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Climate change in the Amazon Basin: Tipping points, changes in extremes, and impacts on natural and human systems

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9.1 INTRODUCTION

The Amazon River system is the single, largest source of freshwater on Earth and its flow regime is subject to interannual and long-term climate variability, which translate into large variations in downstream discharge (Richey *et al*., 1989; Marengo and Nobre, 2001; Marengo 2004, 2005, 2006, 2007; Milly *et al*., 2005, Marengo *et al*., 2008a, b; Cox *et al*., 2008; Zeng *et al*., 2008). To predict future climate (rainfall) change and consequent river variability an understanding of the physical mechanisms related to regional and large-scale atmospheric–oceanic–biospheric forcings is required. The temporal and spatial nature and impact of any variability in the hydrometeorology of the Amazon Basin must be considered in this context.

Today the Amazonian rainforest plays a crucial role in the global climate system via hydrological feedbacks. Amazonian forests absorb solar energy and recycle about half of the regional rainfall, thereby driving atmospheric circulation in the tropics. As it is readily recognized that climate change can affect the global distribution of vegetation it therefore seems likely that future climate change will affect vegetation distribution. Perhaps less obviously, changes in the distribution and structure of the vegetation may also influence climate. The two-way interaction between the climate and vegetation consequently creates the possibility of both positive and negative feedbacks. Human actions that influence vegetation could play an important role in these feedbacks according to the scale of the disturbance. Natural ecosystems in tropical South America have been modified by human land use for centuries, in some cases, millennia. Deforestation and conversion to bare ground or hydrologically simple systems (e.g. grass or soy plantations), have altered large areas of Amazonia and almost all the eastern seaboard of Brazil.

M. B. Bush, J. R. Flenley, and W. D. Gosling (Editors), *Tropical Rainforest Responses to Climatic Change* (Second Edition).

The Amazon region can be categorized as being at great risk from climate variability and change. The risk is not only due to projected climate change but also through synergistic interactions with other threats, such as land clearance, forest fragmentation, and fire. Some model projections exhibit, over the next several decades, a risk of an abrupt and irreversible replacement of forests by savannah with large-scale loss of biodiversity and livelihoods for people in the region (Betts *et al*., 2004; Cox *et al*., 2004; Oyama and Nobre, 2003; Salazar *et al*., 2007; Sitch *et al*., 2008).

Today the Amazon forest is thought to act as a sink for atmospheric CO_2 (Phillips *et al*., Chapter 12 of this book). However, outputs from some climate models indicate that a climatic ''tipping point'' can be reached where the forest becomes a carbon source rather than a sink. After that point is reached, the forest collapses and is replaced by secondary or degraded vegetation. With the establishment of savanna-type vegetation, the soils continue to dry and lose carbon in a process that has been referred as ''savannization'' of the Amazon region. The resilience of the forest to the combined pressures of deforestation and climate change is therefore of great concern.

Temperature increases and disruption in the energy and water cycles have the potential to seriously hamper the functioning of the Amazon as a forest ecosystem. Increasing soil temperature and the reduction of the ecosystem's capacity to retain carbon could eventually force the Amazon through a gradual process of savannization. The issue of Amazonian dieback leapt from climate change projections to global environmental concern with the unexpected Amazonian drought of 2005. However, droughts and floods are part of the natural climate variability of the Amazon Basin, probably linked to the global climate system by El Niño events or sea surface temperature (SST) anomalies in the tropical Atlantic. This natural climate variability means that the drought of 2005 cannot be attributed directly to long-term climate change nor assumed to have resulted from large-scale deforestation in the basin.

The potentially catastrophic impacts of Amazonian dieback make it vital to assess the risk of such an event under scenarios of future climate change. Unfortunately, global climate models differ significantly in their precipitation predictions for regional climate change over Amazonia (Li *et al*., 2006). For instance, the probability of a dangerous climate change due to Amazon forest dieback and subsequent savannization as suggested by the HadCM3 model is not clear in other climate models. As an ecological process, savannization remains uncertain, but as a product of climate change scenarios combined with potential vegetation models, savannization appears to be a plausible outcome. These are projections only, and hardly reflect a definitive outcome of climate change and impacts in Amazonia. However, synergistic interactions with the effects of forest clearing, fragmentation, and fire could flip the ecosystems forest to savanna, having large impacts on biodiversity, human livelihoods, and economic development (Betts *et al*., 2008; Malhi *et al*., 2008).

In the following sections, we will review the current knowledge of climate change in the Amazon region due to the increase in the concentration of greenhouse gasses

(GHGs) and also as a consequence of human drivers. We discuss the extent to which those changes could cause the Amazon system to approach a tipping point that would lead to irreversible changes in the functioning of the tropical forest (Nobre and Borma, 2009; Sampaio *et al.*, 2007; Salazar *et al.*, 2007). In the context of this chapter, savannization has been defined as an environmental change in tropical South America that would lead to changes in the regional climate caused by either land cover change (Nobre *et al.*, 1991; Oyama and Nobre, 2003; Sampaio *et al.*, 2007) or global warming in such way as to increase dry season length, thereby shifting regional climate envelopes into those typical of savannas. Other aspects to be discussed in this chapter are the occurrences of extremes events, focusing on the drought of 2005 and the floods of 2009, and the possible impacts of climate change on natural vegetation and environmental services provided by Amazonian forest.

9.2 CLIMATE CHANGE AND TIPPING POINT IN AMAZONIA

The term "tipping point" commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system (Lenton *et al.*, 2008). The stability of the Amazon forest–climate equilibrium is being perturbed by a number of human drivers (e.g., deforestation, global warming, forest fires, higher atmospheric CO_2 concentrations, and increased frequency of droughts and floods) (Nobre and Borma, 2009; Malhi *et al.*, 2008; Betts *et al.*, 2008). In the case of the Amazon forest, if warming due to an increase in concentrations of GHG (either natural or anthropogenic) is above 3.5–4°C, there is a risk of passing a tipping point leading to savannization. Quantitative assessments for the maintenance of the tropical forest indicate that a tipping point may be passed if the deforested area exceeds 40% of Amazonia (Sampaio *et al.*, 2007) or if global warming results in a temperature increase $> 34°C$ (Cox *et al.*, 2000). The likelihood of crossing a tipping point can be greatly exacerbated by increases in forest fires and droughts, but quantification of those effects is still lacking (Figure 9.1).

Rainfall in Amazonia is sensitive to seasonal, interannual variations in SSTs in the tropical oceans (Marengo, 1992; Fu *et al.*, 2001; Liebmann and Marengo, 2001; Ronchail *et al.*, 2002; Marengo *et al.*, 2008a, b). The warming of the tropical east Pacific during El Niño events suppresses wet-season rainfall through modification of the (East–West) Walker Circulation. Teleconnections leading to simultaneous changes in the Northern Hemisphere extra-tropics alter the flow of moisture into Amazonia and instigate drought events such as those of 1962, 1983, and 1998 (Williams *et al.*, 2005; Ronchail *et al.*, 2002). However, variations in Amazonian precipitation are also known to be linked to SST in the tropical Atlantic (Liebmann and Marengo, 2001). A warming of the tropical north Atlantic relative to the south leads to a north-westward shift in the Intertropical Convergence Zone (ITCZ) and compensating atmospheric descent over Amazonia, sometimes producing intense drought, as in 1963 and 2005 (Marengo *et al.*, 2008a, b).

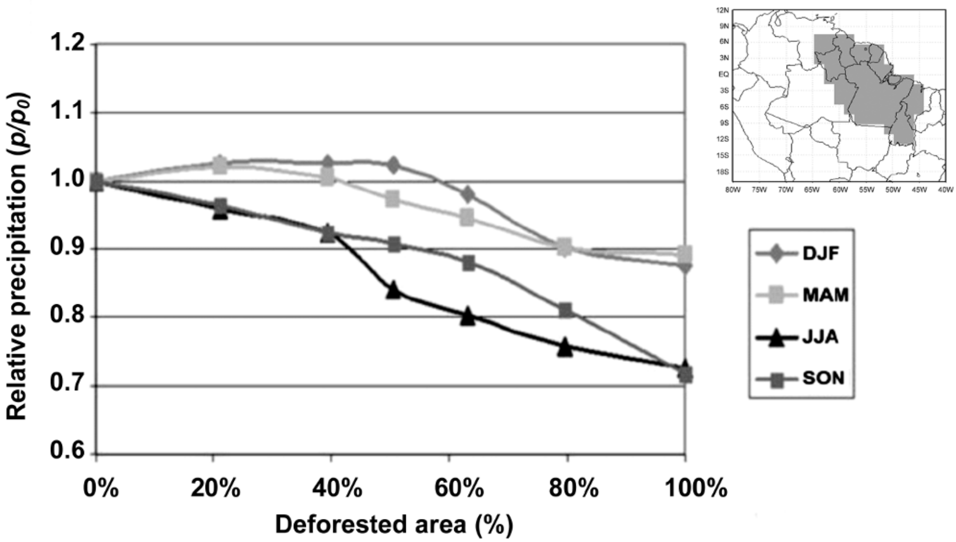

Figure 9.1. Simulated impacts of deforestation on rainfall in Amazonia. The curves show the fraction of rainfall in eastern Amazonia for different levels of deforestation across the whole of Amazonia, compared with the original forest extent, for each season. In the model, deforested land was converted to soybean plantations (Sampaio *et al.*, 2007).

A key question is whether a general long-term trend exists during recent decades toward drought conditions and, if so, whether it is associated with anthropogenic climate change or deforestation. Li *et al.* (2008) show that the Standard Precipitation Index (SPI), a measure of changes in precipitation normalized by the standard deviation, does indeed suggest a more pervasive drying trend over the southern Amazon between 1970–1999. Previously, tendencies studied by Marengo (2004, 2009) for the period 1929–1998 suggested that no unidirectional rainfall trend existed in the entire Amazon region, but a slight negative/positive trend was identified in northern/southern Amazonia. To understand discrepancies between the two studies it is necessary to evaluate the time scales over which the data were collected. Perhaps, the most important aspect of natural Amazonian precipitation change is the presence of interannual and interdecadal variability in rainfall. The negative trend detected by Li *et al.* (2008) for southern Amazonia during 1970–1999 coincided with the mid-1970s–1998 downward rainfall trend of the interdecadal rainfall variability in northern Amazonia (Marengo, 2004). This decadal variability seems to be linked to interdecadal variations in the SST in the tropical Atlantic (Wagner, 1996).

Projections of the Intergovernmental Panel on Climate Change (IPCC) AR4 and regional climate models suggest that the eastern Amazon may become drier in the future, and that this drying could be exacerbated by positive feedbacks with vegetation. At the broadest temporal and spatial scale, most Global Circulation Models (GCMs) predict that greenhouse gas accumulation, and associated increases in the radiative forcing of the atmosphere, will cause a substantial (> 20%) decline in rainfall in eastern Amazonia by the end of the century, with the biggest declines occurring at the end of the rainy season and in the dry season (Meehl *et al.*, 2007; Malhi *et al.*, 2008; Marengo *et al.*, 2009).

Investigation of the possible impact of Amazon deforestation on the regional climate and hydrology, prompted GCM simulations in which forest was replaced by grassland across the whole basin. The results suggested a possible change in both regional and global climates as a consequence of such tropical deforestation (see reviews in Salati and Nobre, 1991; Marengo and Nobre, 2001; Marengo, 2006; Sampaio *et al.*, 2007; Sampaio, 2008). Under a hypothesized Amazon Basin deforestation scenario, almost all models show a significant reduction in precipitation, decreased streamflow, and increased air temperature.

Observations and models suggest large-scale deforestation could cause a warmer and somewhat drier climate by altering the regional water cycle. Model results (Sampaio *et al.*, 2007; Sampaio, 2008) suggest that when more than 40% of the original extent of the Amazon forest is lost, rainfall will decrease significantly across eastern Amazonia. Complete deforestation could cause eastern Amazonia to warm by more than 4°C, and rainfall from July to November could decrease by up to 40%. Crucially, these changes would be in addition to any change resulting from global warming. Reducing deforestation could minimize these impacts as well as reduce emissions of greenhouse gases. It has been suggested that 40% deforestation (Figure 9.1) may be a tipping point beyond which forest loss causes climate impacts which cause further forest loss (Sampaio *et al.*, 2007). Global warming of 3–4°C may also lead to a tipping point. Although the existence of these tipping points still requires clarification, interactions between climate change and deforestation may make them more likely.

Climatic changes induced by deforestation may inhibit forest regeneration on fallowed lands. Contributing to this risk is the large fraction, perhaps as much as 50%, of precipitation in the Amazon Basin that is recycled via evapo-transpiration (Salati *et al.*, 1979). The importance of this hydrology is evident in GCM simulations, which suggest that the climate of Amazonia would dry by *c.* 20–30% and dry seasons would lengthen as summer temperatures increase. It can be presumed that changes to the cycles of water, energy, carbon, and nutrients that result from replacement of Amazonian forest will have consequences for the climate and the environment at local, regional, and global scales. Similarly, the biodiversity and the ecosystem services that forests offer would be negatively impacted. The conversion of primary tropical forest to agricultural areas, or secondary vegetation, represents one of the most profound changes to the natural environment of the present age.

While the large-scale effects of deforestation are relatively well substantiated (Gash and Nobre, 1997), heterogeneous patterns of sub-regional land cover change might result from increased local precipitation through the so-called "forest breeze" effect (Roy and Avissar, 2002; da Silva *et al.*, 2008). The outflowing forest breeze creates an effect of convergence between the forested and deforested patches and this can result in local increases in convection-driven rainfall at the boundary of the forested–deforested region.

On the other hand, modeling studies of surface hydrology suggest that these local responses depend on the scale of changes (D'Almeida *et al.*, 2007). If deforestation of the basin reaches 50%, models suggest evapo-transpiration could be reduced and runoff increased even in the absence of changes in rainfall (Coe *et al.*, 2009). Observations of change over deforested areas confirm increases of surface temperature and decreases in evapo-transpiration (Gash and Nobre, 1997); however changes in precipitation have been harder to detect. Recent analysis of satellite-based estimates of cloudiness and rainfall over deforested areas seem to confirm expectations (Cutrim *et al.*, 1995) of increasing non-precipitating cloudiness and decreasing dry-season precipitation (Wang *et al.*, 2009). Changes in the distribution of cloud condensation nuclei due to biomass burning may inhibit the formation of precipitating droplets in clouds (Andreae *et al.*, 2004) and thereby reduce precipitation.

If tropical climates can exist in multiple stable equilibria, one could ask how does a system get from one equilibrium state to another? Maybe such changes can occur if there is a change in the frequency and nature of extreme events as well as shifts in the mean. A shift in climate, due to natural or anthropogenic causes, can change the frequency and magnitude of disturbance. The change in relative system stability might make a vegetation change irreversible (e.g., Cox *et al.*, 2001; Oyama and Nobre, 2003)—however, it might take a disturbance for the shift to occur. This observation leads to the concept of instability and to the idea of a tipping point as a precursor to a non-linear change in an ecosystem's response to a forcing.

The paleoclimate records show that past climate changes have included both steady, linear changes as well as abrupt, non-linear changes (e.g., Bush *et al.*, 2010), where small increases in global warming produced large impacts once tipping points were passed. Climate scientists now warn that anthropogenic emissions are pushing the planet's climate system toward such a tipping point—sooner than previously expected—and that impacts could be catastrophic.

9.3 CLIMATE CHANGE IMPACTS ON AMAZON VEGETATION

9.3.1 Projected changes to the natural vegetation

Vegetation change in Amazonia is important for several reasons. Deforestation is a key land use change, affecting surface energy exchange through changing surface properties such as albedo, surface roughness, and evaporation. With more than 15% of the original Amazon deforested, substantial changes in precipitation and surface temperature are expected (Gash and Nobre, 1997). Changing vegetation may also alter the recycling properties of the original vegetation. As 30–50% of the precipitation within Amazonia consists of recycled evaporation (Molion, 1975; Salati, 1987; Eltahir and Bras, 1994), changing the evaporative properties of the vegetation will change the recycling potential.

Applying 2050 AD climate scenarios from 15 climate models for two emission scenarios (A2 and B1) from IPCC AR4 to the CPTEC Potential Vegetation Model (PVM) (Oyama and Nobre 2004), Salazar *et al.* (2007) demonstrated a probable reduction of tropical forest and replacement by savannas. The amount and rate of reduction of tropical forests increases with time through the 21st Century; with the greatest reduction occurring in southeastern Amazonia. The predicted decrease in tropical forest vegetation in South America, relative to potential modern vegetation cover under the A2 emission scenario, is 3% for the period 2020–2029, 9% for 2050–2059, and 18% for 2090–2099. The PVM is an equilibrium model (not a dynamic vegetation model), and this is vegetation that potentially would grow under optimum climate conditions. The model needs temperature and rainfall input, from which it calculates the water balance and soil moisture conditions. The vegetation seems to be more sensitive to temperature changes than rainfall, and while all models show warming, predicted changes in rainfall differ widely.

More recently, Salazar (2009) studied the consequences of regional projected climate change on biome distribution in South America in the time-slice 2070–2099, by forcing a regional potential vegetation model (CPTEC-PVMReg2.0) with climate scenarios from the three regional climate models of the CREAS project (RegCM3, Eta CCS, HadRM3; Marengo *et al*., 2009) under the A2 emission scenario. The CPTEC-PVMReg2.0 (Salazar, 2009), a regional version of the CPTEC-PVM2.0 model (Lapola *et al*., 2009), considered seasonality as a determinant factor for the delimitation of forest and savannas. It also took into account physiological responses of vegetation to seasonality (such as primary productivity) under variable atmospheric CO_2 concentrations. As a non-dynamic model, the CPTEC-PVMReg2.0 calculated only equilibrium solutions based on long-term mean monthly climate variables. The consequences of projected climate change on biome distribution in South America were analyzed through a PVM forced with the IPCC climate change scenarios. The results indicated the reduction of tropical forest cover and replacement by savannas mostly over southeastern Amazonia reaching a reduction of 18% for 2090–2099 (A2 emission scenario).

Figure 9.2 shows the current potential vegetation (biome distribution simulated by the CPTEC-PVM2.0Reg model under current climate) and the projected biome distribution for the A2 scenario and the 2070–2099 time-slices, for all the regional models analyzed—including the full fertilization effect. All models show loss of tropical forest in east Amazonia and replacement by savanna (most notably in RegCM3 model). The ETA CCS, output differs from the other models, showing the tropical forest being replaced by seasonal forest and savanna in southwestern Amazonia. The key difference of this output appears to be a greater increase in projected temperature compared with other models The biome changes are explained by the net effect of temperature and CO_2 concentration on net primary productivity and the precipitation decrease effect as dry-season length increases.

Precipitation decreases of 30% in southeastern Amazonia and 40% in the northeast and southwest could represent an increase of dry-season length to more than 4 months and shifts from forest to savanna vegetation. Lapola *et al*. (2009) identified this threshold of <4 months dry-season length as critical to maintaining tropical forest, even allowing for a CO_2 fertilization effect. Some areas in northeast Brazil are predicted to change from Caatinga to semi-desert in HadRM3P and RegCM3 models, due to decreased soil humidity (projections of temperature

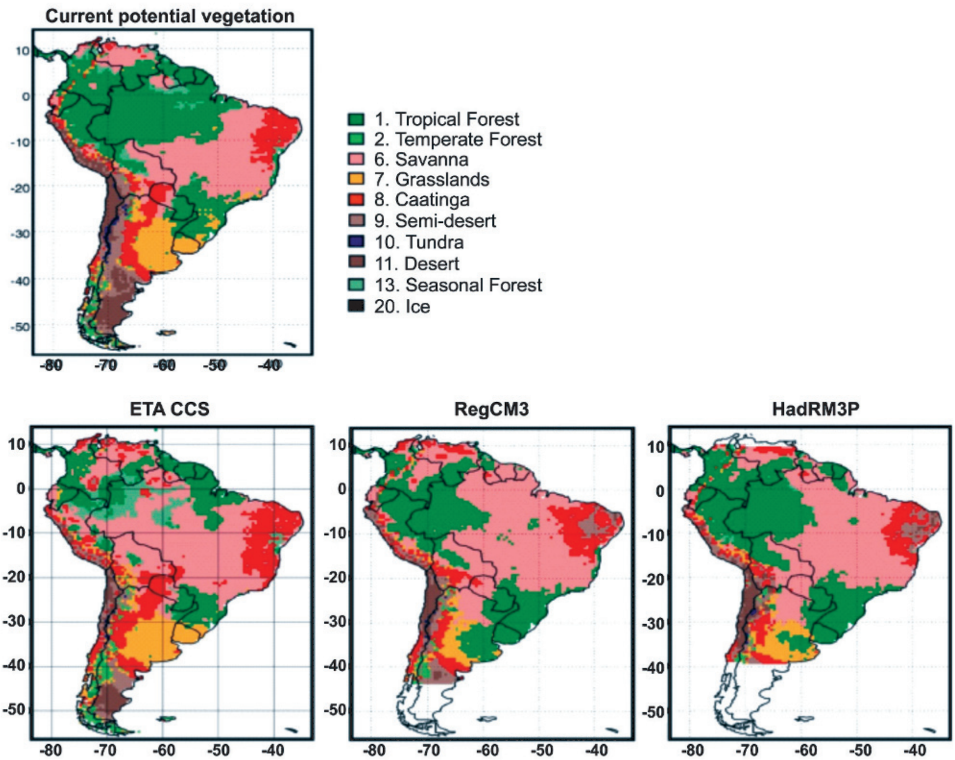

Figure 9.2. Projected distribution of biomes in South America for 2070–2099 from ETA CCS, RegCM3, and HadRM3P models under the A2 high-emission scenario. The top-left plot represents the current potential biomes (biomes in equilibrium with observed climatology) (Salazar, 2009).

increase and precipitation decrease) and net primary productivity. Both these models show an increase of tropical forest in southeast Brazil (Mata Atlántico) at the expense of grasslands in Uruguay and Argentina, due to the projections of increased precipitation and temperature in this region.

Nobre *et al*. (2010) performed analyses to quantify how deforestation, climate change, and fire may combine to affect the distribution of the Amazon forest biome. Changes in land use are modeled for deforestation scenarios of 0%, 20%, 40%, and 50%, with and without fires, under the two greenhouse gas scenarios—B1-low and A2-high—for the period 2015–2034 and 2040–2059 ("2025" and "2050" time-slices), from IPCC AR4. The results show that the area affected in scenario A2 is larger than in the climate scenario B1, and in both cases the effect is cumulative through time. Most important changes occur in eastern and southern Amazonia, with replacement of tropical forest by seasonal forest and savanna. The effect of fire in this region is important under both emissions scenarios (B1 and A2). The effect of 20% deforestation is smaller than the climate change only in the remaining tropical forest area in both emission scenarios. However, as deforestation exceeds 40% of the area its effect is larger than that of climate change alone. For the more extreme case (50% deforestation in the 2050 time-slice) the synergistic effects of climate change, fire, and deforestation reduce tropical forest area under both climate scenarios to between 36% and 38%. Northwestern Amazonia has the smallest changes in its area of tropical forest, indicating that even for substantial land use modifications and global climate change the resulting atmospheric conditions would still support tropical forest in the region.

The natural biome distribution derived from the global and regional climate change scenarios shows considerable uncertainty with respected to rainfall changes, mainly for Amazonia and northeast Brazil. The projected increase in temperature may elevate the rate of evapo-transpiration in tropical regions, which, in turn, could increase soil-moisture deficits, even when rainfall does not change significantly. Changes in rainfall are not consistent among models as some of them show increases and others show decreases in rainfall by 2050. As concluded by Salazar *et al*. (2007) and Salazar (2009), increased evapo-transpiration alone may be sufficient to trigger the replacement of the present-day potential biomes by other vegetation types that are adapted to drier soils. That is, tropical savannas replacing tropical forest in Amazonia.

Sitch *et al*. (2008) investigates changes in the future land carbon cycle, using five dynamic global vegetation models (DGVMs), forced with observed climatology and atmospheric CO_2, to model the contemporary global carbon cycle. The DGVMs are also coupled to a fast "climate analogue model", based on the Hadley Centre GCM, and run into the future for four IPCC emission scenarios: A1FI, A2, B1, and B2. Results show that all DGVMs are consistent with the contemporary global land carbon budget. Under the more extreme projections of future environmental change, the responses of the DGVMs diverge markedly. In particular, large uncertainties are associated with the response of tropical vegetation to drought, and boreal ecosystems to elevated temperatures and changing soil moisture status. Five DGVMs are considered here: the HyLand (HYL) model is based on the Hybrid DGVM (Friend *et al*., 1997; Friend and White, 2000) with modifications as documented in Levy *et al*. (2004); the Lund–Potsdam–Jena (LPJ) DGVM (Sitch *et al*., 2003), with the updated hydrology of Gerten *et al*. (2004); ORCHIDEE (ORC) as described in Krinner *et al*. (2005); Sheffield-DGVM (SHE) (Woodward *et al*., 1995; Woodward and Lomas, 2004), and TRIFFID (TRI) (Cox, 2001).

There is a general consensus among the DGVMs in terms of the qualitative regional response of vegetation stocks to changing climate and atmospheric composition. All models simulate a decrease in vegetation carbon over Amazonia, in response to the reduction in precipitation predicted by HadCM3LC. TRI simulates the strongest Amazon dieback, with woody vegetation replaced by herbaceous plants. LPJ simulates only a moderate Amazon dieback, and a large reduction in boreal forest coverage and large, high-latitude losses in soil carbon. The high initial estimates of boreal forest carbon stocks in LPJ can partly explain the strong reduction in storage under very strong warming accompanied by severe summer drought. HYL simulates large carbon uptake in all ecosystems except over Amazonia, where, similar to TRI, the DGVM simulates a reduction in both vegetation and soil stocks. ORC and SHE both simulate only moderate decreases in vegetation biomass across Amazonia and small increases in soil carbon, the latter being a qualitatively different response to TRI, HYL, and LPJ. Note, the SHE model has fixed vegetation, and does not simulate changes in the coverage of plant functional types.

Biome projections for the first half of the century in tropical South America show a variety of results, depending not only on the climate scenario, but also on the effect of CO_2 fertilization on photosynthesis. In the Amazon, mostly in the east and southeast, projected increases in temperature and decreases in precipitation could support transitions to biomes where the vegetation is relatively sparse, such as transitions from tropical forest to savanna, from savanna to dry shrubland, or semi-desert replacing dry shrubland. On the other hand, CO_2 fertilization can minimize or even compensate for climate change effects on biome distributions.

9.3.2 Dieback of Amazon forest

In the most extreme scenarios GCMs (e.g., HadCM3) predict global warming to result in widespread forest dieback in the Amazon Basin (Cox *et al.*, 2000, 2004). Forest dieback has been explained in terms of sharp reductions of rainfall because of SST forcing from both the Pacific and Atlantic Oceans (Betts *et al.*, 2004; Cox *et al.*, 2000) and the role of vegetation–climate feedback (Betts *et al.*, 2008). Amazon forest dieback, in its turn, would induce a positive feedback as global warming transforms the large Amazonian carbon pool from supposedly being a carbon sink to a strong carbon source by 2050. However, there is uncertainty in climate projections of the hydrological cycle (precipitation) among IPCC AR4 climate models, where models failed to project a consistent change either for decrease or increase of rainfall in Amazonia through the 21st Century (Meehl *et al.*, 2007). One of the sources of uncertainty is the bias of the model in simulation of rainfall, and since models are validated against observations, the quality of the precipitation data used for validation may affect the identification and quantification of biases and systematic errors.

A review by Lenton *et al.* (2008) on tipping points and impacts on the forest shows that the dieback of the Amazon rainforest has been projected to occur with *c.* 3–4°C global warming. The apparent trigger for such a strong climate shift is a more persistent El Niño state that leads to drying over much of the Amazon Basin. However, whether such a state would reflect a more persistent El Niño-like behavior with stronger individual events or more frequent El Niño events, is not clear (Meehl *et al.*, 2007). Different vegetation models driven with similar climate projections also show Amazon dieback (Li *et al.*, 2006), but other global climate models (Salazar *et al.*, 2007) project smaller reductions (or increases) of precipitation and, therefore, do not produce dieback.

Vegetation models driven with a strong drying of the Amazon Basin have shown a dieback, but the magnitude of potential precipitation decrease over the Amazon remains controversial (Kriegler *et al.*, 2009; Sitch *et al.*, 2008). Figure 9.3 shows the simulations of the HadCM3 and the IPSL (Institute Pierre and Simon Laplace—University of Paris) models, for the carbon fluxes from ocean to air and

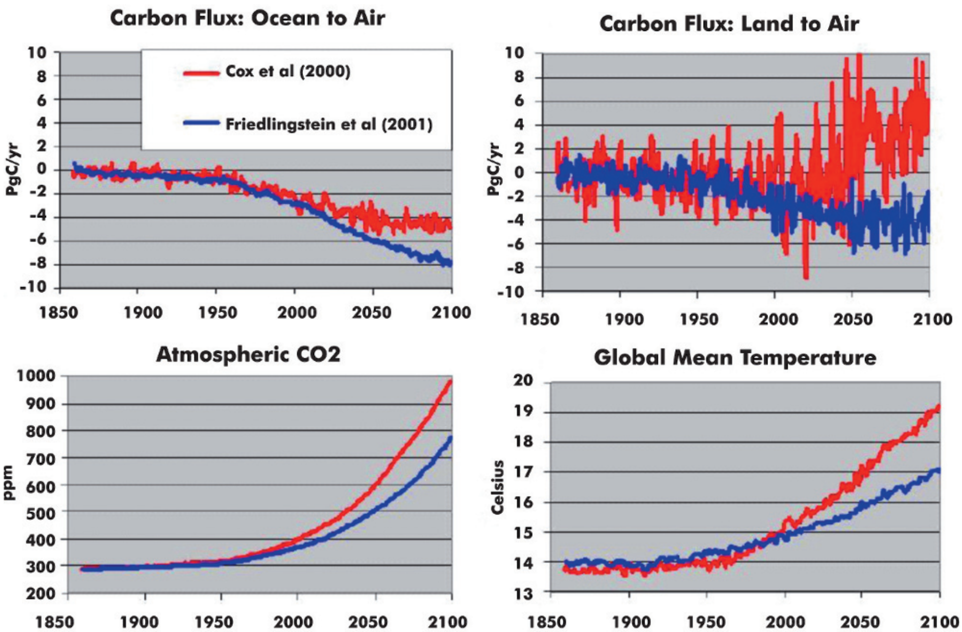

Figure 9.3. Carbon fluxes, CO_2 concentration, and global mean temperature as derived by the HadCM3 (red line) and IPSL (blue line) global coupled models until the end of the 21st century (Source: R. Betts)

land to air, together with the atmospheric CO_2 and warming increase. We notice that both coupled climate–vegetation models project dramatically different futures (CO_2, vegetation, temperature) using different ecosystem models. The HadCM3 model shows that near 2050 the Amazon regions become a net emitter of carbon as forests dry and dieback, while the IPSL model shows a more stable future.

The HadCM3 model projects that forest cover will begin to decrease in northeastern Amazonia by 2020 due to climate change, and that the changes will intensify after 2050. Between 2050 and 2090 forest cover in northern and central Amazonia will also decrease markedly. The loss of the forest biome in these simulations is purely attributable to climate change and does not include impacts of deforestation due to human activities.

The relative importance of the CO_2 fertilization effect versus altered precipitation was studied by Rammig *et al*. (2009). They "corrected" rainfall projections of 24 IPCC AR4 climate models by weighting functions derived from the performance of each model in representing the current climate. Rammig *et al*. (2009) concluded that the main source of uncertainty was in the effect of CO_2 fertilization and that differences in rainfall projections induced relatively small variances. Soil nutrients were another source of uncertainty, but were not analyzed here. The CO_2 fertilization effect was further studied by Salazar (2009) using three, high-resolution (50 km) regional climate models forced by HadCM3 global climate projections. They found that the maximum forest replacement would occur in eastern and southeastern Amazonia. In the absence of a CO_2 fertilization effect, a temperature increase of 2–3°C would be sufficient to change the moist tropical forest into seasonal forest or savanna. However, if a CO_2 fertilization effect is included, such changes would take place at temperature increases of 4–5°C. The potential effect of CO_2 fertilization on the tropical forests is clearly important, and is a factor that needs to be properly quantified.

An additional environmental driver of change in Amazonia is the increase in the occurrence of forest fires. Almost all modern fires in Amazonia are caused by human activities. However, natural fires have long played a critical role in determining the forest–savanna transition. Hirota *et al.* (2010) used a simplified climate–vegetation–natural fire model to assess the susceptibility of the forest–savanna transition to environmental changes in South America. Under current climate conditions, the modeling calculations suggest that the tropical forest would penetrate 200 km into the savanna domain in the absence of lightning-triggered fires.

Fire occurrence could increase the vulnerability of tropical forest ecosystems in Amazonia. Even a single fire can contribute to forest fragmentation and spread of fire-prone biomes (Barlow *et al.*, 2003). With repeated fires the probability of progression toward savanna increases. Consequently, land-use change alone could potentially bring forest cover to a critical threshold. Thus, the fate of the Amazon may be determined by a complex interplay between direct land-use change and the response of regional precipitation, to forcing from El Niño and the tropical Atlantic.

Crucially, the impacts of deforestation are greater under drought conditions, as fires set for forest clearance burn larger areas. Reducing deforestation may help to maintain a more resilient forest under a changing climate. Forest fires, drought, and logging increase susceptibility to further burning while deforestation and smoke can inhibit rainfall, exacerbating fire risk. If SST anomalies (such as El Niño episodes) and associated Amazon droughts of the last decade continue into the future, approximately 55% of the forests of the Amazon will be cleared, logged, damaged by drought, or burned over the next 20 years (Nepstad *et al.*, 2008).

Malhi *et al.* (2009) examine the evidence for the possibility that 21st Century climate change may cause a large-scale dieback or degradation of Amazonian rainforest by using 19 models from IPCC AR4. Most tend to underestimate current rainfall and also vary greatly in their projections of future climate change in Amazonia. Their analysis suggests that dry-season water stress is likely to increase in eastern Amazonia over the 21st Century, but the region tends toward a climate more appropriate to seasonal forest than to savanna. Such forests may be resilient to seasonal drought, but are likely to face intensified water stress caused by higher temperatures. Reduced leaf area index, increased seasonality, and episodic drought all increase the currently low risk of natural fire in Amazonia. Any increase in fire-frequency, whether associated with climate change, logging, or road construction is likely to trigger positive feedback mechanisms that promote establishment of fire-dominated, low-biomass forests (Barlow *et al.*, 2003; Cochrane and Laurance, 2008). Conversely, deliberate limitation of deforestation and fire may be an effective intervention to maintain Amazonian forest resilience in the face of imposed 21st Century climate change.

Unlike the studies of Cox *et al*. (2000, 2004) and Betts *et al*. (2004), which project the diebacks, Mahli *et al*. (2009) fix the evaporation value at 3.33 mm day^{-1}, or 100 mm month^{-1}. This is the value used to define a dry month in Amazonia under present climates (Sombroek, 2001). By fixing this value, Mahli *et al*. (2009) do not allow large water deficits to develop and thereby constrain the extent of the dieback.

All these projected changes in Amazonia may have climatic, ecological, and environmental implications for the region, the continent, and Earth. A sound knowledge of how the natural system functions is thus a prerequisite to defining optimal development strategies. The complex interactions between the soil, vegetation, and climate must be measured and analyzed so that the limiting factors to vegetation growth and soil conservation can be established. New knowledge and improved understanding of the functioning of the Amazonian system as an integrated entity, and of its interaction with the Earth system, will support development of national and regional policies to prevent the exploitation trends from bringing about irreversible changes to it. Such knowledge, in combination with enhancement of the research capacities and networks between the Amazonian countries will stimulate land managers and decision makers to devise sustainable alternative land use strategies along with forest preservation strategies.

9.4 EXTREME EVENTS IN THE AMAZON BASIN

9.4.1 The drought of 2005

Tropical droughts may intensify and become more frequent this century as a result of anthropogenic climate change (Christensen *et al*., 2007). In addition to affecting Amazonian peoples and biodiversity directly, such events appear capable of strongly altering the regional carbon balance and thereby accelerating climate change. The intense drought over the western and southwestern Amazon in 2005 gave rise to several studies analyzing the meteorological, ecological, and hydrological responses that arose from the anomalous warming of the tropical North Atlantic (Saleska *et al*., 2007; Marengo *et al*., 2008a, b; Zeng *et al*., 2008; Arago *et al*., 2008; Phillips *et al*., 2009; Tomasella *et al*., 2010a). Large sections of southwestern Amazonia experienced one of the most intense droughts of the last hundred years. The drought severely affected human population along the main channel of the Amazon River and its western and southwestern tributaries, the Solimões, and the Madeira Rivers. Water levels fell to historic lows forcing navigation along these rivers to be suspended. The drought did not affect central or eastern Amazonia, a pattern different from the El Niño-related droughts in 1926, 1983, and 1998. Figure 9.4(a) and (b) show rainfall anomalies in western and southern Amazonia reaching up to 70–100 mm lower than normal (normal being 200–400 mm month^{-1}), particularly at the beginning of the austral summer (Figure 9.4a).

The causes of the drought in 2005 were not related to El Niño but to the anomalously warm tropical North Atlantic, the reduced intensity in northeast trade wind moisture transport into southern Amazonia during the peak summertime

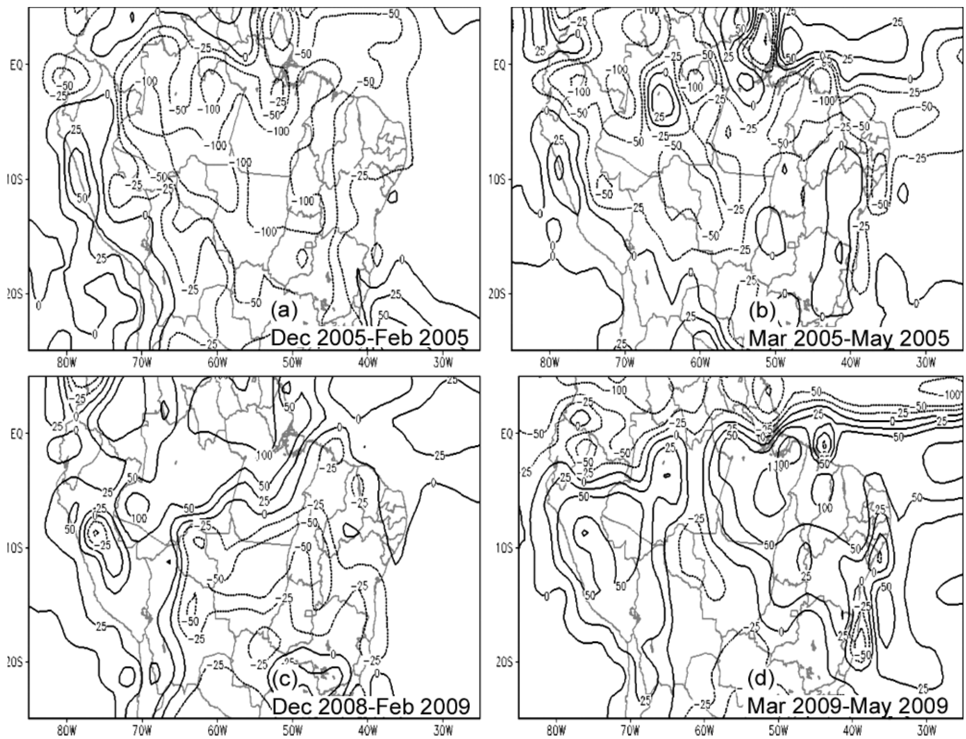

Figure 9.4. Seasonal rainfall anomalies (in mm) during (a) December 2004–February 2005, (b) February–May 2005, (c) December 2008–February 2009, (d) February–May 2009. Anomalies are relative to the 1961–2009 long-term mean (LTM1903–1986). Source: CPTEC/INPE.

season, and the weakened upward motion over this section of Amazonia. The net result of these influences was reduced convective development and rainfall. The drought conditions intensified during the dry season into September 2005 when humidity was lower than normal and air temperatures were 3–5°C warmer than normal. Due to the extended dry season, forest fires became unusually common in southwestern Amazonia.

During the drought period, there appears to have been a greening of the vegetation (Saleska *et al*., 2007), a phenomenon often seen during the dry season in terra firme forests. This flush of growth is attributed to increased radiation and evapo-transpiration (it is often forgotten that tropical rainforests are light-limited systems) for areas with annual rainfall in excess of 1,700 mm and ecological adaptations such as deep roots and hydraulic redistribution mechanisms (Nepstad *et al*., 2004).

Previously, the drought of 1998 in north and central Amazonia was generally considered to have been the most intense of the last 118 years (Kirchoff and Escada, 1998). However, Williams *et al*. (2005) suggested that the most severe drought in tropical South America during the 20th century occurred in 1926 during the El Niño of 1925–1926. They established that the drying in the northern portion of the Rio Negro Basin in 1925 also contributed to the overall drought in 1926, through both a depletion of soil moisture and possibly via negative feedbacks on rainfall from abundant smoke aerosols. The annual rainfall deficits were broadly consistent with the reduction in annual river discharge for 1926—estimated at 30–40%. The reduction in peak discharge during 1926 was closer to 50%. Sternberg (1987) describes an unparalleled drop in the floodwater levels of the Rio Negro at Manaus during the El Niño event in 1925–1926. During the severe dry season of that year a great fire blazed for over a month, scorching the vegetation along the main channel. The drought also affected the Orinoco Basin with widespread and drought-related fires in the savannas.

9.4.2 The flood of 2009

During austral summer and fall 2009, the Amazon Basin, drained by the Amazon River and its tributaries was hit by heavy flooding. Water levels rose higher, and stayed at flood stage for longer, than in the past several decades. According to national and international press coverage, almost 376,000 people were left homeless and 40 deaths resulted from the flooding. Communities living on the river banks and in urban areas (e.g., Manaus), suffered the impacts of the rising waters. Populations of already endangered species were adversely influenced. Damages are estimated in the order of US$200 million in the Brazilian state of Amazonas.

Total rainfall during the summer of 2008–2009 was very high across all of Amazonia (Figure 9.4(c,d)), with some areas doubling their normal precipitation. Initially (December–February) northern and northwestern Amazonia were especially wet, but by February–May, the strongest anomalies were evident in the transition region between eastern Amazonia and northeast Brazil. In central Amazonia, rainfall in April, May, and June was between normal and above normal. Rainfall anomalies reached values of about 100 mm above normal for most of central and eastern Amazonia in December 2004–February 2005 and over northeast Brazil in March–May 2009.

According to the measurements of the State University of Manaus (UEA), the abundant rainfall during January–February 2009 in northwest Amazonia caused high stands of the Solimões River at Tabatinga in March–April, with the levels reaching 12.5 m compared with the long-term pattern of 11.8 m. The higher levels of the Rio Negro at Manaus and the Amazonas at Òbidos were delayed by a few months. The Rio Negro at Manaus reached its maximum discharge between May and July. The measurements at the Manaus site reflect both the contributions of the Rio Negro and the Rio Solimões. It took about 4–5 months for rainfall that fell on the upper basin of the Rio Negro in northwest Amazonia to travel downstream to the Manaus gauge site. Therefore, the anomalously high levels measured during June and July were due mostly to the intense rainfall that fell during January and February 2009 over northwestern Amazonia. Rainfall in May and June over central Amazonia,

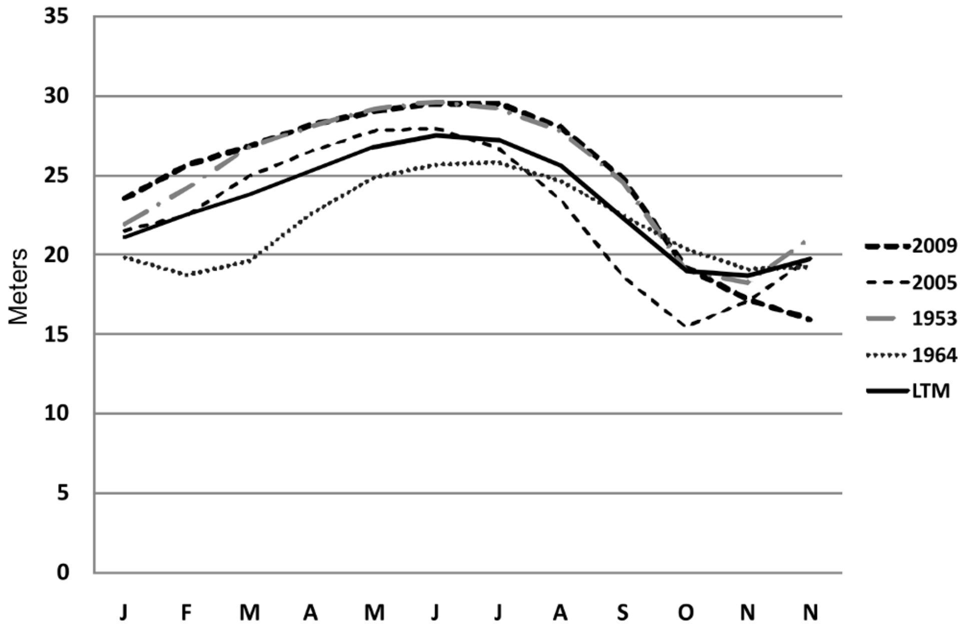

Figure 9.5. Annual values of the levels of the Rio Negro in Manaus, Brazil (in meters), for some extreme years: dry (1964, 2005), wet (1953, 2009), compared with the LTM for 1903–1986. Source: CPTEC/INPE.

where the rainfall takes 1 month or less to reach the gauge site at Manaus, was probably a relatively minor component of this discharge.

According to the Brazilian Geological Survey, the floods in Amazonia in 2009 were the highest in recorded history. The rise of the Amazon rivers began as early as March 2009. By July 2009, the levels of the Rio Negro in Manaus had reached 29.75 m, a new record high since the beginning of data collection in 1903. The five previous record highs observed in Manaus were: 1953 (29.69 m), 1976 (29.61 m), 1989 (29.42 m), 1922 (29.35 m), and 1908 (29.17 m). The Amazon River at Òbidos and the Tapajos River at Santarem also showed records high water levels since the beginning of data collection (Figure 9.5). Similarly, the levels of Peruvian rivers, the Amazonas, Marañón, Napo, and Corrientes Rivers also experienced record level/discharge highs, according to SENAMHI (the meteorological service of Peru).

The immediate cause of the unusually heavy rains across northern Brazil (Amazon and northeast Brazil regions) was associated with anomalously warm conditions in the tropical south Atlantic Ocean and a southward position of the ITCZ. Normally, the ITCZ, and its related rainfall, moves northward in April, but in 2009 it remained near its southern limit until May. Consequently, the moisture transport from the tropical Atlantic into the Amazon region was very intense. Almost simultaneously, La Niña conditions were detected in the tropical equatorial Pacific in 2009. Such mechanisms intensified the upward branches of the Walker and Hadley Cells, leading to persistent ITCZ episodes that caused very abundant precipitation conditions, sometimes concentrated over a few days, in most of the Amazon region. This pattern was especially evident in central and eastern Amazonia.

9.4.3 Climate change and extreme events in the Amazon Basin

Extreme droughts can lead to widespread forest fire regardless of whether they are caused by a very strong El Niño event or an anomalously warm tropical North Atlantic. Forest fires are exacerbated by man-made agricultural fires which run out of control and initiate fires in drought-stressed adjacent forest areas. In summary, land-use and land-cover change, droughts, and fire, reinforce each other through positive feedbacks (Nobre and Borma, 2009).

If severe droughts become more frequent in the future, which is a common projection for a warmer planet, then the process of savannization of eastern Amazonia may accelerate. Cox *et al*. (2008) suggest that intense droughts, such as those of 2005 could become more frequent and intense as climates warm in the second half of the 21st century. The probability of a "2005-like" year occurring in the HadCM3 run with aerosols, is approximately a 1-in-20-year event, but will become a 1-in-2-year event by 2025 and a 9-in-10-year event by 2060. These thresholds obviously depend on the rate of increase of CO_2, which is itself dependent on the emissions scenario chosen, resulting in a rapidly increasing risk of 2005-like droughts in Amazonia under conditions of reduced aerosol loading and increased greenhouse gases.

Phillips *et al*. (2009) used records from multiple, long-term monitoring plots across Amazonia to assess forest responses to the 2005 drought, and treated it as a possible analog of future events. Affected forest lost biomass, reversing a large long-term carbon sink, with the greatest impacts observed where the dry season was unusually intense. Therefore, the Amazon forests appear vulnerable to increasing moisture stress, with the potential for large carbon losses to exert feedbacks on climate change.

On the wetter side, even though model projections suggest drier conditions in central and eastern Amazonia for the future, the risk of intense rainfall events, especially in the western side of Amazonia is higher for the last 30 years of the 21st Century. While increased likelihood of flooding in northern Amazonia (Marengo *et al*., 2009; Tebaldi *et al*., 2006) is a qualitative projection, quantitative estimates of the probabilities of these events are lacking.

9.5 IMPLICATIONS FOR ECOSYSTEM AND ENVIRONMENTAL SERVICES IN AMAZONIA

In general, biodiversity plays an important role in ecosystem functions that provide support, provisions, regulations, and cultural services essential to human well-being. For example, people rely on biodiversity for food, medicine, raw materials, and ecosystem services such as water supply, nutrient cycling, waste treatment, and pollination. Forest ecosystems also provide a wide array of goods and services.

Human responses to a warmer climate are likely to increase demand for freshwater to meet urban and agricultural needs. Likely results will be decreased flow in rivers and streams, causing a loss of ecosystem services.

The Amazon forest is sufficiently large to have a significant impact on the regional and even global climate system, and provides a host of ecosystem services that are threatened by deforestation. As deforestation approaches this critical threshold, we can expect the marginal value of the forest ecosystem to rise rapidly, approaching the infinite if we believe that the loss of the Amazon ecosystem is unacceptable. Compounding the uncertainty of how much forest loss the climate system can tolerate before it can no longer generate adequate rainfall to sustain itself, are the regional effects of global climate change.

Studies of the hydrological cycle in the Amazon suggest that it recycles as much as 50% of its rainfall, and that if as little as 30% of the Amazon is cleared, it will be unable to generate enough rainfall to sustain itself, leading to a positive feedback loop of more forest loss and less rainfall. Rainfall in other words is essential for sustaining the Amazonian ecosystems and all the ecosystem services they generate. Indeed, the value of the Amazon as a water-regulating eco-utility becomes indistinguishable from the value of all ecosystem services generated by the Amazon. The Amazon forest releases water vapor to the atmosphere daily, transferring heat, moderating weather conditions and supplying Brazil and the La Plata Basin further south with rainfall on which US$1 trillion of agribusiness, hydro-power, and industry depend. Reduced rainfall in the Plata Basin would impact agriculture, industry, and hydro-electricity. These sectors are responsible for 70% of the GNP of five Latin American nations. Rainfall in the Plata Basin is derived from moisture from the Amazon Basin together with local evaporation in the Plata Basin, cold fronts from the south, and air masses from the South Atlantic. The major economic region of Latin America depends to an as yet unknown extent on rainfall from the Amazon.

These ecological services provided by the Amazon Basin may be threatened by global warming through a middle-century, climate-driven dieback and substitution of forests by savannah-like vegetation. Changes in rainfall and atmospheric moisture transport resulting from declines in Amazonian forest cover will need to be considered in addition to changes resulting from global climate change. Further research is needed to investigate the role of the forest in the economic well-being of the continent and to integrate this information into policies and practical activities to conserve the Amazon and provide benefits to its inhabitants. The introduction of payments for environmental services offers an opportunity for traditional and indigenous populations to be compensated for contributing to carbon sequestration in meeting the challenge of ameliorating global warming (Hall, 2008).

Besides the environmental impacts of expanding agribusiness and poor forestry practices, unsustainable development in the Amazon has also led to significant poverty and social inequality (Viana, 2009). Forests have historically been seen as valueless and forestry as backwards—neither of them worthy of inclusion in "development" strategies or in the usual set of policy instruments encouraging relevant investment, such as tax incentives and credit. Yet the significant problems deforestation causes now suggest that forests need to be regarded as valuable assets to individuals, families, businesses, and governments. In short, public, non-profit and private sector policies have to be guided by a simple message: ‘‘forests are worth more standing than cut’’. This paradigm shift has to be translated into broad cross-sectorial policies in areas such as finance, education, health, energy, and sustainable land use systems.

Tropical forests are ‘‘eco-utilities’’ providing critical ecosystem services that underpin food, energy, water, and climate security on local to global scales. Currently, these services are unrecognized and unrewarded in international policy and financial frameworks, causing forests to be worth more dead than alive. Some valuations of standing forests in the Amazon have produced very positive results. On the one hand are the results of public policies aiming to increase the value of forest products—such as honey and managed timber—supporting private sector investment and social–environmental entrepreneurship. On the other hand, environmental services such as carbon sequestration and storage have big potential and are a key part of the equation too. The more valuable environmental services are the more resources will be available for investment in improving local people’s quality of life and ability to generate income.

Trivedi *et al.* (2009) described the tropical forest eco-utility in the form of (a) carbon capture and sequestration—mitigating climate change, (b) water pumping moderating surface temperatures, (c) rainfall recycling—supporting energy and food security. The Amazonian eco-utility can be assessed in the form of standing forests, frontier forests, and deforested and degraded land. Standing forests support human populations that are not currently clearing large areas of forest. In contrast, frontier forests are under direct and immediate threat from human activities, as in the ‘‘arc of deforestation’’. In such areas, the eco-utility services are being replaced by other ecosystem services such as agricultural production and forestry operations. Finally, there are large areas that were once forest but have been converted to agriculture and are now degraded of their natural capital. Conservation and sustainable development activities should aim to support the standing forests, stabilize the frontier, and restore the degraded forests.

Looking to the future, the conservation of Amazonian forests may prove to be based in green economics, while the greatest threat may come from the brown economics of forest destruction and climate-changing pollution. Much attention is currently focused on REDD (Reducing Emissions from Deforestation and forest Degradation) and afforestation and reforestation as mitigation options (Trivedi *et al.*, 2009). In short, the more profitable sustainably harvested forest products become, and the more realistic the accounting of ecosystem-services offered by forests, the less attractive deforestation becomes.

9.6 SUMMARY

The dieback of Amazonian forest in the 21st Century remains a distinct possibility, even though the uncertainties are still high. As a consequence of this dieback, some model experiments predict a large-scale substitution of Amazon forest by savannalike vegetation by the end of the 21st century. To minimize the potential risk of this dieback and savannization, a reduction in global greenhouse gas emissions is needed, and reducing land use cover change is one of the forms of mitigation. The stabilization of Amazonian deforestation and degradation would be an opportunity for local adaptation to climate change, as well as a potential global contributor toward mitigation of climate change. Maintaining forest cover would be the best strategy for climate change mitigation, regional development, and biodiversity conservation.

El Niño–Southern Oscillation (ENSO) and tropical North Atlantic feedbacks are likely to increase the severity and frequency of droughts and floods, as the Earth warms. The century-scale events of 2005–2010, in which severe droughts, floods, and fires, exerted pressure on Amazonian ecosystems, may become the norm rather than the exception by mid-century. Synergies of climate change and land clearance pose the greatest of all threats to Amazonia, threats that to some extent could be mediated by appropriate policy. Proper accounting of the benefits of ecosystem services offered by forests must be a priority for the development of forest conservation policy under climate change.

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