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ECONOMICS, ECOLOGY AND THE ENVIRONMENT

Working Paper No. 199

**Marine Ecosystems and Climate Change:
Economic Issues**

by

Clem Tisdell

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Clem Tisdell²

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¹ This is a draft of a chapter for a book by C.A. Tisdell, 'Economics and Environmental Change: The Challenges We Face' being prepared for publication by Edward Elgar. It is being distributed for possible feedback to the author.

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The *Economics, Environment and Ecology* set of working papers addresses issues involving environmental and ecological economics. It was preceded by a similar set of papers on *Biodiversity Conservation* and for a time, there was also a parallel series on *Animal Health Economics*, both of which were related to projects funded by ACIAR, the Australian Centre for International Agricultural Research. Working papers in *Economics, Environment and Ecology* are produced in the School of Economics at The University of Queensland and since 2011, have become associated with the Risk and Sustainable Management Group in this school.

Production of the *Economics Ecology and Environment* series and two additional sets were initiated by Professor Clem Tisdell. The other two sets are *Economic Theory, Applications and Issues* and *Social Economics, Policy and Development*. A full list of all papers in each set can be accessed at the following website: http://www.uq.edu.au/economics/PDF/staff/Clem_Tisdell_WorkingPapers.pdf

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Marine Ecosystems and Climate Change: Economic Issues

ABSTRACT

Marine ecosystems, and the services they provide, are predicted to alter considerably as a result of climate change. This paper outlines important expected alterations in these ecosystems, considers their economic consequences, and examines economic policies that may be adopted in response to these changes. In doing so, it focuses on two main cases, namely findings about the impact of ocean acidification (and climate change generally) on the Norwegian fisheries and predictions about alterations in coral reef systems. A number of theoretical issues are raised. These include the possibility that if economic impact analysis is used to measure economic value, the global economic value of coral reefs could rise as their area is reduced. This, however, is not necessarily an appropriate measure of economic value, even though it is often used for this purpose. Also the importance of taking into account the opportunity costs involved in conserving marine ecosystems is stressed. Furthermore, several dynamic aspects of variations in marine ecosystems are shown to be important for valuation purposes as well as for economic policy. Both the economics of mitigation and adjustment policies are discussed. Optimal economic policies for responding to climate change are shown to be sensitive to the dynamics of ecosystem change and are likely to vary regionally.

Keywords: climate change, climate adjustment strategies, climate mitigation strategies, coral reefs, economic valuation, ecosystem services, marine ecosystems.

JEL Classification: Q51, Q54, Q57, Q58.

Marine Ecosystems and Climate Change: Economic Issues

1. Introduction

Marine areas supply many ecosystem services of economic value to humanity. Costanza et al. (2014) estimated the value of ecosystem services provided by these areas was \$49.7 trillion US for 2011; a much lower aggregate value than in 2007. These services consist of marketed, partially marketed and unmarketed ones. For example, for the most part, their provision of fish is marketed, their tourism and recreational services are partly marketed, and their value in moderating rising atmospheric temperatures, caused by elevated levels of greenhouse gases (GHG), is unmarketed. However, rising atmospheric levels of greenhouse gases (GHG), particularly CO₂, due to well-known anthropogenic factors, are throwing the supply of marine ecoservices into disequilibrium. As a result, the economic value and supply of these services is expected to alter drastically and spatially in coming decades. Most communities which depend on marine resources for their livelihood will need to adjust to these changing conditions. Governments will need to consider whether and when they should intervene to enable affected communities to adapt to altered marine environments or if possible, to select policies to retard the pace of anticipated adverse changes in these environments.

This paper unfolds as follows: first, it outlines major changes in marine environments which are anticipated by natural scientists to occur as a result of elevated levels of GHG in the atmosphere and considers their general implications for the presence of living organisms, and for the supply of marine ecoservices. Secondly, attention is given to insights obtained from a Norwegian investigation of the economic impacts of GHG-induced changes in marine ecosystems. Third, GHG-induced losses of coral reefs and their potential economic impacts are discussed. Relevant issues involving dynamic changes in marine ecosystems are considered. Proposed policies for responding to predicted changes in marine ecosystems are then examined, and this is followed by further discussion of the findings and concluding comments.

Why is this topic important? Globally marine ecosystems have been estimated to provide a very large percentage of the flow of the economic value of ecosystem

services. Based on the estimates of Costanza (2014), it can be deduced that marine ecosystems in 2011 accounted for 39% of the aggregate economic value of the flow of ecosystem services, a total marine flow of \$49.7 trillion US. However, if their estimated flow of the value of ecosystem services from tidal marshes and mangroves is added to these figures, the total value of the flow of marine ecosystems in 2011 increases to \$74.5 trillion US, 59.7% of the global flow. Aggregate human wellbeing could be severely reduced as a result of losses in these services as a result of climate change. Furthermore, the potential distributional consequences of changes in marine ecosystems as a result of climate change are important because many communities depend heavily on marine resources for their welfare. The topic is also of significance because the discussion of it illustrates the challenges we face in developing adequate economic and ecological models to predict changes in the provision of marine ecosystem services and in their economic values as a result of climate changes. Moreover, this paper highlights the inadequacies (both from an economics and an ecological point of view) of assessing changes in the provision of ecosystem services and their economic value of examining changes in ecosystems in isolation from one another.

2. The Predictions of Natural Scientists about Changes in Marine Ecosystems as a Result of Elevated GHG-Levels

Elevated levels of GHG in the atmosphere are causing global warming (mainly as a result of increased levels of CO₂) and climate change as well as physical and chemical changes in marine environments. In turn, this is altering marine ecosystems and the populations of living organisms they support. Consequently, the supply of marine ecosystem services is changing and is expected to continue to do so as GHG-levels in the atmosphere rise. Many human communities will be worse off as a result even though some may gain economically. Predictions about the economic and social impacts of such changes are vitally dependent on the prognosis of natural scientists about the abiotic and biotic changes to be expected as a result of climate change. In order to assess their economic impacts and to identify rational policy responses, the nature, geographical location, and timing of changes in marine ecosystems attributable to GHG-emissions (and other causes) need to be identified. This is a complex and

formidable task. Therefore, it is not surprising that most scientific opinions about the dynamics and spatial aspects of changes in marine ecosystem change are subject to significant degrees of uncertainty. This results inevitably in economic assessments reliant on those informed opinions being subject to uncertainty; uncertainty which is compounded (as a rule) by shortcomings in economic data and analysis. While this does not mean that it is impossible to make useful economic assessments of the cost-benefit and economic impact issues raised by GHG-induced changes in marine ecosystems, it is important to keep in mind their likely limitations.

The first challenging aspect which might be noted is the considerable variety of marine ecosystems. Table 1 provides an initial indication of that variety. However, in practice, types of ecosystems are much more heterogeneous than indicated. For example, the type of environmental conditions experienced by coral reefs can be expected to vary geographically. This results in differences in the community of living organisms which they support. Furthermore, the functioning of many of these ecosystems is interdependent and therefore, they are not independent entities.

Table 1: An indication of the heterogeneity of marine ecosystems based on Brierley and Kingsford (2009, Table 2, p. R606)

Ecosystem identifiers	Sets of ecosystems
In coastal locations	Salt marshes, mangroves, estuaries
On rocky substrates	Rocky intertidal, kelp forests, coral reefs
On soft substrates	Sandy shores, seagrass meadows, shelf sea benthos
Vast oceanic ecosystems	Pelagic, polar and ice-edge, deep sea.

A variety of changes in marine environments are already occurring or are confidently expected to occur as a result of elevated GHG-levels in the atmosphere. These include:

- Increasing *acidification* of marine waters induced by higher levels of atmospheric CO₂. This is expected to have adverse consequences for the

survival and growth of calciferous organisms, particularly molluscs and hard corals and to a lesser extent, crustaceans.

- The area of the ocean suffering serious *oxygen depletion* is predicted to increase. Oxygen deficient areas become virtual dead zones and support few, if any, organisms of value to human beings.
- *Sea level rises* are expected as a result of global warming. This is because this warming expands the volume of water in the oceans and also melts global ice cover thereby adding to this volume. The effects on marine ecosystems depends on the speed of sea level rise; the faster and more pronounced the rise, the more difficult is it for existing ecosystems to adjust. Some coral reefs are likely to be drowned, and dislocation can be expected in mangroves, coastal wetlands and estuaries.
- *Changes* seem to be likely in *ocean circulation (currents), upwelling and the vertical (heat) stratification of oceans*. Among other things, this is likely to affect the local availability of fish.
- *Rising ocean temperatures* affects the distribution of marine species. Among other things, they can result in coral bleaching, the overgrowth of corals by algae and a likely reduction in their areal range.
- *Increasing storm frequency and severity* in some regions is expected to have adverse economic consequences. For example, mariculture is likely to be adversely impacted by increased damage to fish pens and marine-based installations and seaweed beds are more prone to destruction. Furthermore, erosion of coral reefs is likely to accelerate thereby reducing the supply of this valuable natural resource.

All of the above mentioned factors will cause the abiotic components of existing marine ecosystems to alter as a result of increased levels of atmospheric GHG and in turn, this will alter their biotic components. As a result, many existing marine ecosystems (possibly most) will be replaced by new ecosystems. However, the change will not be instantaneous and the dynamic pathways which existing ecosystems will follow in their transition are likely to vary with diverse economic consequences. Predicting their economic consequences is difficult because ecologists are uncertain about the dynamics of the adjustment of marine ecosystems in response to climate change. However,

present indications are that some countries will benefit economically from such changes, for instance, Norway. Others, such as Australia, are likely to be disadvantaged. Modelling by Armstrong et al. (2012) suggests that Norway will make economic gains as a result of an increase in available fish stocks. On the other hand, loss of coral reefs may disadvantage Australia economically and many lower income countries. Let us consider the economic modelling of Armstrong et al. (2012) for Norway and then discuss the possible economic consequences of loss of coral reefs due to climate change, ocean acidification, and other factors.

3. The Economic Impact of Climate Change and Ocean Acidification on Norwegian Fisheries

Armstrong et al. (2012) undertook the heroic task of estimating the economic impact of ocean acidification and climate change on the aggregate gross revenues generated by the Norwegian fisheries and mariculture. They estimate this for the 100-year period 2010–2110. Because they assume that the real prices which prevailed for Norwegian fish in the period 2001–2010 will continue to prevail in the period 2010–2110, their results principally depend on anticipated changes in the volume of fishing output during the focal one-hundred year period. Their findings rely primarily on the results of the meta-analysis conducted by Kroeker et al. (2010) of the effects of ocean acidification on marine organisms and to a lesser extent on the estimates of Hendriks et al. (2010). A problem of relying on such meta-estimates is that these estimates do not relate to particular regions and are aggregative in nature. They are, for example, not specific to the Norwegian exclusive economic zone (EEZ). Moreover, the estimates of changes in survival, growth and calcification of species relate to broad groupings of species, for example, ‘all’ fish, molluscs and crustaceans are considered as separate groups (see Kroeker et al., 2010, p. 1426). This ignores any variability within categories.

Armstrong et al. (2012) assume that the composition of fish species in the Norwegian EEZ does not alter over the hundred-year period they consider. However, this is unlikely to be so. Fish species appear, for example, to be altering their geographic location due to global warming and other effects of climate change. Furthermore, the dynamics of changes in fish abundance for a hundred-year period are far from certain: it

may not accord with the linear relationship assumed by Armstrong et al. in their analysis.

In their economic analysis, Armstrong et al. limit their attention to changes in the supply of provisioning services (food) expected to occur as a result of the effects of ocean acidification on Norwegian marine fish and aquaculture. They estimate the changes in the gross revenue which will be obtained when the revenue streams change for fish, molluscs and crustaceans separately and for these combined. These estimates can be regarded as being variations in the level of first-round monetary injections into the Norwegian economy. Hence, they represent a form of economic activity analysis rather than cost-benefit analysis. Estimates for best and worst case scenarios are provided for fish, molluscs and crustaceans as well as for the aggregates of their changed revenue streams. Armstrong et al. (2012) estimate that the combined total change in revenue for the period 2010-2110 in the best scenario case, is an increase of 105,059 million 2010-NOK in revenue and in the worst case, a decrease in revenue of 3,926 million 2010-NOK.

It could be argued on the basis of Laplace's principle of insufficient reason that these end-values and all those values in between are equally probable. In this case, the probability distribution of changes in total revenue is rectangular and the expected change in the gross revenue obtained in Norwegian fisheries and aquaculture is an increase of 50,566.6 million 2010-NOK for the period 2010-2110. Furthermore, given this probability distribution, the likelihood (0.06) of a negative effect is very low. Therefore, it seems highly likely (probability 0.94) that in aggregate, Norwegian fisheries and aquaculture will generate increased revenue as a result of ocean acidification.

Armstrong et al. (2012) also provide discounted values for these changed revenue streams but they do not explain their rationale for doing this. It is unclear in this context whether the discounting is assumed to indicate time-preference in relation to the current generations or the coefficient of concern of current generations for future generations.

The Norwegian results are heavily influenced by the fact that the bulk of Norway's marine food production and revenue is obtained from fish with only a small proportion

being obtained from molluscs and crustaceans. Moreover, if Laplace's principle is adopted, their estimates reveal that the expected change in revenue from mollusc and crustacean production are both negative, but small in relation to the expected increase in revenue from fish production. Nevertheless, given Laplace's principle of insufficient reason, it is highly probable (probability 0.80) that revenue generated by mollusc production will fall. The likelihood of a negative change in revenue from crustacean production is less; 0.55.

Note that even if the results of Armstrong et al. are reliable for Norway, it cannot be concluded that all countries will obtain increased revenue from marine food production as a result of ocean acidification. For example, in Australia's case, crustacean and mollusc production accounts for a high proportion of the revenue generated by its marine food production. Furthermore, it is highly likely that Australia's coral-reef based fisheries will be adversely affected. Moreover, coral reef deterioration as a result of global climate change may have an adverse impact on Australia's revenues generated by tourism.

A problem in undertaking economic analysis of this type is that ecologists are uncertain about the impacts of climate change on the biological composition of ecosystems and the dynamics of changes in these. For example, according to the modelling of Cooley et al. (2012), the lead times before mollusc productivity is adversely affected by climate change could be very long and are predicted to vary considerably between countries. They predict that virtually no reduction in mollusc production will occur until a 'transition decade' is reached in which aragonite saturation of sea water begins to fall below a critical level. Taking 2010 as the base year, their lead times vary from a minimum of 14 years for Ecuador to a maximum of 45 years in North Korea. This implies that Ecuador's transition decade would begin in 2024 whereas that of North Korea would not start until 2055. The lead times predicted for Australia and the USA are respectively 17 and 18 years and imply that their transition decade would start in 2027 and 2028 respectively.

How accurate these predictions are is difficult to tell. They indicate however, that some countries would have to prepare for a reduction in their mollusc production at an earlier stage than others. Furthermore, the nature of the impact on the productivity of molluscs

predicted by Cooley et al. (2012) differs from that assumed in the analysis of Armstrong et al. (2012) because the analysis of Armstrong et al. is based on declining mollusc productivity from 2010 onwards.

An additional limitation of current ecological knowledge about the consequences for marine ecosystems of GHG-emissions is that it is based on partial analysis. For example, the consequences of GHG-emission for marine organisms, including their location, depend on the multiple effects (listed in the previous section). Ocean acidification is just one of these effects. For the purposes of economic evaluation, the combined multiple effects of GHG-emissions need to be taken into account, not just one. For example, in the Norwegian case, what is the likelihood that fish species in its EEZ will alter and what is the probability that the primary production of available food for fish will increase or decrease due to changing ocean currents or the increased rate at which ice sheets in the Arctic are melting?

The discussion of the Norwegian case study of the consequences of GHG-emissions for marine productivity should alert us to the following: some regions and marine-based industries are likely to make economic gains whereas others will experience economic losses as a result of global environmental changes induced by rising levels of GHG. Furthermore, the state of ecological modelling makes it very difficult to predict confidently the timing and spatial patterns of change in marine productivity as a result of global warming. This compounds the difficulty of obtaining reliable estimates of the economic impact of global climate change.

4. Coral Reefs and Climate Change

Costanza et al. (2014, Table 3) argue that the value of ecosystem services per ha provided in 2011 by coral reefs was by far the highest for any biome. They also supply data to support their view that this biome recorded the greatest reduction in the annual economic global value of ecosystem services provided by any biome comparing this supply in 2011 to that in 1997. This is so if their hypotheses are accepted that (1) the global area of coral reefs more than halved in this period (and that their vacated areas were replaced by seagrass and algal beds) and (2) the estimated real price per ha of coral

reefs in 2011 provides a more suitable basis for estimating the change in the total global value of this biome than does the use of 1997 real unit values. Their method involves valuing ecosystem services in both 1997 and 2011 either by the real unit values prevailing in 1997 or those prevailing in 2011. Dollar-values for 1997 and 2011 are adjusted to the value of the US dollar in 2007.

They find on this basis, that there was a reduction in the total value of coral reef ecosystem services provided in 2011 compared to 1997 of \$10.9 trillion US. This was only offset to a relatively small extent by the estimated increase in the total value of seagrass and algal biomes. Although the real value per ha of ecosystem services provided by seagrass and algal biomes were lower than for coral areas, their total real economic value rose by \$1.0 trillion US per year. This was because of their increased areal extent based on the assumption that they replaced depleted coral-reef areas. Consequently, the decline in the net amount of the aggregate annual economic value of ecosystem services attributed to reduced coral cover is \$9.9 trillion US, given the estimates of Costanza et al. (2014).

The way in which Costanza et al. (2014) estimate changes in the aggregate value of ecosystem services provided by biomes is heavily influenced by their choice of whether to determine those based on 1997-real values per ha or to do so based on 2011-real values per ha. They favour the latter. They state ‘Given the more comprehensive unit values employed in the 2011 estimates, this is [these give] a better approximation than using the 1997 unit values, but certainly still are conservative estimates’ (Costanza et al., 2014, p. 156). However, they do not address the question of whether it would be even more appropriate to use 1997-real unit values for valuing the ecosystem services provided in 1997 and the real unit values prevailing in 2011 for valuing those services supplied in 2011. If this procedure is used, different conclusions follow from those of Costanza et al. Given this alternative approach, the aggregate economic value of the ecosystems services generated by coral reefs in 2011 is much higher than in 1997, when these values are expressed in terms of 2007-US dollars. This is so despite the area of coral reefs being more than halved. This is because the increased value of coral areas ecosystem services per unit of their remaining area more than compensates for the reduction in these areas, given the data used by Costanza et al. This result is plausible

on economic grounds, but depends on how economic value is measured. Consider how this can happen.

4.1 Why might the estimated aggregate economic value of coral reefs increase despite their global area being reduced?

Costanza et al. estimated that, based on 2007 real constant values, the value of ecosystem services provided per ha by coral reefs was \$8,364 in 1997 but in 2011, this rose to \$352,249. The 2011 figure is 42 times that for 1997. On the other hand, it was estimated that the global area covered by coral reefs in 2011 was 0.45 of that in 1997. The relative decrease in this area is far outweighed by the comparative increase in the estimated value of coral reefs per ha. Consequently, according to these estimates, coral reefs yielded annual ecosystem services of much greater aggregated global value in 2011 than in 1997. How could this be so? One possibility is that the data is faulty but there are also other possible economic reasons for this result. Consider some of these.

Two different and often conflicting approaches to economic valuations can be found in the literature. One is based on economic activity or impact analysis and the other relies on traditional economic welfare analysis. Although legitimate doubts exist about whether economic activity analysis should be regarded as a valuation technique, it is often applied as if it is and of course, it does have economic implications. While some environmental losses can increase aggregate expenditure obtained by industries reliant on affected environments, at the same time, economic welfare (based on traditional economic welfare analysis) can fall (Tisdell, 2012). Take the loss of coral reefs as an example.

In Figure 1, the Y-axis represents an index of the price of private commodities which have a high degree of complementarity with the size of the available coral reef area, X. The demand relationship for these commodities is shown by the line AD and its corresponding marginal revenue relationship is shown by the line marked AMR. Suppose that the supply of reef-related marketed commodities is proportional to the reef area. Then if initially the reef area is X_2 and subsequently reduced to X_1 , the equilibrium price of marketed reef-related commodities will rise from P_1 to P_2 . Total expenditure on these commodities will increase, given that the reef area falls from X_2 to X_1 . Total

expenditure on these commodities rises because marginal revenue is in its negative range when $X > X_0$. Consequently, loss of the reef area stimulates economic activity in reef-related industries. However, consumers' surplus falls because it now costs more to obtain reef-related commodities which are marketed. Depending on the spatial nature of reef loss, areas where there has been little or no loss of reefs can expect to obtain increased income as a result of reef loss elsewhere. This is so even if global economic welfare is reduced. In addition, global expenditure on marketed reef-related commodities could rise.

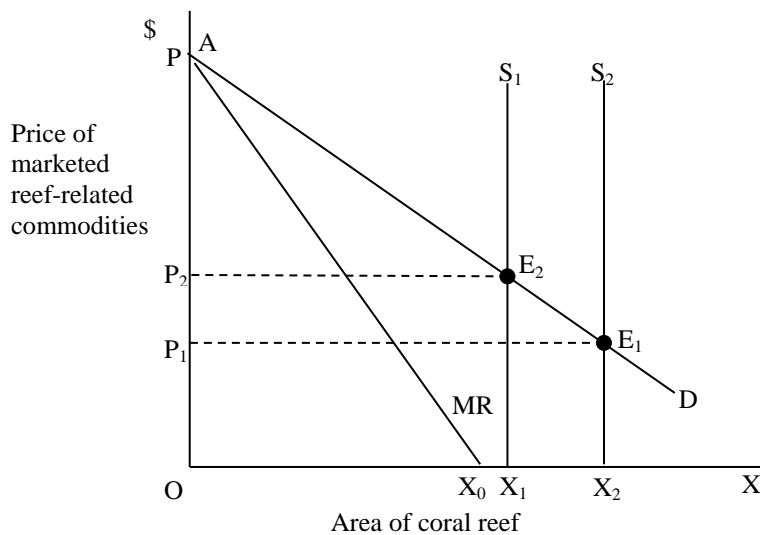


Figure 1: An illustration that as a result of a reduction in the global area of coral reefs, total expenditure on marketed reef-related commodities may rise.

The relationship in Figure 1 implies that total expenditure on reef-related commodities as a function of the area of coral reef is of an inverted U-shape and reaches a maximum at X_0 . If initially, $X > X_0$, some reduction in X will increase total expenditure but it will decline for further reduction in X once $X < X_0$. In the latter case, both total expenditure and consumers' surplus will decrease.

If the demand schedule for marketed reef-related commodities shifts upwards, other

things being held constant, this will increase their price, total related expenditure and may increase consumers' surplus despite a fall in reef area. However, consumers' surplus will be lower than it would have been had the reef area not been reduced.

The above analysis does not take account of the economic value of non-marketed services associated with coral reefs. There is considerable evidence that this constitutes the major part of the value of some coral reef systems, such as the Great Barrier Reef (Stoeckl et al., 2014). Now if the sum of the marginal valuations of the area of coral reefs is positive for its non-marketed attributes, then a fall in its area will reduce the aggregate value of its non-marketed components, other things being held constant. For example, if the line ABC in Figure 2 represents the sum of the marginal valuation of the public good attributes of the reef area, a fall in this area from X_2 to X_1 (the quality of the intact reef constant) will reduce economic value by an amount equivalent to the hatched area. On the other hand, if at the same time as the area of reef is reduced, the aggregate marginal valuation of its non-marketed attributes rises say to DEF (because of increased incomes, increased education or other factors) the aggregate economic value of available reef area may increase. For example, depending on how much the marginal evaluation curve shifts upward, the dotted area in Figure 2 can exceed the hatched area. Nevertheless, the total non-marketed value of the reef will be lower than it would have been in the absence of the loss in size of the reef. In the case illustrated, it is less than it would have been by an amount equivalent to the area of quadrilateral BCFE.

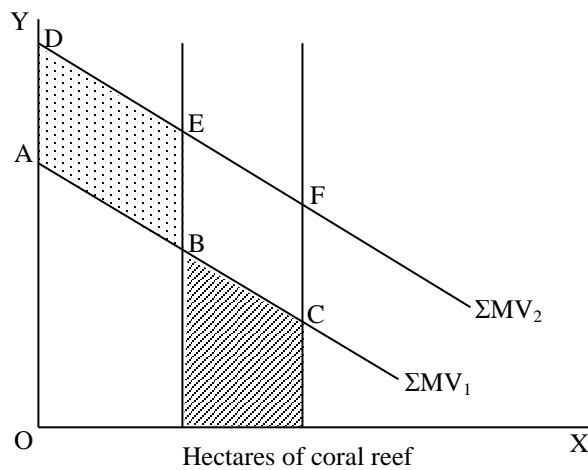


Figure 2: Possible changes in the non-marketed economic value of a coral reef ecosystem as a function of its size, the quality of surviving reef assumed to be constant

Traditional welfare economics provides clear guidelines about the impacts on economic welfare of ecosystem loss. It postulates that if the collective marginal use plus non-use value of an ecosystem is positive as a function of its area or quality, any reduction in these variables will reduce its aggregate economic value. On the other hand, changes in the level of economic activity (expenditure) set in train by this loss are not a reliable guide to changes in economic welfare. For example, as the discussion surrounding Figure 1 indicates, rising aggregate expenditure consequential to ecosystem loss may be associated with reduced economic welfare collectively. This is so even if some groups benefit from the increased expenditure which is shown to rise in the particular case illustrated. It is also worth noting that per ha economic values of ecosystems estimated by Costanza et al. (2014) and by de Groot et al. (2012) are the averages of marginal values. They are based on meta-values calculated for selected (limited) reef areas. This raises two potential problems. It is possible that on the whole, these economic values have only been estimated for the most valuable reefs. If so the estimates will overstate values per ha for coral reefs in aggregate. This is a potential benefit transfer problem (Rolfe and Windle, 2012). A second problem arises given that the values used in these studies are marginal values because mean marginal values are not mean average

aggregate values. Multiplying marginal values per ha of an ecosystem by its total area will only provide a reliable guide to its aggregate economic value if marginal and average values of the ecosystem are a constant function of its area and equal. This is effectively assumed in the above mentioned studies. However, the above economic analysis implies that this assumption is unlikely to be satisfied. Furthermore, Costanza et al. (2014) suppose that coral reef areas (and other ecosystem areas) which were lost in the period between 1997 and 2011 transited entirely from one type of ecosystem to another. However, the discussion in Section 6 of this paper indicates that such an assumption is ecologically suspect.

These observations are not meant to deprecate the above mentioned pioneering attempts to provide economic estimates of the economic values of coral reefs and other ecosystems. Nevertheless, they do indicate that one can only have limited confidence in their reliability.

5. Opportunity Costs, Coral Ecosystem Loss and Changes in Economic Value and Welfare

Most studies of the economic consequences of the loss of coral reefs are limited to the reduction in the economic value of these reefs alone. They often do not take account of the value of ecosystems which replace them. Usually these are not worthless. Secondly, and more importantly, they fail to take account of the economic value of anthropogenic activities which are the drivers of such losses. In other words, they ignore opportunity costs. When all these economic values are taken into account (despite a fall in the economic value of coral reefs due to their loss), the aggregate economic value of economic and environmental changes associated with this loss can be, but need not be, positive. This can be so even though the allocation of resource use or utilization of ecosystems is not ideal from a collective economics point of view. This is not to suggest that no serious economic deficiencies exist in human use of natural ecosystems. They do because of the existence of market failures and other identifiable problems. However, it is irrational and unscientific when assessing the economic consequences of a change in a particular ecosystem to focus only on the alteration in *its* economic values. Consider this matter in more detail.

As pointed out above, Costanza et al. (2014) provide evidence to indicate that the global economic value of coral reefs fell by \$10.9 billion US between 1997 and 2011. On the other hand, they assumed that seagrass and algal biomes replaced the areas vacated by coral reefs and that the global value of this biome increased by \$1.0 trillion US. Consequently, the net change in the value of the area once occupied by coral reefs was \$9.9 trillion US. Apart from whether or not their assumption about the dichotomous nature of marine ecosystem change is ecologically accurate, this figure of \$9.9 trillion US does not measure the change in the aggregate value of human activities and developments associated with this change.

Loss of coral reefs can be attributed to multiple factors of which elevated levels of GHG in the atmosphere is just one. Terrestrial developments, such as agriculture extension and intensification and growing urbanization in watersheds which drain into coral reef systems, also take their toll on reefs because nutrient levels and sediment increase in reef areas as a result of water run-off. These are considered to be major problems in conserving the Great Barrier Reef, even though they are not the only anthropogenic problems of concern. However, it is undeniable that terrestrial economic developments have economic value. Consequently, the main issue which needs to be addressed is whether the extra economic value obtained as a result of terrestrial development and activity exceeds any economic loss which it generates by altering marine ecosystems.

Figure 3 provides a crude representative of the relevant economic problem. There the relationship OAB represents the net annual economic value generated by a marine area in relation to the level of terrestrial economic activities and developments. The marine area may but need not consist entirely of the same biome. The terrestrial activities could include those increasing the emission of GHG. In this particular case, it is assumed that up to level x_1 , there is complementarity between the economic value of the marine area and terrestrial economic development and activity. The relationship OCD represents the annual economic value generated as a result of terrestrial activity and development which impacts on the environment of the focal marine area. OEF indicates the total annual economic value obtained from the focal marine area plus that flowing from terrestrial economic activity and development. Note that the drawing is not to scale but is constructed so as to highlight the critical relationship.

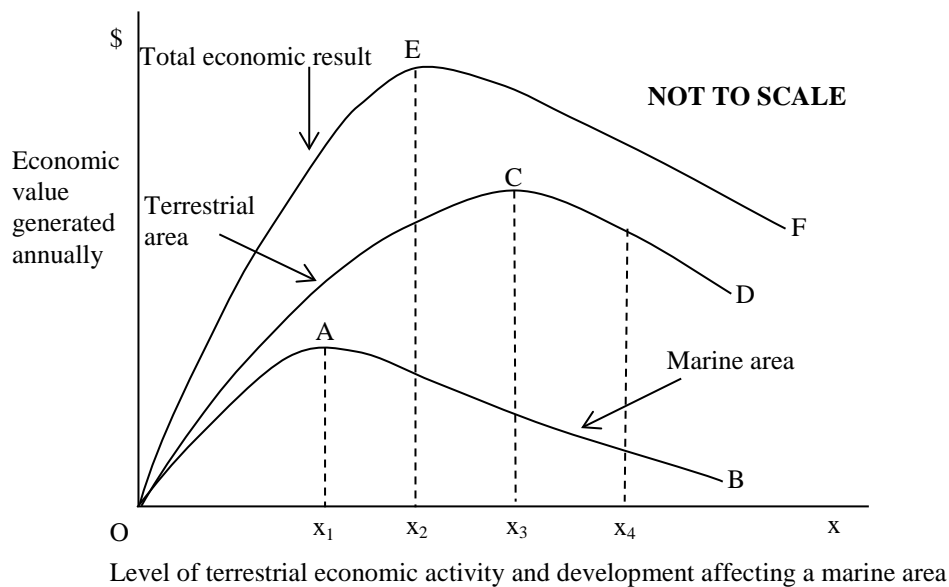


Figure 3: An illustration of the importance of taking into account opportunity costs when evaluating the economics of changes in marine ecosystems.

It is assumed that neither the relevant marine area nor the terrestrial area contribute economic value in the absence of terrestrial economic development. With increasing terrestrial economic activity and development, the flow of the economic value from the terrestrial area and the associated marine area both increase until $x = x_1$. After that, due to negative environmental spillovers from terrestrial development, the economic value of ecosystem flows from the marine area begins to decline. However, the economic flow of value from terrestrial activity and development continues to increase until x reaches the level of x_3 . The combined flow of economic value obtained from this relevant terrestrial area and marine area reaches a maximum for the level of terrestrial activity and development of x_2 . At this point the marginal increase in the flow of value from terrestrial activity and development equals the marginal reduction in the flow of economic value from the focal marine area.

If the relationships in Figure 3 represent social economic values, then the optimal degree of terrestrial economic activity and development is x_2 . Compared to the situation prevailing at x_1 , it is socially optimal to degrade the focal marine area to some extent.

However, market and political failures may result in terrestrial activity and development being substantially in excess of x_2 (for example, at x_4) resulting in economic welfare being lower than is attainable. The extent to which this is happening is the major economic issue which needs to be addressed in considering environmental change. It is uneconomic to adopt a policy which maximizes the economic value of the flow of ecosystem services from a marine area by treating it as an independent entity. This is because to do so ignores opportunity costs.

The illustration in Figure 3 assumes a steady state situation. Consequently, it ignores sustainability issues and the dynamics of changes in ecosystems. The dynamics of ecosystem changes (particularly of marine ecosystems) in relation to stresses is complex and uncertain. This creates serious complications for the economic valuation of the consequences of climate change. Let us consider briefly some aspects of the dynamics of marine ecosystem change.

6. The Dynamics of Changes in Marine Ecosystems and Consequences for Economic Valuation

In order to satisfactorily determine the economic consequences of changes in ecosystems, it is necessary to pay particular attention to the trajectories of these changes. These are usually more complex and uncertain than is assumed in contemporary economic assessments of these changes (for example, that of Costanza et al., 2014). For instance, coral reefs seem to be more resilient to heat stress than is commonly supposed and this influences the way in which they alter the composition of these reefs and the timing of their alterations.

6.1 The adaptability of marine ecosystems to climate change – the example of coral reef ecosystems

Ecologists have found that not all areas of coral are equally susceptible to global warming and heat stress and that some recover from bleaching events rather rapidly. Consequently, in these areas, coral reefs continue to be the dominant ecosystems. Ecological reasons for this resistance can include the following:

1. Coral species (or varieties) present in the area which are more resistant to heat stress multiply to replace less heat-resistant ones;
2. Heat-resistant coral species and symbionts may migrate to the area from elsewhere.
3. Darwinian selection may favour species and varieties which are more tolerant of heat stress;
4. Some corals may exhibit genetic plasticity in response to heat stress. To some extent this epigenetic factor is Lamarckian in nature. It implies that some corals undergo genetic transformation in response to heat stress and that the genetic inheritance of their offspring makes them more resistant to heat stress than their parents.

The above factors can influence the trajectories of the presence of coral reefs and their economic consequences. Moreover, the time at which each of these factors is likely to become a major influence on the composition of species in a reef area can be expected to vary. For example, factors (1) and (2) may dominate prior to factors (3) and (4). It is therefore, probable that the biological diversity of some coral reef areas will initially decline in response to heat stress (that is, following bleaching) and then subsequently increase in biodiversity compared to their nadir. Consequently, their economic value may change in a similar pattern. This is not to deny that some areas of coral reefs may be replaced 'permanently' by different ecosystems.

Scientific evidence exists to support the hypothesis that coral reef systems can exhibit considerable adaptability to climate change, although the composition of coral reef species may alter. For example, Adjeroud et al. (2009) found that coral assemblages in Moorea, French Polynesia showed significant resilience following one cyclone and four bleaching events between 1991 and 2006. Although the presence of turf algae increased considerably following these events, it was unable to dominate the reef system for very long. The reef returned to its pre-disturbance coral cover within a decade. However, the composition of the coral community changed. There was an increase in the presence of *Porites*, the cover of *Acropora* returned to pre-disturbance levels but the presence of *Montipora* and *Procellipora* was reduced. Therefore, this coral reef exhibited a high degree of resilience but changed its composition of coral species. Similarly, Roff et al. (2014) found that populations of *Porites* corals in the Rangiroa Atoll, French Polynesia,

showed remarkable ability to recover from mass coral bleaching despite initial populations experiencing significant partial mortality. The offspring of more heat-resistant numbers of *Poritos* which survived the bleaching event rapidly re-colonized the skeletal remains of members succumbing to bleaching.

In the above cases, it seems likely that reef resilience is primarily due to Darwinian selection *in situ*. Furthermore, in some cases, persistence may be achieved by the migration of coral species that show greater resistance to heat stress or their symbionts (Ortiz et al., 2014). Moreover, epigenetic changes may occur in some corals which increase the adaptability of their populations to climate change. Mumby et al, Online Appendix (2011) state, in this regard: “It is known or assumed that sublethal stress induces temporal gene expression that allow cells to acquire cytoprotection or more permanent structural changes to enable organisms to survive stressful conditions that are normally lethal.”

Of course, the above scientific findings do not imply that coral reef systems are impervious to climate change. They do, however, imply that the responses can be quite varied. Undoubtedly, some coral-dominated systems can be replaced permanently by an algal dominated system due to environmental changes attributable to climate change and the adverse effects of regional anthropogenic stresses, such as elevated levels of nutrients and sediments in sea water due to land-based economic activities. Therefore, an existing marine ecosystem may change from one type to another. Consider some of the dynamics of such adjustments and their implications for economic valuation.

6.2 *The ‘flipping’ of marine ecosystems to new equilibria*

Climate change and other stressors are liable to throw coral-dominated ecosystems into disequilibrium. One can imagine two alternative possible stable equilibria for areas currently dominated by coral reefs. If stress is kept below some threshold they may remain in that state but should it reach high enough levels they may gravitate towards algal dominated systems (Hoegh-Guldberg et al., 2007, p. 1739). Even if global environmental change cannot be controlled, it may be possible by managing other stressors to prevent or delay the transition of a coral-dominated area to an algal dominated one. For example, Hoegh-Guldberg et al. (2007) suggest that by allowing the

population of reef-grazing fish to increase in parts of the Caribbean (by reducing the catch of fish which consume algae), this can delay or prevent coral reefs from becoming algal dominated for some time. However, they do not explore the economics of adopting such a policy.

Depending upon where coral reefs are located, other stresses can be potentially reduced to lower the speed at which areas of coral reefs stressed by climate change can alter to algal dominated ones. For example, the run-off of water from terrestrial economic activities (such as agriculture) in the Great Barrier Reef region stresses coral in some areas and favours algal growth. This is because it increases the level of nutrients and sediments in several areas where corals now exist. In other words, these terrestrial activities generate negative environmental externalities because of their adverse impacts on coral reefs. The economics of policies to reduce these stresses will be considered later in this paper (see Figure 6 and surrounding discussions).

It was noted above that in some circumstances, hard corals show considerable ability to recover from events commonly associated with global warming. This ought to be given greater attention in considering economic policies to cope with global warming. The trajectories of changes in marine ecosystems generated by climate change are important for determining several aspects of economics and economic policy. Different trajectories have very different economic consequences, change economic valuations and alter the nature and timing of appropriate economic policies. For example, the modelling of Armstrong et al. (2012) of the effect of ocean acidification on mollusc productivity differs from that of Cooley et al. (2012). Armstrong et al. suppose that the process has already begun whereas Cooley et al. are of the view that it will not occur until several years hence, with the highly variable lead time between countries. Consequently, it may be many years before some countries experience reduced mollusc production as a result of ocean acidification. Given this time-delay, investment and re-investment in mollusc production is likely to remain profitable for several years yet in many countries. The length of life of many aquacultural projects which are commenced now will be less than the number of years before increased acidification impacts on mollusc production. Therefore, it would be irrational not to proceed with these projects in the short-term if they are profitable.

The flow of economic value from Norway’s fisheries estimated by Armstrong et al. (2012) is very sensitive to the predicted pattern of its fish productivity. For example, Armstrong et al. predict a linear relationship like ABC in Figure 4. However, it might be that the actual relationship turns out to follow a path like ABDE. In that case, factors associated with climate change initially increase the level of Norway’s fish production but subsequently they cause it to decline. Changes in Norway’s fish production will not only be influenced by alterations in ocean acidification, but probably also by factors such as changes in currents, in ocean upwelling, ocean warming and variations in the rate of melting of Arctic ice cover. This highlights the limitation of only considering the economic impact of just one environmental change associated with global warming. The combined effects of these changes can also be expected to change the composition of wild fish species in many cases, and different species may have different economic values.

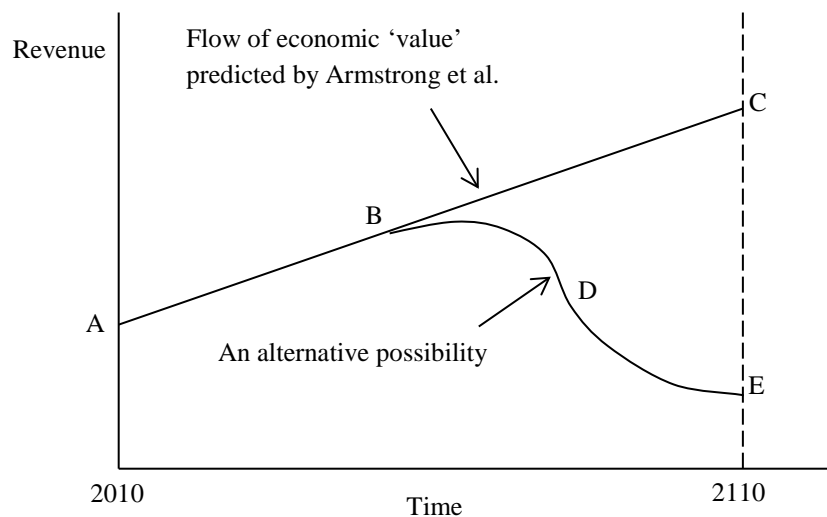


Figure 4: When all the effects of climate change (not only acidification) are taken into account, the impact on the aggregate receipts obtained by Norwegian fisheries may follow a different pattern to that predicted by Armstrong et al. (2012)

Many different trajectories for the adjustment of marine ecosystems to climate change are possible and these will have different implications for the economic values associated with these changes. Armstrong et al.'s case for Norwegian fisheries indicates continual increase in the economic value of Norwegian fisheries' production as a result of climate change. The following is just a sample of other possible changes in the economic value of a marine area as a function of time in response to climate change.

1. This may at first increase and then subsequently decline to reach a higher level than initially.
2. This may initially increase and then decline to a level lower than initially.
3. This may initially decline and then increase to a level higher than originally.
4. This may fall at first and then increase to a level less than in the first place.
5. This may initially increase then plateau at a higher level than in the beginning.

Figure 5 provides an example of the third case. It indicates that the economic value of the marine area is constant until t_1 when it then starts to be affected by climate change. Its economic value then drops until time t_2 after which it rises again. It subsequently reaches a plateau at t_3 . Subsequently, the flow of its economic value is higher than initially. The reason for this pattern could be that between t_1 and t_3 the area alters from being dominated by one type of ecosystem to being dominated by another which in the new equilibrium is more valuable than the original. However, for a period of time, the mixed ecosystem is less valuable than the one corresponding to the initial stationary state.

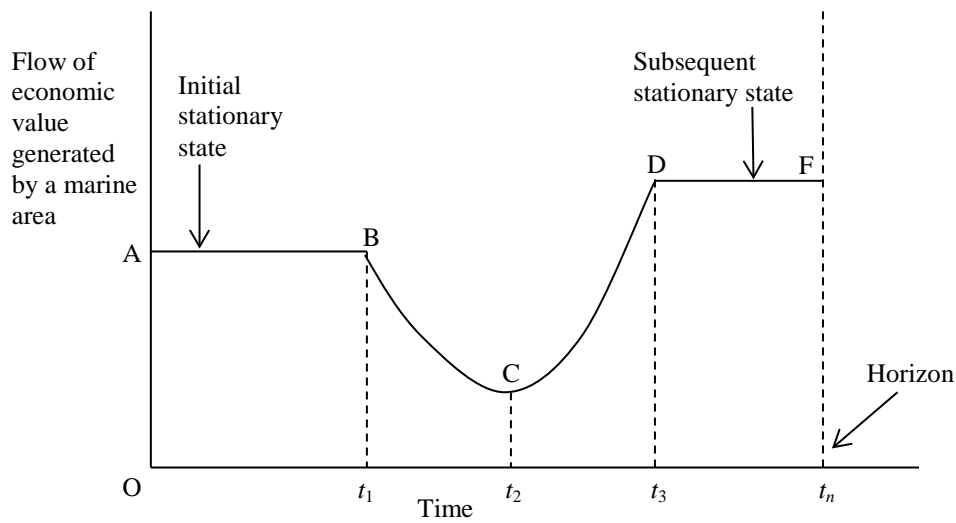


Figure 5: One of many possible patterns of change in the economic value of a marine area as a result of climate change.

It is also possible that the type of changes listed above could come about without the type of ecosystem dominating an area changing. For example, a coral reef system may still survive but as a result of climate change it might become less diverse, less productive and of reduced economic value initially but may subsequently make some recovery, the magnitude of which could vary.

6.3 *Economic valuation of alternative trajectories of the flow of economic value*

It is difficult to know how best to value the economic worth of the flow of ecosystem services. However, in case 1 above, it is clear that changes in the flow of economic value as a result of ecosystem change compared to the initial state are superior to persistence of the initial state. In case 5, while the flow of value as a result of ecosystem change always remains higher than if the initial state persists, it does reach a maximum and then shows some decline. Therefore, according to one criterion of sustainability (which requires economic value to never decline), it is considered to be undesirable (Tisdell, 2015, Ch. 4). However, sustainability criteria would reject all the other cases as undesirable compared to this initial state.

If the capitalized values of alternative paths are used to determine the desirability of alternatives, then both cases 1 and 5 would be rated as more desirable than the initial state. Case 4 would be rejected as less desirable. However, depending on the pattern of the trajectory, and the discount rates applied to future flows, cases 2 and 3 may be rated as more desirable than the initial state. It ought to be borne in mind, however, that sustaining (existing) ecosystem functions and associated economic values in all places should not be an ultimate economic goal. This is because the economic benefits from anthropogenic changes outside a particular area (which adversely affect its economic functioning) may exceed the loss in economic benefits obtained from this area.

7. Proposed Economic Policies for Responding to Changes in Marine Ecosystems Caused by Climate Change

Two types of policies can be considered:

- Policies to retard ecosystem change (migration strategies).
- Policies which are based on the inevitability of ecosystem change and which are designed to cope with it (adjustment strategies).

In some cases, these policies may be pursued in conjunction. For example, ecosystem change may be retarded but it may still be necessary to adopt policies for economic and social adjustment to the changing ecosystem. Let us consider economic aspects of the first mentioned type of policy response initially and then pay attention to the second type of policy response.

7.1 Economic aspects of policies to slow changes in marine ecosystems

It is generally accepted that even if there are stresses on marine ecosystems caused by global climate changes, in some cases, it is possible to retard changes in these systems by reducing local anthropogenic stresses. The possibility of doing this depends on locational factors and the type of marine ecosystem being placed under stress. The deterioration of coral reefs in some locations may, for example, be retarded by reducing the run-off of nutrients and sediment from nearby land areas where run-off is a function of anthropogenic activity. This is a policy option being pursued for helping to conserve parts of the Great Barrier Reef. The basic economics of such a policy can be illustrated

by Figure 6.

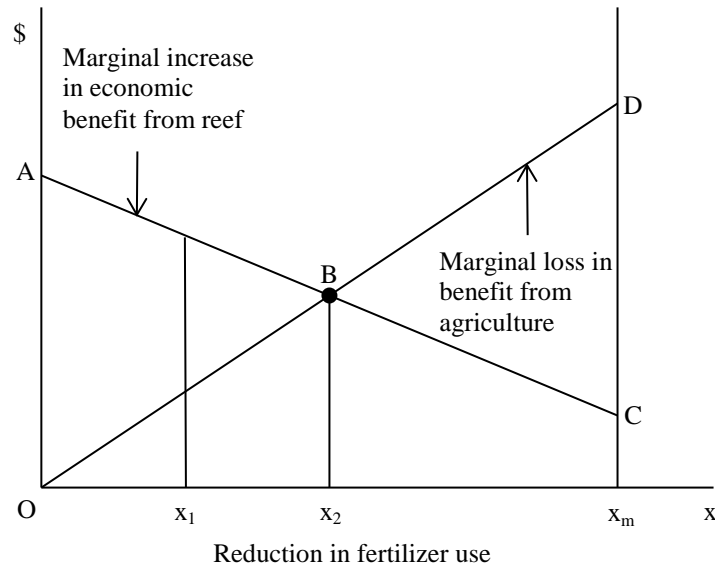


Figure 6: A case in which reducing fertilizer use in agriculture helps to conserve coral reefs. However, the economic benefits from greater reef conservation needs to be compared with the loss in economic benefits from agriculture as a result of agriculture being required to reduce its fertilizer use.

In Figure 6, O represents the level of fertilizer used in agriculture in a geographical area where it has a spillover effect on coral reefs. The variable x represents the amount of fertilizer used. The marginal increase in economic benefits from the impacted coral reef area as a function of a reduction in fertilizer use as shown by line ABC and line OBD represents the marginal loss in economic benefits obtained from agriculture if its fertilizer use is reduced. The value x_m represents the extent to which existing fertilizer use can be reduced: it corresponds to the amount of existing fertilizer use.

From an economics point of view, a reduction in fertilizer use of x_2 is optimal. A reduction of less than x_2 , for example, x_1 , is less than optimal and so is a reduction of greater than x_2 . In particular, it is uneconomic to reduce this stressor to its maximum

possible extent, x_m .

The extent to which it is economic to limit local stressors on marine ecosystems can be expected to vary with the locality. It may, for example, be the case that adverse spillovers on nearby reefs increase with the proportion of land allocated to intensive agriculture in river catchments, the water of which drains into nearby reef areas. One can expect the loss in economic benefits incurred from restricting the areal extent of intensive agriculture in different regions to vary and also the benefits to be had by delaying the deterioration of impacted reefs to differ. The opportunity cost of limiting the areal extent of agricultural intensification in some cases may be low and in other areas high. Similarly, the benefits from delaying reef deterioration by this action may be high in some areas and low in others. Consequently, different degrees of restriction on agricultural development may be called for in different regions. Consider the example, illustrated by Figure 7.

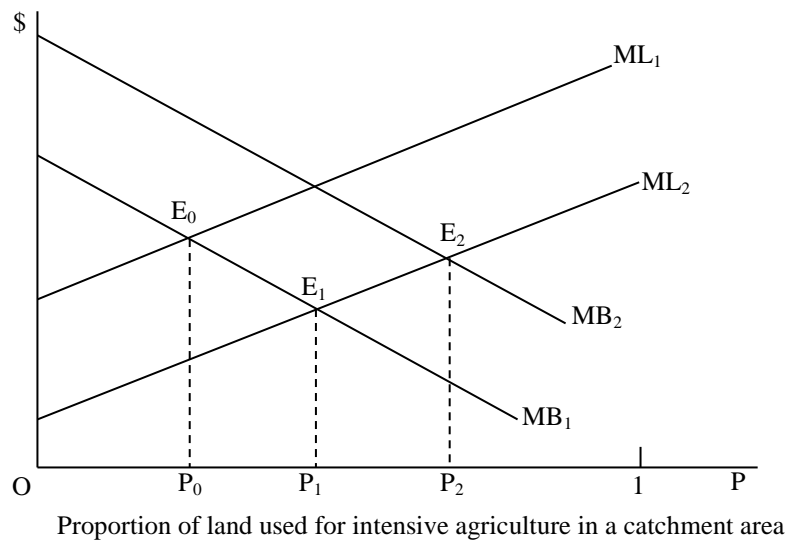


Figure 7 An illustration that optimal economic measures intended to slow the impact of climate change on alterations in marine ecosystems can be expected to vary spatially.

In Figure 7, P represents the proportion of a catchment area allocated to intensive agriculture. The line identified by MB_1 represents the marginal economic benefit from the proportion of land in catchment area one used for intensive agriculture and the line identified by MB_2 represents that for catchment two. The higher is the proportion of land used for intensive agriculture in each catchment the faster is the rate of deterioration in associated coral reefs and the larger their reduction in economic value. The assumed marginal reduction in the economic value of the reef associated with catchment one is indicated by the line identified by ML_1 and for catchment two, the marginal loss in the economic value of its associated reef is identified by the line ML_2 . Consequently, in catchment one it is economically optimal to use P_0 of its area for intensive agriculture, whereas a higher proportion, P_2 , is optimal for catchment two. Even if it were the case that the marginal loss in economic value of the reef associated with catchment one was the same as for catchment two, the line identified by ML_2 , it would still be optimal to allocate less land to agriculture in region one than in catchment two, that is the proportion P_1 rather than P_2 . The marginal opportunity costs of conserving the coral reef in area one is lower than in area two.

In countries such as Australia, where coral reefs are spread geographically over very large areas, it is unlikely to be economically optimal to adopt spatially uniform measures to conserve reef areas affected by human activity. Appropriate measures will depend on relative economic values. For example, if in the *most* northerly region of the Great Barrier Reef the economic value of intensified agriculture is low relative to the loss in economic value caused to coral reefs which it impacts on, this weakens the case for encouraging the intensification of agriculture in this area.

The above analysis may also be applied to changes in other marine ecosystems. For example, increases in nutrient loads and sediments in the China Sea contribute to the increased frequency and the extent of red tides in this area and these have adverse impacts on the fisheries located there. Therefore, China needs to consider in what areas and to what extent priority should be given to reducing nutrient and sediment discharges into the China Sea.

Spatial issues of the above kind have received little attention from economists. However, given that it is unlikely to be economic to conserve existing marine

ecosystems everywhere, they are important. There is no escaping the fact that it is desirable to consider economic trade-offs in making decisions about the conservation of ecosystems.

7.2 Adjustment policies based on the assumption that changes in marine ecosystems are inevitable

Despite attempts to counter changes in marine ecosystems attributable to climate change, some changes seem to be inevitable. That raises the question of what policies, if any, should be adopted by governments to respond to the elements of climate change which they do not individually control. This is a very complex matter given that the timing of ecosystem changes due to climate change and their nature are still subject to considerable uncertainty.

Views about the extent to which governments should intervene in adjustments to climate change can vary substantially. On the one hand, the view may be adopted that, at the very most, only limited government intervention is called for. Particularly if environmental change is slow, communities may adjust adequately to it of their own accord. At the other end of the spectrum is the belief that governments should play a leading role in preparing individuals and communities for such changes and mandate that particular precautionary actions be taken.

The timing of adjustment to climate change can be problematic. In terms of timing, some adjustments to climate change may be premature and in other cases not made early enough. For example, there may be projects for which the length of their economic life is such that if they are proceeded with now, they will give a sufficient return to make them worthwhile before the full impact of climate change adversely affects them. However, at a later time, these projects may no longer be economic given the increased immediacy of significant adverse environmental impacts from climate change. For instance, some types of mariculture may no longer be economic once impacts from climate change become significant. Prior to this they may still be economic even if some impacts from climate change are apparent.

The question of the extent to which governments should prepare communities for

climate change and direct their responses is complex. Those who favour minimal government intervention in the economy might argue that the government ought to limit itself to providing public goods to facilitate adjustment to climate change and other commodities that cannot be adequately supplied by markets. The supply of public goods could include the supply of information about the expected nature and timing of climate change. However, there is the problem that information provided by governments is not always reliable. Furthermore, there may be a case for governments undertaking works to provide local public goods which delay some consequences of climate change, for example, in some cases building or raising dikes to respond to sea level rises.

To some extent, insurance markets can be expected to respond to changes in the risks associated with climate change. For example, insurance premiums for mariculture operations facing increasing risks as a result of climate change can be expected to rise. This should send a market signal to mariculturalists that adjustments are called for.

8. Concluding Comments

Natural scientists predict that rising atmospheric levels of GHG will alter several physical and chemical properties of marine environments. These developments will include increasing warming and acidification of sea water. Consequently, marine ecosystems will alter but the exact patterns and timings of these changes are not yet clear. Several scientific studies have aimed to determine the influence of single stressors, such as acidification on marine ecosystems, but in practice it is necessary to consider simultaneously the effects on ecosystems of all abiotic changes likely to occur as a result of climate change. This means that partial analysis of changes in marine ecosystems caused by climate change is of limited value for prediction purposes.

Economic predictions based on partial scientific findings about GHG-induced changes in marine ecosystems are consequently limited in their predictive ability. This was noted in relation to a study of the predicted impact of ocean acidification on the economic value of Norwegian fisheries. Doubts were also expressed about whether the revenue obtained by these fisheries is an appropriate measure of economic value. The Norwegian study does, however, highlight the possibility that climate-induced changes

in marine ecosystems will economically benefit some regions and disadvantage others. It predicts that it is highly probable that Norway's fisheries in aggregate will experience an economic gain as a result of climate change.

According to Costanza et al. (2014), in 2011 coral reefs provided the largest flow of economic value per ha of any biome and showed the greatest reduction in economic value between 1997 and 2011. However, the latter result is based on their view that the real global economic values per ha estimated for coral reefs for 2011 are also the most reliable estimates of values for 1997. Their results were shown to be highly sensitive to this assumption. Furthermore, the theoretical economic underpinnings of the analysis are questionable because they assume linear economic relationships. For example, despite their assumption that the global area covered by coral reefs in 2011 was less than half of that in 1997, they suppose the real value of economic reefs per ha was unaltered. This is inconsistent with normal economic demand and supply relationships.

It was also pointed out that alterations in expenditure generated by changes in marine ecosystems are likely to be a poor guide to variations in economic welfare. Economic welfare can decrease as a result of ecosystem loss when total expenditure and associated ecosystem services may rise. Furthermore, the economic consequences of a deterioration in a marine area should not be evaluated in isolation. As demonstrated, it is important to take into account opportunity costs when evaluating the economics of changes in marine ecosystems.

The dynamics of changes in marine ecosystems as a result of climate change need to be carefully accounted for in economic valuations of alterations in ecosystems. Consideration should be given to the extent to which marine ecosystems are liable to adapt to climate change. If they transit from an initial equilibrium to a subsequent one, the path they follow is also relevant.

If it is assumed that rises in global GHG-levels cannot be controlled at the regional or national level, there may be scope for adopting regional policies which slow changes in local marine ecosystems. Scope may exist to reduce local environmental stresses on such systems. As was demonstrated, the economics of doing this is likely to vary from region to region.

This raises the following question: To what extent should governments intervene to counter the onset of biophysical consequences of climate change and to facilitate economic and social adjustments to the uncontrolled effects of climate change? To some extent, private decisions and markets (for example, insurance markets) will adjust to take account of some of the consequences of climate change. Nevertheless, because of various market failures (such as environmental externalities, the presence of attributes associated with public goods), relying solely on private decisions and markets to determine adjustments to climate change will be sub-optimal from an economics point of view, for example, if the potential Paretian improvement or Kaldor-Hicks economic criterion is applied. Government intervention in responding to climate change can therefore be potentially beneficial from an economics point of view. However, the economic benefit of such intervention will be limited by political and administrative failures (impediments the social decision-making and its execution) and the accuracy of information available to politicians and public administrators, including its possible distortion by them. The study in this paper of the consequences of increased atmospheric levels of GHG for the functioning of marine ecosystems and the economic effects of alterations in their functioning illustrates the intricacies of the policy issues which are raised by such changes. The discussion in this article also supports the view of Stoeckl et al. (2011, p. 126) that in order to devise appropriate economic policies for the management of ecosystems, “we do not just need information about total and marginal values [of the services they provide] but we also need information on the social, temporal and spatial distribution of these values”. This is especially important in the case of ecosystems which change their nature in response to alterations in environmental conditions, such as those associated with elevated levels of atmospheric GHG. It is also desirable that these valuations be based on sound and explicit economic theory and pay adequate attention to the state of ecological knowledge, including its limitations. Current economic studies have as yet been unable to achieve this goal.¹

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