Water and the Environment
Pontifical Academy of Sciences, *Scripta Varia* 108, Vatican City 2007
www.pas.va/content/dam/accademia/pdf/sv108/sv108-nobre.pdf

CLIMATE AND LAND USE CHANGES IN AMAZONIA: IMPACTS ON THE HYDROLOGICAL CYCLE AND ON BIOME DISTRIBUTION

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1. INTRODUCTION

Climate and vegetation interact biodirectionally on many time and spatial scales. One clear manifestation of such interactions is the global pattern land cover and its relationship to climate. It can be said that climate is the single factor that exerts the largest influence on vegetation and its characteristics on a global context (Prentice, 1990). Thus, deserts, tropical forests, savannas, and other types of vegetation are determined to a first approximation by climate. And climate change affects the global distribution of vegetation from the distant past and likely into the future. On the other hand, changes in the distribution and structure of the vegetation may influence climate. The biophysical characteristics of vegetation and soils control to a great extent the exchanges of energy, water, momentum and trace gases between the land surface and the atmosphere. Changes in vegetation imply changes in many biophysical parameters of the vegetation such as the surface albedo and roughness, total leaf area, root density and depth, and all affect the energy balance at the surface and the soil water availability.

A large fraction of the land surface is being used by agriculture, grazing or other human activities such as urban areas. These uses represent about 35% (55 million km^2) of land cover. Significant agriculture expansion can only take place, excluding very cold and desert area, over the tropical forests of South America, Africa and Southeast Asia and also over the boreal forests of Canada and Russia (Foley *et al.*, 2003). Currently, a great amount of the tropical forests has been converted to agricultural land or is degraded. (Nepstad *et al.*, 2002). Particularly for Amazonia, total deforestation of the tropical forests over the last 40 year has reached an area in excess of 650.000 km^2 (18% of the forest area) in Brazilian Amazonia alone (INPE, 2006) due mostly to cattle raising and agriculture expansion into the forest, including that of the soy bean agriculture in the last decade (Soares-Filho *et al.*, 2006). The tropical forest plays an important climate regulation role in view of the relatively large recycling of water vapor into the atmosphere throughout the year via evapotranspiration (Gash *et al.*, 1996; Rocha, 2001).

In addition to land cover and use changes, global warming due to increase greenhouse gases emissions by human activities present another challenge for natural ecosystems of the world, reflecting as one more serious threat to biodiversity. Past climate changes are known to coincide with large changes in species composition in ecosystems and even episodes of mega-extinctions of animals and plants. The acceleration of human-driven climate change poses serious questions and challenges to conservation strategies to cope with the expected changes in the distribution, physiology and ecology of most species, and this is specially true for the tropical forests with its tremendous species diversity.

The ecosystems of Amazonia are subjected to two different, but interconnected climatic driving forces: one is regional deforestation and other land use changes such as biomass burning and forest fragmentation, which affects local and regional climate; changes associated to global climate change are the second one (Salati *et al.*, 2006). Many studies indicate that both of these changes in climate will contribute to regional increases in temperature, but the uncertainly is still considerably high for projections of regional changes of the hydrological cycle (e.g., Li *et al.*, 2006 and Figure 3, see page 229).

In Amazonia there remains the largest contiguous tropical forest of the planet. The vegetation, including its deep root system, is efficient in recycling water vapor, which may be an important mechanism for the forest's maintenance. Deforestation and forest fragmentation can alter the hydrological cycle and causes other impacts as well. For instance, in the event of severe droughts the forest can become highly susceptible to fires due to soil water deficits (Nepstad *et al.*, 2001).

In a recent study, Soares-Filho *et al.* (2006) have shown that if the current high deforestation rates are to continue into the future, about 40% of the Amazonian tropical forests will have disappeared by 2050 (Figure 1, see page 227). In principle, deforestation and global warming acting synergistically could lead to drastic biome changes in Amazonia. Oyama e Nobre (2003) have shown that two stables vegetation-climate equilibrium states are possible in Tropical South America. One equilibrium state corresponds to the current vegetation distribution where the tropical forest covers most the Basin. The other equilibrium state corresponds to a land cover in which most of the eastern Amazonia is covered by savannas. It is not a trivial scientific question to find out at which point the current stable state could switch (perhaps abruptly) to the second state, given the combined forcings of deforestation, forest fragmentation, increased forest fire, global warming with a likely consequence of more intense droughts such as the severe drought which affected western and southwestern Amazonia in 2005. All these factors may accelerate the 'savannization' of Amazonia and if the current pace of change is kept unaltered we may well only find out that the second equilibrium climate vegetation has been reached after we have passed the threshold for its establishment.

In the sections below we describe some of the impacts of land use change and climate on the tropical forests on Amazonia, including future biome changes due to global climate change.

2. Deforestation and Changes in the Hydrological Cycle in Amazonia

Most of the water vapor participating in rainfall over Amazonia is transported from the Tropical Atlantic Ocean by the trade winds. The rainfall is made of water vapor directly imported from the ocean and of water vapor originated by local evapotranspiration. A number of studies attempted to quantify the water balance of the Amazon Basin. Some of the earlier studies examined periods when deforestation was not much high, that is, up to the 1970s (Salati *et al.*, 1979, Salati e Marques, 1984; Salati, 1987). That was followed by many other studies (Nobre *el al.*, 1991; Matsuyama, 1992; Eltahir e Bras, 1994; Marengo *et al.*, 1994; Vorosmarty *et al.*, 1996; Costa e Foley, 1999; Zeng, 1999; Roads *et al.*, 2002; Marengo, 2004, 2005) which highlighted the difficulties of water balance closure for the basin. For instance, estimates of evapotranspiration range from about 35% to over 80% of precipitation. The closure of the water balance of the Amazon Basin is a scientific goal yet to be achieved and the difficulties arise mostly due to the scarcity of reliable observations of precipitation and atmospheric moisture transports in the Basin.

The lack of agreement about the magnitude of the water budget can be seen in Figure 2 (see page 228)(Marengo *et al.*, 2006) in which results of 4 different calculations yield quite different results for the basin evapotranspiration, from 59% to 82% as percent of precipitation.

Due to the strong interaction between vegetation and atmosphere in Amazonia, it is highly likely that deforestation will alter components of the water balance, decreasing evapotranspiration and in consequence, if deforestation is relatively localized, an enhancement of river flow due to an increase of surface runoff in the deforested areas. That, in turn, will reduce the available moisture for the soil-plant system and its residence time for the ecosystems.

There is interesting temporal and spatial variability in Amazonia that has to be accounted for. For instance, for one tropical forest site in central-eastern Amazonia – the Santarem area – measurements of evapotranspiration showed higher values for the dry season (3.96 mm/day) than for the wet season (3.18 mm/day). In that area seasonal patterns of evapotranspiration are controlled by solar radiation and not by soil moisture deficits in the dry season due to the effectiveness of very deep roots reaching deeper than 6 m to extract water (Nepstad *et al.*, 1994) and also due to the nigh-time hydraulic redistribution through the root system from deeper layers to the surface roots (Oliveira *et al.*, 2005). In other forest measurement sites, such as central Amazonia (Manaus) and SW Amazonia (Rondonia), less seasonal variability was observed (Gash *et al.*, 1996). It is noteworthy, however, that in all sites, dry season evapotranspiration ranged from 3.5 to 4 mm/day, clearly indicating high levels of water recycling. This moistening of the atmospheric boundary layer during the dry season may be critically important for facilitating dry season rainfall episodes. Although the amount of rainfall is not high during the dry season, it may be particularly relevant to keep a moist liter and upper soil layer, contributing to the functioning of the tropical forest and diminishing the likelihood of forest fires.

Considering the current deforestation area and patterns in Amazonia, can we say anything about observed changes in the hydrological cycle? For the basin as a whole, the Amazon river streamflow does not show any trend over the last 30 years. There have been few studies based on analyses of satellite-derived rainfall observations for the last 20 decades, comparing rainfall over deforested and forest areas for parts of Amazonia. The results of such studies are inconclusive even with respect to the sign of the observed rainfall differences for the two contrasting land covers: one study revealed an amplification of the seasonal cycle of rainfall for deforested areas, with more rain in the wet season and less rain in the dry season (Laurent *et al.*, 2002) whereas a similar analyses showed increase in the dry season rainfall over deforested areas (Negri *et al.*, 2004) or decrease at the end of the rainy season and increase at the end of the dry season (Chagnon and

Bras, 2005). These discrepancies are likely the result of intrinsic error in satellite-derived rainfall estimates.

On the other hand, impact of land cover change may be already evident for large river sub-basins of the Amazon Basin. Costa *et al.* (2003) showed an increase of 24% in the Tocantins river streamflow by comparing two 20-year periods (1949-1968 and 1979-1998). Throughout the analysis period, rainfall did not change significantly and the authors, thus, concluded that sub-basin evapotranspiration declined due to the change of the savanna-dominated land cover to agriculture and grazing lands (pasture). Their results are explained in terms of increased surface runoff during the wet season due to the shallower rooting system of the grassy vegetation. The area of the sub-basin converted to agriculture and pasture increased from about 30% in 1960 to 50% in 1995 (Costa *et al.*, 2003). These land cover alterations can lead to increases in streamflow during the wet season and decrease during the dry season as suggested by Bruijnzeel (1990), although the reduction of dry season streamflow was not evident for the Tocantins river.

3. Impacts of Climate Change Scenarios for 2070-2099 on the Biomes of South America

Field observations (e.g.,Gash and Nobre, 1997) and numerical studies (e.g., Nobre *et al.*, 1991) revealed that large scale deforestation in Amazonia could alter the regional climate significantly. Evapotranspiration is reduced and surface temperature is increased for pastures. That effect might lead to a 'savannization' of portions of the tropical forest domain. Recently, as mentioned above, Oyama and Nobre (2003) showed that a second stable biome-climate equilibrium with savannas covering eastern Amazonia and semi-deserts in Northeast Brazil may exist. However, there have been fewer studies on the impact of global climate change on South America, particularly on its biomes such as Cox *et al.* (2000). This session addresses this question by showing one calculation (Nobre *et al.*, 2005) on how natural biomes could change in response to various scenarios of climate change.

Figures 3 and 4 (see pages 229-230) show average temperature and rainfall anomalies for the decade 2070-2099 derived from 6 different Global Climate Models (GCM) available at the IPCC Data Distribution Center (IPCC DDC, 2003): models from the Max Planck Institute for Meteorology (ECHAM), Germany; Geophysical Fluid Dynamics Laboratory (GFDL), USA; Hadley Centre for Climate Prediction (HADCM3), UK; CSIRO (CSIRO-Mk2), Australia; Canadian Climate Center (CGCM2), Canada; and, CCSR/NIES, Japan. Two different GHG emissions scenarios (IPCC, 2000) were used: the A2 emissions scenario of high GHG emissions and B2, of low GHG emissions (the figures show only the scenarios for the high emissions scenarios A2). Typical model horizontal resolution is about 300 km. Analyses of these figures reveal larger differences in temperature and rainfall changes among models than among emission scenarios for the same model. As expected, the main source of uncertainty for regional climate change scenarios is that one associated to rather different projections from different GCMs. The projected temperature warming for South America range from 1 to 4°C for emissions scenario B2 and 2 to 6°C for A2. The analysis is much more complicated for rainfall changes. Different climate models show rather distinct patterns, even with almost opposite projections. For instance, GFDL GCM indicates increase in rainfall for tropical South America, whereas other GCMs show reduction (e.g., HADCM3) or little alteration. In sum, current GCMs do not produce projections of changes in the hydrological cycle at regional scales with confidence. That is a great limiting factor to the practical use of such projections for active adaptation or mitigation policies.

The CPTEC Potential Vegetation Model (PVM) (Oyama and Nobre, 2004) was used to study the possible alterations of South American biomes in response to the projected climate changes of Figures 3 and 4 for the decade 2070-2099. PVM is a model that describes reasonably well the large-scale distribution of world's biomes as a function of five climate variables. Figure 5 (see page 231) shows the projected biome redistributions in South America. As could have been foreseen, the major differences in biome distributions are found among different models rather than from the two emissions scenarios for a given model. In 5 out of the 6 GCMs a tendency for reduction in the tropical forest area can be seen and, in general, replacement for drier climate biomes (savannas replacing forests, dry shrubland replacing savannas, semi-desert vegetation replacing dry shrubland) in tropical South America. Impact on extratropical South America is somewhat smaller. The combination of warming and rainfall changes indicates less water availability for large portions of tropical South America in 5 out 6 GCMs. Impacts on agriculture and water resources can be expected for those regions.

Figure 6 (see page 232) shows changes in model calculated global land cover for tropical forests and savannas for three 30-year time-slices in the future for two emissions scenarios (A2 for high GHG emissions and B2 for low GHG emissions). Consistently, there is a reduction of 1/3 of areas covered by tropical forests for A2 and 22% for B2 and a corresponding increase of areas covered by savannas, indicating that, in general, the scenarios of future climate may favor the expansion of tropical savannas worldwide. By and large, other similar projections of vegetation changes in response to climate change lend credence to a substantial reduction of forest areas (e.g., White *et al.*, 1999; and Cramer *et al.*, 2001) or a complete forest die-back (Cox *et al.*, 2000; Jones *et al.*, 2003; Cox *et al.*, 2004).

In simple terms, the increase in temperature induces larger evapotranspiration in tropical regions. That, in turn, reduces the amount of soil water, even when rainfall does not reduce significantly. That factor by itself can trigger the replacement of the present-day biomes by other vegetation types which may be more adapted to less soil water. That is, tropical savannas replacing tropical forests, dry shrubland replacing savannas, semi-desert replacing dry shrubland. 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 could accelerate, since there is a higher probability for that area to experience droughts in the forest-covered areas of Amazonia (Hutyra *et al.*, 2005).

Another disturbance factor arises as a consequence of the increasing forest fire frequency. The dense primary forest of Amazonia has been by and large impenetrable to fire due to the high level of soil and litter layer humidity. However, forest fragmentation mostly due to selective logging and the widespread use of fire in agricultural practices in that region account for a substantial increase of the frequency of forest fires in the last two decades. For instance, the large forest fire that took place in northern Amazonia from January through March 1998 is an illustration of what may be in store for the future. Caused by an intense and persistent drought associated to the strong 1997-98 El Niño and the indiscriminate use of fire in agriculture, over 13,000 km^2 of forests burned in which is likely to have been the largest forest fire of modern times in Amazonia (Nobre *et al.*, 2005).

The synergistic combination of regional climate impacts due to deforestation and climate impacts resulting from global warming, resulting in warmer and possibly drier climates, and the increasing forest fire frequency, adds tremendously to the vulnerability of tropical forest ecosystems. The more adapted species to withstand the new conditions are typically those of the tropical and subtropical savannas, which are naturally more adapted to hotter climates with marked seasonality in rainfall and long dry seasons and where fire plays an important ecological role.

4. Concluding Remarks

The future of biome distribution in tropical South America in face of the synergistic combination of impacts due to both land cover and climate changes points out to 'savannization' of portions of the tropical forests of Amazonia and 'desertification' of parts of Northeast Brazil. For Amazonia, that trend would be greatly exacerbated by fires (Nepstad *et al.*, 1999). Considering that the time scale for ecosystem migration of centuries to millennia is much larger than the expected time scale of decades for GHG-induced climate change, global change has the potential of profoundly impacting ecological diversity of plant and animal species on a mega-diverse region of the planet. In sum, one cannot really expect effective adaptation policies when it comes to the potential of massive ecosystem disruptions that could be brought about by the project climate changes of this century. That would reinforce the case of mitigating climate change to avoid a dangerous interference with the ability of natural ecosystems to adapt to it.

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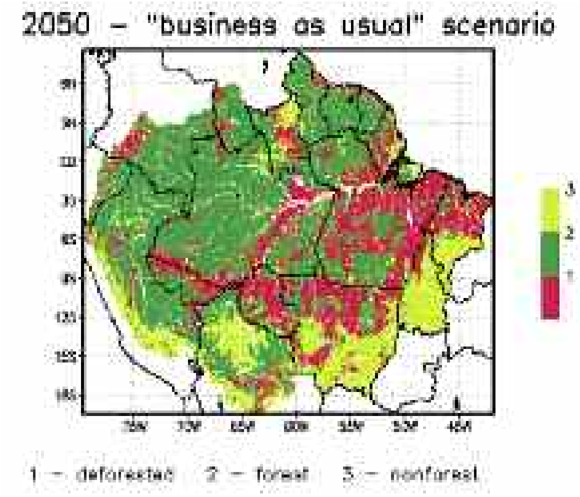

Figure 1. Projected land use change for Amazônia in 2050 for a 'business-as-usual' scenario. Areas in red represent deforestation, in green, forest areas and areas in yellow and white are non-forest (Courtesy of Soares-Filho, Federal University of Minas Gerais, Brazil).

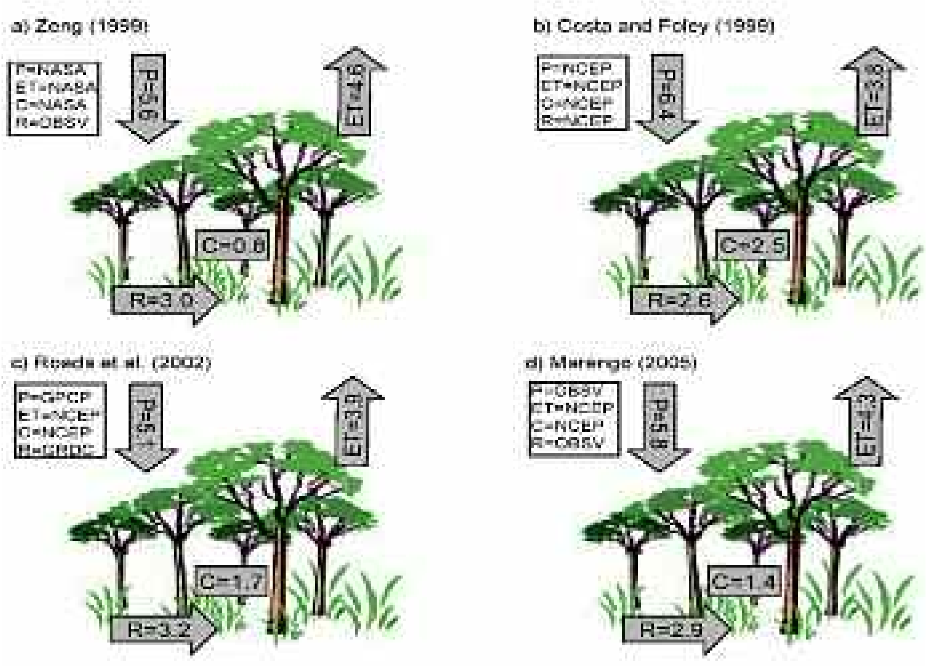

Figure 2. Summary of surface and atmospheric water balance calculations for the Amazon Basin based on four studies: (a) Zeng (1999), (b) Costa e Foley (1999), (c) Roads *et al.* (2000) e (d) Marengo (2005). P = precipitation; E = evapotranspiration; C = atmospheric moisture convergence; R = surface runoff. Units = mm/day (Marengo *et al.*, 2006).

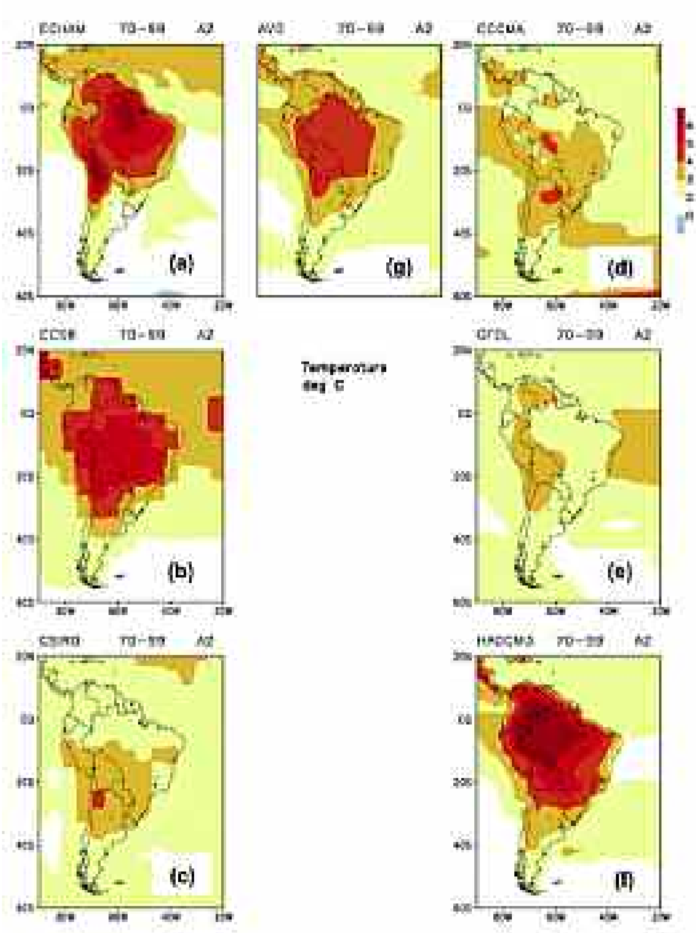

Figure 3. Climate change projections for 2070-2099 of surface temperature anomalies (C) for 6 Global Climate Models (a-f) (with respect to each model's average temperature for the base period 1961-1990) for emissions scenario A2. The top, center panel (g) shows the average of the 6 model anomalies for the same period (Nobre *at al.*, 2005).

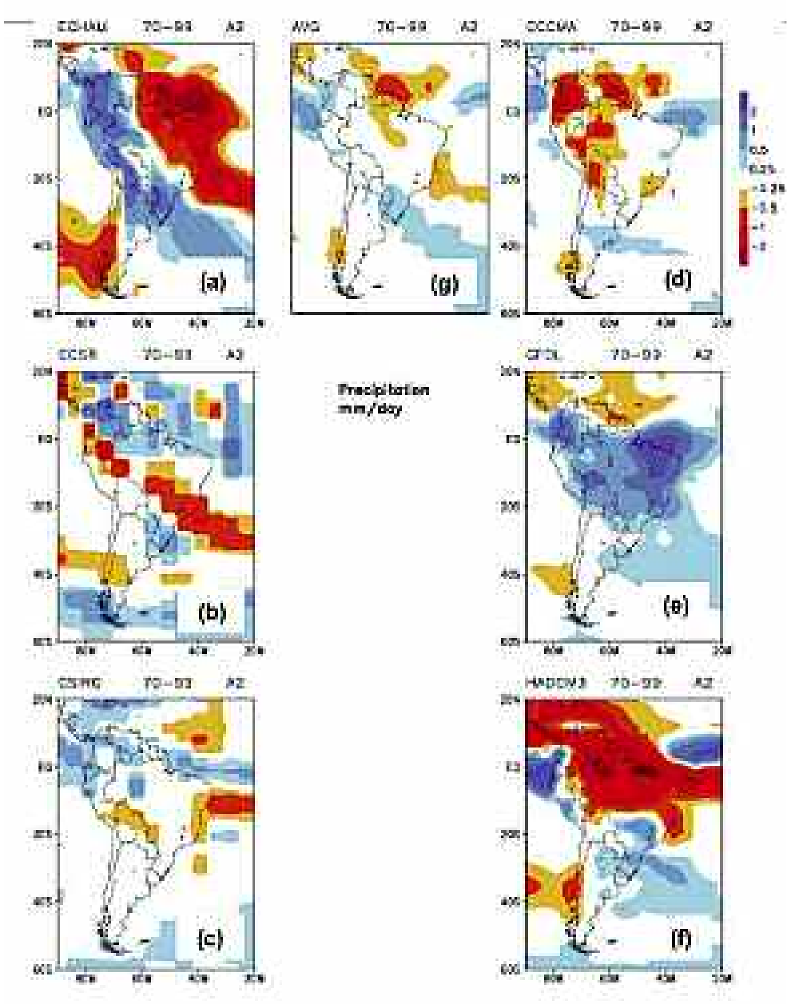

Figure 4. Climate change projections for 2070-2099 of precipitation anomalies (mm/day) for 6 Global Climate Models (a-f) (with respect to each model's average precipitation for the base period 1961-1990) for emissions scenario A2. The top, center panel (g) shows the average of the 6 model anomalies for the same period (Nobre *at al.*, 2005).

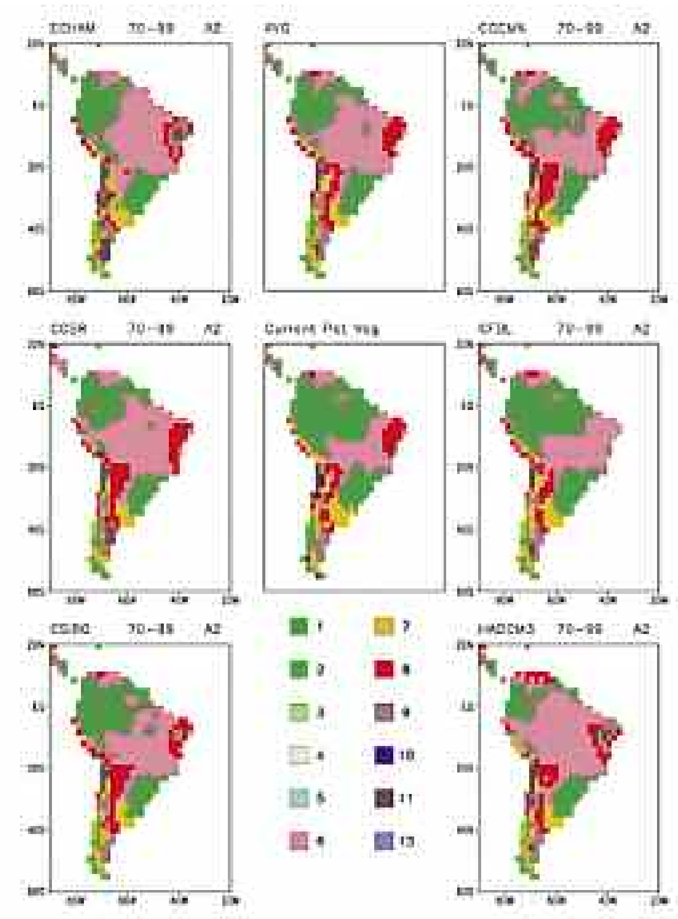

Figure 5. Projected distribution of natural biomes in South America for 2070-2099 based on the climate scenarios of Figures 3 and 4 from 6 Global Climate Models for the A2 emissions scenarios. The calculations of the biomes in equilibrium with the new climate were carried out with the use of CPTEC Potential Vegetation Model (PVM). PVM associates the main world's biomes to 5 climate variables, derived from monthly distribution of surface air temperature and precipitation. The main biomes for South America are represented by the following color code: green = tropical forest; pink = savanna; red = dry shrubland; yellow = extratropical grasslands; light brown = semi-desert; dark brown = desert; light green = deciduous Forest. The center panel labeled 'current pot veg' represents the natural biomes in equilibrium with the current climate. Notice that they represent the potential biomes, but not the actual vegetation distribution, which is a result of historical land use and land cover change. The upper, central panel labeled 'avg' represents the projected biome distributions for the averaged temperature and precipitation scenarios of Figures 3 and 4, respectively.

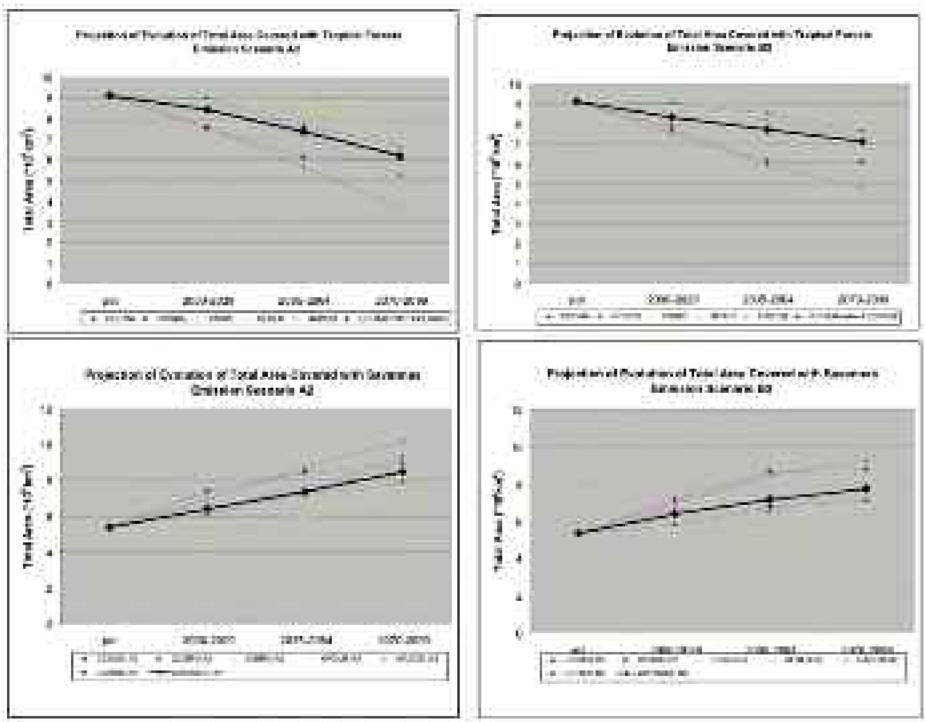

Figure 6. Projections of evolution of total area (in million km^2) covered with tropical forests (upper panels) and savannas (lower panels) for the period 2000 through 2100 for two emissions scenarios (left-hand panels for A2 and right-hand panels for B2). The black line represents the average for the 6 different projections.