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Classical decision rules and adaptation to climate change*

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One approach to rationalising policies for addressing potentially catastrophic climate change when such policies may prove unnecessary is to suppose the policies provide a form of social insurance even in the presence of pure uncertainty. Then, provided the policies are effective, such insurance can be justified as a precautionary or minimax response. Even if the policies are potentially ineffective however, intervention can be justified as an attempt to minimise the regret experienced by future generations. This reasoning extends to justify 'all weather' policies provided such policies always reduce policy costs. If, however, policy decisions provide 'all weather' benefits in only certain states of the world, this rationale breaks down. Minimising regret can establish a case for 'mixed' policy responses provided adopting a policy mix precludes the chance that intervention will fail altogether. Precautionary policies and policies which minimise regret are computed for a simple, dynamic, adaptive climate change planning problem and sufficient conditions for policy maker pessimism provided.

Key words: climate change, adaptation, decision rules, regret, minimax

1. Introduction

The derivation of adaptation policies for dealing with possible consequences of climate change is considered when, as seems realistic, a policy maker has close to non-existent probability information about the likelihood of various effects and events. For example, in considering the temperature and rainfall implications of climate change on biodiversity resources there is considerable pure uncertainty about both the scale of climatic changes and impacts of given changes on biodiversity (Clarke 2007).

Our approach to this problem eschews use of probability information and instead uses classical decision theory ideas of minimax and minimax regret (Chisholm and Clarke 1993; Bretteville 1999) to motivate policy. The quest is to determine robust decision rules that avoid catastrophically large costs or opportunity cost losses and which account for the possibility that policy may prove ineffective and climate change costs may prove to be less expensive than feared.

The specific problem is the derivation of anticipatory, strategies to facilitate adaptation to climate change. Policies with uncertain effectiveness are adopted now to try to ameliorate consequences of severe climatic change

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should these occur in the future. Section 2 sets out a decision model where, in the absence of an intervention, climate change may or may not have catastrophic consequences and where policy may or may not be effective. Section 3 shows how arguments for precautionary and regret minimising responses depend on the prospects for policy ineffectiveness. Section 4 examines 'all weather' policies. Section 5 shows that classical decision approaches struggle to recognise the virtues of mixed policies. Section 6 examines adaptive management in a two-period model. Finally Section 7 provides conclusions.

2. Basic model

Ignore intermediate climate change impacts and suppose that such changes either have negligible (zero) impacts or very substantial, though known, catastrophic impacts costing society $L > 0$ dollars. Suppose, initially, that a unique, preferred technology for adapting to climate change is known and costs $C > 0$ dollars. Suppose $L > C$ so the cost of the policy is less than that of the catastrophe – there is otherwise no interesting social decision problem. The only uncertainty about the adaptation technology is whether or not it is effective in adapting to climate change. This uncertainty interacts with whether or not climate change itself has negligible or substantial impacts.

Following Chisholm and Clarke (1993), focus on these extreme states of the world where catastrophic consequences of climate change either do or do not occur. If they occur, situations where the preferred adaptation technology is or is not successful must also be considered. There are thus three, known policy-relevant states of the world:

S_1 = a catastrophe is averted as a consequence of a successful adaptation policy,
S_2 = no catastrophe occurs,
S_3 = a catastrophe occurs *even though* an adaptation policy action has been taken.

Given the probabilities of these events $p = \text{prob}\ (S_1)$, $q = \text{prob}\ (S_2)$ and $r = \text{prob}\ (S_3)$ (where $p + q + r = 1$) the expected value of taking an adaptation policy exceeds that of not taking action provided the expected loss avoided by taking action pL exceeds the cost of the adaptation policy C so:

$$pL > C.$$

Interest here lies in approaches to this decision problem when policy makers cannot even approximately estimate p, the probability policy actions will prove worthwhile.

3. Minimax and minimax regret

Suppose policy makers are infinitely risk-averse and seek to avoid the worst possible outcome. These policy preferences are consistent with pursuing a

Table 1 Minimax payoff matrix

Minimax – minimise the worst possible outcome				
	State of world			
Policy	S_1	S_2	S_3	Minimax Payoff
Adapt	0	0	L	L
Do not Adapt	$L - C$	$-C$	$L - C$	$L - C$

minimax welfare criterion that chooses the policy with the best 'worst-case' outcome since the worst outcome lies in the set of avoided outcomes. If the choice set is binary using minimax amounts to avoiding the worst possible outcome and pursuit of minimax can be viewed as a mathematisation of what environmentalists term the 'precautionary principle' – avoiding outcomes with asymmetrically large downside possibilities. Broader interpretations of this principle can be provided (Quiggin 2005).

Given the cost of the possible catastrophe L and the associated cost of dealing with it, C, a minimax payoff matrix can be constructed for the two alternative policy options: (i) adapt – take action to initiate adaptation or; (ii) do not adapt – take no action.

The payoff matrix is illustrated as Table 1. To specify payoffs for each policy choice and state of the world a base case must be selected and assigned a base payoff. Other payoffs can then be computed as deviations from this. Suppose this base case involves taking action and dealing with a non-negligible climate problem successfully and assign base payoff value 0.

According to the minimax criterion of eliminating the worst possible eventuality it is best in this situation to take no policy action because, with S_3 possible, this avoids the worst case possibility of incurring policy cost C simultaneously with the catastrophic climatic cost L.

If, alternatively, policy makers are sure the policy adopted will have a successful impact if needed, so state of the world S_3 never arises, then minimax supports the sensible outcome of always adapting since $L > C$ and $C > 0$.

The optimal minimax policy response when policy effectiveness is uncertain is not a particularly sensible stance if, for example, policy cost is very low relative to the possible catastrophic damage. Applying this decision criterion would bind a policy maker from ever taking a policy action that might fail to avoid a disaster even if action was inexpensive.

An alternative possible approach to decision-making builds on this latter idea. The minimax-regret criterion seeks to minimise the maximum-regret future generations, with hindsight, would experience on the basis of the current generation's decision. Minimax regret focuses on large negative payoffs but also considers the upside of policy choices in terms of avoiding costs inexpensively. It therefore accounts for the opportunity costs of an incorrect

Table 2 Minimax-regret payoff matrix

Minimax regret – minimise the regret				
	State of world			
Policy	S_1	S_2	S_3	Maximum regret
Adapt	0	C	C	C
Do not Adapt	$L - C$	0	0	$L - C$

decision under the implicit assumption that the different states of nature are equally probable (Baumol 1977, pp. 463–464).

The minimax-regret payoff matrix for the policy problem posed is illustrated as Table 2. Here if one adapts and either the state of the world S_2 or S_3 occurs, resource C would have been wasted which is the regret. If one did not adapt but the disaster occurred then cost L occurs but the amount saved is the cost of the action C so regret is $L - C$. The minimax-regret criterion then selects the policy leading to least regret.

This gives the appealing conclusion that, in seeking to minimise the regret experienced, one takes action to avoid the threat if $L - C > C$ or if $L > 2C$. Thus one must weigh up the climate induced losses against the cost of policy. In particular, take action if – as seems sensible – C is small relative to L. This seems a sensible 'insurance' heuristic in the absence of probability information. Take out insurance at cost C if this cost is low relative to the possible cost of the catastrophe. The robustness of this heuristic is examined in later sections.

Note that if there are several distinct targets of adaptation (e.g. biodiversity, agriculture, sea level changes) and an equal number of linearly independent policy tools to address these targets (e.g. investment in conservation corridors, water resource investments, coastline protection) that all targets should be able to be pursued by the instruments (Tinbergen 1970). If policies only impact on a single target then the analysis above can be applied separately to each instrument given its policy cost and the specific possible loss. If, however, policies are interdependent in the sense that (i) incurring the costs of one might impact on the costs of implementing another via cost synergies and (ii) pursuing one policy may impact on several policy targets, the present analysis is not so straightforward. The issues are discussed in Clarke and O'Mullane (2008) but some insight is provided by looking at policies with 'all weather' impacts.

4. All weather policies

As Bretteville (1999, p. 18) suggests the case for minimax-regret policies strengthens if 'all weather' policy options are available that yield *some* return even if either (i) the climate change disaster does not occur or (ii) if it does occur but the policy proves useless in offsetting it.

Table 3 Minimax and minimax-regret payoffs with an 'all weather' policy

Minimax – minimise the worst possible outcome				
	State of world			
Policy	S_1	S_2	S_3	Payoff
Adapt	0	0	L	L
Do not Adapt	$L - C + B$	$B - C$	$L - C + B$	$L - C + B$
Minimax regret – minimise the regret				
	State of world			
Policy	S_1	S_2	S_3	Maximum regret
Adapt	0	$C - B$	$C - B$	$C - B$
Do not Adapt	$L - C + B$	0	0	$L - C + B$

For example, consider biodiversity conservation policies such as tree planting or limiting the clearing of existing forests to reduce salinity problems. These are 'all-weather' policies since while they are advanced to improve the resilience of conserved biodiversity they have spin-off benefits to agriculture irrespective of whether climate change costs are catastrophically large or less than expected.

Suppose that agricultural sector benefits B occur as a spill-over consequence of spending C in addressing climate change. Suppose the base case to arise when a disaster occurs and action is taken to successfully deal with it, providing benefits B. Assigning that payoff 0 the respective payoff matrices for minimax and minimax-regret policy criteria are in Table 3.

Now the minimax case for not taking action is weakened to $B < C$ which will be satisfied in situations of interest. If $B > C$ then the biodiversity adaptation policy would be independently justified in terms of promoting agricultural benefits irrespective of effects on climate change. It would then always be optimal to adapt since this policy has positive net benefits for agriculture independent of any advantage in limiting impacts of climate change. The minimax rule rejecting the case for action would then implausibly be independent of the size of possible catastrophic damages.

The minimax-regret case for adaptation is strengthened to $L < 2(C - B(C))$, creating a stronger case for activist intervention than without 'all weather' benefits (when the case required $L < 2C$) but one that, again, sensibly balances the cost of a disaster against those of taking action net of spill-over benefits to agriculture. In short, 'all weather' benefits that accrue irrespective of the eventual state of the world intensify the case for activism on the basis of a minimax-regret criterion. Such 'all weather' benefits simply lower the policy costs so this is a straightforward result.

Having 'all weather' policy options mutes some of the impacts of sunk costs in assessing policies for adapting to climate change in a 'real options' framework (Pindyck 2007). Here there are traditionally two 'irreversibility' forces that drag a policy maker in opposite directions with respect to timing and intensity of climate change adaptation (or mitigation) policy. Sunk-cost effects provide incentives to delay action, and reduce the intensity of initial actions when taken, because the policy maker can learn about the future by waiting. Other irreversibilities, such as species extinctions, make the policy maker want to bring actions forward and increase the intensity of action. The net effect of these opposing forces is a priori indeterminate.

But 'all weather' options reduce sunk costs because they offer a payoff irrespective of the eventual state of the world. Hence they lead to more weight being placed on irreversibilities, such as extinction possibilities, that increase the case for action. This can overturn the bias others have deduced for waiting by motivating a prompter, more intense policy response (Pindyck 2000).

The above way of accounting for 'all weather' benefits is restrictive and unrealistic since spill-over payoffs occur irrespective of the state of the world and hence only effectively reduce net costs. Alternative types of policies, some with and some without 'all weather' benefits, are not considered. One extension is to allow for different types of policies with respect to their specificity. Consider relatively 'inexpensive' specific policies (cost C_l) that can only ever be effective in addressing climate change and alternative, more expensive, all weather policy options (cost $C_h > C_l$) that also deal effectively with climate change, should it eventuate, but provide an 'all weather' benefit B only if dramatic climate change effects do not arise. Assume that pursuing greater policy flexibility involves additional cost and again that there is some prospect that neither type of policy will work effectively.

Now take as the base case the situation where adaptation is not made and where a severe climate change problem eventuates. Assign this payoff 0. If the policy maker had instead adapted in that situation using the no-regrets policy the benefit obtained is $C_h - L < 0$ while, using the specific policy, the net benefit is $C_l - L < 0$. If the climate change problem did not occur, an extra benefit B would be generated with the 'all weather' policy but not with the specific policy. Finally, if policy was to prove ineffective, no extra costs would be incurred if the 'do not adapt' policy was adopted although policy costs would be incurred if specific or 'all weather' policy actions were taken.

Again the minimax policy is to not adapt given that policy may be ineffective: See Table 4. If this option is excluded then policy choice will be the specific rather than the 'all weather' policy since $C_l < C_h$. The 'all weather' benefits B are irrelevant since, the situation where these come into play, is never the most costly possible outcome.

Now consider pursuit of the minimax-regret policy. The policy of not adapting would involve regret of $L - C_l$ if climate change did occur while pursuing the 'all weather' policy would involve regret in not taking the cheaper specific policy thereby saving $C_h - C_l$. No regret would attach to using

Table 4 Minimax and minimax-regret payoffs with alternative policy options

Minimax – minimise the worst possible outcome

	State of world			
Policy	S_1	S_2	S_3	Payoff
Adapt (specific)	$C_l - L$	$C_l - L$	C_l	C_l
Adapt (all weather)	$C_h - L$	$C_h - L - B$	C_h	C_h
Do not Adapt	0	$-L$	0	0

Minimax regret – minimise the regret

	State of world			
Policy	S_1	S_2	S_3	Maximum regret
Adapt (specific)	0	C_l	C_l	C_l
Adapt (all weather)	$C_h - C_l$	$C_h - B$	C_h	C_h
Do not Adapt	$L - C_l$	0	0	$L - C_l$

the cheaper specific policy since it would eliminate the catastrophe at minimum cost. Using an 'all weather' policy when there is no need involves a policy cost less the all-weather benefit while in using the specific policy only the policy cost is relevant. Finally, if policy is ineffective and climate change occurs anyway the only regrets are the direct policy costs. The maximum regrets corresponding to each policy choice are set out in the final column of the lower tableau in Table 4.

Note that the 'all weather' policy can never be the maximum source of regret since $C_h > C_l$. The policy of adopting a specific adaptation policy is again optimal if $C_l < L - C_l$ or if $L > 2C_L$ as in Section 3 of this article. This is somewhat counterintuitive since the 'all weather' policy has intuitive appeal. It occurs because the policy maker is only concerned with minimising disappointment. Therefore they never place weight on 'all weather' benefits that arise if the worst that can happen does not in fact occur since this is not a source of maximum regret.

The minimax-regret decision criterion sensibly balances policy costs with possible costs of inaction. It does not however, assist in selecting between policies on the basis of their ability to provide robust rewards in several states of nature. If an 'all-weather' policy was only marginally more expensive than a specific adaptation policy then intuition would motivate selecting it if it yielded a significant enough benefit in the situation where a catastrophic loss did not occur.

If as in Section 2 we knew the probabilities p, q, r, it is easy to see that the 'all weather' adaptation policy will be selected if:

$$C_h < C_l + qB.$$

Table 5 Minimax-regret payoffs with a possible mixed response

Minimax regret – minimise the regret				
	State of world			
Policy	S_1	S_2	S_3	Maximum regret
Adapt (specific)	0	C_l	C_l	C_l
Adapt (all weather)	$C_h - C_l$	$C_h - B$	C_h	C_h
Mixed policy	$\alpha(C_h - C_l)$	$\alpha C_h + (1 - \alpha)C_l - \alpha B$	$\alpha C_h + (1 - \alpha)C_l$	$\alpha C_h + (1 - \alpha)C_l$
Do not adapt	$L - C_l$	0	0	$L - C_l$

This sensibly compares the respective costs as well as the expected value of the ‘all weather’ payoff should a catastrophe not eventuate. Of course, implementing this rule this requires probability information. It seems difficult to provide a classical decision rule that motivates reasonable ‘all weather’ adaptation options if probability information is unavailable.

5. Mixed policies

Employing a mixture of policy responses makes sense if policies are independent and decision makers are risk averse and uncertain of the effectiveness of individual policies (Brainard 1967). This is related to the portfolio theory idea of ‘not putting all your eggs in one basket’. This defensive policy stance, while intuitive, seems unjustifiable in classical decision theory terms. In a minimax framework the worst that could happen is that all policies are employed but all fail to stop a catastrophe. Hence ‘mixed’ or combination policies will never be employed on the basis of the minimax decision approach.

In thinking about the scope for minimax-regret motivations for ‘mixed’ policy responses a further row can be added to the lower tableau in Table 4 above (to provide Table 5) indicating costs associated with a mixed response that draws on specific and adaptive policies. Suppose this response has costs $\alpha C_h + (1 - \alpha)C_l$ where $1 \geq \alpha \geq 0$ is a parameter reflecting the weight policy makers place on each of the respective policies. For example, if the total policy package consists of n identical ‘all weather adaptations’ and m identical ‘specific policy adaptations’, costing c_h and c_l, respectively, then adaptive and specific policies can be combined as the mix $C_h = \alpha n c_h$, $C_l = (1 - \alpha)m c_l$, respectively. If a mixed policy had been employed and it dealt with warming successfully the regret would be the difference between the mixed response costs and the costs of the cheaper specific policy C_l which is $\alpha(C_h - C_l)$. If the policy was unnecessary it is reasonable to suppose the ‘all weather’ policy now yields side benefits αB so the regret is $\alpha C_h + (1 - \alpha)C_l - \alpha B$. If losses, L, are large enough the maximum regret always occurs when climate change occurs but is unaffected by the mixed policy.

Table 6 Minimax-regret payoffs when a mixed response is always effective

Minimax regret – minimise the regret				
	State of world			
Policy	S_1	S_2	S_3	Maximum regret
Adapt (specific)	0	C_l	C_l	C_l
Adapt (all weather)	$C_h - C_l$	$C_h - B$	C_h	C_h
Mixed policy	$\alpha(C_h - C_l)$	$\alpha C_h + (1 - \alpha)C_l - \alpha B$	na	$\alpha C_h + (1 - \alpha)C_l - \alpha B$ if $C_l - \alpha B > 0$
Do not adapt	$L - C_l$	0	0	$L - C_l$

Since $C_h > C_l$ the choice of the specific adaptation policy, rather than the mixed policy, is confirmed if $\alpha C_h + (1 - \alpha)C_l > C_l$ which is true since $\alpha(C_h - C_l) > 0$. Thus the minimax-regret option is the specific adaptation policy, never the mixed policy.

It is interesting to consider the value of the minimax-regret criterion in the last situation if employing the mixed policy eliminates *any* possibility of the adaptation policy being ineffective, so S_3 never arises. This secure policy outcome is often what is sought with a mixed response. Now the maximum regret with a specific policy is C_l, the regret occurring when there is no climate change problem. The maximum regret with an 'all weather' policy remains C_h. The mixed policy has maximum regret in state of the world S_2 if $\alpha(C_h - C_l) < \alpha C_h + (1 - \alpha)C_l - \alpha B$ which is possible whenever $C_l > \alpha B$ when the maximum regret is $\alpha C_h + (1 - \alpha)C_l - \alpha B$. Otherwise the maximum regret is $\alpha(C_h - C_l)$. These possibilities are illustrated in Table 6.

If L is large the policy 'do not adapt' will not have the minimum-regret property. Since $C_h > C_l$ the 'all weather' adaptation policy will never be appropriate either. Will the mixed policy ever dominate the specific adaptation policy so that a case for mixed policies can be provided by minimax regret?

Consider two situations:

- $C_l - \alpha B > 0$. Now the mixed policy is the minimax-regret policy if $\alpha C_h + (1 - \alpha)C_l - \alpha B < C_l$ or, equivalently, when $C_h < C_l + B$, so the difference between the high and low cost adaptation benefit is less than the cost of the side benefit with the high cost 'all weather' policy, which is possible with the restrictions so far imposed.
- $C_l - \alpha B < 0$. Now the mixed policy is optimal if $\alpha(C_h - C_l) < C_l$ or $C_l > (\alpha/(1 + \alpha))C_h$, so the regret from the mixed policy is less than the cost of the low cost adaptation policy. This is again possible.

Hence if utilising a mixed policy eliminates the prospect that policy will be ineffective a mixed policy response can be the minimax-regret policy response.

6. An integrated adaptive planning model

The preceding decision framework is now modified to allow for secondary adjustment dynamics to promote adaptation should initially selected policies turn out to be inappropriate. The setting we have in mind is Australia's Murray-Darling Basin where policies for adapting to climate change are being developed both for biodiversity and agricultural outputs (see the contributions in Crase 2008).[1]

Consider a social planner with welfare function SWF(agric, bio) defined on agricultural output 'agric' and levels of biodiversity conservation 'bio', each indexed in some way. Assume this function is homothetic, monotonically increasing with strictly convex indifference curves. Suppose, the economy has a production possibility frontier $F(\text{bio}, \text{agric}, T) = 0$ for agriculture and biodiversity that depends on climate indexed as T. For given T, F is concave in the output variables.

Consider this economy over two periods ('now' and 'the future'). Suppose that, in the future, temperature increases can alter production possibilities and that:

(1) Initially the economy operates on its efficiency frontier but, from the viewpoint of social welfare, produces too little biodiversity and too much agriculture. Biodiversity has public good attributes provides external benefits to agriculture so it has been undersupplied.

(2) Without an adaptive policy response, one of two future states of the world occurs:

State S_L: climate change has significant ('large but not catastrophic') effects on the economy but with temperature change effects on agricultural outputs lower than those on unmanaged biodiversity. This makes sense in a fragmented landscape where biodiversity cannot readily relocate in response to climate change but where farmers can more readily adapt agricultural production techniques (Clarke 2007).

State S_{SQ}: climate change has insignificant economic impacts (the 'status quo').

The optimal steady state with fixed climate T_0 is described by the maximisation of SWF(bio, agric) with $F(\text{bio}, \text{agric}, T_0) = 0$. Suppose optimum outputs are $y^* = (\text{bio}^*, \text{agric}^*)$ yielding social welfare SWF*. Since markets have not realised this optimum due to the public good/externalities character of biodiversity, actual outputs are $y_0 = (\text{bio}_0, \text{agric}_0)$ with $\text{bio}_0 < \text{bio}^*$ but with $\text{agric}_0 > \text{agric}^*$.

If state S_L eventuates and climate changes to T_1, agricultural production possibilities are reduced a little but biodiversity falls markedly to

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[1] Much government policy effort is devoted to the MDB. At the time of writing important current CSIRO information was at <www.csiro.au/science/ps1f2.html> and by the Department of the Environment, Water, Heritage and the Arts at <www.environment.gov.au/water/mdb/index.html>.

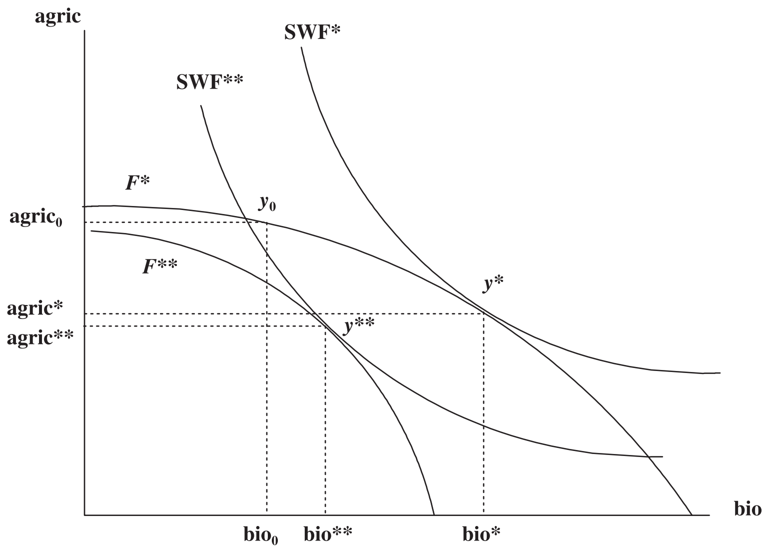

Figure 1 Agricultural and biodiversity planning with climate change.

y^{**} = (bio**, agric**) with SWF** < SWF*. Assume that $\text{bio}_0 < \text{bio}^{**} < \text{bio}^*$ so the initially over-depleted biodiversity stock is less than the stock that is optimal with strong climate change effects on biodiversity. Effects on the economy of alternative degrees of climate change are described in Figure 1.

Initially the economy under-provides biodiversity by $\text{bio}^* - \text{bio}_0 > 0$ and over-provides agriculture by $\text{agric}_0\text{–agric}^* > 0$. If severe climate change occurs, the social under-provision of biodiversity compared to first period output falls to $\text{bio}^{**} - \text{bio}_0$ and the social over-provision of agriculture increases to $\text{agric}_0\text{–agric}^{**}$. These changes occur because climate change has less impact on previously over-provided agricultural outputs than on under-provided biodiversity. The slope of the tangent to SWF* at y^* is steeper than the tangent to SWF** so marginal biodiversity output values increase with severe climate change.

6.1 Integrated policies

To analyse climate change adaptation policies, policy criteria are needed as is a quantification of the adjustment costs involved in changing land use.

Suppose that, whatever the initial policy, it is always successfully achieved *before* the future climate becomes known. Thus initially targeted biodiversity provisions are always realised in the period referred to as ‘now’. A further policy is then taken if anticipated climatic conditions do not eventuate.

Assume that adjustment costs referred to mainly reflect costs of *adding to* stocks of biodiversity. Thus assume agricultural sector adjustments can be made at low cost. To add realism, suppose all policy costs incurred, after the future climate of the world becomes clear, are discounted by $0 < \beta < 1$.

The two benchmark policies considered are:

Policy 1: An ***optimistic policy*** which assumes climate change will not involve substantial economy-wide productivity effects so that only current distortions need be addressed. Then the economy should shift from y_0 to y^* involving adjustment costs, say $C^+(\text{bio}^* - \text{bio}_0)$, of increasing biodiversity from bio** to bio_0. If the presumption that climate change will not involve substantial costs is not realised then, since initial biodiversity targets are met, a subsequent discounted cost of converting land back into agriculture of $\beta C^-(\text{bio}^* - \text{bio}^{**}|S_L)$ must be incurred to achieve the steady state optimum with climate change, namely y^{**}.

Policy 2: A ***pessimistic policy*** assumes that climate change will have substantial productivity costs. Optimally these costs involve expanding biodiversity resources by incurring costs, say, $C^+(\text{bio}^{**} - \text{bio}_0)$. If the assumption that climate change is severe turns out to be erroneous, so there are no economy-wide productivity effects, the stock of biodiversity needs to subsequently be further increased at discounted cost $\beta C^+(\text{bio}^* - \text{bio}^{**}|S_{sq})$.

This latter policy involves a more determined shift of economic activity out of agriculture and into conservation. It suggests that, post-climate change, the overexploited natural environment a society inherits may be closer to its socially optimal level of provision simply because the natural environment, along with agriculture, has become less productive.

6.2 Minimax policies

Choice between the policies advanced is supposed to depend on their respective costs. With probability information about the respective states of the world this can be resolved by examining expected minimum cost. Without probability information one can seek the minimax policy.

What constitutes policy failure in this setting? The first phases of both pessimistic and optimistic policies could fail to achieve policy targets but, as these occur in the absence of significant climate change effects, this seems unlikely. It would reflect a *pre-existing* failure in current conservation planning and knowledge. The interesting prospect of policy failure occurs if climate change is much more severe than even envisaged by the pessimistic policy so a catastrophic loss, L, occurs after the first phase of either adaptive policy irrespective of the policy having been taken. To conform with Section 2 refer to the state of the world where this catastrophe occurs despite either type of adaptation as S_3.

The costs associated with each of the two active and the 'do not adapt' policies given the respective states of the world are in Table 7. Here it is assumed that, if society does not adapt at all and significant climate change occur, costs are L_1 while if does not adapt but insignificant climate change costs occur it costs L_2. Finally, even without adaptation there is the chance of

Table 7 Costs of optimistic and pessimistic policies

Policy	S_L	S_{SQ}	S_3	Maximum
P_1(optimistic)	$C^+(\text{bio}^* - \text{bio}_0) + \beta C^-(\text{bio}^* - \text{bio}^{**} \mid S_L) - L$	$C^+(\text{bio}^* - \text{bio}_0) - L$	$C^+(\text{bio}^* - \text{bio}_0)$	$C^+(\text{bio}^* - \text{bio}_0) + \beta C^-(\text{bio}^* - \text{bio}^{**} \mid S_L)$
P_2(pessimistic)	$C^+(\text{bio}^{**} - \text{bio}_0) - L$	$C^+(\text{bio}^{**} - \text{bio}_0) + \beta C^+(\text{bio}^* - \text{bio}^{**} \mid S_{sq}) - L$	$C^+(\text{bio}^{**} - \text{bio}_0)$	$C^+(\text{bio}^{**} - \text{bio}_0) + \beta C^+(\text{bio}^* - \text{bio}^{**} \mid S_{sq})$
Do not adapt	$L_1 - L$	$L_2 - L$	0	0

a disastrous climate change costing L where $L > L_1 > L_2$. Take as the base case the situation where adaptation does not occur but where a catastrophic event occurs.

The minimax policy is again not to adapt since the worst that can happen is a catastrophic climate event which makes either active policy useless. Then relative costs of optimistic vs. pessimistic policy are irrelevant since these policies are irrelevant.

If there is confidence the optimistic and pessimistic policies *will* eventually realise their objectives then S_3 can be eliminated and the policy choice involves selecting between optimistic, pessimistic and ‘do not adapt’ policies. Further supposing that costs of either an optimistic and pessimistic policy fall short of the respective costs of not taking action, choice centres on these two policies alone.

Assuming there are constant costs in investing in additional biodiversity adaptation the pessimistic policy P_2 is the minimax policy if and only if:

$$\begin{aligned} &C^{+}(\text{bio}^{**} - \text{bio}_0) + \beta C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{sq}) \\ &< C^{+}(\text{bio}^{*} - \text{bio}_0) + \beta C^{-}(\text{bio}^{*} - \text{bio}^{**}|S_L). \end{aligned} \tag{*}$$

Otherwise the optimistic policy will be the minimax policy. The four terms in this expression are discussed, in turn:

$C^{+}(\text{bio}^{**} - \text{bio}_0)$ measures the cost now of moving towards long-term biodiversity targets, assuming severe climate change eventually occurs. This is the first phase of a pessimistic policy and is less costly than pursuing statically optimal biodiversity targets because long-term biodiversity targets are less ambitious. A relatively small expansion of biodiversity resources is sought along with a substantial reduction of land use in agriculture when the cost of making adaptations is low because climate change has not yet occurred. This is a relatively low cost policy and most costs will be born by farmers moving out of agriculture.

$\beta C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{sq}})$ is the discounted cost of being mistaken with a pessimistic policy and having to restore substantial biodiversity and to a less extent agriculture because climatic change is less severe than expected. This policy revision is made under favourable climatic conditions – severe climate change did not occur – and there are present value savings in biodiversity conservation effort because it is deferred. The cost is relatively low.

$C^{+}(\text{bio}^{*} - \text{bio}_0)$ is the ‘large’ cost incurred in meeting current static biodiversity targets in one swoop. Current land use inefficiencies are myopically addressed. This first phase of an optimistic policy will be more costly than pursuing long-term targets because it is much more ambitious in terms of sought biodiversity targets. These costs will be large compared to the initial phase of the pessimistic policy and largely publicly borne.

$\beta C^{-}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{L}})$ is the discounted cost of mistakenly pursuing the optimistic policy. This is the cost of cutting back conservation effort and marginally reducing land used in agriculture under unfavourable climatic conditions. This will have low policy cost, first because it is discounted and, second, because adverse climate change will promote the natural destruction of biodiversity resources automatically so the main conservation efforts is a ‘holding operation’ on a reduced set of biodiversity resources.

Since most adjustment costs are associated with varying biodiversity levels the presumption must be that the pessimistic policy is the minimax policy. Initially it provides lower costs than the optimistic policy and, should it need to be reversed, this occurs under the favourable climatic conditions enjoyed initially with an optimistic policy and its costs are deferred.

This can be reasoned more formally. Since we have assumed constant costs in conserving extra biodiversity there are no scale economies in implementing biodiversity conservation. Thus costs of hitting optimistic biodiversity targets can be split into costs of hitting pessimistic targets plus costs of moving from pessimistic to optimistic targets. The latter equal current costs of doing the same thing when a planner realises they have been excessively pessimistic, so:

$$C^{+}(\text{bio}^{*} - \text{bio}_{0}) = C^{+}(\text{bio}^{**} - \text{bio}_{0}) + C^{+}(\text{bio}^{**} - \text{bio}^{**}). \qquad (^{**})$$

Furthermore, that most costs of making adaptations relate to biodiversity conservation, the costs of shifting from pessimistic to optimistic targets now equal the then current cost of making this move once it is known that an unduly pessimistic climate change future was forecast:

$$C^{+}(\text{bio}^{*} - \text{bio}^{**}) = C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{sq}}). \qquad (^{***})$$

Here restoration of additional land with a mistaken pessimistic policy occurs under the same climatic conditions as an optimistic policy taken initially. Substituting Equation (***) into Equation (**) and substituting in Equation (*) the condition for the pessimistic policy to be the minimax policy is:

$$(\beta - 1)\,C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{sq}}) < \beta C^{-}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{L}}).$$

This is satisfied whenever $\beta < 1$ or whenever the future is discounted since the left-hand-side of this expression is then negative while the right-hand-side is positive. In this case the optimal minimax policy is the pessimistic policy of assuming the worst. This policy avoids the need for an eventual costly reversal of policy stance whereby land converted to biodiversity initially must be later converted back to agriculture and defers the cost of increasing biodiversity stocks from bio** to bio*.

Moreover in policy terms this case is stronger still if one holds the plausible belief that climate change is likely to be severe and likely to have an impact.

This finding is robust even if complementarities between agriculture and biodiversity services vanish so outputs become perfect substitutes. The only requirement for the result to go through is that, post-climate change it is technically easier to provide agricultural services so the slope of the linear transformation curve becomes steeper. Nor would the result change significantly if climate change increased, rather than reduced the productivity of agriculture provided biodiversity productivities diminish more as a consequence of the change.

6.3 Minimax-regret policies

It is also of interest to consider minimax-regret policies as analysed in Table 8. The regret experienced in undertaking an optimistic policy when significantly costly climate change occurs is the extra policy cost of taking a revisionary second period adjustment. Similarly the regret from undertaking a pessimistic policy when the outcome is optimistic is the extra policy cost that results from the wrong assumption of pessimism. If a pessimistic or optimistic policy is untaken when that policy *is* required there is no regret. There is also no regret when no policy is taken and it would not have worked anyway. If adaptive policies had not been taken when taking them would avert a loss then the regret is the respective loss less the policy cost.

With the presumption of the minimax analysis conducted above, that the pessimistic policy provides lower policy cost than the optimistic policy, the pessimistic policy remains the minimax-regret choice if:

$$L_1 > 2C^{+}(\text{bio}^{**} - \text{bio}_0) + \beta C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{sq}})$$

which generalises the earlier analysis. If the loss from failing to adapt a pessimistic policy when severe climate change occurs is low relative to the cost of undertaking the initial phase of a pessimistic policy plus the discounted cost of revising the pessimistic policy should it prove wrong it makes sense to be pessimistic even if no policy will be effective.

Finally, the case for pessimism can be readily put in an expected cost setting by assuming specific probabilities. If $\text{prob}(S_L) = p$ and $\text{prob}(S_{\text{sq}}) = 1 - p$ and, accepting Equation (**), the expected cost of a pessimistic policy will be lower than the expected cost of an optimistic policy if:

$$pC^{-}(\text{bio}^{*} - \text{bio}^{**}|S_L) > (1 - p)C^{+}(\text{bio}^{*} - \text{bio}^{**}|S_{\text{sq}}).$$

This is satisfied if the probability of a catastrophic event multiplied by the cost of reversing an optimistic policy exceeds the probability of not having a catastrophe multiplied by the cost of reversing a pessimistic policy. It is difficult to infer whether this is likely because the crucial probability p is unknown. For policy pessimism to be optimal here a relatively high probability of substantial climate change is required together with substantial policy costs of ultimately needing to reverse an optimistic view of the world.

7. Conclusions

Policies for helping biodiversity adapt to climate change include building wildlife corridors to link up different reserve areas and facilitate natural species migrations; increasing the size of existing public reserve areas to increase environmental resilience, relocating endangered species and using captive breeding programs.

Land use policies involving diversion of large tracts of land to corridors and reserves might well prove to be high cost policies though they offer side benefits of improved agricultural values should such investments prove unnecessary because climate change is less severe than expected. Relocating endangered species and captive breeding programs might be less expensive but have no side benefits in the event they prove unnecessary.

Simple minimax decision rules only provide a case for dealing with climate change by employing adaptation policies if the effectiveness of policy is assured. Moreover, from a precautionary perspective, provided policy is known to be effective, an adaptation policy response should always be taken if the possible damage from not taking action exceeds the policy cost. Minimax does not provide a sensible policy heuristic when there is the prospect of policy ineffectiveness since policy action is never taken now even if policy costs are negligible relative to possible catastrophic losses.

An alternative decision criterion is the minimax-regret rule that seeks to minimise the regret experienced across all possible future states of the world. Even with the possibility that policy may be ineffective, the highest costs now arise when a catastrophic cost could have been avoided at low cost. A decision to proceed with an adaptive policy is now appropriate if policy costs are low, specifically less than half, of policy costs.

'All weather' benefits that provide benefits irrespective of the state of the world lower net policy costs. The minimax case for not making a precautionary response is reversed in the extreme case where the 'all weather' benefit is greater than cost even in the absence of a climate change problem so that there is an independent case for pursuing it. However the minimax-regret case for pursuing active policy is strengthened by the existence of 'all weather' benefits since now the cost of taking action is always reduced.

An interesting feature of 'all weather' policies in a broader dynamic context with dynamic learning about costs and benefits, is that such policies reduce 'sunk cost' motivations for delaying policy actions.

If different types of adaptation policies are admitted, namely, specific inexpensive policies and more expensive 'all-weather' policies, then pursuing a minimax-regret policy inevitably steers choice towards specific policies irrespective of the rewards more flexible policies offer should non-catastrophic climatic outcomes eventuate.

Thus the sensible insurance implications of utilising the minimax-regret decision criterion do not help in selecting sensibly between alternative adaptation technologies. Even if 'all weather' policies provide large side benefits with no serious climate change there is a limited case for them.

Similarly classical decision rules struggle to recognise the virtues of mixed policy strategies drawing on both specific and 'all weather' policies. There is only a case for a mix of specific and 'all weather' policies if pursuing the mix precludes the possibility that policy fails overall.

Further extensions in using classical decision rules could allow for biodiversity protection against climate change effects to be contingent on the scale of investment in adaptation to suggest something more specific about how much should be spent on adaptation.

Finally, a simple model of integrated planning for biodiversity and agricultural sector adaptations to climate change is provided. If policies once introduced are known to be successful then, most plausibly, the minimax policy is to assume the worst and to conserve biodiversity by maintaining existing biodiversity resources and by converting socially excessive agricultural holdings and land that will become socially excessive as a consequence of severe climate change. Then if climate change proves less problematic than anticipated, expand conservation effort. This case extends into a minimax-regret setting where adapting a pessimistic policy stance is optimal if the costs of each possible phase of the program in aggregate are low relative to the costs of not taking action.

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