Protecting the Amazon with protected areas

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This article addresses climate-tipping points in the Amazon Basin resulting from deforestation. It applies a regional climate model to assess whether the system of protected areas in Brazil is able to avoid such tipping points, with massive conversion to semiarid vegetation, particularly along the south and southeastern margins of the basin. The regional climate model produces spatially distributed annual rainfall under a variety of external forcing conditions, assuming that all land outside protected areas is deforested. It translates these results into dry season impacts on resident ecosystems and shows that Amazonian dry ecosystems in the southern and southeastern basin do not desiccate appreciably and that extensive areas experience an increase in precipitation. Nor do the moist forests dry out to an excessive amount. Evidently, Brazilian environmental policy has created a sustainable core of protected areas in the Amazon that buffers against potential climate-tipping points and protects the drier ecosystems of the basin. Thus, all efforts should be made to manage them effectively.

climate change | deforestation | environmental policy | tipping point

Recently, much scientific attention has focused on the Amazonian environment, given its biodiversity and its massive reservoirs of carbon and water (1). This attention has raised concerns about climate–land interactions and implications for the long-run sustainability of the forest. Two concerns in particular have surfaced in this regard. One involves the impact of global warming on the Amazonian forest and the specter of a "die-back" resulting from drier conditions (2–4). The other involves the impact of deforestation on regional climate and the possible existence of a tipping point beyond which positive feedbacks between deforestation and rainfall reductions will also lead to die-back, with transition to drier, fire-adapted systems (5, 6). The present article addresses this latter concern, within the context of current Brazilian policy aimed at maintaining the integrity of Amazonian ecosystems. This policy is founded, in large part, on the setting aside of tracts of land, or protected areas (PAs). This article poses the question of whether PAs buffer against tipping points in the Amazon basin. Specifically, do PAs protect the relatively dry forests and woodlands of the south and southeastern basin from transition to semiarid and fire-prone vegetation?

Our answer to this question proceeds in two steps. First, we apply a regional climate model to predict annual rainfall across the so-called "Amazonia Legal," or AML, assuming that all land outside PAs is deforested. We then use our precipitation projections to determine the extent of the ecosystem areas inside PAs subject to both drier and wetter conditions. Given our deforestation assumption, the analysis provides a conservative test of whether PAs by themselves can conserve enough Amazonian forest to avoid passing a climate-tipping point and ecosystem desiccation because of deforestation, under climate variability.

Amazonian Protected Areas (PAs)

Brazil has long sought to protect its environment, with legislation dating back to the early 1930s (7). Nevertheless, the creation of conservation areas in Amazonia is relatively recent and follows mostly in the wake of democratic reform in the 1980s. By 2000, ≈10% of Brazil's AML had been placed under conservation management after implementation of the Brazilian National System of Nature Conservation Units, or SNUCs (Law 9985 July 18, 2000; Decree 4340, August 22, 2002). Since 2000, conservation areas (both federal and state lands) have increased 5-fold, to >1.25 million km^2, nearly one-quarter of AML land area. SNUC is a comprehensive system that classifies PAs into two major groups, Integral Protection Units (IPUs) and Sustainable Use Units (SUUs). Biodiversity protection is the main objective of the IPUs, which include parks, biological reserves, ecological stations, natural heritage reserves, and wildlife refuges. SUUs allow varying degrees of resource exploitation, with biodiversity conservation as a secondary objective. These units cover production forests, extractive reserves, sustainable development reserves, environmental protection areas (APAs), and private natural heritage reserves (RPPNs) (Law 9985, July 18, 2000; Decree 4340, August 22, 2002).

Also important to AML conservation, and included as PAs in the analysis, are indigenous reserves. The 1988 Brazil Constitution guarantees the protection of Amerindian peoples and Convention 169 of the International Labor Organization recognizes their rights to the exploitation of natural resources within their territories. Nevertheless, an expectation of indigenous environmental stewardship is explicit in Chapter 26 of Agenda 21 stemming from the Rio Summit (8) and in the 1996 Indigenous Lands Project of the G7 Pilot Program to Conserve the Rainforest (9). These expectations are further enhanced by Brazilian law in the Forestry Code (see www.funai.gov.br) and in the National Plan for Protected Areas (Decree 5758, April 13, 2006). Research has shown that indigenous reserves are capable of resisting the encroachment of loggers, farmers, and ranchers, even when located nearby active settlement frontiers (10–17).

Historically, the position of Brazil on indigenous peoples has aimed at assimilation, but a great deal of land has been declared indigenous territory in recent years (9). As with conservation areas, the boost to indigenous claims came with democratic reform in the 1980s (9). The Constitution of 1988 accelerated the contentious process of reserve demarcation for 375 reserves encompassing nearly 1.06 million km^2, approximately one-fifth of AML. Thus, SNUC, its state counterparts, and indigenous reserves cover an estimated 2.3 million km^2, or 43% of AML. The question we seek to answer is whether or not this is enough. Worded another way, would AML reach a tipping point with deforestation at ≈60%, given the system of AML PAs currently in place?

Analysis

Climate Modeling. To answer the tipping point question, we implemented a regional climate model (RCM), specifically the

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Regional Atmospheric Modeling System (RAMS) version 4.4 (18), a limited-area atmospheric model that takes land cover as data input. As with other such models, RAMS focuses attention only on the atmospheric component of the hydrologic cycle, specifically evapotranspiration and precipitation. RAMS simulates many key processes of surface hydrology as well as or better than other regional and global climate models, but it does not close the hydrologic cycle by considering impacts on runoff and stream flow. Such impacts are implicitly assumed to have little bearing on precipitation recycling, the hydrologic phenomenon of greatest consequence to the vegetative changes of interest to the article.

The RAMS model domain, 210×130 grid points, covered the Amazon Basin at a 20-km horizontal grid spacing with 34 vertical levels. As such, RAMS is capable of representing mesoscale processes such as convection, which have been theorized to impact rainfall regimes in the Amazon basin (19). For the present application, surface and vegetation characteristics were governed by the LEAF-2 submodel (20), and regional land cover parameters (e.g., albedo, fractional cover) were assigned to appropriate Global Land Classification classes. Weekly surface sea temperatures were obtained from the National Oceanic and Atmospheric Administration (www.cdc.noaa.gov/cdc/data.noaa.oisst.v2.html).

The simulation approach is detailed in ref. 21. In essence, two sets of five annual simulations were performed by using a 1-min time step; one simulation set addressed a baseline scenario defined for the current amount of deforestation, and the other set, a development scenario in which deforestation is assumed up to the boundaries of all PAs. The five replications in each set were undertaken to represent variation in boundary conditions, accomplished by using 5 years of the National Centers for Environmental Prediction (NCEP) reanalysis data from 1997 to 2001 (including the 1997–1998 El Niño Southern Oscillation (ENSO)). Simulations were run on dual-core AMD Opterons with 8 gigabytes of memory connected through Infiniband and operating at 2.2 GHz. Even with substantial computational power, each simulation required $\approx$8 months to complete, given a model structure of 928,000 points for calculation at 60-s time steps for 364 days. Thus, multiple simulations were run simultaneously, with progress checked frequently along the way to identify possible problems. Storage of only the minimal output data consumed >2 tetrabytes of disk space.

RAMS has been extensively validated for the Amazon Basin and over time has developed parameterizations that reflect Amazonian deep-soil moisture profiles, LAI phenologies, and other regional biophysical features (19, 22–24). To assess accuracy for the present application, and in particular the ability of RAMS to respond to strong external forcing, simulated results were compared with rainfall data from the Climate Research Unit (CRU) TS2.1 (25, 26), and the Tropical Rainfall Measuring Mission (TRMM). Fig. 1 shows boxplots for CRU gridded observed rainfall (*Top*), RAMS baseline simulated rainfall (*Middle*), and TRMM rainfall (*Bottom*) for the strong ENSO period from July 1997 to June 1998. The upper and lower quartiles are defined by the box, with the median passing through it as a line. Filled circles represent extreme (>75% or <25%) outliers. As the figure indicates, model performance generally tracks the empirical data and is similar to RAMS validation results reported in ref. 19, although for a different time span.

The land cover input to the climate model for the development scenario assumed complete deforestation outside the PAs and replacement by cropland (23, 24); hence, no distinction is drawn between pasture and soy (27, 28). The PAs in the analysis included all federal and state lands designated as integral protection or sustainable use units, with the exception of APAs and RPPNs, both of which allow private property and extensive land uses. In contrast, extractive and sustainable use reserves

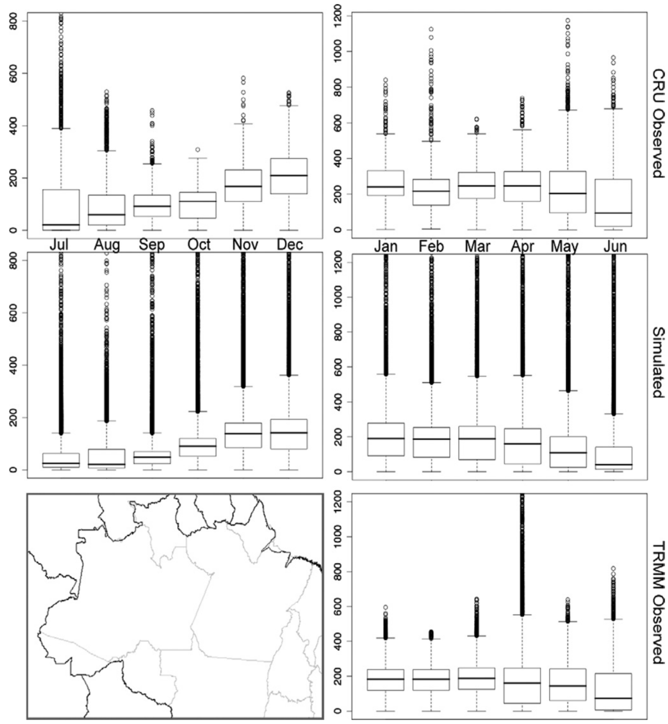

Fig. 1. RAMS validation runs for extremal forcing.

belong to the government, and local populations are granted usufruct rights provided they develop a management plan approved by environmental authorities in the interest of biodiversity conservation (SNUC Law 9985, July 18, 2000; Decree 4340, August 22, 2002).

The extent of PAs assumed for modeling purposes thus covers $\approx$37% of the basin (Fig. 2). Already deforested areas within the PAs, as identified by PRODES 2004 (29), were added to the total extent of deforested lands. Thus, the development simulations reflect the potential impact of the PAs after forest losses that had occurred up to 2004. Some deforestation has taken place within them since 2004, but this is a small amount, on the order of 0.37%; a large component of the PA system has been added since that time.

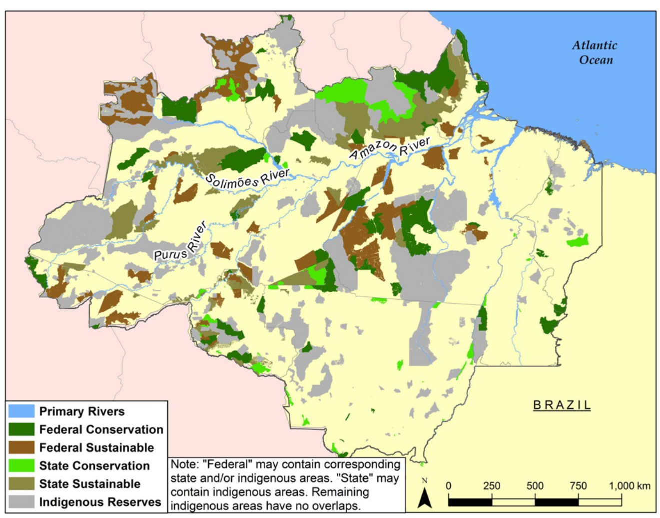

Fig. 2. Protected areas in the legal Amazon.

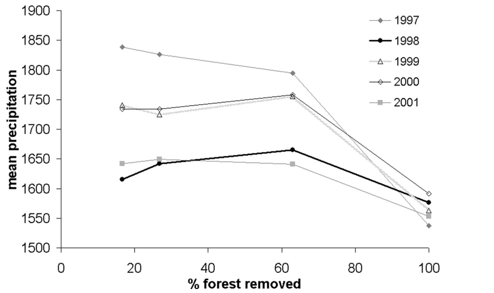

Fig. 3. Mean precipitation versus percent forest removed.

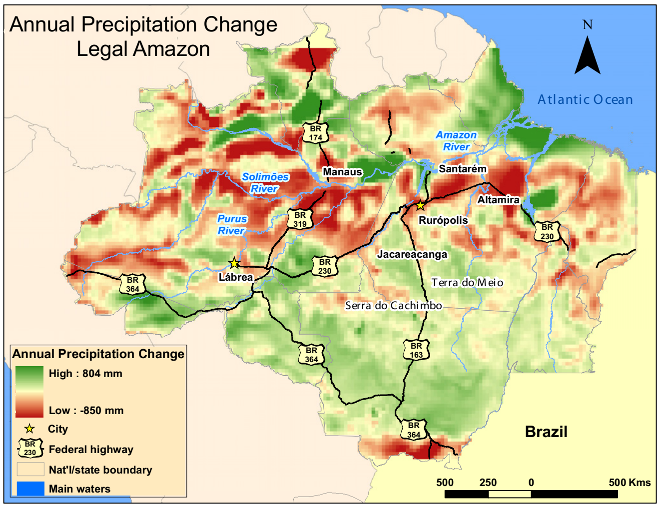

Fig. 4. Annual precipitation change: legal Amazon.

The data used in the ecological analysis are derived from simulated rainfall for the two scenarios, averaged for the 5-year period described (1997–2001). These outputs were then used to produce total annual rainfall and dry-season rainfall. Identification of the dry season presents conceptual issues, given spatial variation in onset and end across the basin. Thus, an approach was implemented based on the Standardized Precipitation Index (SPI) following ref. 30, using a 13-day moving average to smooth the data. The analysis of the dry season after SPI starts when the moving average falls below 1.0 standard deviation of the mean daily rainfall and ends when the index value reaches and exceeds it. The dry-season length so defined was compared with Sombroek (31, map 2) and showed good agreement across the basin.

Aggregate functional relationships between basin-averaged annual precipitation and varying levels of deforestation for the 5 years of analysis are given in Fig. 3. The low value of deforestation ($\approx$17%) is the baseline scenario of the present analysis (32). The rainfall values simulated at $\approx$27% and 100% deforestation are taken from an identical application of RAMS, as reported in ref. 21; the rainfall values at $\approx$63% deforestation represent the development scenario of the present analysis, with total land clearance outside the PAs. As Fig. 3 shows, the relationship between annual precipitation and deforestation is not linear and depends on external forcing. For the years 1998, 1999, and 2000, rainfall climbs over a range of increasing deforestation. These findings are consistent with speculation that rainfall may increase with Amazonian deforestation before declining (1, 23, 33).

Mechanisms for Climate Effects. A drier Amazon has been predicted for the 21st century, given the increasing regularity of "El Niño-like" conditions under global warming (34). This is postulated to occur by virtue of higher sea surface temperatures, which will alter the Hadley and Walker circulations that bring moisture to the basin (35, 36). However, the results underlying Fig. 3 show that even under El Niño conditions, rainfall increases across the basin with deforestation. A common view is that deforestation in the Amazon disrupts water recycling and reduces rainfall in monotone fashion, rendering forests increasingly vulnerable to desiccation and die-back (37). However, regional climate models suggest that basin-wide rainfall might actually increase over a range of deforestation (1, 23, 33). Fig. 3 further corroborates the nonlinearity of the link between deforestation and basin-scale precipitation. Thus, the Amazonian tipping point may occur at levels of deforestation considerably beyond the 30–40% that has been suggested (6, 38, 39).

Analysis of vertical moisture fluxes indicates that deforestation patterns are influencing synoptic rainfall via the Hadley circulation over the Amazon. Evidently, intensified convection arising from increased contrasts in latent and sensible heat fluxes between forested and deforested areas enhances rainfall over PAs where moisture is still abundant for fueling convective rainfall, in the absence of strong synoptic forcing (e.g., the ITCZ). In addition, removal of forest cover leads to a pronounced decline in stratiform rainfall for deforested areas. In many parts of the basin, this intensified convection appears to provide a counterbalance to projected decreases in moisture transport that follow disruptions in the Walker–Hadley circulation. Thus, intensified convection arising from increased surface temperatures, landscape heterogeneity, and albedo countervail decreases in moisture transport that result from disrupted Walker–Hadley circulation (24, 40). The implication is that even with massive deforestation, the spatial configuration of the AML PAs would enhance mesoscale circulation while retaining sufficient moisture to entrain for precipitation (19, 22, 24). Thus, model results suggest that Brazilian PAs are potentially capable of avoiding climatic tipping points over a considerable range of deforestation. Empirical research has shown localized instances of rainfall increase over deforested landscapes that would appear consistent with the mechanisms driving these results (41).

Spatial Results. To use model results to address the impact of Amazonian PAs on ecosystem integrity in the face of development, it is necessary to describe the spatial redistribution of annual and dry-season rainfall with respect to ecosystem distributions. The aggregate results of Fig. 3 mask considerable spatial variation, as depicted by Fig. 4, which gives pixel-level differences between the two sets of averaged simulations (calculated as the difference: development − base rainfall). Fig. 4 shows that total annual rainfall increases on more land than it decreases under the development scenario. In general, Western AML (west of BR-319 and BR-174) shows a more pronounced decrease (in annual and dry-season rainfall) than eastern AML. Both sections of the basin also show latitudinal partitioning, with rainfall increasing to the north and south and decreasing near middle latitudes. The area of rainfall decline in western AML, much more extensive than in the east, is concentrated near Manaus and upstream through the Solimões Basin. The north–south extent of rainfall decline narrows considerably in the east and organizes around BR-230, which forms a sharp divide between wetter and drier areas in places, particularly near Altamira, Rurópolis, and Jacarecanga. The northern area of increased rainfall organizes along the main stem of the Amazon River, at least in eastern AML, with dramatic increments between Manaus and Santarém, the terminus of BR-163. To the south and southeast, an extensive contiguous region of increased annual rainfall occurs in Tocantins, Southern Pará, Mato Grosso, Rondônia, and Acre, bounded by BR-230 to the north, and the Purus River to the west,

Table 1. Dry-season changes for ecosystems in protected areas

	Area, km^2		Calculated for drier areas only: Dry-season precipitation, mm/day			Dry-season length,* days		
Ecosystems	Drier	Wetter	Base line	Development scenario	%	Duration base line	Change	%
Dense moist forest	611,243	392,317	2.85	2.51	88	154.77	1.62	1.59
Open moist forest	207,883	281,800	2.32	2.06	89	170.18	4.52	3.34
Forested campinarana (tropical heath forest)	41,868	22,562	3.12	2.76	88	159.55	−9.43	−5.59
Wooded campinarana (tropical heath woodland)	9,689	2,625	3.13	2.70	86	167.74	−9.85	−5.62
Campinarana (heath shrubland)	4,128	2,440	3.57	2.95	82	161.69	1.24	1.31
Wooded (shrub) savanna	31,510	29,785	1.59	1.47	92	181.71	−4.42	−0.02
Savanna parkland	31,144	10,820	1.43	1.32	92	181.53	−0.88	0.00
Semideciduous forest	27,110	22,039	1.10	1.02	92	192.46	−4.12	−0.02
Forested savanna	8,633	20,509	1.41	1.32	94	175.92	3.33	0.02
Deciduous forest	4,004	8,212	3.39	3.13	92	209.15	−5.42	−0.03
Grassland savanna	3,732	1,718	1.04	0.92	88	181.40	−10.13	−0.06
Fluvial shrub pioneers (wetlands)	8,991	1,648	1.37	1.24	91	190.00	1.18	0.72
Fluvial herbaceous pioneers (wetlands)	5,883	10,448	1.00	0.81	81	145.99	7.91	6.41
Totals	995,818	796,475						

Development scenario precipitation was calculated with base scenario dry season, to preserve comparability. Development scenario dry-season length was used in calculation of dry-season change. Savanna systems included here are south of the Rio Negro and main stem of the Amazon River, east of Manaus.
*Each of the three entries under Dry-season length is an average calculated over all pixels in that part of the ecosystem that grew drier.

with deviations in areas (e.g., Terra do Meio and Serra do Cachimbo). The edges of AML to the south in Mato Grosso and Tocantins reveal some seasonal drying.

Despite these results, the expansive Tocantins watershed, which covers the southeastern corner of AML, reveals no recent trending in precipitation (42), and cloud data have been interpreted to suggest increasing seasonality of rainfall in the southern basin, with likely desiccation (43). Nevertheless, the regional partitioning of total rainfall change under the development scenario appears consistent with empirical analysis showing rainfall increases in the southern part of the basin and decreases in the north (44). Although some have explained any observed increases in Amazonian rainfall over recent years as a result of external forcing (41, 44, 45), the analysis of the present article indicates that rainfall may also rise with deforestation as a function of internal landscape structure.

Ecological Impacts

The tipping point is a climatic concept with ecological implications. To assess these implications, we overlaid changes in dry-season on POESIA ecosystem maps (46, 47) to assess impacts of development out to the boundaries of the PAs; dry-season characteristics play a decisive role in determining vegetative cover (48, 49). Results are presented in Table 1, which gives (*i*) PA ecosystem areas affected by both wetter and drier conditions, during dry season; (*ii*) daily dry-season rainfall for the scenarios; and (*iii*) changes in dry-season length. In general, development impacts on the length of dry season are not great and in many cases tend to reduce it. Thus, the discussion focuses mainly on simulated dry-season rainfall rates, reported in millimeters per day. Our primary interest focuses on the drier systems of AML, notably the savannas (cerrados) and deciduous forests in the *Middle*. As Table 1 shows, development makes some of these areas wetter and some drier during the dry season, although more land becomes drier than wetter. Rainfall reduction, even when it occurs, never falls below ≈92% of the base-line magnitude, with the exception of savanna grasslands, a relatively small system.

Nor do the moist systems that grow drier with development appear to experience extreme desiccation. Dry season rainfall for both dense and open moist forests falls little >10%, and daily precipitation remains above base-line magnitudes observed for the savannas. The deciduous forest presents a potential anomaly in this regard, with a very high daily rainfall during dry-season in the baseline scenario. The components of this system experiencing desiccation, however, are indigenous reserves found in the maritime zone of Maranhão, south of the bay of San Marcos. As such, they probably reflect anthropogenic disturbances associated with long-term occupation by indigenous peoples.

Governance Issues and Policy

The ecosystem analysis suggests that, even with high levels of deforestation, desiccation-driven savannization is not an immediate threat to the Amazon Basin. As such, the results support state-based governance of AML insofar as the spatial disposition and size of Amazonian PAs mitigate the climate impacts of deforestation on resident ecosystems, particularly in drier areas in the south and southeast basin. Of course, this conclusion rests on the optimistic assumption that the PAs remain largely preserved, even though deforestation is presently occurring in certain components of the system (50). As noted, there is diversity in the degree of protection across types of PAs under SNUC, something the analysis ignores. That said, the analysis assumes complete deforestation on all private lands, a highly pessimistic assumption. In Brazil, forest code legislation mandates a "reserva legal" requiring that forests cover up to 80% of private landholdings of 100 ha or larger. Such requirements are strengthened by programs like ProAmbiente, aimed at securing international funds for carbon sequestration by identifying means of paying communities and private landholders to avoid deforestation (51). Moreover, the United Nations Climate Conference in Bali in 2007 endorsed

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a mechanism to pay for carbon via avoided deforestation (52). Such initiatives support conservation on private holdings and make it likely that deforestation outside AML PAs will not be universal.

Evidently, Brazilian federal and state governments have created a sustainable core of PAs in Amazonia that buffers against potential climatic tipping points and protects the drier ecosystems of the basin. Thus, all efforts should be made to manage them effectively. Although existing PAs can help prevent basin-wide forest die-off, it is important to recognize that their current extent may still not be sufficient to maintain desired levels of biodiversity. Sustaining Amazonia's diverse ecological treasures over the long run will require the retention of forest on private lands, as required by law, and possible expansion of the current system of PAs.

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