ME, Bankes SC. When we don’t know the costs or the benefits: Adaptive strategies for abating climate change. *Clim Change* 1996, 33:235–274.
50. Lempert RJ. Shaping tomorrow today: near-term steps toward long-term goals. *Proceedings of a Conference*, Rand Corporation; 2009. http://www.rand.org/pubs/conf_proceedings/CF267/. (Accessed July 1, 2010).
51. Ha-Duong M, Grubb MJ, Hourcade JC. Influence of socioeconomic inertia and uncertainty on optimal $CO_2$-emission abatement. *Nature* 1997, 390:270–273.
52. Webster MD. Incorporating path-dependency into decision-analytic methods: an application to global climate-change policy. *Decis Anal* 2008, 5:60–75.
53. Polborn S. The political economy of carbon securities and environmental policy. Economics Department, Penn State University, January 29, 2010. www.personal.psu.edu/sep211/pol_econ_carbon_securities_polborn.pdf. (Accessed July 10, 2010).
54. Grossman GM, Helpman E. Protection for Sale. *Am Econ Rev* 1994, 84:833–850.
55. Tol RSJ. Short-term decisions under long-term uncertainty. *Energy Econ* 1998, 20:557–569.
56. Webster M, Paltsev S, Reilly J. The Hedge value of international emissions trading under uncertainty. *Energy Policy* 2010, 38:1787–1796.


  

## FURTHER READING

Füssel H-M. Modeling impacts and adaptaion in global IAMs. *WIREs Clim Change* 2010. doi:10.1002/wcc.40.

Jones RN, Preston BL. Adaptation and risk management. *WIREs Clim Change* 2011. doi:10.1002/wcc.97.

National Research Council (NRC). *Adapting to the impacts of climate change*. Report of the Panel on Adapting to the Impacts of Climate Change, America's Climate Choices. Chapters 2 and 4, 2010. http://www.nas.edu.

Weyant JP, De La Chesnaye FC, Blanford G. Overview of EMF-21: multigas mitigation and climate policy. *Energy J* 2006, 1-32.

  