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DEFORESTATION IN BRAZILIAN AMAZONIA

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Introduction

Tropical deforestation represents one of the world's great environmental problems, and Brazilian Amazonia has particular importance owing to the current rate of forest loss and the vast area of remaining forest at risk of future deforestation. Approximately two-thirds of the Amazon Basin is in Brazil. Brazil's "Legal Amazonia" region refers to a 5 million km^2 administrative area covering all or part of nine states; about three-fourths of this area was originally covered by Amazonian forest and one-fourth by *cerrado* (central-Brazilian savanna) or other non-forest vegetation. The "Amazonia Biome" is the area where the predominant original vegetation was Amazon forest; with the exception of a minuscule area in the state of Maranhão, the Amazonia Biome is entirely contained within Legal Amazonia. When the distinction between these two official Amazon areas is not important, the term "Brazilian Amazonia" is used. Deforestation threatens environmental services in maintaining biodiversity, avoiding greenhouse gas emissions, and recycling water that is essential to maintaining rainfall in Amazonia and in other locations that water vapor is transported to (including São Paulo). Understanding the diverse causes of deforestation in the region is essential to effective efforts to slow and contain the process. This article begins with general compendia, followed by sections covering deforestation monitoring, deforestation causes, deforestation actors, infrastructure, agriculture and ranching, forest loss through extreme degradation, deforestation impacts, deforestation control, protected areas, environmental services, and REDD (reducing emissions from deforestation and degradation). The causes of deforestation in Brazilian Amazonia vary considerably among different parts of this vast region, among landholdings within any given part of the region, and over time at any particular location. Both cumulative and annual statistics for Amazonia represent sums of these diverse actions. A major decline in deforestation rates occurred from 2004 to 2012, followed by oscillation around a lower plateau through 2015. Official statements invariably claim that government control programs can be credited with all of the decline, and they often imply that the decline continues. However, most of the decline occurred in the 2004–2008 period, when virtually all of the change can be explained by falling international prices of soy and beef together with a worsening exchange rate for Brazilian currency from the point-of-view of commodity exporters. After 2008, however, prices recovered while deforestation declined further. The key event in 2008 that appears to explain this change is a resolution of Brazil's Central Bank barring agricultural credit from government banks for properties with pending environmental fines. The fines themselves can be postponed almost indefinitely through repeated appeals, but the Central Bank decision has no appeal and has an immediate effect on larger landholders who have enjoyed generously subsidized loans for expanding their operations. The loan restriction gives real "teeth" to the Ministry of the Environment's efforts to control deforestation, greatly increasing the effect of the same investment in inspection and repression. However, the restriction on loans is a fragile protection, as it could be reversed at the stroke of a pen. This is one of the priorities of the powerful "ruralist block" representing large landholders in the National Congress. Another change in 2008 was the government's publication of "blacklists" of municipalities (counties) with high deforestation rates, thus restricting credit in these municipalities and making them the focus of command-and-control efforts. Events in other years include agreements with major purchasers of soy (in 2006) and beef (in 2009) to bar sales by properties with recent deforestation; these agreements had some effect, despite problems of "laundering" and "leakage." Although the government's deforestation-control program is essential, most of the government's actions are on the other side of the equation: vast plans for more roads, dams, and other infrastructure in Amazonia lead to more rather than less deforestation. The notion that deforestation is under control and that roads and dams can therefore be built without consequences is a dangerous illusion.

General Overviews

General compendia contain chapters by many authors who have worked with Amazonian deforestation: its causes, impacts, and possible alternatives. The volumes selected here begin with Hemming 1985 on change in the Amazon Basin, covering many fields related to deforestation. Goodman and Hall 1990, on the future of Amazonia, contains an impressive array of threats to the forest, but ends with some suggestions for more sustainable alternatives. Anderson 1990, published in the same year, concentrates on alternatives. Léna and de Oliveira 1991 reviews the various social groups and processes on Amazonian frontiers in the first twenty years since the Transamazon Highway provoked many of these changes. Wood and Porro 2002 looks at the implications of the different land uses in the region for deforestation and for the human populations involved. Laurance and Peres 2006 has more biological information on deforestation and degradation impacts, as well as alternatives such as avoided deforestation to mitigate global warming. Posey and Balick 2006 concentrates on traditional knowledge, particularly that of indigenous peoples, as a value to be protected and presents multiple examples of the contrast between traditional practices and the destruction in Amazonia's dominant deforestation-based economy. Keller, et al. 2009 contains results from LBA, a massive international research program underway since 1998 to study the relations between Amazon forest and climate, including the process and impacts of deforestation. Fleischresser 2001 presents the views on deforestation causes from researchers convened by Brazil's Ministry of the Environment.

Anderson, A. B., ed. 1990. *Alternatives to deforestation: Towards sustainable use of the Amazon Rain Forest*. New York: Columbia Univ. Press. [ISBN: 9780231068925][class:book]

Contains chapters on the process and causes of deforestation, on the non-sustainability of the predominant land uses following deforestation, and on various alternatives to current land uses. These include timber management, extraction of non-timber forest products, agroforestry, use of secondary forests and means of recuperating degraded pastures. Available in Spanish from Fundación Natura/Editorial Abya-Yala, Quito, Ecuador.

Fleischresser, V., ed. 2001. *Causas e Dinâmica do Desmatamento na Amazônia*. Brasília, Brazil: Ministério do Meio Ambiente.[class:book]

Convened by Brazil's Ministry of the Environment, this looks at causes of deforestation in Amazonia. The lack of enforcement of Brazil's 1965 Forest Code is clearly shown.

Goodman, D., and A. Hall, eds. 1990. *The future of Amazonia: Destruction or sustainable development?* London: Palgrave Macmillan. [ISBN: 9780333464908][class:book]

Contains chapters on existing development strategies such as private and government-organized colonization, hydroelectric dam construction, mining and military initiatives, and on the various social conflicts these cause. The concluding chapters suggest some more sustainable alternatives.

Hemming, J., ed. 1985. *Change in the Amazon Basin*. 2 vols. Manchester: Manchester Univ. Press. [ISBN: 9780719009679][class:book]

This two-volume compendium covers a wide variety of issues related to deforestation, including underlying factors such as population migration and growth—and the impacts on indigenous and other traditional peoples in the region. It includes perspectives from agencies such as the World Bank, as well as from workers in an array of social and natural science disciplines.

Laurance, W. F., and C. A. Peres, eds. 2006. *Emerging threats to tropical forests.* Chicago: Univ. of Chicago Press. [ISBN: 9780226470214][class:book]

Although this compendium includes other parts of the tropics, the majority of it is devoted to Brazilian Amazonia. It includes threats from climate change, fire, hunting (including elimination of dispersers), and forest fragmentation. Avoided deforestation for climate-change mitigation is discussed, as well as payments for conservation and protected-area strategies.

Léna, P., and A. E. de Oliveira, eds. 1991. *Amazônia: A Fronteira Agrícola 20 Anos Depois*. Pará, Brazil: Museu Paraense Emílio Goeldi. [ISBN: 9788570980281][class:book]

Contains chapters on a wide variety of social groups in the first two decades following the beginning of construction of the Transamazon Highway in 1970, inaugurating the modern era of deforestation. This includes both the actions of small-farmer colonists, ranchers, gold miners, and others and their impacts on indigenous and non-indigenous traditional residents.

Keller, M., M. Bustamante, J. Gash, and P. da Silva Dias, eds. 2009. *Amazonia and global change.* Geophysical Monograph Series. Vol. 186. Washington, DC: American Geophysical Union. [ISBN: 9780875904764][class:book]

This volume contains a wide range or results from the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), including the "human dimensions" portion of this massive international program. There are chapters on deforestation rates and patterns, logging, fire, econometric and dynamic deforestation simulation models, and the prospects of different land uses in maintaining soil fertility. The English-language version is very expensive but the Portuguese-language version is available free *online[http://lba.daac.ornl.gov/amazonia_global_change/]*.

Posey, D. A., and M. J. Balick, eds. 2006. *Human impacts on Amazonia: The role of traditional ecological knowledge in conservation and development*. New York: Columbia Univ. Press.[ISBN: 9780231105897][class:book]

Darrell Posey, who died five years prior to the publication of this volume, was a pioneering figure in studying the traditional knowledge of Amazonia indigenous peoples and in arguing for their intellectual property rights. This volume includes chapters showing the unsustainability of most of what follows Amazonian deforestation. It also includes proposals for environmental services in various forms as an alternative to this destruction. Traditional knowledge, particularly indigenous knowledge, is emphasized throughout.

Wood, C. H., and R. Porro, eds. 2002. *Deforestation and land use in the Amazon*. Gainesville: Univ. Press of Florida. [ISBN: 9780813024646][class:book]

This compendium has chapters on national policies and regional patterns, including population growth and migration. It also treats land-use decisions and deforestation, especially by small farmers, and the trend to ranching and concentration of land ownership. The prospects for intensification of cattle ranching are examined and found unlikely to reduce deforestation. The volume concludes with examples of participatory management and land-use planning.

Deforestation Monitoring

Brazil’s National Institute for Space Research (INPE) has monitored deforestation in the country’s Amazon region since 1988 using LANDSAT or equivalent imagery; with only one exception (1993), the “PRODES” monitoring has been annual (Brazil, INPE 2016). Clearings 6.25 hectares and larger are detected. Since 2004 INPE has also maintained a program for “Detection of Deforestation in Real Time” (DETER) (Diniz, et al. 2015). This uses the coarser-resolution MODIS satellite data, which can only detect clearings 25 hectares or larger but gives sufficiently frequent imagery to provide monthly estimates. INPE also has the “Terra Class” program to classify land uses in the deforested areas beginning in 2008, but without annual coverage (Brazil, INPE 2014a). INPE’s DEGRAD program interprets forest degradation, as from logging and fire, but with greater uncertainty than for deforestation monitoring (Brazil, INPE 2014b). The Institute for People and the Environment in Amazonia (IMAZON), a nongovernmental organization, has independently monitored deforestation using MODIS (IMAZON 2016). The group has also used LANDSAT to estimate both deforestation and degradation (Souza, et al. 2013). The presence of independent monitoring has been important in encouraging the government to increase the transparency of the official programs over the years. In the first years of monitoring the official programs had numerous problems of political interference with the release of results when the news they brought was bad (Fearnside 1997). Although not entirely free of such problems today, transparency has increased tremendously since the early years. As an example of other possible monitoring techniques, synthetic aperture radar (SAR) has been tested for detection of Amazonian deforestation and found capable of accurate estimates (Mesquita, et al. 2008). Radar is able to penetrate cloud cover, thus avoiding one of the major limitations of optical sensors such as LANDSAT and MODIS; unfortunately, regular coverage of vast areas such as Amazonia is not available. One sign of a high risk of deforestation is the appearance of "endogenous" roads, also known as "clandestine" or "unofficial" roads, which can be detected on LANDSAT imagery (Brandão and Souza 2006).

Brandão, A. O. Jr., and C. M. Souza Jr. 2006. Mapping unofficial roads with Landsat images: A new tool to improve the monitoring of the Brazilian Amazon rainforest. *International Journal of Remote Sensing* 27.1: 177–189. [doi:10.1080/01431160500353841][class:journalArticle]

LANDSAT imagery interpreted from 1985 to 2001 in central Pará shows the density of unofficial roads doubling in ten years, and the density in deforestation hotspots averaging more than four times the average for the region under study as a whole. The methodology has potential to improve monitoring and the targeting of enforcement efforts.

Brazil, INPE[nonPersonal]. 2014a. *Terra Class[http://www.inpe.br/cra/projetos_pesquisas/terraclass.php]*. São José dos Campos: INPE.[class:dataSet-Item-database]

Terra Class presents interpretation for land use in deforested areas, but at infrequent intervals (last data are for 2012). Data available for 2008, 2010, and 2012.

Brazil, INPE[nonPersonal]. 2014b. *Sistema DEGRAD[http://www.obt.inpe.br/degrad]*. São José dos Campos, Brazil: INPE.[class:dataSetItem-database]

Presents the Brazilian government's system for monitoring forest degradation through such processes as logging and fire. Because degradation is more difficult to detect than deforestation, uncertainty is higher.

Brazil, INPE[nonPersonal]. 2016. *Projeto PRODES: Monitoramento da Floresta Amazônica Brasileira por Satélite[http://www.obt.inpe.br/prodes/]*. São José dos Campos, Brazil: INPE.[class:dataSet-Item-database]

Presents updated data from various types of satellite imagery: PRODES interprets annual data with 30-meter resolution, taken in the dry season (July and August); DETER interprets monthly data with 250+ m resolution, released at three-month intervals; fire pixel counts and maps (but not areas) from NOAA-AVHRR are also available.

Diniz, C. G., A. A. D. A. Souza, and D. C. Santos, et al. 2015. DETER-B: The New Amazon Near Real-Time Deforestation Detection System. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 8.7: 3619–3628. [doi:10.1109/JSTARS.2015.2437075][class:journalArticle]

Explains Brazil's National Institute for Space Research (INPE) DETER system for interpreting MODIS data and compares it to the annual data from the institute's

PRODES program for interpreting LANDSAT and equivalent higher-resolution satellite data.

Fearnside, P. M. 1997. Monitoring needs to transform Amazonian forest maintenance into a global warming mitigation option. *Mitigation and Adaptation Strategies for Global Change* 2.2–3: 285–302. [doi:10.1023/B:MITI.0000004483.22797.1b][class:journalArticle]

Exposes the multiple problems with the Brazilian government's monitoring of deforestation in the 1980s and 1990s. The monitoring program is now much more transparent.

IMAZON[nonPersonal]. 2016. *Transparência Florestal[http://imazon.org.br/categorias/transparencia-florestal/]*.[class:dataSetItem-database]

This nongovernmental organization monitors deforestation monthly at 250+ meters resolution in an independent program similar to DETER, but with more frequent data release and with more commentary on causes.

Mesquita, H. N. Jr., C. A. Dupas, M. C. Silva, and D. M. Valeriano. 2008. *Amazon deforestation monitoring system with ALOS SAR complementary data[http://www.isprs.org/proceedings/XXXVII/congress/8_pdf/11_WG-VIII-11/09.pdf]*. In *XXIst Congress of the International Society for Photogrametry and Remote Sensing (ISPRS), Beijing, China. Technical Commission VIII*. Edited by Chen Jun, Jiang Jie, and A. Peled, 1067–1070. ISPRS Archives – Vol. XXXVII Part B8. Hannover**,** Germany: ISPRS. [class:report]

Synthetic aperture radar (SAR) data from Japan's Advanced Land Observing Satellite (ALOS) was tested with data from a strip through the state of Pará, showing good agreement with PRODES LANDSAT data in distinguishing forest from non-forest.

Souza, C. Jr., J. Siqueira, M. Sales, and A. Fonseca, et al. 2013. Ten-year Landsat classification of deforestation and forest degradation in the Brazilian Amazon. *Remote Sensing* 5.11: 5493–5513. [doi:10.3390/rs5115493][class:journalArticle]

This IMAZON study analyzes LANDSAT from 2000 to 2010, confirming the accuracy of the government's PRODES monitoring program with deforestation within 2 percent of the official value. The study also estimated degradation from logging and fire, finding 50,815 km^2 had been degraded during this period, an area 30 percent the size of the 169,074 km^2 of outright deforestation. While deforestation slowed, the annual area degraded increased over the period.

Deforestation Causes

Deforestation causes vary widely in space and time in Amazonia (Fearnside 2005). Some of the causes are explained by classical economics, where people clear in order plant crops or pasture to earn a profit from the products they sell (Margulis 2004), including sales in response to international trade (Faria and Almeida 2016). Prices of commodities were an important predictor of deforestation up to 2008 (Assunção, et al. 2015). However, in many frontier locations and in the critical early stages of the deforestation process, much of the clearing in Amazonia is primarily for other reasons, such as establishment of land tenure, land speculation, money laundering, and capturing government subsidies (Fearnside 2001). Even when no longer in a "frontier" phase, such as areas of ranch expansion in Mato Grosso in the 2001–2004 period, speculation plays a role along with the profitability per hectare from cattle production itself (Mann, et al. 2014). Small-farmer settlements in Brazil's agrarian-reform program are significant contributors to deforestation (Schneider and Peres 2015 and Yanai, et al. 2016), and this is especially true when the areas involved were previously dominated by large ranches (Pacheco 2009). Road access is a key factor by bringing population and investment and in increasing the profitability of deforestation, whether it be for agricultural production or for land speculation (Laurance, et al. 2002). Deforestation can be modeled using two types of approach: bottom up and top down. With a bottom-up approach, the overall amount of forest clearing represents the sum of individual decisions in response to opportunities such as new roads, and responses to restrictions such as creation of protected areas. In a top-down approach, deforestation is a "demand-driven" process based on, for example, either expected values for gross national product or a projection of past deforestation trends. This external determination of the total cleared will lead to any specific action having no effect on the overall amount of deforestation (i.e., 100 percent "leakage"), the results being limited to indicating where deforestation is most likely to occur (e.g., Soares-Filho, et al. 2006). The pushes and pulls of opportunities and restraints only affect where the clearing takes place, rather than the overall total. However, in reality decisions such as building roads or creating reserves do affect the overall amount of deforestation (see *Infrastructure* and *Protected Areas*).

Assunção, J., C. C. Gandour, and R. Rocha. 2015. *Deforestation slowdown in the Legal Amazon: Prices or policies?[http://climatepolicyinitiative.org/publication/deforestation-slowdown-in-the-legal-amazon-prices-or-policie/]*. *Environment and Development Economics* 20.6: 697–722. [doi:10.1017/S1355770X15000078][class:journalArticle]

An econometric analysis with data showing that for 2004–2008 the slowdown is explained by prices of commodities such as soy and beef, but after this period prices recovered while deforestation rates continued to drop through 2011, indicating effect of public policies. Conclusions on the 2004–2008 period are more clear in the earlier working paper.

Faria, W. R., and A. N. Almeida. 2016. Relationship between openness to trade and deforestation: Empirical evidence from the Brazilian Amazon. *Ecological Economics* 121:85–97. [doi:10.1016/j.ecolecon.2015.11.014][class:journalArticle]

Export trade is an increasingly important factor in Brazil's Amazonian deforestation, and the country's openness to trade is reflected in this pressure. This paper examines municipality (county) data from 2000 to 2010. Beef and soy exports are important predictors of deforestation, as well as a property-rights indicator representing the proportion of squatter land claims in the total number of establishments. Protected areas are negatively associated with deforestation rate.

Fearnside, P. M. 2001. Land-tenure issues as factors in environmental destruction in Brazilian Amazonia: The case of southern Pará. *World Development* 29.8: 1361–1372. [doi:10.1016/S0305-750X(01)00039-0][class:journalArticle]

The role of invasions by landless migrants, “regularization” of invasions, and establishment of government settlement projects. These processes are especially important in central and southern Pará.

Fearnside, P. M. 2005. Deforestation in Brazilian Amazonia: History, rates and consequences. *Conservation Biology* 19.3: 680–688. [doi:10.1111/j.1523-1739.2005.00697.x][class:journalArticle]

Major swings in deforestation rates are explained by macroeconomic events such as the economic depression from 1987 to 1992, the effect of the Real Plan in 1994 virtually halting inflation and leading to investment in deforestation in 1995, followed by falling land prices in 1996–1997 decreasing speculative clearing. Effects of fiscal incentives, money laundering, and other factors are also discussed.

Laurance, W. F., A. K. M. Albernaz, G. Schroth, P. M. Fearnside, S. Bergen, E. M. Venticinque, and C. da Costa. 2002. Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography* 29:737–748. [doi:10.1046/j.1365-2699.2002.00721.x][class:journalArticle]

Spatial statistics quantifying effects on deforestation from different explanatory factors, including population growth.

Mann, M. L., R. K. Kaufmann, D. M. Bauer, S. Gopal, M. Nomack, J. Y. Womack, K. Sullivan, and B. S. Soares-Filho. 2014. Pasture conversion and competitive cattle rents in the Amazon. *Ecological Economics* 97:182–190. [doi:10.1016/j.ecolecon.2013.11.014][class:journalArticle]

The rent (profit) per hectare from cattle pasture calculated for different locations in Mato Grosso in the 2001–2004 period was directly proportional to the probability of land being converted to this use. Speculation also played a role, with conversion to pasture being partially explained by the potential for future speculative gains from reselling the land to soy planters.

Margulis, S. 2004. **Causes of deforestation in the Brazilian Amazon*[https://openknowledge.worldbank.org/bitstream/handle/10986/15060/277150PAPER0wbwp0no1022.pdf?sequence=1]*. World Bank Working Paper No. 22. Washington, DC: World Bank. [ISBN: 9780821356913][class:report]

A good presentation of deforestation in areas dominated by traditional economic logic based on production from agriculture and ranching (i.e., not effects such as land speculation, land-tenure establishment, and money laundering).

Pacheco, P. 2009. Agrarian reform in the Brazilian Amazon: Its implications for land distribution and deforestation. *World Development* 37:1337–1347. [doi:10.1016/j.worlddev.2008.08.019][class:journalArticle]

Agrarian reform settlements increase deforestation most in areas dominated by large cattle ranches and least where the preexisting pattern is one of small landholders.

Areas occupied by smallholders do not have more deforestation than those occupied by large landholders. The agrarian reform program has had little effect on the highly skewed size distribution of land holdings in the region.

Schneider, M., and C. A. Peres. 2015. Environmental cost of government-sponsored agrarian settlements in Brazilian Amazonia. *PLoS ONE* 10.8: e0134016. [doi:10.1371/journal.pone.0134016][class:journalArticle]

This study of 1911 settlements shows that they have consistently accelerated deforestation as compared to areas outside of the settlements but within the same municipality. Factors strongly increasing deforestation are human population density, road access, and regional markets.

Soares-Filho, B. S., D. C. Nepstad, and L. M. Curran, et al. 2006. Modelling conservation in the Amazon Basin. *Nature* 440.23: 520–523. [doi:10.1038/nature04389][class:journalArticle]

Looks at spatial simulation of deforestation based on past trends, with location of clearing mainly determined by previous clearings and roads. Because the total amount of clearing is independent of roads, reserves, or other actions, there is 100 percent leakage.

Yanai, A. M., E. M. Nogueira, P. M. L. A. Graça, and P. M. Fearnside. 2016. Deforestation and carbon-stock loss in Brazil's Amazonian settlements. *Environmental Management* [doi:10.1007/s00267-016-0783-2]. [class:journalArticle]This study of 2,740 of the 3,325 settlements in Legal Amazonia show that the settlements studied accounted for 17 percent of all clearing (forest + non-forest) by 2013. The estimated premodern (pre-1970s) carbon stock of 6.36 PgC in these settlement areas had been reduced to 3.78 PgC in 2013.

Deforestation Actors

The question of who is responsible for the bulk of Amazonian deforestation has long been a central policy issue in Brazil. Different interest groups invariably accuse others of being the main agents. The Brazilian press has often placed the blame on small farmers, but the coincidence of deforestation with parts of the region dominated by larger properties provided a first demonstration of the opposite conclusion, with approximately 30 percent of the clearing attributable to landholdings with 100 hectares or less (the official definition of "small" properties in Brazilian Amazonia), the remaining 70 percent being by medium and large landholdings (Fearnside 1993). More refined data are now available, showing that the relative role of large landholdings decreased disproportionately during the deforestation slowdown from 2004 to 2011, while the area cleared by small farmers declined much less; their percentage of the total was 13 percent in 2011 (Godar, et al. 2014). In government settlement projects small farmers come from diverse backgrounds that affect their behavior and deforestation (Moran 1981). Outside of government-organized settlement areas, small squatters are often in conflict with large ranchers and *grileiros* (land thieves who obtain public land through a variety of illegal means) (Schmink and Wood 1992). These and other actors clear for a variety of "ulterior" motives such as maintaining land claims (whether legal or not) that provide profits from timber stocks and land speculation, in a sequence of events that is virtually entirely outside of government control (Fearnside 2008). These frontier areas contrast with areas dominated by large ranchers and soy planters who are influenced by government policy decisions such as those affecting agricultural credit. They also differ from international market filters such as those that led to major soy companies agreeing to a "moratorium" on purchases from land deforested for soybeans and a similar agreement among large slaughterhouses on purchasing cattle from properties with illegal deforestation (Gibbs, et al. 2015 and Gibbs, et al. 2016; Nepstad, et al. 2014). The force of soybeans has been greatly increased in Mato Grosso by trade and other influences from China, making this country a significant actor in Amazonian deforestation (Fearnside, et al. 2013).

Fearnside, P. M. 1993. Deforestation in Brazilian Amazonia: The effect of population and land tenure. *Ambio* 22.8: 537–545.[class:journalArticle]

Shows that about 30 percent of Brazil's Amazonian deforestation was being done by "small" landholders (officially defined as having ≤ 100 hectares), the remaining 70 percent being by medium and large landholders. Available in Portuguese and French.

Fearnside, P. M. 2008. *The roles and movements of actors in the deforestation of Brazilian Amazonia[http://www.ecologyandsociety.org/vol13/iss1/art23/]*. *Ecology and Society* 13.1: 23.[class:journalArticle]

Presents actors such as *grileiros* (large "land thieves" who appropriate public land and often obtain title through a variety of illegal means), organized landless farmers (*sem terras*), individual squatters (*posseiros*), settlers in government agrarian reform projects, soy planters, ranchers, and others.

Fearnside, P. M., A. M. R. Figueiredo, and S. C. M. Bonjour. 2013. Amazonian forest loss and the long reach of China's influence. *Environment, Development and Sustainability* 15.2: 325–338. [doi:10.1007/s10668-012-9412-2][class:journalArticle]

Econometric analysis of deforestation in the state of Mato Grosso shows the significance of exports to China, especially of soybeans. Other influences include Chinese land purchases, exports of beef and timber, and Chinese funding of infrastructure construction.

Gibbs, H. K., J. Munger, J. L'Roe, P. Barreto, R. Pereira, M. Christie, T. Amaral, and N. F. Walker. 2016. Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? *Conservation Letters* 9.1: 32–42. [doi:10.1111/conl.12175][class:journalArticle]

In two agreements in 2009, major slaughterhouses committed to refrain from purchasing cattle from properties with illegal deforestation and from properties that had not registered with georeferenced forest areas in the rural agricultural register (CAR). This study indicates that the agreements had a measurable effect in reducing deforestation through 2013. The study also notes that ranchers who were interviewed indicated frequent "cattle laundering," where animals from noncompliant properties were bought by middlemen who sold them to the slaughterhouses.

Gibbs, H. K., L. Rausch, and J. Munger, et al. 2015. Brazil's soy moratorium. *Science* 347:377–378. [doi: 10.1126/science.aaa0181][class:journalArticle]

The 2006 soy moratorium, in which large soy companies agreed not to purchase soy from properties that have cleared Amazonian forest for planting this crop, is shown to have had an effect in limiting deforestation. The moratorium has been successively renewed.

Godar, J., T. A. Gardner, E. J. Tizado, and P. Pacheco. 2014. Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proceedings of the National Academy of Science of the USA* 111.43: 15,591–15,596. [doi:10.1073/pnas.1322825111] [class:journalArticle]

This study uses remote sensing data from 2004 to 2011 in combination with agricultural census data by census block: a much smaller geographical unit than the municipalities (counties) used in other studies. Deforestation by large ranchers decreased more than that of small farmers during the deforestation crackdown.

Moran, E.F. 1981. *Developing the Amazon: The Social and Ecological Consequences of Government-Directed Colonization along Brazil's Transamazon Highway.* Bloomington, Indiana, U.S.A.: Indiana University Press. [class:book]

Colonist agricultural production and behavior, including deforestation, depend on a variety of cultural differences among "types" of settlers. Agronomic and institutional limitations also contribute to deforestation producing modest results.

Nepstad, D. C., D. McGrath, and C. Stickler, et al. 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* 344:1118–1123. [doi:10.1126/science.1248525][class:journalArticle]

Discusses explanations for the decline in deforestation rates after 2004, giving particular emphasis to the 2006 soy moratorium and the 2009 agreements with the beef industry indicating an effect on decreasing deforestation. Recommends a territorial performance approach rather than inducing a transition to more sustainable production chains.

Schmink, M., and C. H. Wood. 1992. *Contested frontiers in Amazonia*. New York: Columbia Univ. Press. [ISBN: 9780231076609][class:book]

A classic book on the deforestation actors and processes in southern Pará in the 1970s. Twenty years later, Marianne Schmink revisited these areas; much had changed but many of the same conflicts remained, as shown in a video of the return entitled "São Felix do Xingu: Stories of Occupation in the Heart of Amazonia," available *online[https://vimeo.com/81135233]*.

Infrastructure

Government infrastructure projects such as highways, dams, waterways, railroads, and transmission lines are key features in the deforestation process (e.g., Nepstad, et al. 2001). Roads represent a major factor, complemented by influences from distance to markets, agricultural potential, credit, and the time since migrants gained access to the area (Pfaff 1999). Road effects are significant up to 100 km from the census tract through which the road passes (Pfaff, et al. 2007). An infrastructure-driven projection of deforestation was made by Laurance, et al. 2001, assuming hypothetically that all of the infrastructure projects planned under the government's *Avança Brasil* program were built immediately. The decisions to undertake these projects are made by the government, but most of the processes that lead to subsequent deforestation are outside of government control. An example is provided by the Santarém-Cuiabá (BR-163) Highway: an assumption of "governance" greatly decreases deforestation (Soares-Filho, et al. 2004), but this is far from the reality along this highway route (Torres 2005). The Manaus-Porto Velho (BR-319) Highway would cause even greater impact on deforestation because, together with planned side roads, it would open approximately half of what remains of Brazil's Amazon forest to the entry of deforesters (Fearnside and Graça 2009). The highway would connect the "arc of deforestation" to Manaus in central Amazonia, but an already-existing network of roads would carry migrants on to Roraima, increasing deforestation in the northernmost portion of Amazonia (Barni, et al. 2015). Dams are another driver of deforestation, as has been shown for the Belo Monte Dam on the Xingu River (Barreto, et al. 2011) and simulated for planned dams and associated waterways in the Tapajós River basin (de Sousa, et al. 2014).

Barni, P. E., P. M. Fearnside, and P. M. L. A. Graça. 2015. Simulating deforestation and carbon loss in Amazonia: Impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho). *Environmental Management* 55.2: 259–278. [doi:10.1007/s00267-014-0408-6][class:journalArticle]

Simulates the impact of the proposed reopening the BR-319 (Manaus-Porto Velho) Highway on areas to which migrants from Rondônia would be likely to proceed in Roraima, an area far removed from the highway itself.

Barreto, P., A. Brandão Jr., H. Martins, D. Silva, C. Souza Jr., M. Sales, and T. Feitosa. 2011. **Risco de Desmatamento Associado à Hidrelétrica de Belo Monte*[http://www.imazon.org.br/publicacoes/livros/risco-de-desmatamento-associado-a-hidreletrica-de-belo-monte/at_download/file]*. Belém, Brazil: Instituto do Homem e Meio Ambiente da Amazônia (IMAZON). [class:dataSetItem-database]

Estimates deforestation provoked by construction of the controversial Belo Monte Dam, showing increase in the surrounding area due to population migration and other factors.

de Sousa, W. C. Jr., ed. 2014. **Tapajós: hidrelétricas, Infraestrutura e Caos: Elementos para a Governança da* Sustentabilidade *em uma Região Singular*[http://www.bibl.ita.br/download/Tapajos_Ebook.pdf]*. 1a. ed. São José dos Campos, Brazil: ITA.[class:report]

Includes calculations of the impact of proposed dams on the Tapajós River in increasing deforestation.

Fearnside, P. M., and P. M. L. A. Graça. 2009. *BR-319: A rodovia Manaus-Porto Velho e o impacto potencial de conectar o arco de desmatamento à Amazônia central[http://www.periodicos.ufpa.br/index.php/ncn/article/viewFile/241/427]* [BR-319: Brazil's Manaus-Porto Velho Highway and the potential impact of linking the arc of deforestation to central Amazonia]. *Novos Cadernos NAEA* 12.1: 19–50.[class:journalArticle]

Shows the great potential impact of reopening a highway that has been abandoned since 1988, which would connect central Amazonia to the "arc of deforestation" in the southern part of the region. A 2006 English-language version presents these arguments but without the environmental impact study (EIA) released in 2008 (*Environmental Management* 38 [5]: 705–716).

Laurance, W. F., M. A. Cochrane, and S. Bergen, et al. 2001. The future of the Brazilian Amazon. *Science* 291:438–439. [doi:10.1126/science.291.5503.438][class:journalArticle]

Spatial calculation of deforestation based on all announced infrastructure being built. Deforestation is mainly driven by roads.

Nepstad, D. C., G. Carvalho, and A. C. Barros, et al. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management* 154.3: 395–407. [doi:10.1016/S0378-1127(01)00511-4][class:journalArticle]

Feedbacks between fire, climate change, logging, forest mortality, and the behavior of deforesters are detailed. The authors then calculate that the road reconstruction projects announced under the government's *Avança Brasil* (Forward Brazil) would stimulate these processes leading to 120,000–270,000 km^2 of additional deforestation.

Pfaff, A. S. P. 1999. What drives deforestation in the Brazilian Amazon? *Journal of Environmental Economics and Management* 37.1: 26–43. [doi:10.1006/jeem.1998.1056][class:journalArticle]

An econometric study of municipality-level data in Brazilian Amazonia for 1978–1988 indicates that roads are a major driver of deforestation. Other factors are distance to markets, soil quality, and vegetation type. Credit infrastructure, however, did not affect deforestation. Population density did not affect deforestation overall, but the initial settlement has a significant effect, with the first migrants to a municipality having a greater impact than later ones.

Pfaff, A. S. P., J. Robalino, and R. Walker, et al. 2007. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. *Journal of Regional Science* 47.1: 109–123. [doi:10.1111/j.1467-9787.2007.00502.x][class:journalArticle]

An analysis of census-tract data, which are at a finer scale than municipality data, shows that roads lead to more deforestation not only in the census tracts where they pass but also in neighboring tracts through a "spillover" effect. Deforestation increases in census tracts with no roads if they are less than 100 km from a tract with a road.

Soares-Filho, B. S., A. Alencar, D. C. Nepstad, G. Cerqueira, M. del C.V. Diaz, S. Rivero, L. Solórzano, and E. Voll. 2004. Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: The Santarém-Cuiabá corridor. *Global Change Biology* 10.5: 745–764. [doi:10.1111/j.1529-8817.2003.00769.x][class:journalArticle]

A simulation of the effect of reconstructing the BR-163 Highway. See Torres 2005 for a less-optimistic vision of these impacts.

Torres, M., ed. 2005. *Amazônia Revelada: Os Descaminhos ao Longo da BR-163*[http://philip.inpa.gov.br/publ_livres/livros%20inteiros/Amazônia%20Revelada.pdf]*. Brasília, Brazil: Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). [class:book]

Chapters present actors and processes on the BR-163 (Santarém-Cuiabá) Highway and the potential for deforestation from reconstructing the highway to allow export of soybeans from Mato Grosso via ports with access to the Amazon River. Some of the material is available in English in *Environmental Management* 39 (5): 601–614 (2007). [doi: 10.1007/s00267-006-0149-2].[class:journalArticle]

Agriculture and Ranching

Agriculture and ranching are the principal replacements for Amazon forest after deforestation. In the case of small farmers in government-organized settlement projects, the scale of agriculture is limited by the family labor available in each property, supplemented by hired labor that can be paid with funds from government-sponsored agricultural credit (Fearnside 1986). Credit access is critical for these settlers, along with effects from wealth, lot size, product markets, and off-farm labor opportunities (Caviglia-Harris 2004). In the case of larger ranches, in the 1970s and 1980s the government offered generous subsidies both through subsidized credit and through write-offs on taxes owed on activities in other parts of Brazil. This led to substantial areas being cleared in order to capture the subsidies, even though agronomic prospects were poor (Binswanger 1991). Livestock in very low-productivity pastures spread as a means of maintaining claim to land for speculative purposes, the capital gain from reselling the land being more important than the income from actual beef production (Hecht 1993). During Brazil's period of hyperinflation, which lasted until the "Real Plan" economic reforms in 1994, the search for ways to protect the value of assets caused land values throughout Brazil, and especially in Amazonia, to increase even faster than the general rate of inflation. Speculation is still an important factor wherever new highways are planned, causing the value of newly accessible land to skyrocket. Within individual properties the rate that pasture can expand depends on the availability of external capital that is independent of profits made by the ranch operation itself (Walker, et al. 2000). Models calculating the probability of extensive ranching based on beef production alone show the unfavorability of this option in much of the region unless land is obtained for free through "land grabbing" (*grilagem*), and shows the importance of speculation in the spread of ranching (Bowman, et al. 2012). For the choice between soybeans and intensive pasture (not extensive ranching), rainfall is a critical determinant (Chomitz and Thomas 2003). Soybeans have spread rapidly both in *cerrado* (central Brazilian savanna) and in Amazon forest areas in Mato Grosso, with a significant part being by replacement of existing cattle pastures (Fearnside 2001; Morton, et al. 2006). However, the portion of this expansion that replaces pasture is not without impact on deforestation: the ranching activity in Mato Grosso is displaced to Pará, where forest is cleared for pasture (Arima, et al. 2011).

Arima, E. Y., P. Richards, R. Walker, and M. M. Caldas. 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters* 6:024010. [doi:10.1088/1748-9326/6/2/024010][class:journalArticle]

Shows that converting cattle pasture to soybeans in Mato Grosso, either in the *cerrado* (savanna) or the Amazon forest portions of the state, results in displacement of ranching activity to Pará, where more forest is cleared to accommodate the pastures. This displacement has been known anecdotally for years and has now been shown statistically. See also: P. D. Richards, R. T. Walker, and E. Y. Arima. *Global Environmental Change* 29 (2014):1–9.

Barona, E., N. Ramankutty, G. Hyman, and O. T. Coomes. 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters* 5.2: 024002. [doi:10.1088/1748-9326/5/2/024002][class:journalArticle]

Examines municipality (county) level data on soy and pasture. Most deforestation is attributable to pasture, but this article finds indications of indirect effect of soy replacing pasture in Mato Grosso leading to more deforestation for pasture elsewhere in the Amazon region.

Binswanger, H. P. 1991. Brazilian policies that encourage deforestation in the Amazon. *World Development* 19.7: 821–829. [doi:10.1016/0305-750X(91)90135-5][class:journalArticle]

Generous fiscal incentives offered by the Brazilian government for Amazonian cattle ranches in the 1970s and early 1980s were major motives for deforestation despite poor pasture productivity. Financing at rates below inflation and the privilege of companies owing taxes on activities elsewhere in Brazil applying the money instead as investment in ranches made these operations highly profitable.

Bowman, M. S., B. S. Soares-Filho, F. D. Merry, D. C. Nepstad, H. Rodrigues, and O. T. Almeida. 2012. Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land Use Policy* 29.3: 558–568. [doi:10.1016/j.landusepol.2011.09.009][class:journalArticle]

A spatially explicit rent model (counting income from beef sales, not speculation or other “ulterior” gains) calculates that extensive cattle ranching has medium to high profitability (thirty-year average net present value > 250 US$/hectare) in 17–80 percent of Legal Amazonia if the land is obtained for free through “land grabbing” (*grilagem*), but only 9–13 percent if the land is purchased. This shows the importance of speculation and the need to control it.

Caviglia-Harris, J. L. 2004. Household production and forest clearing: The role of farming in the development of the Amazon. *Environment and Development Economics* 9:181–202. [doi:10.1017 /S1355770X03001165][class:journalArticle]

Deforestation decisions by 152 households in 1996 and 2000 in a settlement area in Rondônia are influenced by access to credit, wealth, lot size, product markets, and off-farm labor opportunities. Planting crops is largely determined by credit. Pasture for milk production in this area is attractive due to market availability, making more sustainable choices unlikely to be adopted.

Chomitz, K. M., and T. S. Thomas. 2003. Determinants of land use in Amazonia: A fine-scale spatial analysis. *American Journal of Agricultural Economics* 85.4: 1016–1028. [doi:10.1111/1467-8276.00504][class:journalArticle]

This study based on census-tract data shows that excessive rainfall decreases pasture productivity and the probability that an area will be used or agriculture or intensive livestock production, other things being equal. Note, however, that extensive ranching is not included in this result.

Fearnside, P. M. 1986. *Human carrying capacity of the Brazilian rainforest*. New York: Columbia Univ. Press. [ISBN: 9780231061049][class:book]

Simulates the agricultural system of colonists settled on the Transamazon Highway, showing the limited potential of agriculture to sustain populations. Documents social processes and land-use change in the colonization areas for small farmers in the early 1970s, including deforestation.

Fearnside, P. M. 2001. Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28.1: 23–38. [doi:10.1017/S0376892901000030][class:journalArticle]

Discusses the advance of soybeans and resulting deforestation. Climate and soil limitations restrict soy growing in many rainforest areas that lack sufficient dry periods, but soy still causes deforestation in these areas by the roads built through them to transport soy, unleashing deforestation processes for other land uses.

Hecht, S. B. 1993. The logic of livestock and deforestation in Amazonia. *Bioscience* 43.10: 687–695. [doi:10.2307/1312340][class:journalArticle]

Shows how increasing land value makes deforestation for extensive cattle ranching profitable for landholders even though beef production is minimal.

Morton, D. C., R. S. DeFries, and Y. E. Shimabukuro, et al. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences U.S.A.* 103.39: 14,637–14,641. [doi:10.1073/pnas.0606377103][class:journalArticle]

Documents the spread of soybeans in Mato Grosso, both in former cattle pastures and by clearing native vegetation, both in Cerrado (savanna) and in Amazon forest areas.

Walker, R., E. Moran, and L. Anselin. 2000. Deforestation and cattle ranching in the Brazilian Amazon: External capital and household process. *World Development* 28.4: 683–699. [doi:10.1016/S0305-750X(99)00149-7][class:journalArticle]

Interview and satellite data from Pará both from areas with small farmers and those with large ranchers show the dominance of cattle in the economy. The availability of hired labor is a key limitation on expansion of cattle pasture for small farmers.

Forest Loss Through Extreme Degradation

"Deforestation" is the conversion of a land use that is classified as "forest" into one that is classified as "non-forest." This can not only occur by clearcutting using chainsaws but also by the forest being thinned by degradation to the point where it is no longer a forest. One way that this can occur is by selective logging, which affects a greater area of forest than does outright deforestation (Asner, et al. 2005). Another mechanism is through forest fires, which are much more likely to occur in areas disturbed by logging; the fires burn through the understory and preferentially kill large trees (Barlow, et al. 2003). During severe El Niño events, as in 1997–1998, large areas burned in Pará (Alencar, et al. 2006) and Roraima (Barbosa and Fearnside 1999). Severe droughts can kill trees even in the absence of fire (Lewis, et al. 2011; Phillips, et al. 2009). Large trees are particularly susceptible, as has been shown experimentally (Nepstad, et al. 2007). The combination of fire and drought can lead to rapid loss of forest biomass, and only a few return events can eliminate a forest (Berenguer, et al. 2014).

Alencar, A. A., D. C. Nepstad, and M. C. V. Diaz. 2006. Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: Area burned and committed carbon emissions. *Earth Interactions* 10.6: 1–17. [doi:10.1175/EI150.1][class:journalArticle]

Estimates that 39,000 km^2 of forest understory burned in Brazil's Amazon region during the 1997–1998 El Niño drought, of which 26,000 km^2 were in states other than Roraima. Fires in the area outside Roraima caused a committed emission 0.024 to 0.165 Pg of carbon. See Barbosa and Fearnside 1999 for data on Roraima. The area burned was thirteen times greater during the 1997–1998 El Niño as compared to a non–El Niño year (1995).

Asner, G., D. Knapp, E. Broadbent, P. Oliveira, M. Keller, and J. Silva. 2005. Selective logging in the Brazilian Amazon. *Science* 310:480–482. [doi:10.1126/science.1118051][class:journalArticle]

Uses LANDSAT satellite imagery to estimate areas affected by logging in five of the nine states in Brazilian Amazonia (covering most of the areas with substantial logging). Carbon emissions are estimated at 80 million tons per year.

Barbosa, R. I., and P. M. Fearnside. 1999. Incêndios na Amazônia brasileira: Estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). *Acta Amazonica* 29.4: 513–534. [doi:10.1590/1809-43921984143528] [class:journalArticle]This study measured areas burned in the 1997–1998 "great

Roraima fire" at 11.394–13.928 km^2. Greenhouse-gas emissions for the fire as a whole were estimated at 6.1–7.0 million tons of CO_2-equivalent carbon, including trace gas emissions. English version available *online[http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/RR-Fire-Acta-engl.pdf]*.

Barlow, J., C. A. Peres, B. O. Lagan, and T. Haugaasen. 2003. Large tree mortality and the decline of forest biomass following Amazonian wildfires. *Ecology Letters* 6.1: 6–8. [doi:10.1046/j.1461-0248.2003.00394.x][class:journalArticle]

Assesses tree mortality from forest fires in an El Niño year, showing that large trees die after a delay of one to three years, more than doubling the emissions from estimates that only count immediate mortality. Large trees hold a disproportionately large share of the biomass and carbon stock in Amazonian forests. See also: *Philosophical Transactions of the Royal Society B* 363 (2008):1787–1794. [doi:10.1098/rstb.2007.0013].

Berenguer, E., J. Ferreira, and T. A. Gardner, et al. 2014. A large-scale field assessment of carbon stocks in human-modified tropical forests. *Global Change Biology* 20.12: 3713–3726. [doi:10.1111/gcb.12627][class:journalArticle]

This study estimates carbon stocks in biomass in areas that have undergone different numbers of fire events and with and without selective logging. It shows massive losses from forest degradation through logging and fire. Logged forests that have burned have, on average, 40 percent less biomass than undisturbed forest.

Lewis, S. L., P. M. Brando, O. L. Phillips, G. M. F. van der Heijden, and D. C. Nepstad. 2011. The 2010 Amazon drought. *Science* 331:554. [doi:10.1126/science.1200807][class:journalArticle]

Maps extent of forest affected by the major droughts of 2005 and 2010. Carbon emissions are estimated at about 1.4 Pg as a result of the 2010 event.

Nepstad, D. C., I. M. Tohver, D. Ray, P. Moutinho, and G. Cardinot. 2007. Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology* 88.9: 2259–2269. [doi:10.1890/06-1046.1][class:journalArticle]

An important experimental result, where an array of plastic sheets was erected over 1 hectare of the forest floor to exclude 60 percent of the rainfall from reaching the soil. With time, trees died for lack of water. This implies potential impacts of climate changes predicted for eastern Amazonia.

Phillips, O. L., L. E. O. C. Aragão, S. L. Lewis, et al. 2009. Drought sensitivity of the Amazon rainforest. *Science* 323:1344–1347. [doi:10.1126/science.1164033][class:journalArticle]

Shows that even without fire, droughts exceed the tolerance of Amazonian trees causing substantial mortality, reduced growth and biomass loss. The forest lost 1.2 to 1.6 Pg C during the 2005 Atlantic-dipole drought in southern Amazonia, whereas in non-drought years the standing forest acts as a carbon sink of about 0.4 PgC per year.

Deforestation Impacts

Amazonian deforestation has a diverse array of impacts affecting both local populations and, particularly through effects on climate, populations in distant locations. Impacts on soil through such processes as erosion, leaching and phosphorus fixation affect the sustainability of production (Luizão, et al. 2009). Carbon loss from biomass and soil makes a significant contribution to global warming through emissions with each year's deforestation, and the potential for future impact is much greater due to the large amounts of carbon that could be released should the vast areas of remaining forest be lost (Fearnside 2000, and Fearnside and Barbosa 1998). Deforestation greatly decreases evapotranspiration, eliminating most of the water recycling now performed by the forest. These losses are projected to cause reduced rainfall during the dry season (Sampaio, et al. 2007), which is the period when water is most needed for maintaining tropical forests. Simulation of the effect of the area deforested by 2007 shows that the severe droughts in southern Amazonia in 2005 and 2010 (which were driven by reduced water vapor supply to Amazonia provoked by ocean temperature changes rather than directly by deforestation) were made more severe by the effect of lost evapotranspiration resulting from this present-day level of clearing and that this effect is concentrated in the season and location most affected by these mega-droughts (Bagley, et al. 2014). Aside from climatic effects, deforestation has direct consequences for the region's economy. The typical "boom-bust" pattern is one where economic output and human welfare are low when the deforestation process begins, rise on the basis of exploiting the forest and soil resources, and then crash as these resources near exhaustion (Celentano, et al. 2012 and Rodrigues, et al. 2009). Urbanization and replacement of pioneer smallholders by wealthier groups (such as soybean planters) can lead to subsequent increases in welfare as measured by averages at the municipality level (e.g., Caviglia-Harris, et al. 2016). At the level of individual smallholders, forest conservation has benefits by providing a form of insurance against agricultural failures (Pattanayak and Sills 2001). Programs that provide benefits under integrated forest conservation and development projects increase household income but have had disappointing effects on increasing the material assets of the recipients, their means of production, and their contribution to forest conservation (Bauch, et al. 2014). Deforestation (and forest conservation) affects public health, with malaria, acute respiratory infections and diarrhea being negatively correlated with the area under strict environmental protection at the municipality level (Bauch, et al. 2015). However, proximity to forest also increases malaria incidence, creating a health cost for forest conservation (Valle and Clark 2013).

Bagley, J. E., A. R. Desai, K. J. Harding, P. K. Snyder, and J. A. Foley. 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *Journal of Climate* 27:345–361. [doi:10.1175/JCLI-D-12-00369.1][class:journalArticle]

This study performs simulations (20 × 20 km resolution) of rainfall in the portion of the Amazon Basin south of the equator using data for 2003–2010, a six-year period composed of two years with major droughts, two rainy years, and two "normal" years. Simulations were run with the land cover present in 2007 and with the "potential" land cover (i.e., without deforestation). The study shows that current levels of deforestation increased the intensity of drought, especially over southern

Amazonia, including the epicenters of the 2005 and 2010 mega-droughts. Movement of recycled water is tracked in the simulation, showing the particular importance of this rainfall source in drought years and in the southern portion of the region.

Bauch, S. C., A. M. Birkenbach, S. K. Pattanayak, and E. O. Sills. 2015. Public health impacts of ecosystem change in the Brazilian Amazon. *Proceedings of the National Academy of Science of the USA* 112.24: 7414–7419. [doi:10.1073/pnas.1406495111] [class:journalArticle]

Municipal-level data show that malaria is negatively correlated with an area under strict environmental protection, and conservation scenarios show that expanding protected areas would reduce incidence of the disease. The same holds for acute respiratory infections and diarrhea.

Bauch, S. C., E. O. Sills, and S. K. Pattanayak. 2014. Have we managed to integrate conservation and development? ICDP Impacts in the Brazilian Amazon. *World Development* 64.1: S135–S148. [doi:10.1016/j.worlddev.2014.03.009][class:journalArticle]

An integrated conservation and development project (ICDP) associated with commercial timber management in the Tapajós National Forest in Pará shows that the project increased the income of participating households. However, this had no discernible impact on household assets, livelihood portfolios, or forest conservation.

Caviglia-Harris, J., E. Sills, A. Bell, D. Harris, K. Mullan, and D. Roberts. 2016. Busting the boom–bust pattern of development in the Brazilian Amazon. *World Development* 79:82–96. [doi:10.1016/j.worlddev.2015.10.040][class:journalArticle]

Municipality-level census and deforestation data for 1991, 2000, and 2010 in Brazil's Amazonia biome confirms the "boom-bust" pattern if a cross-sectional analysis is used. Here welfare rises as the forest and soil resources are exploited and crashes when they are exhausted. However, analysis of panel data indicates that both heavily and lightly deforested Amazonian municipalities are undergoing a "convergence" with indicators from the rest of the country in terms of development. Recent urbanization has a likely role in this convergence. The decoupling of socioeconomic welfare from deforestation means that deforestation is not necessary for development.

Celentano, D., E. Sills, M. Sales, and A. Veríssimo. 2012. Welfare outcomes and the advance of the deforestation frontier in the Brazilian Amazon. *World Development* 40.4: 850–864. [doi:10.1016/j.worlddev.2011.09.002][class:journalArticle]

Municipal-level analysis of welfare indicators and deforestation indicates different relationships depending on the stage to which deforestation has advanced and the factors underlying production, such as soil quality, climatic suitability, and land-tenure security. Most areas are subject to a "boom-bust" pattern as the frontier phase passes, where welfare is supported by predatory exploitation of the forest and crashes when the resource is depleted, even as deforestation continues. Welfare can subsequently rise at high levels of deforestation in areas with highly favorable conditions for agriculture, such as those supporting soybean plantations.

Fearnside, P. M., and R. I. Barbosa. 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management* 108.1–2: 147–166. [doi:10.1016/S0378-1127(98)00222-9][class:journalArticle]

Conversion of Amazon forest to cattle pasture that is maintained under typical extensive management results in emission of soil carbon to the atmosphere. Release from extensively managed pasture is 13.7 MgC/ha, and for all pastures is 12.0 MgC/ha, while for the equilibrium landscape, which is dominated by pastures (productive and degraded) and secondary forest derived from pasture, the release averages 8.5 MgC/ha. This is added to the large release from forest biomass on conversion of forest to pasture.

Fearnside, P. M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* 46.1–2: 115–158. [doi:10.1023/A:1005569915357][class:journalArticle]

The study calculates net committed emissions of greenhouse gases from biomass and soil. This is the emission resulting from conversion of forest to the mosaic of pasture, agriculture, and secondary forest that trends imply as an equilibrium landscape after clearing. The study indicates significant contribution to global warming from deforestation both on a year-to-year basis and in terms of the potential for future emissions should deforestation be allowed to release the large carbon stocks present in the remaining forest.

Luizão, F. J., P. M. Fearnside, C. E. P. Cerri, and J. Lehmann. 2009. The maintenance of soil fertility in Amazonian managed systems. In *Amazonia and Global Change*. Edited by M. Keller, M. Bustamante, J. Gash, and P. da Silva Dias, 311–336. Geophysical Monograph Series. Vol. 186. Washington, DC: American Geophysical Union. [ISBN: 9780875904764][class:bookChapter]

The potential for agriculture and pasture development in most of Brazilian Amazonia is severely limited by soil fertility and by excessively high temperature and moisture. Although some measures can improve agricultural prospects over the 21st-century norm, the limitations to expansion of intensified land uses are serious. Development should emphasize the natural forest, which can maintain itself without external nutrient inputs.

Pattanayak, S. K., and L. O. Sills. 2001. Do tropical forests provide natural insurance? The microeconomics of non-timber forest product collection in the Brazilian Amazon. *Land Economics* 77:595–612. [doi:10.2307/3146943][class:journalArticle]

Small farmers in Brazilian Amazonia use collection of non-timber forest products as a fallback strategy to cope with crop failures or other lean times. Farmer behavior gives priority to minimizing risk rather than maximizing average expected returns. In addition to diversifying crops, their allocation of significant time in learning to locate and exploit non-timber forest resources represents an investment in insurance.

Rodrigues, A. S. L., R. M. Ewers, L. Parry, C. Souza Jr., A. Veríssimo, and A. Balmford. 2009. Boom-and-bust development patterns across the Amazon deforestation frontier. *Science* 324:1435–1437. [doi:10.1126/science.1174002][class:journalArticle]

Analysis of deforestation and human development indicators in 286 Amazonian municipalities shows that human welfare is low as deforestation begins, rises as the forest resource is exploited, and then falls to low levels again in a "bust" once the forest is largely gone.

Sampaio, G., C. A. Nobre, M. H. Costa, P. Satyamurty, B. S. Soares-Filho, and M. Cardoso. 2007. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophysical Research Letters* 34:L17709. [doi:10.029/2007GL030612][class:journalArticle]

A simulation of climate in eastern Amazonia with deforested areas of 20 percent, 50 percent, 80 percent, and 100 percent, and with spatial distribution as indicated in a business-as-usual simulation, the climate becomes hotter and dryer, particularly in the dry season (June, July, and August). If the deforested percentage passes 40 percent the dry season precipitation decreases sharply. Simulations were run with either pasture or soybeans as the replacement for forest, showing similar results.

Valle, D., and J. Clark. 2013. Conservation efforts may increase malaria burden in the Brazilian Amazon. *PLoS ONE* 8(3):e57519. [doi:10.1371/journal.pone.0057519]. [class:journalArticle]

Deforestation has two opposing effects on malaria incidence: the "land-clearing effect" increasing malaria and at the same time greater distance from remaining forest acting to decreasing malaria. This study of 1.3 million malaria cases shows distance to forest having an effect 25 times more powerful than the land-clearing effect. Forest conservation therefore has a health cost that must be mitigated.

Deforestation Control

Brazil's 1965 Forest Code contained regulations prohibiting deforestation on steep slopes, on hilltops, and within specified distances from watercourses and stream headwaters, as well as requiring a given portion of each property to remain in forest. The 1965 Forest Code was rarely enforced until the Ministry of the Environment's "crackdown" began in 2004, a change that spurred the "ruralist block" (representatives of large landholders) to mobilize to repeal or relax many of the code's restrictions. In 2012 the National Congress approved revising the Forest Code, gutting many of its deforestation restrictions (Soares-Filho, et al. 2014). Before the federal government's crackdown in 2004, a state-government deforestation-control system had been implanted in Mato Grosso (Fearnside 2003), but its initial success was reversed when "soy king" Blairo Maggi was elected governor in 2002 (Rajão, et al. 2012). Beginning in 2004 the federal government's repression program has been conducted under the Plan of Action for Prevention and Control of Deforestation in Legal Amazonia (PPCDAm) (Brazil, MMA 2013). The effectiveness of this program in explaining the deforestation decline is a matter of some debate (see *Deforestation Causes*). From 2004 to 2008 deforestation rates closely track commodity prices, but thereafter the prices of soy and beef rose while deforestation continued to decline until 2012 (Assunção, et al. 2013). The advent of the Detection of Deforestation in Real Time (DETER) program in 2004 gave a critical technological tool to the repression program, permitting enforcement efforts to focus on the most active areas of clearing (Assunção, et al. 2013). After 2008 the crackdown had an effect, as shown by decreases in deforestation in locations targeted for inspection in some (but not all) of the Amazonian states (Börner, et al. 2015) and by greater reduction in deforestation rates in municipalities (counties) that were targeted as compared to those that were not (Arima, et al. 2014 and Cisneros, et al. 2015). The various economic factors that can explain deforestation trends are unable to explain sharp peaks coincident with elections changing the presidential administration (Rodrigues-Filho, et al. 2015). As elections approach, there is general anticipation of relaxed enforcement, as well as increased government spending for roads and agricultural credit. Further reduction of deforestation will require a series of command-and-control and other measures (Moutinho, et al. 2016).

Arima, E. Y., P. Barreto, E. Araujo, and B. Soares-Filho. 2014. Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. *Land Use Policy* 41:465–473. [doi:10.1016/j.landusepol.2014.06.026][class:journalArticle]

Compares deforestation data for municipalities (counties) in the 2009–2011 period with and without special targeting of inspections and fines by the federal environmental agency, finding significant effect in reducing deforestation in the targeted municipalities.

Assunção, J., C. Gandour, and R. Rocha. 2013. *DETERing deforestation in the Amazon: Environmental monitoring and law enforcement[http://climatepolicyinitiative.org/wp-content/uploads/2013/05/DETERring-Deforestation-in-the-Brazilian-Amazon-Environmental-Monitoring-and-Law-Enforcement-Technical-Paper.pdf]*. Rio de Janeiro: Climate Policy Initiative, Núcleo de Avaliação de Políticas Climáticas, Pontifica Universidade Católica (PUC). [class:report]

Shows significant role of the DETER (Deforestation Monitoring in Real Time) program since 2004 using MODIS imagery. These data improve the efficiency of deforestation repression efforts by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA).

Börner, J. K., Kis-Katos, J. Hargrave, and K. König. 2015. Post-crackdown effectiveness of field-based forest law enforcement in the Brazilian Amazon. *PLOS ONE* 10.4: e0121544. 1–19. [doi:10.1371/journal.pone.0121544][class:journalArticle]

Shows the effect of IBAMA inspections and fines on deforestation in the areas surrounding the locations targeted over the 2009–2010 period. Repression had a significant effect in Mato Grosso and Pará but not elsewhere. In one area (the southern portion Amazonas state) a counterintuitive result indicating a positive effect was found.

Brazil, MMA[nonPersonal]. 2013. *Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal - PPCDAm 3ª Fase[http://www.mma.gov.br/images/publicacoes/florestas/Catalogo/Tema3_Preven cao-Controle-Desmatamento/PPCDAm_3afase.pdf]* (2012–2015). Brasília, Brazil: MMA.[class:report]

This presents the early-21st-century version of the Ministry of Environment’s plan for controlling deforestation, which has been implanted since the “crackdown” began in 2004.

Cisneros, E., S. L. Zhou, and J. Börner. 2015. Naming and shaming for conservation: Evidence from the Brazilian Amazon. *PLoS One* 10.9: e0136402. [doi:10.1371/journal.pone.0136402][class:journalArticle]

In 2008 IBAMA (Brazilian Institute for the Environment and Renewable Natural Resources) initiated a “blacklist” of municipalities with high deforestation. IBAMA focused its inspection effort on these municipalities, and landholders faced additional hurdles for licensing deforestation, had restrictions on agricultural credit, and had increased assistance from NGOs in registering properties in the Rural Environmental Register (CAR). Blacklisted municipalities had greater reduction in deforestation than non-blacklisted municipalities.

Fearnside, P. M. 2003. Deforestation control in Mato Grosso: A new model for slowing the loss of Brazil’s Amazon forest. *Ambio* 32.5: 343–345. [doi:10.1579/0044-7447-32.5.343][class:journalArticle]

Shows the initial success of this state-level licensing and deforestation control program. At a time when other Amazonian states had increasing deforestation rates, municipalities (counties) in Mato Grosso that still had substantial areas of standing forest at the beginning of the program showed declines in deforestation rates through 2001.

Moutinho, P., R. Guerra, and C. Azevedo-Ramos. 2016. Achieving zero deforestation in the Brazilian Amazon: What is missing? *Elementa: Science of the Anthropocene* 4:000125. [doi:10.12952/journal.elementa.000125][class:journalArticle]

Focuses on the approximately 5,000 km^2/year deforestation rate that continues after the 2004–2012 “slowdown,” proposing six strategies to address each of six categories of threat. Strategies include social and environmental safeguards for planned infrastructure, positive incentives for sustainable commodities, sustainability requirements for rural settlements, enforcing the Forest Code, protecting indigenous and traditional peoples, and creation of protected areas.

Rajão, R., A. Azevedo, and M. C. C. Stabile. 2012. Institutional subversion and deforestation: Learning lessons from the system for the environmental licensing of rural properties in Mato Grosso. *Public Administration and Development* 32:229–244. [doi:10.1002/pad.1620][class:journalArticle]

Shows how the Mato Grosso state government’s deforestation control program has been perverted. Initial success of the Mato Grosso program up to 2001 (see Fearnside 2003 in *Deforestation Control*) was compromised in subsequent state government administrations.

Rodrigues-Filho, S., R. Verburg, M. Bursztyn, D. Lindoso, N. Debortoli, and A. M. G. Vilhena. 2015. Election-driven weakening of deforestation control in the

Brazilian Amazon. *Land Use Policy* 43:111–118. [doi:10.1016/j.landusepol.2014.11.002][class:journalArticle]

Peaks in deforestation rates in 1995 and 2004, which coincide with federal elections when presidential administrations changed, cannot be explained by the alternative variables considered in the study: soy, beef and timber prices, exchange rate with the US dollar, and state-level migration rate. However, see Fearnside 2005 in *Deforestation Causes* for an alternative explanation of the 1995 peak based on the June 1994 Real Plan.

Soares-Filho, B. S., R. Rajão, and M. Macedo, et al. 2014. Cracking Brazil's forest code. *Science* 344:363–364.[doi:10.1126/science.1246663][class:journalArticle]

Shows the impact of the reform (gutting) of Brazil's Forest Code in 2012 in allowing more "legal" deforestation.

Protected Areas

Creation and reinforcement of protected areas represent essential tools in efforts to avoid deforestation. Unlike repression through command and control, protected areas have a continuing effect long into the future. Brazil's National System of Conservation Units (SNUC), inaugurated in 2000, has both areas designated as being for "integral protection" and others for "sustainable use" (Brazil, MMA 2015). "Conservation units" refer to the various kinds of parks and reserves in the SNUC, which is coordinated by the Ministry of the Environment. "Indigenous lands" (*terras indígenas*), which are under the Ministry of Justice, are also protected areas and account for more Amazonian forest than the conservation units. Over half of the Legal Amazonia region is now under some form of protection (Veríssimo, et al. 2011). Indigenous lands have been most effective in resisting deforestation (Nepstad, et al. 2006). The internationally financed Amazon Region Protected Areas (ARPA) program was critical in expanding the network of conservation units and its effectiveness in slowing deforestation (Soares-Filho, et al. 2010). Reserve programs face choices between creating new areas with minimal protection on the ground ("paper parks") versus reinforcing existing areas, between expensive areas near the deforestation frontier versus inexpensive areas far from the frontier, and between politically difficult "integral protection" areas versus politically easy "sustainable use" ones (Fearnside 2003). The location of protected areas is important in assuring their defensibility (Peres and Terborgh 1995) and effectiveness in avoiding deforestation (Nolte, et al. 2013). Sustainable-use protected areas with high deforestation threat avoid more deforestation over an eight-year period than do integral-protection areas farther from the frontier, despite sustainable-use areas allowing more clearing (Pfaff, et al. 2014). Unfortunately, despite the major advances in creating new protected areas, there is also a trend to reversing past commitments to protection by reducing the areas of existing reserves, by reclassifying them to categories with less protection, or by eliminating them altogether (Bernard, et al. 2014).

Bernard, E., L. A. O. Penna, and E. Araújo. 2014. Downgrading, downsizing, degazettement, and reclassification of protected areas in Brazil. *Conservation Biology* 28:939–950. [doi:10.1111/cobi.12298][class:journalArticle]

This study found ninety-three events downgrading, downsizing, degazetting, or reclassifying protected areas from 1981 to 2012, affecting 73,000 km^2. The frequency of events increased since 2008, mainly due to hydroelectric dams and transmission lines.

Brazil, MMA[nonPersonal]. 2015. Cadastro Nacional de Unidades de Conservação. Ministry of the Environmental. Brasília, Brazil: Ministério do Meio Ambiente (MMA). [http://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs/mapas].[class:dataSetItem-database]

This presents the national register of conservation units, with the location and features of each. Conservation units are an essential part of efforts to contain deforestation.

Fearnside, P. M. 2003. Conservation policy in Brazilian Amazonia: Understanding the dilemmas. *World Development* 31.5: 757–779. [doi:10.1016/S0305-750X(03)00011-1][class:journalArticle]

This presents a series of dilemmas facing efforts to limit deforestation and provide alternatives, including forest management and creation of protected areas of different types and with different levels of threat. Available in Portuguese *online[http://philip.inpa.gov.br/publ_livres/2010/Dilemas%20de%20conservacao-Serie_completa.pdf]*.

Nepstad, D. C., S. Schwartzman, and B. Bamberger, et al. 2006. Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology* 20:65–73. [doi:10.1111/j.1523-1739.2006.00351.x][class:journalArticle]

Shows that indigenous lands have been the type of protected area that best resists deforestation. (Note, however, that indigenous areas are not resistant to illegal logging.)

Nolte, C., A. Agrawal, K. M. Silvius, and B. S. Soares-Filho. 2013. Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America* 110.13: 4956–4961. [doi:10.1073/pnas.1214786110][class:journalArticle]

This study examined 292 protected areas in Brazilian Amazonia in two time periods to assess the effect of the type of protected area and the level of deforestation pressure on effectiveness in avoiding deforestation. “Integral” protection (strictly protected areas) avoided more deforestation than sustainable use areas at all pressure levels. Indigenous lands were especially effective in locations with high deforestation pressure.

Peres, C. A., and J. W. Terborgh.1995. Amazonian nature reserves: An analysis of the defensibility status of existing conservation units and design criteria for the future. *Conservation Biology* 9:34–46. [doi:10.1046/j.1523-1739.1995.09010034.x][class:journalArticle]

Argues for defensibility as a necessary criterion in choosing sites for protected areas.

Pfaff, A., J. Robalino, E. Lima, C. Sandoval, and L. D. Herrera. 2014. Governance, location and avoided deforestation from protected areas: Greater restrictions can have lower impact, due to differences in location. *World Development* 55:7–20. [doi:10.1016/j.worlddev.2013.01.011][class:journalArticle]

Protected areas in the state of Acre in the “integral protection” category are in locations with lower deforestation threat than in “sustainable-use” protected areas, including extractive reserves and indigenous lands. Deforestation data over the 2000–2008 period indicate that the sustainable-use areas avoided more deforestation than did integral-protection areas, despite their permitting more clearing. This shows that over the time scale relevant to REDD+ projects, sustainable-use areas in locations with high threat can produce greater mitigation benefits.

Soares-Filho, B. S., P. Moutinho, and D. Nepstad, et al. 2010. Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences USA* 107.24: 10,821–10,826. [doi:10.1073/pnas.0913048107] [class:journalArticle]

Shows that protected areas created by the Amazon Region Protected Areas (ARPA) program have helped slow deforestation.

Veríssimo, A., A. Rolla, M. Vedoveto, and S. M. Futada, eds. 2011. **Protected areas in the Brazilian Amazon: Challenges & opportunities*[https://www.socioambiental.org/pt-br/o-isa/publicacoes/protected-areas-in-the-brazililian-amazon-challengs-opportunities]*. Belém and Pará, Brazil: Instituto do Homem e Meio Ambiente na Amazônia (IMAZON).[class:report]]

This report by the non-governmental organizations IMAZON and ISA catalogues the status and threats to each protected area and provides general discussion of their role in limiting deforestation. A Portuguese-language version is available *online[http://imazon.org.br/PDFimazon/Ingles/books/Areas_Protegidas_Amazonia.pdf]*.

Environmental Services

Amazon forests provide environmental services to Brazil and to the world as a whole by storing carbon, recycling water, and maintaining biodiversity. Deforestation destroys these services. The value of the services to human society is far greater than the profit that can be made by deforesting, but the services are currently not rewarded economically (Fearnside 1997, Fearnside 2008). Better quantification of the services is an essential part of efforts to have them economically rewarded, thereby creating incentives to maintain forest rather than destroying it. Amazon forest biomass is proportional to the carbon stock, and estimates are still highly uncertain (Fearnside 2016). Advances in remote sensing have great potential in improving estimates (Baccini, et al. 2012 and Saatchi, et al. 2011), but results are inconsistent (Mitchard, et al. 2014). The limitation is inadequate ground truth to calibrate interpretation of the imagery. The largest data set for ground measurements is the approximately 3,000 one-hectare plots measured by the RADAMBRASIL surveys mapped by Nogueira, et al. 2015. These maps have been used to estimate emissions from Amazonian deforestation (e.g., Aguiar, et al. 2012). The magnitude of greenhouse-gas emissions from deforestation represents the benefit that could be gained by not deforesting. The same is true of other environmental services. Biodiversity maintenance, although recognized for its great importance, faces a variety of challenges in being incorporated into the economy (Fearnside 1999) and lags behind global climate change in terms of short-term prospects for rewarding environmental services. Water cycling by Amazon forests is essential for maintaining rainfall in Brazil and in neighboring countries (Arraut, et al. 2012). Deforestation and forest degradation cause loss of water recycling, among other environmental services (Foley, et al. 2007). This should provide ample reason for Brazil to curb Amazon deforestation but has less appeal than avoiding global warming and biodiversity loss for inducing contributions from other parts of the world. Programs for payment for environmental services (PES) in Brazilian Amazonia face a variety of challenges, including the widespread lack of secure land tenure (Wunder, et al. 2008).

Aguiar, A. P. D., J. P. Ometto, and C. Nobre, et al. 2012. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: The INPE-EM framework applied to the Brazilian Amazon. *Global Change Biol*ogy 18.11: 3346–3366. [doi:10.1111/j.1365-2486.2012.02782.x][class:journalArticle]

Applies the forest portion of the biomass map by Nogueira, et al. 2015 to calculate greenhouse gas emissions from deforestation.

Arraut, J. M., C. A. Nobre, H. M. Barbosa, G. Obregon, and J. A. Marengo. 2012. Aerial rivers and lakes: Looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America. *Journal of Climate* 25.2: 543–556. [doi:10.1175/2011JCLI418][class:journalArticle]

Presents data on water vapor transport by “flying rivers,” or pathways of the South American Low-Level Jet carrying water vapor from Amazonia to Brazil’s southeast region, including São Paulo.

Baccini, A. S. J. Goetz, and W. S. Walker, et al. 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change* 2.3: 182–185. [doi:10.1038/nclimate1354][class:journalArticle]

This study mapped biomass using satellite LiDAR data and MODIS imagery calibrated from ground plots. The analysis is for all of the world’s tropical forests and does not report how many of the study’s 283 0.16-ha plots are in Amazonia or Brazil. The small size of the plots and their small number both imply substantial uncertainty.

Fearnside, P. M. 1997. Environmental services as a strategy for sustainable development in rural Amazonia. *Ecological Economics* 20.1: 53–70. [doi:10.1016/S0921-8009(96)00066-3][class:journalArticle]

Amazonian forests provide services in avoiding global warming, recycling water (water vapor transport from Amazonia is essential for rainfall in other parts of Brazil as well as in the Amazon region) and maintaining biodiversity. These services have much greater value than deforestation.

Fearnside, P. M. 1999. Biodiversity as an environmental service in Brazil's Amazonian forests: Risks, value and conservation. *Environmental Conservation* 26.4: 305–321. [doi:10.1017/S0376892999000429][class:journalArticle]

The different values and uses of Amazonian biodiversity are discussed and their prospects for providing monetary flows that could counter the current financial incentives favoring deforestation. The prospects of significant flows from biodiversity on the time scale needed are much less than in the case of the forest's environmental services in avoiding climate change. Available in Portuguese *online[http://philip.inpa.gov.br/publ_livres/2003/livro%20Floresta%20amazonica%20nas%20mudancas%20globais%202ED%20MIOLO%20web.pdf]*.

Fearnside, P. M. 2008. Amazon forest maintenance as a source of environmental services. *Anais da Academia Brasileira de Ciências* 80.1: 101–114. [doi:10.1590/S0001-37652008000100006][class:journalArticle]

Environmental services of Amazonia are reviewed together with progress in their quantification and transformation into an alternative basis for sustaining rural population and forest. Unresolved issues include accounting procedures, quantification of the benefits of different policy options, and the use of the funds generated from the services.

Fearnside, P. M. 2016. Brazil's Amazonian forest carbon: The key to Southern Amazonia's significance for global climate. *Regional Environmental Change.* [doi: 10.1007/s10113-016-1007-2][class:journalArticle]

Carbon stocks are proportional to greenhouse gas emissions per hectare of deforestation and consequently to the benefit of reducing deforestation. This review indicates large amounts of carbon at risk of emission in both biomass and soils, as well as considerable uncertainty in estimates. Uncertainty must not be used as an excuse for delaying measures to contain deforestation.

Foley, J. A., G. P. Asner, and M. H. Costa, et al. 2007. Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Frontiers in Ecology and the Environment* 5.1: 25–32. [doi:10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2][class:journalArticle]

This study shows that degradation, as through logging, droughts and fire, is reducing the Amazon forest's provision of environmental services such as carbon storage, hydrological functions and water cycling. Results of a simulation show forest loss provoking higher temperatures and lower precipitation in Amazonia, thus adding to changes in the same direction from global warming.

Mitchard, E. T. A., S. A .Saatchi, A. Baccini, et al. 2014. Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites. *Global Ecology and Biogeography* 23.8: 935–946. [doi:101111/geb12168][class:journalArticle]

Compares estimates by Saatchi, et al. 2011 and Baccini, et al. 2012 and finds substantial inconsistencies in the spatial distribution of biomass in the Amazon region.

Nogueira, E. M., A. M. Yanai, F. O. R. Fonseca, and P. M. Fearnside. 2015. Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. *Global Change Biology* 21:1271–1292. [doi:10.1111/gcb.12798][class:journalArticle]

This study maps carbon stocks in both forest and non-forest vegetation types in Brazilian Amazonia using the RADAMBRASIL plots for forests. The loss to deforestation through 2013 is also calculated as compared to the "pre-modern" carbon stock that was present before the large increases in deforestation and degradation that began in the 1970s.

Saatchi, S. S., M. Marlier, R. L. Chazdon, D. B. Clark, and A. E. Russell. 2011. Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. *Remote Sensing of Environment* 115:2836–2849. [doi:10.1016/j.rse.2010.07.015][class:journalArticle]

Maps biomass using space-borne LiDAR (Light Detection and Ranging) data, OSCAT (Global Quick Scatterometer) radar data and MODIS optical imagery calibrated from ninety-six ground plots in primary forest in Brazilian Amazonia. Almost half of the plots are less than 1 hectare in area.

Wunder, S., J. Börner, M. R. Tito, and L. Pereira. 2008. *Pagamentos por Serviços Ambientais: Perspectivas para a Amazônia Legal*[http://www.mma.gov.br/estruturas/168/_publicacao/168_publicacao17062009123349.pdf]. Série Estudos 10. Brasília, Brazil: Ministério do Meio Ambiente (MMA).[class:report]

Commissioned by the Ministry of the Environment, this book discusses the potential for payment or environmental services (PES) in Brazilian Amazonia. It outlines necessary conditions for PES to function, including the need for land-tenure status that assures the providers the right of exclusion. PES also cannot work where opportunity costs for providing the services are too high, for example, where land could be used for soybeans. Various barriers that need to be overcome are identified for different modes of PES. Important issues include assuring benefits for local residents and establishing "additionality" (demonstrating that the environmental services provided are the result of the PES program).

REDD (Reducing Emissions from Deforestation and Degradation)

Reducing Emissions from Deforestation and Degradation (REDD), including REDD+ and REDD++ for variants that encompass actions to recover or enhance forest biomass and to incorporate socioeconomic co-benefits, is the current term for avoided deforestation and related actions. REDD has two distinct forms. One is under "voluntary" markets where companies or individuals can purchase certificates representing carbon benefits but without counting against national mitigation commitments under the United Nations Framework Convention on Climate Change (UNFCCC), better known as the "Climate Convention." The other form of REDD is under the Climate Convention, where agreement has been reached that this will be part of the international effort to mitigate climate change. Until 2007 the Brazilian government opposed any sort of compensation for the climate benefits of avoiding deforestation (Fearnside 2001). After most of the 2004–2012 decline in deforestation rate had occurred, the Brazilian government reversed its position on REDD (Brazil, CIMC 2008), and it is now a central part of the country's proposals on climate mitigation (Brazil, MMA and MCTI 2014 and May, et al. 2011). REDD is a highly controversial topic, with impassioned arguments both for and against. Benefits of REDD are reviewed by Nepstad, et al. 2013. Various controversies and barriers need to be addressed to achieve both the climatic and the socioeconomic benefits of this mechanism (Fearnside 2012a). One is the establishment of realistic "baselines," or reference scenarios, indicating how much deforestation would occur were a REDD project not implanted, as is clearly shown by the example of the first REDD project in the voluntary market (Yanai, et al. 2012). The first REDD project in an indigenous land (the Sete de Setembro Indigenous Land) shows that reasonable baselines can be modeled but that they require a level of information and technical effort that is not available for most such areas (Vitel, et al. 2013). One of the threats to the carbon benefits of REDD is loss of carbon in the protected forests due to drought and fire (Aragão and Shimabukuro 2010). In fact, a fire in 2010 in the Sete de Setembro Indigenous Land has already provided an example (*Ambiência* 8 [2012]: 511–521). Most fundamental is a series of decisions on how the carbon benefits are counted, representing a "theoretical battlefield" that can have more effect on the final results than the various uncertainties concerning forest biomass and other factors (Fearnside 2012b). At REDD+ project sites in Brazilian Amazonia the opportunity to participate in the projects acts in synergy with the rural environmental register (CAR) and land-titling in providing an inducement for greater environmental compliance (Duchelle, et al. 2014).

Aragão, L. E. O. C., and Y. E. Shimabukuro. 2010. The incidence of fire in Amazonian forests with implications for REDD. *Science* 328:1275–1278. [doi:10.1126/science.1186925][class:journalArticle]

Deforestation was estimated in 0.25 degree pixels from 2000 to 2007 from LANDSAT data, and fire frequencies were estimated from AVHRR from 1998 to 2006 for the same pixels. Fire occurrence increased in 59 percent of the area that experienced reduced deforestation rates. The implications for REDD are discussed: fire can release carbon even if no deforestation takes place. For a critique of some aspects of the estimates, see: *Science* 330 (2010): 1627-b [doi: 10.1126/science.1194032].

Brazil, CIMC[nonPersonal] . 2008. *Plano Nacional sobre Mudança do Clima – PNMC — Brasil*[http://www.mma.gov.br/estruturas/imprensa/_arquivos/96_01122008060233.pdf]*. Brasília, DF, Brazil: Ministério do Meio Ambiente.[class:report]

Presents the Brazilian government's national plan for climate change, launched before the 2009 conference of the parties of the Climate Convention in Copenhagen. The proposal establishes a baseline based on the average deforestation rate over a period that includes the 2004 peak in clearing.

Brazil, MMA[nonPersonal]and MCTI [nonPersonal] . 2014. *Brazil's submission of a Forest Reference Emission Level (FREL) for reducing emissions from deforestation in the Amazonia biome for REDD+ results-based payments under the

UNFCCC[http://redd.mma.gov.br/images/Publicacoes/FREL_Complete_October31_FINAL.pdf]*. Brasília, Brazil: MMA. [class:report]

This presents Brazil's official submission to the Climate Convention on the baseline against which proposed rewarding of carbon benefits would be measured.

Duchelle, A. E., M. Cromberg, and M. F. Gebara, et al. 2014. Linking forest tenure reform, environmental compliance, and incentives: Lessons from REDD+ initiatives in the Brazilian Amazon. *World Development* 55:53–67. [doi:10.1016/j.worlddev.2013.01.014][class:journalArticle]

A study of four REDD+ sites in Brazilian Amazonia shows that the opportunity to participate in the REDD+ program is an inducement for completing the Rural Environmental Register (CAR), which also has the major inducement of facilitating land titling. The right of exclusion formalized by titling is essential for payment for environmental services (PES). The synergisms among these processes are valuable as inducements to environmental compliance.

Fearnside, P. M. 2001. Saving tropical forests as a global warming countermeasure: An issue that divides the environmental movement. *Ecological Economics* 39.2: 167–184. [doi:10.1016/S0921-8009(01)00225-7][class:journalArticle]

Over the period between the 1997 Kyoto Protocol and the 2001 agreement ruling out carbon credit for avoiding tropical deforestation until after 2012, debate among national governments and groups of NGOs revealed that the divergent opinions on including tropical forests in the Clean Development Mechanism was largely determined by hidden agendas, conscious or not. Some of these agendas still apply to debates on REDD+, while others are specifically tied to opportunities presented by the Kyoto Protocol's having established national emissions quotas prior to finalizing the rules on mitigation options. Brazil's opposition to any reward for avoiding tropical deforestation depended on a view of deforestation as uncontrollable; this opposition persisted until 2007 (after most of the deforestation "slowdown" had occurred).

Fearnside, P. M. 2012a. Brazil's Amazon forest in mitigating global warming: Unresolved controversies. *Climate Policy* 12.1: 70–81. [doi:10.1080/14693062.2011.581571][class:journalArticle]

Presents the controversies surrounding Reducing Emissions from Deforestation and Degradation (REDD), including the reluctance of European countries to make REDD more than a token part of mitigation efforts, since mitigation "at home," even if resulting in less climate benefit, will produce jobs and increase income in the European countries.

Fearnside, P. M. 2012b. The theoretical battlefield: Accounting for the climate benefits of maintaining Brazil's Amazon forest. *Carbon Management* 3.2: 145–148. [doi:10.4155/CMT.12.9][class:journalArticle]

Reviews a series of outstanding issues in how climate benefits are counted in proposed mechanisms, such as REDD, to reward avoided deforestation. Especially important is the question of the value attributed to time in the calculations. These

issues must be faced if the environmental services of Amazon forest are to provide an alternative form of development for the region’s rural population.

May, P. H., B. Millikan, and M. F. Gebara. 2011. **The context of REDD+ in Brazil: Drivers, agents and institutions*[http://www.cifor.org/publications/pdf_files/OccPapers/OP-55.pdf]*. 2d ed. CIFOR Occasional Paper 55. Bogor, Indonesia: Center for International Forestry Research (CIFOR). [class:report]

This study reviews the history of deforestation, governance arrangements, policies causing deforestation and degradation, the REDD+ policy environment and the high uncertainty over financing REDD+ in Amazonia. Information is given on twenty-five subnational projects as of August 2010. Implications of REDD+ for efficiency, effectiveness and equitability imply both opportunities and various needs for improvement.

Nepstad, D. C., S. Irawan, T. Bezerra, et al. 2013. More food, more forests, fewer emissions, better livelihoods: linking REDD+, sustainable supply chains and domestic policy in Brazil, Indonesia and Colombia. *Carbon Management* 4.6: 639–658. [doi:10.4155/cmt.13.65][class:journalArticle]

Presents a review of potential benefits for climate and also for human livelihoods if REDD projects are implemented on a large scale. See Fearnside 2012a for discussion of both sides of controversies regarding the REDD mechanism.

Vitel, C. S. M. N., G. C. Carrero, M. C. Cenamo, M. Leroy, P. M. L. A. Graça, and P. M. Fearnside. 2013. Land-use change modeling in a Brazilian indigenous reserve: Construction a reference scenario for the Suruí REDD project. *Human Ecology* 41.6: 807–826. [doi:10.1007/s10745-013-9613-9][class:journalArticle]

Simulates deforestation processes in an indigenous area that is already in extensive contact with the surrounding non-indigenous society.

Yanai, A. M., P. M. Fearnside, P. M. L. A. Graça, and E. M. Nogueira. 2012. Avoided deforestation in Brazilian Amazonia: Simulating the effect of the Juma Sustainable Development Reserve. *Forest Ecology and Management* 282:78–91. [doi:10.1016/j.foreco.2012.06.029][class:journalArticle]

Shows how the choice of modeling approaches affecting the baseline for REDD projects can produce radically different results. Leakage effects are also modeled.