CHAPTER 8

Climate change

Thomas E. Lovejoy

In 1896 Swedish physicist Arrhenius asked a new and important question, namely why is the temperature of the Earth so suitable for humans and other forms of life? From that emerged the concept of the greenhouse effect, namely that the concentrations of various atmospheric gases [e.g. carbon dioxide (CO_2), methane, nitrous oxide, chlorofluorocarbons; also called greenhouse gasses] was such that some of the radiant heat received from the sun is trapped, rendering the earth a considerably warmer planet than it otherwise would be. Arrhenius even did a manual calculation of the effect of doubling the preindustrial level of CO_2. His results are precisely what the supercomputer models of Earth's climate predict. We are well on the way toward that CO_2 concentration, having started at preindustrial levels of 280 ppm (parts per million). Current atmospheric levels are 390 ppm of CO_2, and are increasing at a rate above the worst case scenario of the Intergovernmental Panel for Climate Change (IPCC) (Canadell *et al.* 2007).

Modern science is able to study past climate, so we now know that the last 10 000 years were a period of unusual stability in the global climate. This probably has been extremely beneficial to the human species for that period includes all our recorded history as well as the origins of agriculture and of human settlements. It is easy to conclude that the entire human enterprise is based on a freak stretch of relatively unchanging climatic conditions.

A bit less obvious is the realization that ecosystems have adjusted to that stable climate also so they – as well as the benefits society receives in ecosystem goods and services (see Chapter 3) – are vulnerable to climate change as well. Indeed, it is rapidly becoming clear that the natural world is as – or more – sensitive to climate than anything else society is concerned about.

The current levels of greenhouse gas concentration have already led to an overall rise in global temperature of 0.75 degree Celsius (see Figure 8.1). In addition, because there is a lag between attaining a concentration level and the consequent trapping of heat energy, the planet is slated for an additional 0.5 degree (for a total of 1.25 degrees Celsius) even if greenhouse gas concentrations were to cease to increase immediately.

This chapter highlights the effects of human-induced climate change on Earth's physical environments and biodiversity. Possible mitigation options of this predicament are also briefly discussed.

8.1 Effects on the physical environment

Already there are widespread changes in the physical environment, primarily involving the solid and liquid phases of water. Northern hemisphere lakes are freezing later in the autumn and the ice is breaking up earlier in the spring. Glaciers are in retreat in most parts of the world, and those on high peaks in the tropics like Mount Kilimanjaro (Tanzania) are receding at a rate that they will likely cease to exist in 15 years (UNEP 2007). The melt rate of Greenland glaciers is increasing and the seismic activity they generate is accelerating.

Arctic sea ice is retreating at unprecedented rates, as would be predicted by the increased heat absorption capacity of dark open water as compared to reflective ice. This represents a positive feedback, namely the more dark water replaces what had been reflecting ice the more heat is absorbed and the more the Earth warms.

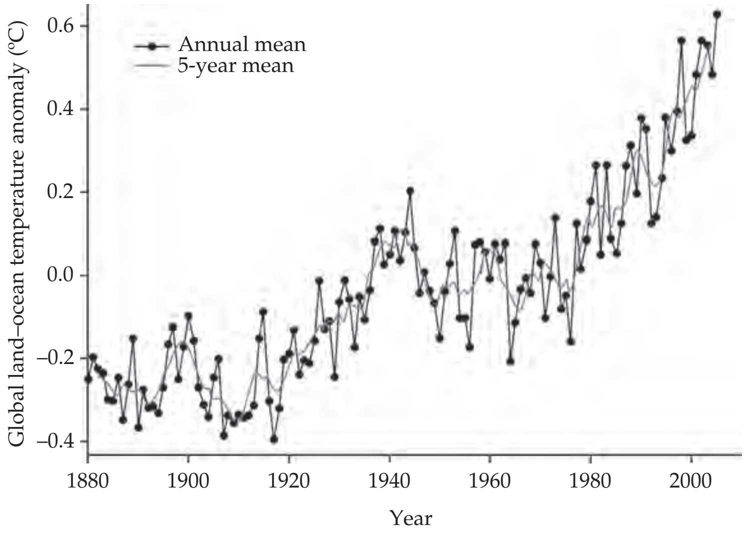


Figure 8.1 Global annual mean temperature anomaly relative to 1951–80. Reprinted from Hansen *et al.* (2006) © National Academy of Sciences, USA.

The danger of positive feedbacks is that they accelerate climate change and can lead to a "runaway greenhouse effect". The first summer with an ice free Arctic Ocean once predicted for 2100 is now possible in 2030, with some predictions suggesting as soon as in next five years.

In addition, there is a statistically significant increase in wildfires in the American West because longer summers and earlier melt of the snow pack have led to dryer environments and higher fire vulnerability (Flannigan *et al.* 2000). Argentina, the American southwest, and Australia in 2009 were experiencing unusual drought, and parts of southern Australia had extraordinarily high temperatures and devastating fires in the summer of 2008–2009. In addition there is the possible increase in the number of intense tropical cyclones like Katrina, although there is still some uncertainty on the matter. Another additional system change was previewed in 2005 when Atlantic circulation changes triggered the greatest drought in recorded history in the Amazon. The Hadley Center global climate model and other work predict similar but relatively permanent change at 2.5 degrees Centigrade with consequent Amazon dieback (mostly in the eastern half of the basin) (Malhi *et al.* 2009).

Other possible examples of system change would be methane release from thawing permafrost in the tundra – another dangerous positive feedback loop. The first signs of this have been observed in Siberia and Alaska. These are all part of how the Earth system functions. Although understanding of the Earth system is only preliminary it clearly includes thresholds and teleconnections (changes in one part of the globe can trigger changes in some far distant part). Increasing climate change is taking the planet in that dangerous direction.

Oceans are also threatened by acidification caused by elevated CO_2 levels in the atmosphere. A significant part of that CO_2 is absorbed by the oceans but some of it becomes carbonic acid. As a consequence the acidity of the oceans has increased 0.1 pH unit since pre-industrial times – a number that sounds trivial but being on a logarithmic scale is equivalent to 30% more acid.

All these changes to the physical environment have consequences for biodiversity.

8.2 Effects on biodiversity

Populations, species and ecosystems are responding to these physical changes all over the planet.

Many species are changing the timing of their life histories (phenology) (Root *et al.* 2003; Parmesan 2006). Wherever there are good records in the northern hemisphere many plant species are flowering earlier in the spring as in central England (Miller-rushing and Primack 2008). Similarly, animal species are changing the timing in their life cycles, such as tree swallows (*Tachycineta bicolor*) nesting and laying their eggs earlier (Dunn and Winkler 1999). Some species are changing their migration times and in North America, one hummingbird species has ceased to migrate (Parmesan 2006).

In addition, the geographical distribution of some species is changing. In western North America, the change both northward and upward in altitude of Edith's checkerspot butterfly (*Euphydryas editha*) is well documented (Parmesan 2006). In Europe, many butterfly species have moved northward as well, including the sooty copper (*Heodes tityrus*), which now occurs and breeds in Estonia (Parmesan *et al.* 1999).

There is considerable change among Arctic species because so many life histories are tied to the ice which decreased dramatically both in area and thickness in 2007 and 2008. The polar bear (*Ursus maritimus*) is the best known by far with stress/decline being observed in a number of the populations (Stirling *et al.* 1999). Many bird species feed on the Arctic cod (*Arctogadus glacialis*), a species that occurs near the edge and just under the ice. Nesting seabirds like the black guillemot (*Cepphus grylle*) fly from their nests on land to the edge of the ice to feed and return to feed their young. So as the distance to the edge of the ice increases, there is a point at which the trip is too great and first the individual nest, then eventually the seabird colony fails.

Species that occur at high altitudes will, as a class, be very vulnerable to climate change simply because as they move upslope to track their required conditions, they ultimately will have no further up to go. The American pika (*Ochotona princeps*), a lagomorph species with a fascinating harvesting aspect to its natural history, is a prime example. It is comprised of roughly a dozen populations in different parts of the Rocky Mountains that we can anticipate will wink out one by one.

Temperature increase also will be greater in high latitudes and particularly in the northern hemisphere where there is more terrestrial surface. Climate change of course is not only about temperature it is also about precipitation. On land the two most important physical parameters for organisms are temperature and precipitation. In aquatic ecosystems the two most important are temperature and pH. Drying trends are already affecting Australia, the Argentine pampas, the American southwest and the prairie pothole region of the upper Midwest northward into Canada. Prairie potholes are a critical landscape feature supporting the great central flyway of migratory birds in North America.

For well known species such as the sugar maple (*Acer saccharum*), the environmental requirements are fairly well known so it is possible to model how the geography of those requirements is likely to change along with climate. In this case all the major climate models show that at double pre-industrial levels of greenhouse gases, the distribution of this species – so characteristic of the northeastern United States that its contribution to fall foliage is the basis of a significant tourism industry – will move north to Canada. While the tourism and the appeal of maple sugar and syrup are not significant elements of the northeast US economy, they are significant with respect to a sense of place, and are partly why these states have taken a leadership role on climate change. In the mid-Atlantic states, the Baltimore oriole (*Icterus galbula*) will no longer occur in Baltimore due to climate-driven range shift.

In the northern oceans there are changes in plankton (small organisms drifting along the ocean currently) and fish distributions. The eel grass (*Zostera marina*) communities of the great North American estuary, the Chesapeake Bay, have a sensitive upper temperature limit. Accordingly, the southern boundary has been moving steadily northward year after year (http://www.chesapeakebay.net/climatechange.aspx). Similarly, plankton populations have been moving northwards in response to water temperature increase (Dybas 2006). This trend, for example, has resulted in low plankton densities around

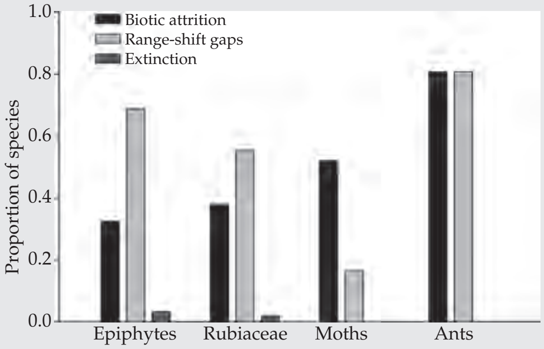
Scotland, likely reducing the densities of plankton-eating fish and bird species there (Dybas 2006).

Changes have been observed not only in the Arctic and temperate regions but also in the tropics (see Box 8.1). There are more than 60 vertebrate species endemic to Australia's rainforests including the grey-headed robin (*Heteromyias albispecularis*) and the ringtail possum (*Pseudocheirus peregrinus*). With climate change the amount of suitable habitat available for them shrinks dramatically such that at 5 degrees Centigrade increase most are doomed to extinction (Shoo *et al.* 2005). The Monteverde cloud forest in Costa Rica, an ecosystem type almost entirely dependent on condensation from clouds for moisture has been encountering more frequent dry days as the elevation at which clouds form has risen. Nest predators like toucans are moving up into the cloud forest from the dry tropical forest below (Pounds *et al.* 1999). The charismatic golden toad (*Bufo periglenes*) of Monteverde could

Box 8.1 Lowland tropical biodiversity under global warming

Navjot S. Sodhi

Global warming may drive species poleward or towards higher elevations. However, how tropical species, particularly those occupying lowlands, will respond to global warming remains poorly understood. Because the latitudinal gradient in temperature levels off to a plateau between the Tropic of Cancer and the Tropic of Capricorn, latitudinal range shifts are not likely for species confined to the tropics. This leaves upslope range shifts as the primary escape route for tropical species already living near their thermal limit. One scenario is that tropical lowland biodiversity may decline with global warming, because there is no "species pool" to replace lowland species that migrate to higher elevations. Colwell *et al.* (2008) speculated on the effects of projected global warming on lowland biotas by using relatively large datasets of plants and insects from Costa Rica. Data on the distribution of 1902 species of epiphytes, understory rubiaceous plants, geometrid moths, and ants were collected from a transect that traversed from sea level to 2900 m elevation. Colwell *et al.* (2008) developed a graphic model of elevational range shifts in these species under climatic warming. Assuming 600-m upslope shifts with 3.2°C temperate increase over the next century, they estimated that 53% of species will be candidates for *lowland biotic attrition* (decline or disappearance in the lowlands) and 51% will encounter the spatial gaps between their current and projected ranges (Box 8.1 Figure). A number of these species will likely face both challenges. Authors cautioned that their local-level data may have underestimated regional elevation ranges and must, in this regard, be considered as a worst case scenario. However, it is also plausible that their results represent a best case scenario, considering that other drivers such as habitat loss, fire, overharvesting and invasive species can synergistically drive species to decline and extinction (Brook *et al.* 2008).



Box 8.1 Figure Proportion of species projected to be affected by global warming. Data for the analysis were collected from a lowland elevational transect in Costa Rica. Proportion sums are greater than one because a species may have more than one response. Reprinted from Colwell *et al.* (2008).

continues

Box 8.1 (Continued)

Most previous studies determining the effects of global warming on tropical species have focused on montane species, reporting their elevation shifts or disappearances (e.g. Pounds *et al.* 1999). Colwell *et al.*'s (2008) findings remind us that lowland tropical biodiversity remains equally vulnerable to the changing climate. Their study is yet another reminder that we need to urgently mitigate the effects of human generated climate changes.

REFERENCES

Brook, B. W., Sodhi, N. S., and Bradshaw, C. J. A. (2008). Synergies among extinction drivers under global change. *Trends in Ecology and Evolution*, **23**, 453–460.

Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C., and Longino, J. T. (2008). Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322**, 258–261.

Pounds, J. A., Fogden, M. P. L., and Campbell, J. H. (1999). Biological response to climate change on a tropical mountain. *Nature*, **398**, 611–615.

well be the first documented terrestrial extinction caused by climate change (Figure 8.2; Pounds *et al.* 1999). The rapid extinction of large numbers of amphibian species in which a chytrid fungus plays a major role may well be in synergy with climate change (Crump *et al.* 1992; Collins and Storfer 2003).

In tropical oceans, coral reefs are quite temperature sensitive. Only a slight increase in temperature causes the basic partnership between a coral animal and an alga to break down. The coral animal expels the alga triggering what are called bleaching events in which most of the color of the communities is lost and productivity, biodiversity and the ecosystems services of the reefs crash. Such occurrences were virtually unknown 40 years ago and become more frequent every year, likely due to the elevation of sea temperature (Hoegh-guldberg 1999). Coral reefs around the globe are threatened (Pandolfi *et al.* 2003). It is hard to envision a reasonable future for tropical coral reefs and the diversity of marine life they support.

Figure 8.2 The golden toad. Photograph from the US Fish and Wildlife Service.

Species of coastal regions will encounter problems with sea level rise. Some will succeed in adapting and others probably will not. The rate of sea level rise will be of significance: generally speaking the more rapid the rise the more species will encounter difficulty in adapting. Low lying island species constitute another class highly vulnerable to climate change, principally because of sea level rise. Islands of course have major numbers of endemic species such as the key deer (*Odocoileus virginianus clavium*) in the Florida Keys. Island species have been particularly vulnerable to extinction because of limited populations. Sea level rise caused by climate change will be the coup de grace for species of low lying islands.

To change the basic chemistry of two thirds of the planet, i.e. ocean, is staggering to contemplate in itself. In addition, the implications for the tens of thousands of marine species that build shells and skeletons of calcium carbonate are very grave. They depend on the calcium carbonate equilibrium to mobilize the basic molecules of their shells and skeletons. This includes obvious organisms like mollusks and vertebrates but also tiny plankton like pteropods (tiny snails with their "foot" modified to flap like a wing to maintain them in the water column). At a certain point of increasing acidity the shells of such organisms will go into solution while they are still alive. Effects have been seen already at the base of the food chain in the North Atlantic and off of Alaska.

Freshwater species will be affected as well. They all have characteristic temperature ranges that will be affected by climate change. Coldwater species like trout and the many species of the food chains on which they depend will no longer be able to survive in many places where they occur today (Allan *et al.* 2005).

These kinds of changes are relatively minor ripples in the living world but are occurring virtually everywhere. Nature is on the move and this no longer is a matter of individual examples but is statistically robust. And this is with only 0.75 degrees Celsius increase in global temperature with at least that much and probably more in store by century's end. The first projection of what double pre-industrial levels of CO_2 might portend for the biota estimated extinction of 18–35% of all species (Thomas *et al.* 2004) – a range confirmed by the 2007 report of the Intergovernmental Panel on Climate Change (IPCC 2007).

With more climate change, the impacts upon and response of biological diversity will change qualitatively and become more complex and harder to manage. Climate change of course is nothing new in the history of life on Earth. Glaciers came and went on a major scale in the northern and temperate latitudes in the last hundreds of thousands of years. Species were able to move and track their required climatic conditions without much loss of biological diversity. The difference today is that the landscapes within which species would move in response to climate change have been highly modified by human activity through deforestation, agricultural conversion, wetland drainage and the like. Landscapes have been converted into obstacle courses for dispersing organisms. Former National Zoo Director Michael Robinson stated that species would move but "Philadelphia will be in the way". Basically these landscapes will result in substantial extinction if they remain in their current condition.

A second difference is that we know from studies of past response to climate change that biological communities do not move as a unit, but rather it is the individual species that move each at its own rate and in its own direction. The consequence is that ecosystems as we know them will disassemble and the surviving species will assemble into new ecosystem configurations that largely defy the ability to foresee. Certainly that was the case as species moved in Europe after the last retreat of the glaciers (Hewitt and Nichols 2005). The management challenge to respond to this is therefore hard to understand let alone plan to address.

We also know that in contrast to the climate change models run on super computers that change will be neither linear nor gradual. We know there have been discontinuities in the physical climate system in the past. For example the global conveyor belt – the gigantic ocean current that distributes heat around the globe – has shut down in the past. Equally disturbing, abrupt threshold change is already occurring in ecosystems. Bleaching in coral reef systems is clearly an example in the oceans (see above).

8.3 Effects on biotic interactions

Relationships between two species can depend on relatively precise timing. Sometimes the timing mechanism of one is based on day length and the other on temperature and has worked well because of the relative climate stability. The seabird nesting-Arctic Cod coupling is just such an example and under climate change leads to "decoupling" (see above). The Arctic hare (*Lepus arcticus*), for example, changes from a white winter pelage that camouflages it in wintry white landscapes to a brownish pelage that blends into the vegetation after the snow and ice disappear. As spring thaw advances earlier with climate change, Arctic hares become vulnerable to predators as they are conspicuously white in no longer wintry landscapes.

Similarly, in terrestrial ecosystems threshold change is occurring in coniferous forests in

North America and Europe as climate change tips the balance in favor of native pine bark beetles. Milder winters allow more to overwinter and longer summers permit an additional generation of beetles. The consequence is vast stretches of forest in which 70% of the trees have been killed. It is an enormous forest management and fire management problem, and being without known precedent it is not clear how these ecosystems will respond. Yet more, there are the first signs of system change, i.e., change on yet a greater scale.

8.4 Synergies with other biodiversity change drivers

Climate change will also have synergistic effects with other kinds of environmental problems such as invasive species (Chapter 7). The emerald ash borer (*Agrilus planipennis*), an Asian species, is causing major mortality of American ash trees (*Fraxinus americana*) – from which baseball bats are manufactured – from the mid-west to Mid-Atlantic States (http://www.emeraldashborer.info/). The borer is over wintering in greater numbers because of milder winters and has a longer active boring season because of longer summers. Another example will be the impact of the introduced bird malaria vector mosquito which causes mortality in most species of the endemic Hawaiian honeycreepers (see Figure 12.4). Of the surviving honeycreeper species most of the vulnerable ones persist only above an altitude – the mosquito line – above which the temperature is too low for the mosquitoes. With climate change the mosquito line will move up and the area safe for honeycreepers diminishes (Pratt 2005).

8.5 Mitigation

All of this bears on probably the most critical environmental question of all time, namely at what point is climate change "dangerous", i.e., where should it be limited. For a long time conservationists asserted that 450 ppm of CO_2 (roughly equivalent to 2 degrees Centigrade warming) should be the limit beyond which it is dangerous. This means limiting peak concentration levels to as low a figure as possible and seeking ways to draw CO_2 out of the atmosphere to return to a lower ppm as soon as possible. It is clear that the grave risk and urgency of climate change has not been recognized (Sterman 2008; Solomon *et al.* 2009). The IPCC (2007) synthesis report suggests 450 ppm of CO_2 itself is dangerous. Remember, the earth is 0.75 degree warmer than pre-industrial times with another 0.5 already in the pipeline. Yet at 0.75 ecosystem threshold change is already occurring.

The last time the Earth was two degrees Centigrade warmer, sea level was four to six meters higher. The current changes in Arctic sea ice, the accelerating melting of the Greenland ice sheet, together with major ecosystem disruption all suggest that 350 ppm of CO_2 is the level above which it is not "safe". That is James Hansen's conclusion as a climate scientist. The insights emerging about biological diversity and ecosystems are convergent with 350 ppm. Yet atmospheric CO_2 is at 390 ppm and climbing at rates beyond the worst case projections.

This means the agenda for "adaptation" – to use the climate convention's terminology – is indeed urgent. Conservation strategies need revision and amplification and the conservation biology of adaptation is a rapidly developing field. Restoring natural connections in the environment will facilitate the movement of organisms as they respond to changing climate (Box 8.2). Reducing other stresses on ecosystems reduces the probability of negative synergies with climate change. Downscaled climate projections to one square kilometer, for example, or similar will provide managers with useful data for making needed decisions.

While existing protected areas will no longer be fulfilling their original purpose, e.g., Joshua trees (*Yucca brevifolia*) will no longer exist inside of the Joshua Tree National Park, they will have the new value of being the safe havens from which species can move and create the new biogeographic pattern. That together with the need for new protected areas for the new locations of important biodiversity plus the need for natural

Box 8.2 Derivative threats to biodiversity from climate change

Paul R. Ehrlich

Besides the obvious direct impacts on biodiversity, climate disruption will have many other effects. For instance, if climatologists are correct, humanity is likely to be faced with a millennium or more of continuously changing patterns of precipitation that likely in itself will be devastating for biodiversity (Solomon *et al.* 2009). But those changes will also require humanity to continually reconstruct water-handling and food-producing infrastructure around the globe. New dams, canals, and pipelines will need to be built, often with devastating impacts on stream and river ecosystems. Lakes behind new dams will flood terrestrial habitats, and changing river flows will have impacts on estuaries and coral reefs, among the most productive of marine environments. Reefs are especially sensitive to the siltation that often accompanies major upstream construction projects.

Changing water flows means that new areas will be cleared for crop agriculture and subjected to grazing, as old areas become unproductive. Roads and pipelines will doubtless need to be built to service new agricultural areas. What the net effects of these shifts will mean is almost impossible to estimate, especially where old areas may be available for rewilding (Box 5.3). It is also likely that warming will open much of the Arctic to commerce, with an accompanying increase in the construction of infrastructure – ports, roads, towns, and so on.

Human society in response to growing climatic problems will also begin to revise energy-mobilizing infrastructure across the planet. Large areas of desert may be claimed by solar-energy capturing devices. Wind turbines are likely to dot landscapes and some near-shore seascapes. New high-speed rail lines may be constructed, natural ecosystems may be plowed under to plant crops for conversion to biofuels (Box 13.3). This is already happening with deforestation in the Amazon now accelerating in response to demand for biofuel crops. Expanding farming operations are also destroying the prairie pothole ecosystem of the northern plains of North America (http://www.abcbirds.org/newsandreports/stories/080226_biofuels.html). That is critical habitat for many bird populations, among other fauna, including ducks much in demand by duck hunters who have in the past proven to be allies of conservationists.

All of these changes will cause multitudes of populations, and likely many species, to disappear, so that conservation biologists should be consulted on each project, and society should be made very aware as soon as possible of the potential conflicts between human and natural capital inherent in revision of water, energy, and transport infrastructure.

REFERENCES

Solomon, S., Plattner, G-K., Knuttic R., and Friedlingsteind, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 1704–1709.

connections between natural areas, clearly mean that more conservation is needed not less.

Simultaneously, the “mitigation” agenda – to use the convention’s term for limiting the growth of greenhouse gas concentrations in the atmosphere – becomes a matter of huge global urgency because the greater the climate change the more difficult is adaptation. Transforming the energy base for human society is the dominant center of mitigation, but biology and conservation play a significant role as well (Box 8.2).

Tropical deforestation (see Chapter 4) plays an important role in greenhouse gas emissions: literally 20% of annual emissions come from the destruction of biomass, principally tropical deforestation and burning (IPCC 2007). In the current rank order of emitting nations after China and the United States are Indonesia and

Brazil because of their deforestation. There is now gathering effort to include "Reductions in Emissions from Deforestation and Degradation" (= REDD) as part of the negotiations. Obviously there are multiple benefits in doing so in reduction of emissions (and thus atmospheric concentration levels), biodiversity benefits and ecosystem services (Chapter 3). There are technical problems in monitoring and measuring as well as issues about "leakage" – when protection of one forest simply deflects the deforestation to another – but none of it seems intractable.

All greenhouse gas emissions involve the release of solar energy trapped by photosynthesis whether ancient (fossil fuels) or present deforestation and other ecosystem degradation. That raises the important question of what role biology and biodiversity might play in removing some of the CO_2 accumulated in the atmosphere. Twice in the history of life on earth high levels of CO_2 concentrations had been reduced to levels on the order of pre-industrial. The first was associated with the origin of land plants and the second with the expansion of angiosperms (Beerling 2007). This suggests substantial potential if the biosphere is managed properly.

In the past three centuries, terrestrial ecosystems have lost 200 billion tons of carbon and perhaps more depending on hard to estimate losses of soil carbon. What is clear is that to the extent that terrestrial ecosystems can be restored, a substantial amount of carbon could be withdrawn from the atmosphere rather than lingering for a hundred to a thousand years. If that number is 160 billion tons of carbon, it probably equates to reducing atmospheric concentrations of it by 40 ppm.

This would be tantamount to planetary engineering with ecosystems – essentially a regreening of what Beerling (2007) terms the Emerald Planet. All other planetary or geo-engineering schemes have potential negative consequences, and only deal with temperature to the total neglect of ocean acidification (Lovelock and Rapley 2007; Shepherd *et al*. 2007). This takes the agenda beyond forests to all terrestrial ecosystems, grasslands, wetlands, and even agro-ecosystems. Essentially it is conservation on a planetary scale: managing the living planet to make the planet more habitable for humans and all forms of life.

Summary

- Massive releases of greenhouse gasses by humans have altered the climate.
- Rapid global warming is responsible for abiotic changes such as receding of glaciers and increase in wildfires.
- Increased CO_2 concentrations in the atmosphere have acidified the oceans.
- Populations, species, and ecosystems are responding to these climatic conditions.
- Urgent actions are needed to reverse the climatic changes.

Suggested reading

Lovejoy, T. E. and Hannah, L., eds (2005). *Climate change and biodiversity*. Yale University Press, New Haven, CT.

Relevant websites

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/.
- Nature reports on climate change: http://www.nature.com/climate/index.html.
- United States Environmental Protection Agency: http://www.epa.gov/climatechange/.

REFERENCES

Allan, J. D., Palmer, M. E., and Poff, N. L. (2005). Climate change and freshwater ecosystem. In T. E. Lovejoy and L. Hannah, eds *Climate change and biodiversity*, pp. 274–290. Yale University Press, New Haven, CT.

Beerling, D. (2007). *The emerald planet: how plant's changed Earth's history*. Oxford University Press, Oxford, UK.

Canadell, J. G., Quéré, C. L., Raupach, M. R., *et al.* (2007). Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 18866–18870.

Collins, J. P. and Storfer, A. (2003). Global amphibian decline: sorting the hypotheses. *Diversity and Distributions*, **9**, 89–98.

Crump, M. L., Hensley, F. R., and Clark, K. L. (1992). Apparent decline of the golden toad: underground or extinct? *Copia*, **1992**, 413–420.

Dunn, P. O. and Winkler, D. W. (1999). Climatic change has affected breeding date of tree swallows throughout North America. *Proceedings of the Royal Society of London B*, **266**, 2487–2490.

Dybas, C. L. (2006). On collision course: ocean plankton and climate change. *BioScience*, **56**, 642–646.

Flannigan, M. D., Stocks, B. J., and Wotton, B. M. (2000). Climate change and forest fires. *The Science of the Total Environment*, **262**, 221–229.

Hansen, J., Sato, M., and Ruedy, R. (2006). Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 14288–14293.

Hewitt, G. M. and Nichols, R. A. (2005). Genetic and evolutionary impacts of climate change. In T. E. Lovejoy and L. Hannah, eds *Climate change and biodiversity*, pp. 176–192. Yale University Press, New Haven, CT.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of world's coral reefs. *Marine Freshwater Research*, **50**, 839–866.

IPCC. (2007). *Climate Change 2007 – impacts, adaptation and vulnerability*. Cambridge University Press, Cambridge, UK.

Lovelock, J. E. and Rapley, C. G. (2007). Ocean pipes could help the Earth to cure itself. *Nature*, **449**, 403.

Malhi, Y., Aragão, L. E. O. C., Galbraith, D., *et al.* (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, in press.

Miller-Rushing, A. and Primack, R. B. (2008). Global warming and flowing times in Thoreau's Concord: a community perspective. *Ecology*, **89**, 332–341.

Pandolfi, J. M., Bradbury, R. H., Sala, E., *et al.* (2003). Global trajectory of the long-term decline in coral reef ecosystems. *Science*, **301**, 955–958.

Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics*, **37**, 637–669.

Parmesan, C., Ryrholm, N., Stefanescu, C., *et al.* (1999). Poleward shifts in geographic ranges of butterfly species associated with regional warming. *Nature*, **399**, 579–583.

Pounds, J. A., Fodgen, M. P. L., and Campbell, J. H. (1999). Biological response to climate change on a tropical mountain. *Nature*, **398**, 611–615.

Pratt, D. H. (2005). *Hawaiian honeycreepers*. Oxford University Press, Oxford, UK.

Root, T. L, Price, J. T., Hall, K. R., *et al.* (2003). Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57–60.

Shepherd, J., Iglesias-rodriguez, D., and Yool, A. (2007). Geo-engineering might cause, not cure, problems. *Nature*, **449**, 781.

Shoo, L. P., Williams, S. E., and Hero, J.-M. (2005). Climate warming and the rainforest birds of the Australian wet tropics: using abundance data as a sensitivity predictor of change in total population. *Biological Conservation*, **125**, 335–343.

Solomon, S., Plattner, G.-S., Knutti, R., and Friedlingstein, P. (2009). Irrevesible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 1704–1709.

Sterman, J. D. (2008). Risk communication on climate: mental models and mass balance. *Science*, **322**, 532–533.

Stirling, I., Lunn, N. J., and Iacozza, J. (1999). Long-term population trends in population ecology of polar bears in western Hudson Bay in relation to climate change. *Arctic*, **52**, 294–306.

Thomas, C. D., Cameron, A., Green, R. E., *et al.* (2004). Extinction risk from climate change. *Nature*, **427**, 145–148.

United Nations Environment Programme (UNEP). (2007). *Global outlook for ice & snow*. UNEP, Nairobi, Kenya.