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Protected Area Effectiveness in Reducing Tropical Deforestation

A Global Analysis of the Impact of Protection Status

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A Global Analysis of the Impact of Protection Status

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Executive Summary

The REDD agenda (Reducing Emissions from Deforestation and Degradation) seeks to mobilize positive incentives for countries to reduce deforestation, the source of 20 percent of anthropogenic greenhouse emissions. To be successful, this agenda requires not only financing and international agreement on procedures, but it also needs practical guidance on how to accomplish such reductions in ways that also promote local environmental and development goals.

Such guidance may come from existing efforts in the establishment of protected areas and indigenous areas. Motivated by biodiversity, environmental, social, and land rights concerns, these interventions encourage forest conservation and sustainable use and would often be expected to reduce deforestation. Protected areas have expanded in recent years and now cover 27 percent of the tropical forest biome. Forests controlled by local and indigenous communities have also expanded. An assessment of the effectiveness of these areas in reducing deforestation could inform the design of interventions to promote REDD: reduced carbon emissions from deforestation and degradation. Yet there is considerable uncertainty and controversy over the impacts and effectiveness of protected areas and very few well-designed evaluations. One area of dispute is the relative effectiveness in deforestation reduction of strictly protected areas versus areas that allow some degree of sustainable use by local people.

This study assesses the impact of tropical protected areas on deforestation fires, which are the best available globally consistent proxy for deforestation at a fine spatial scale. The paper covers the entire tropical forest biome to estimate the avoided deforestation afforded by several thousand protected areas. Building on recent advances, the authors use matching methods to compare protected area points with similar unprotected points, controlling for slope, rainfall, road proximity, and other factors affecting both deforestation and protected area placement. Unlike previous studies, this work provides a continuous measure of the effectiveness of protection as a function of varying degrees of deforestation pressure, as well as for different classes of protection (strict, multi-use and indigenous).

Across the biome, the paper finds that protected areas generally have significantly lower fire rates than comparable nonprotected areas, but this differential declines as remoteness increases. Multi-use protected areas generally provide greater deforestation reduction (in absolute terms) than strict protected areas (see Figures ES.1 and ES.2). This protective effect may be obscured because the multi-use protected areas tend to be established in zones of higher deforestation pressure. Indigenous areas have an even higher protective impact. Estimates for Africa indicate modest impact of strict protected areas, but results are not robust for multi-use areas.

Figure ES.1: Forest Fire Rates in Latin America and the Caribbean, Strict Protection

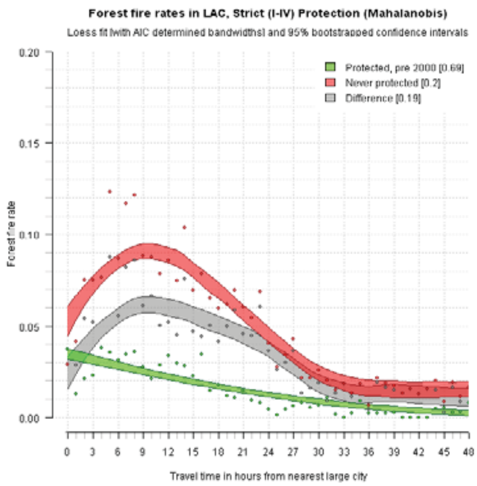
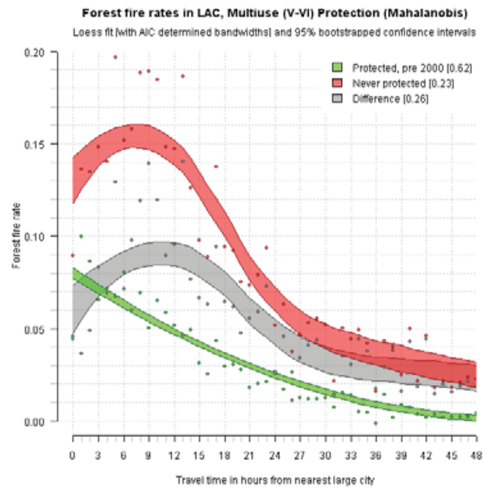


Figure ES.2: Forest Fire Rates in Latin America and the Caribbean, Multi-Use Protection



Chapter 1
Introduction

Tropical deforestation accounts for between one fifth and one quarter of the total human contribution to greenhouse gases (Gullison and others 2007; Kindermann and others 2008), and a larger proportion of emissions from developing countries. Reduction of deforestation therefore contributes to climate change mitigation and may also provide development benefits (Canadell and Raupauch 2008; Miles and Kapos 2008; Chomitz 2007). The REDD (Reduced Emissions from Deforestation and Degradation) agenda seeks to integrate deforestation reduction into the global climate regime under the United Nations Framework Convention on Climate Change, rewarding countries that reduce forest emissions (Canadell and Raupauch 2008; FAO, UNDP, and UNEP 2008). But there is a dearth of rigorous evaluations of the impact of specific interventions on deforestation (Hansen and others 2008; Chomitz 2007).

Although the REDD agenda is new, the forest protection agenda is not. Conservation and sustainable management of forests have been motivated by biodiversity and livelihood concerns for decades. Where deforestation is a threat to biodiversity, successful conservation or sustainable management efforts will have a side benefit of reducing forest carbon emissions. So an evaluation of the effectiveness of past conservation efforts can inform the design of interventions to promote REDD. This is especially salient in the humid tropical forests, where deforestation rates and carbon densities are both high. Their loss is the major source of forest carbon emissions.

Among conservation interventions in tropical forests, the establishment of protected areas has been the most prominent and best funded, by the World Bank, other donors, and host countries. The Global Environment Facility says that its investments in protected areas include $1.6 billion of its own resources and $4.2 billion in cofinancing; much of this has been implemented through the World Bank. Protected areas have expanded rapidly in recent years (UNEP/IUCN 2009; UNEP-WCMC 2008) and now cover around 27.1 percent[1] of the tropical forest estate. In many ways they provide a model for broader classes of intervention, since most efforts to reduce deforestation will involve some kinds of restrictions on land use practices (Chomitz 2007).

Yet there is considerable uncertainty and controversy over the impacts and effectiveness of protected areas, and very few well designed evaluations (Andam and others 2008; Ferraro and Pattanayak 2006). On one hand, protected areas are sometimes characterized as ineffective "paper parks." On the other, there is increasing evidence that deforestation rates are lower in protected areas (see, for example, Nepstad and others 2006). However, this observed impact may be partially illusory, because protected areas tend to be established in areas that are unattractive to agricultural conversion. A small but growing literature has applied increasingly sophisticated statistical procedures to control for this source of bias (Andam and others 2008; Ferraro and Pattanayak 2006; Chomitz and Gray 1996; Cropper, Puri, and Griffiths 2001; Joppa and Pfaff 2009c; Pfaff 2009a; Pfaff and others 2009; Ferraro 2008).

Building on and extending some recent methodological advances (Andam and others 2008; Pfaff

2009a; Pfaff and others 2009; Joppa and Pfaff 2009b), this study is an impact evaluation of the effect of tropical protected areas on deforestation fires, which are the best available consistent proxy for deforestation at a fine spatial scale. It uses the spatial analysis of remote sensing data to characterize the tropical forest biome and matching methods (Morgan and Harding 2006) to control for the effects of location and landscape characteristics to ensure unbiased estimates of the avoided deforestation fires provided by different classes of protection. Thus, location-specific estimates are generated based on almost 3,000 protected areas covering 2 million square kilometers (km) of the tropical forest biome. Unlike previous work, this work provides a continuous measure of effectiveness as a function of varying degrees of deforestation pressure (proxied by travel time to the nearest city).

This study does not evaluate the impact of protected areas on local welfare or livelihoods—a controversial subject on which there is very little rigorous evaluation (Ferraro and Pattanayak 2006; Ferraro 2008). However, it does address the relative impacts on deforestation of strict protected areas versus areas in which local people have greater rights of use and management.

1.1. Assessing protected area effectiveness

Assessing the impact of protection in terms of land cover change is challenging, whether it is assessed as part of a detailed park study, regionally (Nepstad and others 2006), or globally (Bruner and others). Earth observation data provide ever more detailed and more frequent pictures of land cover, climate, and events such as fires and as a result have become a key source of information for such studies, along with other spatial information on population density, transport networks, protected area boundaries, and the like.

As recent studies have demonstrated (Joppa and Pfaff 2009c; Pfaff and others 2009), it is vital to control for the location of the protected area and its characteristics to ensure that any comparison of land cover change—particularly deforestation—between protected and unprotected lands is unbiased. Location must be accounted for, because protected areas may be disproportionately located in areas characterized by higher slopes, greater distance to cities, and lower suitability for agriculture (Joppa and Pfaff 2009b). These factors, which are strongly associated with lower pressures for deforestation, presumably reduce the political and economic costs of imposing land use restrictions (Chomitz 2007). If a protected area is remote, has poor-quality soil or difficult terrain, or is subject to extremely high rainfall, then it may well benefit from de facto protection. Comparing these "low-pressure" areas to unprotected lands in general might show that legislated protection has significant benefits for avoiding deforestation. But if unprotected lands with similarly unappealing characteristics also exhibited little or no change in forest cover, then such legal protection would be minimal.

Conversely, protected areas in "high-pressure" zones, with good access to roads and markets and containing agriculturally suitable environments, may exhibit greater levels of degradation than unprotected lands in general. Again, if only such high-pressure protected areas were compared with unprotected areas facing similar pressures, the result would likely be that such protected areas, although possibly degraded, do provide a degree of protection (Joppa and Pfaff 2009b, 2009c; Adeney, Christensen, and Pimm 2009; Joppa, Loarie, and Pimm 2008).

Joppa and Pfaff (2009c) provide a recent review of the empirical literature on the impact of protected areas on deforestation. Most conventional studies have not fully controlled for the bias in location. However, a number of recent studies have introduced controls for attractiveness of conversion (Chomitz and Gray 1996; Deninger and Minten 2002), econometrics with controls for endogeneity of protected area placement (Cropper, Puri, and Griffiths 2001), and, more recently, matching methods that are thought to be less sensitive to specification error

(Andam and others 2008; Pfaff 2009a; Pfaff and others 2009; Joppa and Pfaff 2009a, 2009b). These methods seek to pair protected forest plots with unprotected but otherwise similar "control" plots.

Andam and coauthors (2008) used matching methods to assess the deforestation-reducing impact of Costa Rica's system of protected areas. They found that protected areas on average did modestly reduce deforestation, but by substantially less than a naïve comparison of mean deforestation rates in protected versus unprotected areas. Pfaff and others (2009) qualify this result, showing that Costa Rican parks had a greater protective effect in areas facing greater pressure, such as those close to the capital. Joppa and Pfaff (2009a) extend the approach of Andam and others to the global set of protected areas, assessing impacts by country on forest cover in 2000 and 2005, and for the 2000–05 change in cover. (Because the two land cover datasets used different methods, the change measure is acknowledged to be "noisy.") They found, again, that deforestation reduction was generally less than a simple comparison would indicate.

In short, there have been several well-defined studies of the effectiveness of protection for avoiding deforestation, but none has simultaneously addressed differences in pressure, location bias, and protection status on a global scale.

This study builds on the matching approach used in Andam and others (2008) and Joppa and Pfaff (2009a). It differs from the latter in several important respects. First, it focuses on the tropical forest biome, where deforestation rates and carbon emission rates are highest. Second, as a result of this focus, it can use what is for the moment the most consistent and up-to-date high-resolution proxy for deforestation: forest fires. Third, it presents results by continent rather than country but disaggregates protected area impacts by distance to a city (a proxy for deforestation pressure). Finally, it breaks out results for multi-use protected areas (International Union for Conservation of Nature [IUCN] categories V and VI, and indigenous areas) to inform the debate about the advantages and disadvantages of strict protection.

The next section briefly describes the most commonly used matching estimators and is followed by a description of the study area and an assessment of the suitability of available spatial data for a global scale analysis of avoided deforestation in the tropical forests. The final section presents the results of the two analyses.

Note

1. Boundary and area data are not available for a small percentage of protected areas, and so this may be a conservative estimate.

Chapter 2
Matching Methods

Recent reviews and evaluations of matching have presented its benefits in providing robust estimates of causal effects (Morgan and Harding 2006) and as a nonparametric preprocessing tool (Ho and others 2007). This chapter provides a brief background to the methods used in this paper.

Matching has become a popular method of causal inference, particularly in econometrics, but also in fields as diverse as law, medicine, and conservation policy (Morgan and Harding 2006; Ho and others 2007; Joppa and Pfaff 2009c; Sekhon 2007). Matching works by identifying a control group that is "very similar" to the treatment group with only one key difference: the control group did not participate in the program of interest. In this case, the program of interest is designated protection: was a patch of land protected (treatment group) or not (control group)? Defining "very similar" based on the covariates of each case is one challenge facing the researcher when applying matching to data. The aim here is to identify a matching control case for each treatment case to produce a balanced dataset, where a perfectly balanced dataset would consist of pairs of cases with identical covariables in the treatment and control groups.

Matching algorithms take different approaches to defining "very similar." A variety of approaches exists; this paper relies on exact matching and nearest neighbor matching.

Exact matching simply identifies pairs of identically matching cases in the two groups, based on all covariables. It can, however, be combined with other matching approaches to force exact matching on a subset of the covariates, for example, to force matching pairs to selected from the same country. Such selective exact matching is an important requirement for this analysis, because it ensures that average results across the biome can be disaggregated by country.

Nearest neighbor matching identifies the most similar treatment cases to each control case by means of a distance measure derived from the difference across all the covariables. One common measure of similarity is the Mahalanobis distance metric, a scale invariant measure of the multidimensional distance between two points. Typically, the algorithm randomly orders the treatment cases and for each one in turn selects the control case with the smallest distance. Poor matches are avoided by assigning a tolerance to judge the quality of the match. This distance tolerance is termed a *caliper* and simply determines the acceptable similarity for a match.

The authors use remotely sensed data on forest fire activity between 2000 and 2008 as a measure of deforestation and used tropical forest cover in year 2000 and information on protected areas to characterize the tropical forest biome in year 2000. The matching aims to provide unbiased estimates of avoided deforestation fires in protected areas in the tropical forests for different classes of protection and for different levels of pressure. The data, the study area, the disaggregation by protection type, and the definition of pressure are described in chapter 3.

Chapter 3
Data and Sampling

All spatial data were projected to equal area sinusoidal projection, with a WGS84 datum and spheroid. Unless otherwise stated, raster resolution is 1 km. The relevant data from each data layer were extracted at 1-km spacing and stored in a PostgreSQL database (version 8.3). The following sections describe these data layers.

3.1. Study area

The study is limited to developing countries (recipient countries of World Bank loans) and the extent of the tropical forest biome. The biome—derived from the World Wildlife Fund's Terrestrial Ecoregions of the World (Olson and others 2001)—contains the maximum spatial extent of the world's tropical and subtropical moist broadleaf forests.

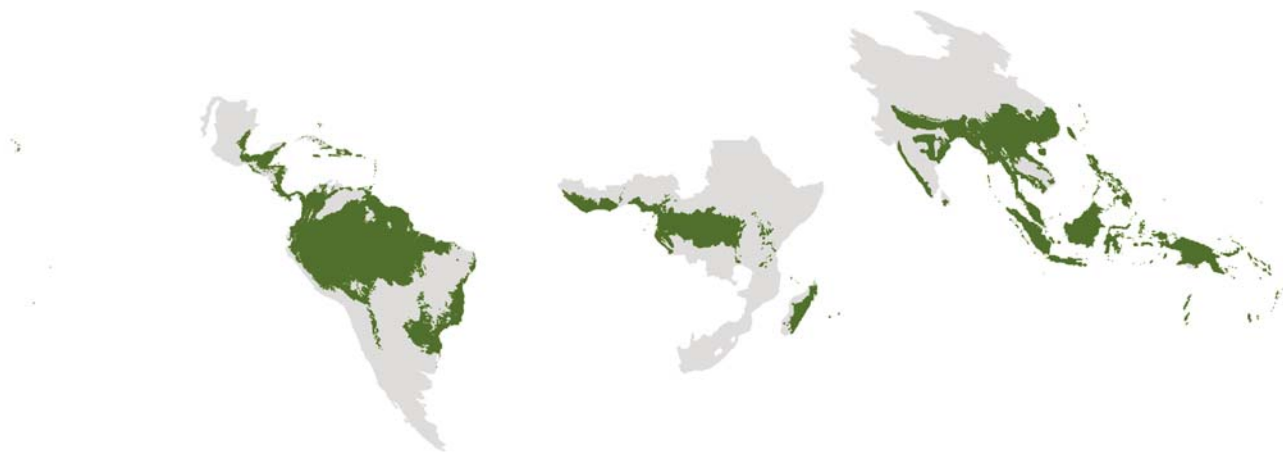
Figure 1 shows the spatial intersection of these countries and the biome. The area in green is the maximum extent of the study area covering 19.73 million km^2. The biome is clearly split across three continents; each will be analyzed separately. Papua New Guinea and Micronesia are considered part of Asia for this analysis.

3.2. Tropical forest area

Within this area, the extent of the remaining tropical forest in 2000 was extracted from two land cover data sources: Global Land Cover for the year 2000 (Bartholome and Belward 2005) derived from ~1 km resolution SPOT data and Percentage Forest Canopy Cover for 2000 (Hansen and others 2003) derived from ~500 m MODIS data.

All 11 land cover classes from GLC2000 that contain forest or forest mosaics were extracted, along with all ~1-km pixels where the average percent forest cover was greater than 25 percent (Hansen and others 2008). This is a higher threshold than the 10 percent used in the FAO Forest Resource Assessment (FAO 2006) and in a recent assessment of global forest protection (Schmitt and others 2009). One justification for using the 10 percent threshold in those global

Figure 1: Extent of the Tropical Forest Biome



analyses was to capture woodland areas in Africa; however, these are not part of the tropical forest biome. Twenty-five percent was chosen to minimize the risk of including tropical woodlands/savannas and other land that was already largely cleared of forest, that was predominantly used for agriculture, and that could exhibit high fire activity that was not necessarily related to deforestation events.

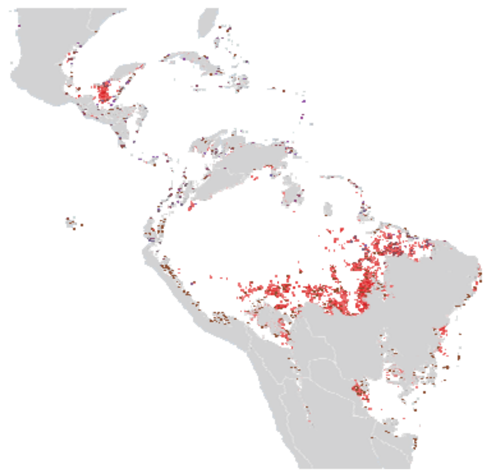
This delineation of tropical forest extent is a conservative estimate based on the common area of both these forest layers within the boundaries of the biome, covering 13.15 million km^2 of tropical forest area in 2000. For reference, a tropical forest extent based on the MODIS data alone or on GLC2000 alone would amount to 15.13 million km^2 or 14.51 million km^2, respectively. Agreement between the two across the biome is 83.1 percent.

3.3. Outcome variable: Fire activity on forests

Fire activity (Figure 2)—overlaid on forest extent—was used as a proxy for tropical deforestation fire events. (The overlay screens out fires used for land management on previously cleared areas such as pastures.) Fire activity was estimated from spatially referenced remote sensing data on forest fires from the MODIS Active Fires dataset (Justice and others 2002). MODIS Active Fire data are provided on two satellite platforms, Terra from October 2000 and Aqua from July 2002, both to present day. Thus, there is partial coverage from October 2000 (two passes per day) and complete coverage from July 2002 (four passes per day), including both day and night passes.

Following Morton and others (2008) in their study of fire activity in the Amazon, this paper extracted only the high-confidence fires—all fires occurring at night and daytime fires with > 330K brightness temperature in the 4 μm channel—from more than 1 million MODIS fires scenes between 2000 and 2008.[1] Some 1.21 million 1-km pixels recorded at least one fire between October 2000 and January 2009 in the tropical forest biome and 0.70 million of these occurred in forested areas (Table 1). Of the 13.15 million 1-km tropical forest pixels, 5.31 percent had at least one fire event in that time frame.

Figure 2: Fire Activity and Forest Extent



The outcome variable is a binary measure of forest fire activity per square km: was there ever a fire event in that pixel during 2000–08? This time period is reflected in the choice of covariables and the definition of the control/treatment groups below. The lack of coverage until October 2000 and then partial coverage until July 2008 implies that the binary measure here is slightly conservative as an estimate of fire-affected area.

Another dataset was considered as a proxy for tropical deforestation events: the recently released MODIS Collection 5 Burned Area Product, which includes global, monthly 500-

Table 1: 1-km Forest and Fire Pixel Statistics in the Tropical Forest Biome (2000–08)

Region	Forest pixels	Fire pixels	Fire rate
Biome	13,154,816	698,514	0.0531
LAC	6,989,019	365,074	0.0522
Africa	2,529,918	142,913	0.0565
Asia	3,635,879	190,527	0.0524

Note: LAC = Latin America and the Caribbean.

meter (m) resolution maps of burn dates.[2] A provisional version of this data was made available for evaluation but is currently offline. A direct comparison between the active fire and burned area data for July 2001–June 2002 made the following pertinent finding for burned area and fire detections by land cover class:

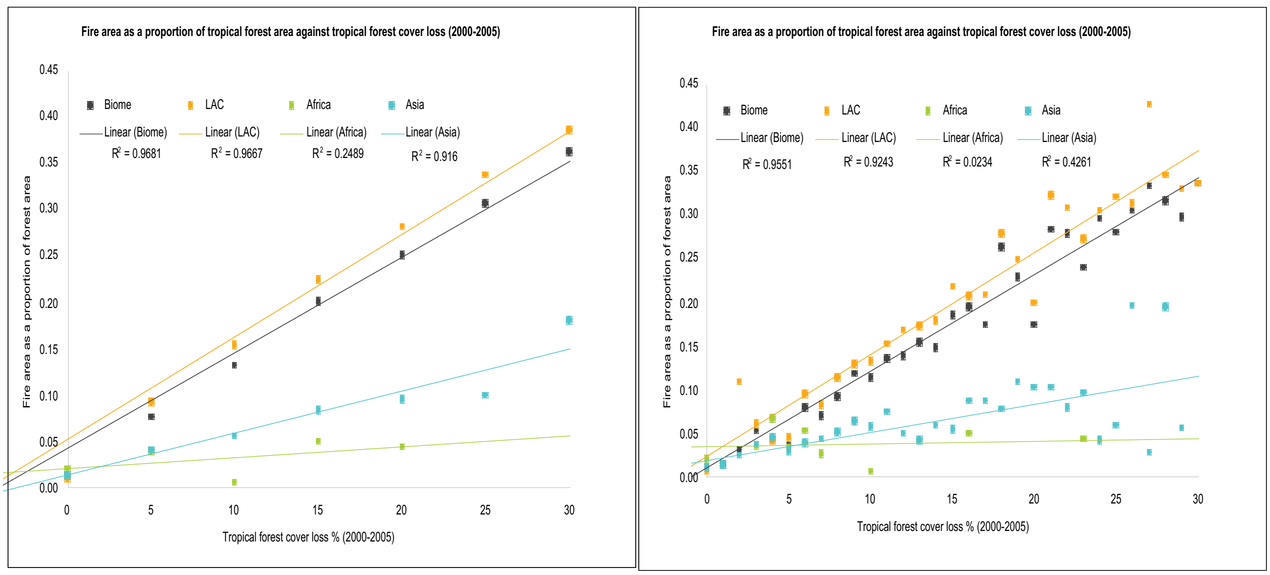
> Savannas, woody savannas, grasslands and shrublands account alone for 85% of the MODIS burned areas (over 3.1×10^6 km^2), a figure consistent but greater than with the active fires detections, which account for 73.7% (over 2.38×10^6 km^2). Conversely, the five forest classes (evergreen needle-leaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf and mixed forest) account for only 5.5% of the global MODIS burned areas (0.20×10^6 km^2) but for 11.6% of the active fire detections (over 0.37×10^6 km^2), highlighting the fact that many forest fires are detected by the active fire product but not by the burned area product (Roy and others 2008).

This higher detection rate, albeit including both medium- and high-confidence fires, and the fact that the burned area data are still provisional, led to a preference for the active fire data over the burned area data as a proxy for tropical deforestation events.

The presence of one or more fires in a 1-km pixel cannot be directly translated into an estimate of deforested area. A fire event may represent anything from a small clearing of a single hectare to complete deforestation of the 1-km pixel. However, it can be assessed whether this fire presence/absence data can be used as a plausible proxy for deforestation activity in the tropical forest biome. The authors compared the binary measure of forest fire activity to a recently published, Landsat-calibrated, biome-wide dataset with a spatial resolution of 18.5 km that quantifies forest cover loss from 2000 to 2005 (Hansen and others 2008). They plotted the area of fire activity for 2000–05 as a proportion of forest area against percent forest cover loss for 2000–05 per 18.5-km pixel (Figure 3). The analysis was repeated for 5 percent (left of figure) and 1 percent (right of figure) bins of forest cover loss.

There is a strong trend of increasing fire activity with increased loss of forest cover across the biome, from 0 to 30 percent forest cover loss. The trend continues for higher forest cover loss percentages, but there are very few 18.5-km pixels (<0.2 percent of the tropical forest biome

Figure 3: Forest Fire Rate (fire area/forest area) against Forest Cover Loss for 2000–05, with Linear Trend Lines



area) in these areas. Latin America and the Caribbean and Asia show the same clear trend as the whole biome, but the case is less clear for Africa. It should be noted that the remote sensing estimate of African deforestation differed drastically from the Forest Resources Assessment (2005) by the FAO (Hansen and others 2008; FAO 2006), so the deviation between the fire measures and the remote sensing measures may not be solely due to misclassification of the fire data.

From this it is reasonably sure that the chosen subset of active fires is a plausible proxy for deforestation events, especially in Latin America and Asia. The case is less convincing for Africa but is still plausible.

3.4. Protected areas and IUCN management classes

The World Database on Protected Areas (WDPA) (UPED/IUCN 2009) is the source for protected area information. Protected area information, including park boundaries (and park center coordinates and area for areas with unknown boundaries), designation date, IUCN protected area management classification, and status were extracted from the WDPA database for all protected areas that were inside or that intersected the tropical forest biome.

This list of protected areas includes all nationally (IUCN protected area management classes I through VI as well as unknown) and internationally (UNESCO MAB reserves, Ramsar sites, and World Heritage sites) recognized parks and amounts to 4.13 million km^2 of protected area within the biome, of which 3.62 million km^2 is forested.

The six management classes as described by IUCN are—

CATEGORY Ia: Strict Nature Reserve: Protected area managed mainly for science.
Definition: Area of land and/or sea possessing some outstanding or representative ecosystems, geological or physiological features and/or species, available primarily for scientific research and/or environmental monitoring.

CATEGORY Ib: Wilderness Area: Protected area managed mainly for wilderness protection.
Definition: Large area of unmodified or slightly modified land and/or sea retaining its natural character and influence, without permanent or significant habitation, which is protected and managed so as to preserve its natural condition.

CATEGORY II: National Park: Protected area managed mainly for ecosystem protection and recreation.
Definition: Natural area of land and/or sea designated to (a) protect the ecological integrity of one or more ecosystems for present and future generations; (b) exclude exploitation or occupation inimical to the purposes of designation of the area; and (c) provide a foundation for spiritual, scientific, educational, recreational, and visitor opportunities, all of which must be environmentally and culturally compatible.

CATEGORY III: Natural Monument: Protected area managed mainly for conservation of specific natural features.
Definition: Area containing one or more specific natural or natural/cultural feature that is of outstanding or unique value because of its inherent rarity, representative or aesthetic qualities, or cultural significance.

CATEGORY IV: Habitat/Species Management Area: Protected area managed mainly for conservation through management intervention.
Definition: Area of land and/or sea subject to active intervention for management purposes to ensure the maintenance of habitats and/or to meet the requirements of specific species.

CATEGORY V: Protected Landscape/Seascape: Protected area managed mainly for landscape/seascape conservation and recreation.
Definition: Area of land, possibly with coast and sea, where the interaction of people and

nature over time has produced an area of distinct character with significant aesthetic, ecological, and/or cultural value, and often with high biological diversity. Safeguarding the integrity of this traditional interaction is vital to the protection, maintenance, and evolution of such an area.

*CATEGORY VI: **Managed Resource Protected Area:*** Protected area managed mainly for the sustainable use of natural ecosystems.

Definition: Area containing predominantly unmodified natural systems, managed to ensure long-term protection and maintenance of biological diversity, while providing a sustainable flow of natural products and services to meet community needs.

Two treatment groups were considered, based on protected areas with boundary information. The first group consists of all protected areas that were designated pre-2000. The second group is restricted to protected areas that were designated between 1990 and 2000. Use of the restricted group allows us to examine the impact of more recently created protected areas and provides a check against the possibility of endogeneity in the matching variables.

Each protected area has been assigned an IUCN management class. These two groups are disaggregated further based on the IUCN management classes:

- Strict protection—IUCN classes I though IV
- Nonstrict or multi-use protection—IUCN classes V and VI
- Unknown protection—Nationally recognized but with no IUCN class
- Indigenous—A subset of the unknown class, but under indigenous stewardship.

Strict protection means areas that are designed specifically for nature protection. *Multi-use protection* means that the areas allow some form of sustainable use. The indigenous group of protected areas occurs in Latin America, predominantly in Brazil, with a few areas in Panama and Colombia. Figure 4 shows the IUCN classified protected areas that were designated before 2000; the dominance of the protected tropical forest area in Latin America and the Caribbean is clear. There were 2,974 IUCN classified (IUCN classes I through VI, plus unknown) protected areas designated before 2000 in the tropical forest biome that contained at least 1 km^2 of tropical forest.

The control groups are based on areas that have never been protected, up through 2008. Thus, any tropical forest area that has ever been protected based on the entire tropical forest coverage of the World Database of Protected Areas (WDPA) park boundaries is excluded. Where boundary data were missing, protected areas were represented by circles around center coordinates.

Summary statistics for tropical forest area and protected tropical forest area are shown in Tables

Figure 4: Protected Areas in the Tropical Forest Biome with an IUCN Management Classification Designated Before 2000

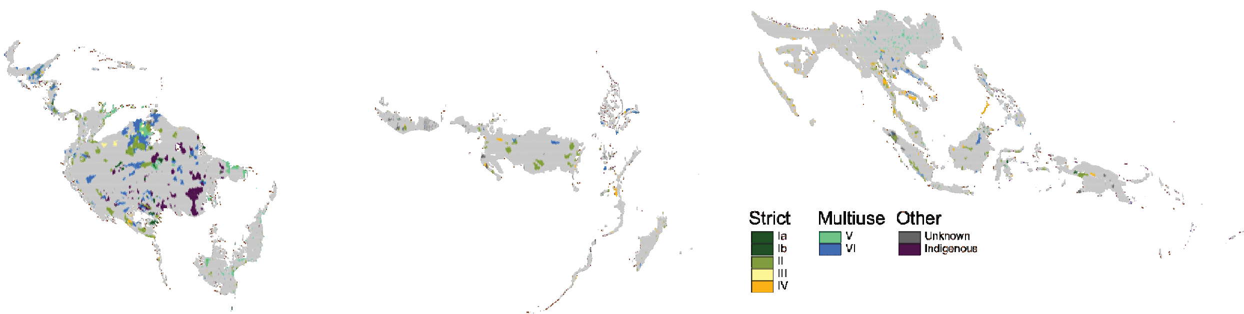


Table 2: Total Tropical Forest Protected (km² and %) by Protection Class and Region

Area	Biome	Latin America and the Caribbean	Africa	Asia
Forest Area	13,154,816	6,989,019	2,529,918	3,635,879
Protected Area	3,619,941 (27.5)	2,719,301 (38.9)	411,761 (16.3)	488,879 (13.4)
Ia	166,892 (1.3)	152,650 (2.2)	1,425 (0.1)	12,817 (0.4)
Ib	21,207 (0.2)	10,415 (0.1)	1,097 (0.0)	9,695 (0.3)
II	740,910 (5.6)	482,193 (6.9)	127,902 (5.1)	130,815 (3.6)
III	57,837 (0.4)	47,140 (0.7)	483 (0.0)	10,214 (0.3)
IV	142,896 (1.1)	21,211 (0.3)	20,447 (0.8)	101,238 (2.8)
Strict (I–IV)	1,129,742 (8.6)	713,609 (10.2)	151,354 (6.0)	264,779 (7.3)
V	239,072 (1.8)	190,400 (2.7)	52 (0.0)	48,620 (1.3)
VI	799,854 (6.1)	716,626 (10.3)	26,069 (1.0)	57,159 (1.6)
Multi-use (V–VI)	1,038,926 (7.9)	907,026 (13.0)	26,121 (1.0)	105,779 (2.9)
Unknown	544,336 (4.1)	215,721 (3.1)	216,377 (8.6)	112,238 (3.1)
Indigenous	850,394 (6.5)	850,394 (12.2)	0 (0.0)	0 (0.0)
Other	56,543 (0.4)	32,551 (0.5)	17,909 (0.7)	6,083 (0.2)

Note: Numbers in parentheses are percentages of the region's total forest area.

2–4. Comparing Tables 2 and 3, it is clear that there has been a massive expansion of the protected area in the biome between 2000 and 2008, from almost 2 million km² to 3.6 million km², or 15–27 percent of the biome, well above the Convention on Biological Diversity target area of 10 percent (Schmitt and others 2009). For Latin America and the Caribbean and Africa, the protected area almost doubled in size, with notable expansions in types Ia, II, V, VI, and indigenous areas in Latin America and the Caribbean. The major gains in Africa and Asia come from the unknown classification. Unknown areas—which may signify an inclusion of new but incomplete protected area data to the WDPA database—increased in all regions.

Table 3: Pre-2000 Tropical Forest Protected (km² and %) by Protection Class and Region

Area	Biome	Latin America and the Caribbean	Africa	Asia
Protected Area	1,972,474 (15.0)	1,418,225 (20.3)	224,362 (8.9)	329,887 (9.1)
Ia	75,391 (0.6)	62,157 (0.9)	671 (0.0)	12,563 (0.3)
Ib	10,785 (0.1)	10,411 (0.1)	257 (0.0)	117 (0.0)
II	588,005 (4.5)	348,957 (5.0)	122,201 (4.8)	116,847 (3.2)
III	40,709 (0.3)	35,557 (0.5)	91 (0.0)	5,061 (0.1)
IV	116,814 (0.9)	15,594 (0.2)	18,949 (0.7)	82,271 (2.3)
Strict (I–IV)	831,704 (6.3)	472,676 (6.8)	142,169 (5.6)	216,859 (6.0)
V	144,595 (1.1)	113,150 (1.6)	52 (0.0)	31,393 (0.9)
VI	487,342 (3.7)	420,399 (6.0)	21,653 (0.9)	45,290 (1.2)
Multi-use (V–VI)	631,937 (4.8)	533,549 (7.6)	21,705 (0.9)	76,683 (2.1)
Unknown	119,808 (0.9)	30,405 (0.4)	54,088 (2.1)	35,315 (1.0)
Indigenous	359,914 (2.7)	359,914 (5.1)	0 (0.0)	0 (0.0)
Other	29,111 (0.2)	21,681 (0.3)	6,400 (0.3)	1,030 (0.0)

Note: Numbers in parentheses are percentages of the region's total forest area.

Table 4: Tropical Forest Protected (km² and %) by Protection Class and Region, 1990–2000

Area	Biome	Latin America and the Caribbean	Africa	Asia
Protected Area	807,704 (6.1)	631,591 (9.0)	46,574 (1.8)	129,539 (3.6)
Ia	19,222 (0.1)	17,892 (0.3)	0 (0.0)	1,330 (0.0)
Ib	10,525 (0.1)	10,411 (0.1)	0 (0.0)	114 (0.0)
II	200,036 (1.5)	102,365 (1.5)	34,617 (1.4)	63,054 (1.7)
III	16,144 (0.1)	14,315 (0.2)	0 (0.0)	1,829 (0.1)
IV	24,512 (0.2)	9,175 (0.1)	0 (0.0)	15,337 (0.4)
Strict (I–IV)	270,439 (2.1)	154,158 (2.2)	34,617 (1.4)	81,664 (2.2)
V	60,229 (0.5)	57,231 (0.8)	0 (0.0)	2,998 (0.1)
VI	195,355 (1.5)	170,830 (2.4)	4,042 (0.2)	20,483 (0.6)
Multi-use (V–VI)	255,584 (1.9)	228,061 (3.3)	4,042 (0.2)	23,481 (0.6)
Unknown	42,100 (0.3)	14,836 (0.2)	3,889 (0.2)	23,375 (0.6)
Indigenous	219,258 (1.7)	219,258 (3.1)	0 (0.0)	0 (0.0)
Other	20,323 (0.2)	15,278 (0.2)	4,026 (0.2)	1,019 (0.0)

Note: Numbers in parentheses are percentages of the region's total forest area.

Table 5. Forest and Fire Area (km²) and Crude Fire Rates per Region/Protection Group

Protection class	Forest pixels	Fire pixels	Fire rate*	Fire rate relative to mean unprotected*	Expected fire pixels at mean un-protected rate*	Avoided fire pixels at mean un-protected rate *
Latin America and the Caribbean						
Never	4,269,718	317,608	0.0744			
Strict (I–IV)	472,676	7,597	0.0161	−0.0583	35,161	27,564
Multi-use (V–VI)	533,549	16,245	0.0304	−0.0439	39,689	23,444
Unknown	30,405	646	0.0212	−0.0531	2,262	1,616
Indigenous	359,914	5,414	0.0150	−0.0593	26,773	21,359
Africa	Never	2,118,157	128,499	0.0607		
Strict (I–IV)	142,169	2,538	0.0179	−0.0428	8,625	6,087
Multi-use (V–VI)	21,705	654	0.0301	−0.0305	1,317	663
Unknown	54,088	3,393	0.0627	0.0021	3,281	−112
Asia						
Never	3,147,000	172,212	0.0547			
Strict (I–IV)	216,859	9,801	0.0452	−0.0095	11,867	2,066
Multi-use (V–VI)	76,683	2,810	0.0366	−0.0181	4,196	1,386
Unknown	35,315	495	0.0140	−0.0407	1,933	1,438

*This table compares aggregate mean fire rates between protected and unprotected areas and does not control for differences in deforestation pressure between protected and unprotected areas.

Comparing Tables 3 and 4, almost half (45 percent) of the pre-2000 protected area expansion in Latin America and the Caribbean happened between 1990 and 2000, though most of this is associated with multi-use and indigenous areas. In Africa there was little expansion (21 percent) of the protected area network during 1990–2000, and that expansion was limited to IUCN classes II, VI, and unknown. This small area will have implications in the interpretation of the following matching analyses for the African 1990–2000 treatment groups. For Asia, the 1990–2000 expansion accounts for almost 40 percent of the pre-2000 protected area network.

The number of observed tropical forest fire pixels and the tropical forest area for each region and protection group (pre-2000 areas only) are shown in Table 5. The last three columns show crude measures of the amount of avoided fire activity without accounting for the nonrandom location of the protected areas or the characteristics of the protected and non-protected areas. In all cases (except unknown protection in Africa), these tabulations show lower fire activity in protected versus unprotected areas, with differences as high as 5.9 percent for indigenous areas. Strict protection has lower fire rates than multi-use protection in Latin America and the Caribbean and Africa by 1.2–1.4 percent, whereas the converse is true in Asia, where strict protection appears quite ineffective compared to multi-use and unknown. Nonprotected rates are higher in Latin America and the Caribbean than in Africa and Asia (7.4, 6.1, and 5.5 percent, respectively), but protected versus nonprotected differentials in Latin America and the Caribbean exceed those in Africa and Asia (differences between protected and nonprotected are –5.3, –3.1, and –1.5 percent, respectively).

When this percentage reduction is related to the protected forest area, the result is an uncorrected measure of the number of avoided forest fire pixels due to protection (remember, fire activity cannot be directly translated to an estimate of area deforested), amounting to some 85,500 1-km pixels or 4.4 percent of the protected areas in the tropical forest biome. This naïve estimate of impact is modified when other factors affected deforestation are controlled (see Figure 4).

3.5. Pressure on protected areas

Some protected areas may be naturally protected because of their remoteness and inaccessibility, regardless of the level and effectiveness of designated protection. Examples of this de facto protection can be observed in the Amazon and Congo basins. Conversely, protected forest areas in densely populated and easily accessible regions—such as those in Ghana that are clearly visible as islands of intact forest—remain forested because of their designated status and enforced or *de jure* protection (Pfaff and others 2009; Joppa, Loarie, and Pimm 2008; Joppa and Pfaff 2009c). The application of the matching approach estimates the average effect of protection across each continent, but there is strong evidence to suggest that the effect will vary depending on the ease of access to the protected area (Pfaff and others 2009).

To assess this, a recent model of travel time to major cities in 2000 (Nelson 2008) was used as a measure of accessibility. (In the Latin American example in Figure 5, deep red areas are remote, and yellow areas are near cities.) Major cities are defined as having a population of 50,000 or more in 2000. Protected pixels that are easily accessible are assumed to face higher pressure for land cover conversion and require *de jure* protection; conversely, those that are remote face a much lower pressure of land cover change are assumed to have a degree of de facto protection.

As a first, crude estimate of the relationship between tropical forest fire activity and pressure, the fire activity (fire area/forest area) for the tropical forest biome is plotted against travel time for protected (for protected areas designated pre-2000 with any type of protection) and unprotected forest areas and the difference between the two, for the biome (Figure 6) and each continent (Figure 7). Again, these (unmatched) estimates are naïve: they do not correct for other determinants of deforestation pressure and make no correction

Figure 5: Accessibility to Cities

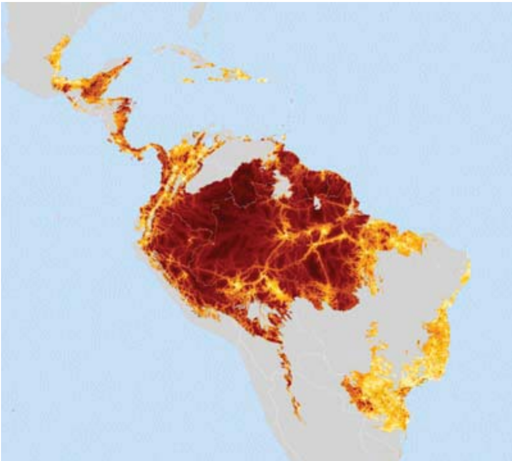
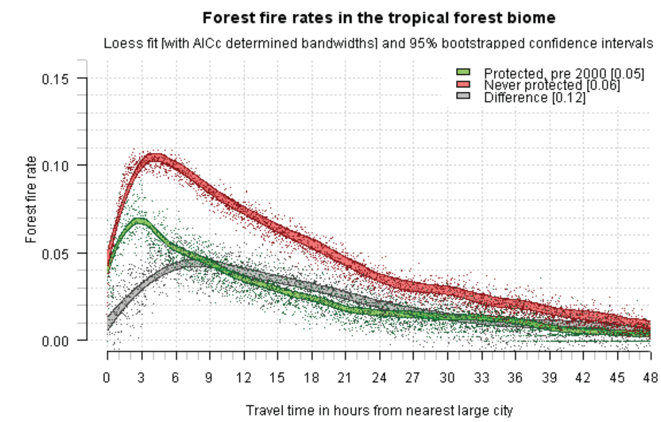


Figure 6: Crude Forest Fire Rate (fire area/forest area) against Travel Time for the Tropical Forest Biome (no controls for other variables)



for the bias in location of the protected areas or their environmental similarity or lack of it with unprotected areas.

The lines in Figures 6 and 7 show the 95 percent confidence limits around a best fitting loess curve[3] through the points. The best fit was determined via cross validation assessed by the Akaike Information Criterion. The confidence limits were derived from bootstrapping the loess fit with 1,000 replications.

The average fire rates across the biome are 0.0649 and 0.0255 for unprotected and protected areas, respectively (with a difference of 0.0393), but this varies considerably in both protected and unprotected areas, with more accessible regions having the expected higher fire rate and the greater difference between protected and unprotected. The rates are above average for travel times less than 12–15 hours, and the difference between fire rates in protected and unprotected areas becomes negligible at around 48 hours travel time.

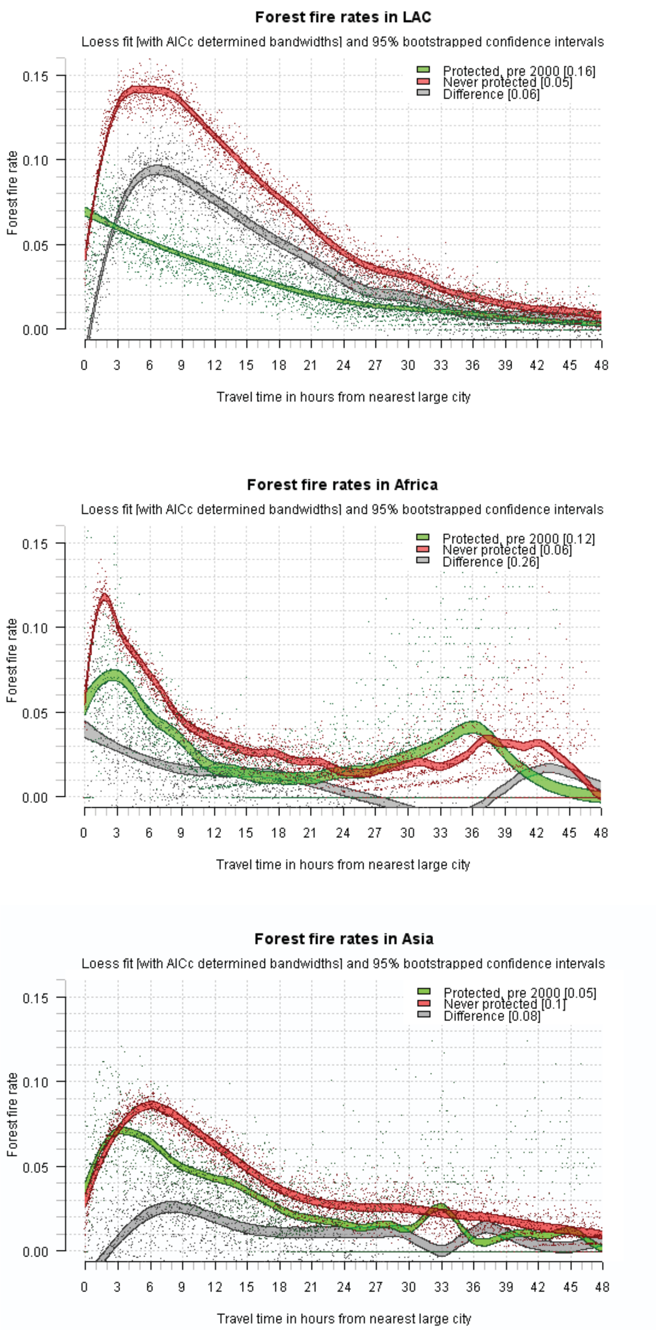
The same trend, although much more pronounced, is visible in Latin America and the Caribbean (Figure 7, top); the average rates across the region are 0.0744 and 0.0214 for unprotected and protected areas, respectively (with a difference of 0.0530). The rates are above average for travel times less than 18–21 hours. The greatest difference is in the 0–12-hour range, peaking at 6–7 hours.

Rates across Africa (Figure 7, middle) vary too, but the difference between protected and unprotected is only more than 2–3 percent in very accessible regions. The average rates across Africa are 0.0607 and 0.0302 for unprotected and protected areas, respectively (with a difference of 0.0304, 2 percent lower than Latin America and the Caribbean). The rates are above average for travel times of less than 6–9 hours, and the difference between fire rates in protected and unprotected areas becomes negligible at around 24 hours travel time. Fire activity peaks in very accessible areas (0–3 hours travel time).

The plot for Asia (Figure 7, bottom) shares characteristics with both Latin America and the Caribbean and Africa. The average rates across Asia are 0.05548 and 0.0399 for unprotected and protected areas, respectively (with a difference of 0.0149). The rates are above average for travel times less than 12–15 hours. Fire activity peaks in accessible areas (0–9 hours travel time).

These plots suggest that deforestation pressure, and the protective effect of protected areas, might differ systematically with remoteness from cities. Hence exact matching on travel time is used as a covariable in the model. This allows computation of treatment effects per travel time

Figure 7: Crude Forest Fire Rate (fire area/forest area) against Travel Time for Latin America and the Caribbean, Africa, and Asia (no controls for other variables)



Note: In all four cases the fire activity varies with accessibility, with peaks of activity in highly accessible regions and much lower rates in more distant forest areas. Rates in protected areas are consistently lower than in unprotected areas, with average differences ranging from 5.3 percent in Latin America and the Caribbean to 1.5 percent in Asia, but these differences can be as large as 9 percent in high-pressure areas of Latin America and the Caribbean (c.f. Figure 7, top, at the seven-hour mark).

zone, as well as the average treatment effect. Aggregation is to 15-minute zones, which allows for further aggregation, to compute fire rates per 1-hour zone, for example.

When the four protection classes (strict, multi-use, unknown, and indigenous) are combined across three continents, the result is 10 cohorts of control/treatment samples (ignoring the combinations for indigenous protection in Asia and Africa). Each cohort is used as input to the matching procedures described in chapter 2 (nearest neighbor matching based on Mahalanobis distance with/without calipers)—thus there are two analyses per cohort. A description of the other covariables that will be considered for their role as controlling factors, and the sampling procedure used to create the cohorts for matching, follows.

3.6. Environmental characteristics

In addition to the proxy of pressure for conversion (described in section 3.5), a suite of spatial data layers was collected to characterize the different environments within the biome.

Distance to road network. Roads provide quick and easy access to areas. In this case, they make forest areas accessible to small- and large-scale deforestation agents (Chomitz and Gray 1996).

A similar distance measure—distance to roads (Figure 8)—was created based on a vector road network extracted from the fifth edition of the Vector Smart Map Level 0 dataset (NIMA 2000). The primary source for the database is the 1:1 million scale Operational Navigation Chart series. The reference period is 1979–99 (Nelson, de Sherbinin, and Pozzi 2006).[4] Here red indicates proximity to roads; green indicates extreme remoteness.

Distance to major cities. The proximity of a patch of land to a potential market is a key explanatory variable for land use change (Barbier and Burgess 2001). The major problem is the identification of such markets from a dataset of populated places.

Figure 8: Distance to Roads

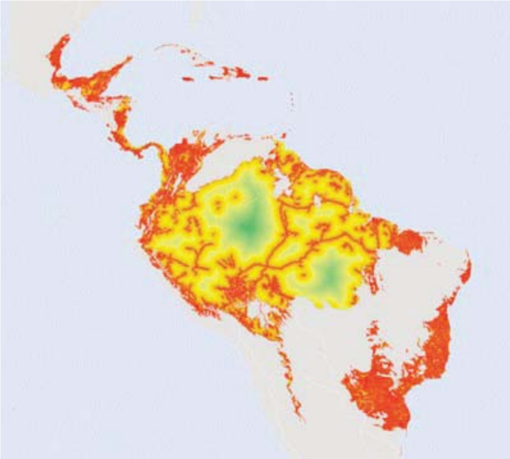
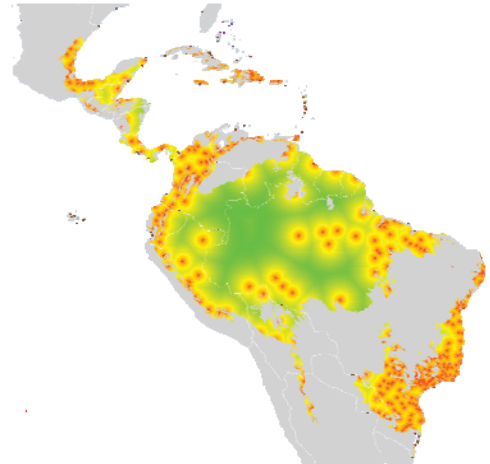


Figure 9: Distance to Major City



A similar distance measure—distance to major cities (Figure 9)—was created based on a point dataset of city centroids (CIESIN 2004). Following the definition of major cities in the travel time layer, the distance to the nearest city with an estimated population of at least 50,000 in 2000 was measured.

Terrain. Terrain is a factor for land use suitability. Mild slopes and lower elevations are likely to be more accessible, more productive, more valuable, and thus more attractive for conversion to agriculture. As well as having a direct relation to suitability, slope and elevation are proxies for physical soil properties, and elevation is a proxy for temperature.

Elevation (Figure 10) and slope (Figure 11) were derived from the Consortium for Spatial Information (CGIAR-CSI) version (Reuter, Nelson, and Jarvis 2007) of the 90-m resolution SRTM digital elevation model from NASA (Farr and Kobrick 2000). The CGIAR-CSI version of the data has filled in the data void areas with auxiliary digital elevation model data and topographically correct interpolation algorithms. The mean and variance of both slope and elevation were extracted at 1-km resolution, so each 1-km estimate is based on 100 or so elevation or slope values.

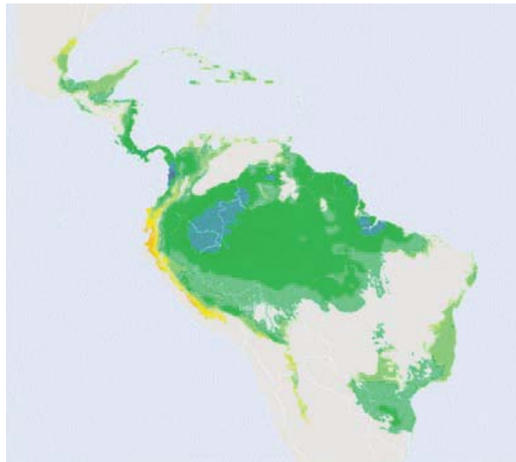
Rainfall. Rainfall is another factor for land use suitability. Areas of extremely high rainfall are unlikely to be converted to agriculture, and the associated cloud cover and humidity preclude the use of fire activity as a reliable measure of deforestation.

Rainfall estimates (Figure 12; lighter areas indicate low rainfall and darker areas high rainfall) were extracted from data provided by the Tropical Rainfall Monitoring Mission, specifically from the 3B42-TRMM-Adjusted Merged-Infrared Precipitation product (Huffman and others 1997). This dataset provides monthly estimates of rainfall rates at a ¼-degree resolution. These rates were converted to millimeters (mm) per month, then aggregated into annual

Figure 10: Elevation

Figure 11: Slope

Figure 12: Rainfall



rainfall estimates and finally into an estimate of the average annual rainfall in mm for 2000–08.

Country. Detailed country boundaries were extracted from the Global Administrative Areas database (Hijmans and others 2008). This information is used for exact matching to ensure that each control/treatment pair belongs to the same country.

Summary statistics for all the above variables in the tropical forest and protected tropical forest areas are shown in Table 6. In general, protected tropical forest areas are more remote, have lower fire incidence rates, and have higher elevation/slope than the tropical forests as a whole.

3.7. Sampling strategy and software

All data layers were stored as a table in a PostgreSQL database (version 8.3), amounting to some 19 million records, one record per 1-km pixel. The matching analysis was split into three geographic regions: Latin America and the Caribbean, Africa, and Asia. A list of points that would be used to form the control and treatment groups was extracted from the database for each region. The list of points for the treatment group was based on a 10 percent random sample of points.[5] The treatment points had to meet the following criteria:

- Were designated as protected pre-2000 based on protected area boundary information from the WDPA
- Classified as forest cover in 2000, based on the 11 land cover classes in GLC2000 that are forest or forest mosaic
- Met the 25 percent forest cover threshold from MODIS forest cover for 2000
- Fell into the relevant protection group (strict, multi-use, unknown, indigenous) for the cohort.

The two forest criteria reflect the conservative estimate of tropical forest area in 2000.

The corresponding control group was based on another random sample that was five times as large. The control points had to meet the following criteria:

- Had never been protected up to the end of 2008
- Classified as forest cover in 2000, based on the 11 land cover classes in GLC2000 that are forest or forest mosaic
- Met the 25 percent forest cover threshold from the MODIS forest cover for 2000.

The *never protected* area takes into account any form of recognized protection from the WDPA through the end of 2008 and including protected areas with information on their designation date. Those protected areas with boundary information

Table 6: Summary Statistics for Variables in Tropical Forest Areas

	Forest Area			Protected forest area		
Region/Variable	**Mean**	**St. Dev.**	**Median**	**Mean**	**St. Dev.**	**Median**
Biome						
Travel time (minutes)	1,353	1,401	817	1,678	1,528	1,181
Rainfall (mm)	2,135	712	2,051	2,102	621	2,026
Dist. to cities (km)	185	142	149	207	139	180
Dist. to roads (km)	47	73	14	72	94	28
Fire pixels (proportion)	0.053	0.224	0	0.026	0.158	0
Elevation (meters)	410	483	245	449	510	281
Slope (degree)	6.4	6.9	3	6.9	7.2	4
Latin America and the Caribbean						
Travel time (minutes)	1,772	1,564	1,323	1,913	1,596	1,481
Rainfall (mm)	2,197	571	2,186	2,099	499	2,060
Dist to cities (km)	226	150	200	235	141	208
Dist to roads (km)	76	87	44	94	101	54
Fire pixels (proportion)	0.052	0.223	0	0.022	0.145	0
Elevation (meters)	314	439	181	361	449	229
Slope (degree)	4.8	5.8	2	5.5	6.3	3
Africa						
Travel time (minutes)	646	563	486	889	652	736
Rainfall (mm)	1,569	408	1,533	1,632	482	1,587
Dist to cities (km)	145	92	131	166	97	160
Dist to roads (km)	9	11	5	13	12	9
Fire pixels (proportion)	0.057	0.231	0	0.030	0.170	0
Elevation (meters)	493	362	441	581	533	446
Slope (degree)	4.2	3.9	3	5.2	4.6	4
Asia						
Travel time (minutes)	1,039	1,180	558	1,201	1,354	685
Rainfall (mm)	2,410	885	2,365	2,436	905	2,438
Dist to cities (km)	132	129	85	117	107	87
Dist to roads (km)	18	28	7	19	29	9
Fire pixels (proportion)	0.052	0.223	0	0.040	0.195	0
Elevation (meters)	540	584	348	741	605	629
Slope (degree)	11.3	8.1	11	14.0	7.9	14

are simply masked out. Protected areas with no boundary information but with latitude/longitude point location and area information are treated as circles centered on their latitude/longitude coordinate, and those areas are also masked out.

The analysis is on 1-km resolution data. The outcome variable is a binary measure of fire presence/absence from 2000–08 as a proxy for deforestation events. The treatment variable is protected/nonprotected. The covariates represent factors that affect deforestation and the location of protected areas. The covariates are:

1. Average elevation
2. Average slope

3. Average rainfall (2000–08)
4. Distance to roads
5. Distance to cities
6. Country
7. Travel time to nearest city in 15-minute increments.

The slope, rainfall, and distance covariates are similar to those used in the Andam and coauthors (2008). The last two covariates were used as exact matches, to ensure that each control/treatment pair belonged to the same country and faced comparable pressure for land conversion as well as having similar environmental characteristics.

Several matching software libraries, for use in common statistical packages, are available (for example, Ho and others 2007; Sekhon 2007; Abadie and others 2004). The matching package (Sekhon 2007) (version 4.7-6) running in the open source statistical program R (version 2.8.1) on MS Windows XP SP3 was used.

Matching was performed on all cohorts of protected areas defined by geographic region and protection type, using the Mahalanobis distance metric, both with and without a 0.5SD caliper. Matching was performed with replacement and bias adjustment.

Notes

1. http://modis-fire.umd.edu/MOD14.asp.
2. http://modis-fire.umd.edu/MCD45A1.asp.
3. Loess is a form of local polynomial regression fitting that acts something like a moving average; the bandwidth is analogous to the width of the window used for the moving average.
4. The start date is debatable; the third edition of VMAP0, published 1997, also has a 20-year reference period—1974–94! The fifth edition was published in 2000, but given the minor changes throughout editions (1st in 1992, 2nd in 1995, 3rd/4th in 1997, and 5th in 2000), it is unlikely to have much post-1990 data.
5. Ten percent was chosen to comply with the memory and time limits that arise from matching on large datasets, based on personal communication with Lucas Joppa, Duke University. A control/treatment group of around 100,000 points and 7 covariables requires around 20 hours on a fast PC running Windows XP. Fortunately, most of the samples in the following analyses are smaller than this. Both samples were saved into a temporary table in PostgreSQL, and this table was then read directly into R (via an ODBC connection) for analysis in the matching package. This was repeated for each analysis, with results saved as text files.

Chapter 4
Results

4.1 Average estimate of avoided forest fires area due to protection

Table 7 shows the results of the matching analyses—the estimated avoided fire activity as a proportion of all pre-2000 protected areas—alongside the crude estimates from Table 5.[1] Table 8 repeats but uses the 1990–2000 protected areas as the treatment group.

Looking at the results for pre-2000 against never protected (Table 7) in the Latin America and the Caribbean region, the matched results for strict protection suggest a much lower level of avoided fire activity than the crude (uncorrected) estimates. Nonetheless, protected areas reduced the incidence of forest fires by 2.7–4.3 percentage points against a mean loss of 5.8 percent (Table 5) over 2000–08. Multi-use protected appears to be more effective than strict by approximately 2 percentage points, and this also translates into a larger area. "Unknown" is less effective, but the area is quite small. Indigenous areas are shown to reduce forest fire incidence by 16.3–16.5 percentage points, more than two and a half times as much as the crude estimates (5.9 percent) and twice as effective as any other group in the matched results, with a greater estimated avoided fire pixel area than strict, multi-use, and unknown combined. Strictly protected areas in Africa are only one-quarter as effective (about a 1 percentage point impact), as the uncorrected estimates would suggest. The estimated impacts for multi-use areas are not robust: a significant 3 percent for the Mahalonobis, but 0 percent (with wide

Table 7: Estimated Impact on Fire Incidence (cumulative over 2000–08) Comparing All Pre-2000 Protected Areas against Never Protected

		Mahalanobis			Mahalanobis with calipers		
Region/Protection	Crude	Estimate	[SE]	Pairs	Estimate	[SE]	Pairs
Latin America and the Caribbean							
Strict	−0.058	−0.027	[0.002]	46,015	−0.043	[0.001]	28,039
Multi-use	−0.044	−0.048	[0.003]	52,505	−0.064	[0.002]	29,993
Unknown	−0.053	−0.038	[0.010]	2,232	−0.023	[0.004]	511
Indigenous	−0.059	−0.165	[0.003]	36,166	−0.163	[0.003]	28,482
Africa							
Strict	−0.043	−0.010	[0.002]	13,507	−0.013	[0.001]	7,582
Multi-use	−0.031	−0.030	[0.008]	1,592	§ −0.001	[0.004]	715
Unknown	0.002	§ −0.010	[0.007]	4,980	§ 0.000	[0.004]	2,306
Asia							
Strict	−0.010	−0.017	[0.003]	20,683	−0.020	[0.002]	12,101
Multi-use	−0.018	−0.049	[0.006]	7,408	−0.043	[0.004]	4,319
Unknown	−0.041	§ −0.010	[0.005]	3,528	−0.044	[0.003]	1,072

§ All estimates significant at $p < 0.001$ except those marked with §.

Table 8: Estimated Impact on Fire Incidence (cumulative over 2000–08, not annualized) Comparing 1990–2000 Protected Areas against Never Protected

		Mahalanobis			Mahalanobis with calipers		
Region/Protection	**Crude**	**Estimate**	**[SE]**	**Pairs**	**Estimate**	**[SE]**	**Pairs**
Latin America and the Caribbean							
Strict	−0.065	−0.038	[0.003]	14,409	−0.077	[0.002]	5,749
Multi-use	−0.030	−0.062	[0.004]	21,972	−0.075	[0.003]	15,032
Unknown	−0.063	−0.026	[0.006]	889	too few points		80
Indigenous	−0.061	−0.128	[0.004]	21,813	−0.127	[0.003]	15,276
Africa							
Strict	−0.047	−0.022	[0.004]	2,730	−0.045	[0.004]	1,056
Multi-use	−0.060	too few points		153	too few points		12
Unknown	−0.059	−0.066	[0.008]	203	too few points		18
Asia							
Strict	−0.022	−0.029	[0.005]	7,355	−0.031	[0.002]	2,536
Multi-use	0.031	−0.067	[0.020]	1,832	−0.051	[0.008]	559
Unknown	−0.049	−0.023	[0.006]	2,349	−0.070	[0.004]	569

Note: The full set of *balance* metrics and other outputs from these matching analyses are available on request.

error bands) for the estimate with calipers. In Asia, strictly protected areas perform better than in the crude estimates, but multi-use is twice as effective as strict.

Table 8 estimates suggest that, with the exception of indigenous areas, protected areas designated between 1990 and 2000 offer better protection than pre-2000 protected areas as a whole, with improvements ranging from 1 to 3.5 percentage points, disregarding results with few matched pairs. In Latin America and the Caribbean, multi-use protected areas appear to be as effective or more effective than strict, but indigenous areas are almost twice as effective as any form of protection. In Asia, strictly protected areas perform better than in the crude estimates, but multi-use is twice as effective. In Africa, these recently established protected areas appear much more effective than the larger set considered in Table 7, with a robustly estimated impact of about 4.5 percentage points. There are too few points to estimate an impact for multi-use areas.

Table 9 summarizes the results. The range of estimates represents a robustness test—use of two kinds of matching procedures and a more or less broad scope of protected areas, each with advantages and disadvantages. The conclusion that protected areas are effective is seen to be robust.

At first glance, it may seem paradoxical that in some cases the mean reduction in fire incidence is greater than the mean incidence of fires—for instance, in the case of Latin American indigenous areas. This implies that the protected areas are located in regions of higher-than-average deforestation pressure. For further insight, the next section disaggregates impacts by remoteness—a strong correlate of pressure.

4.2. Disaggregated estimates

To assess the importance of location when estimating the effectiveness of protection, the fire rate in the matched treatment and control groups is disaggregated by travel time. This is done only for the pre-2000 treatment group, as the 1990–2000 group often has too few points to allow disaggregation.

The fire rate per travel time band was plotted and a loess curve was fitted through them using cross validation and Akaike's information criterion to

Table 9: Summary of Estimate Protected Area Impacts on Fire Incidence (%)

Area	Mean fire incidence	Mean reduction due to strict protected areas	Mean reduction due to multi-use protected areas	Mean reduction due to indigenous areas
Latin America and Caribbean	7.4	2.7–4.3	4.8–6.4	16.3–16.5
		3.8–7.7	*6.2–7.5*	*12.7–12.8*
Africa	6.1	1.0–1.3	(0.1)–3.0	Not applicable
		4.4–4.5	*Not calculated*	
Asia	5.5	1.7–2.0	4.3–5.9	Not applicable
		2.9–3.1	*6.7–5.1*	

Note: Italics indicate estimates for protected areas established between 1990 and 2000.

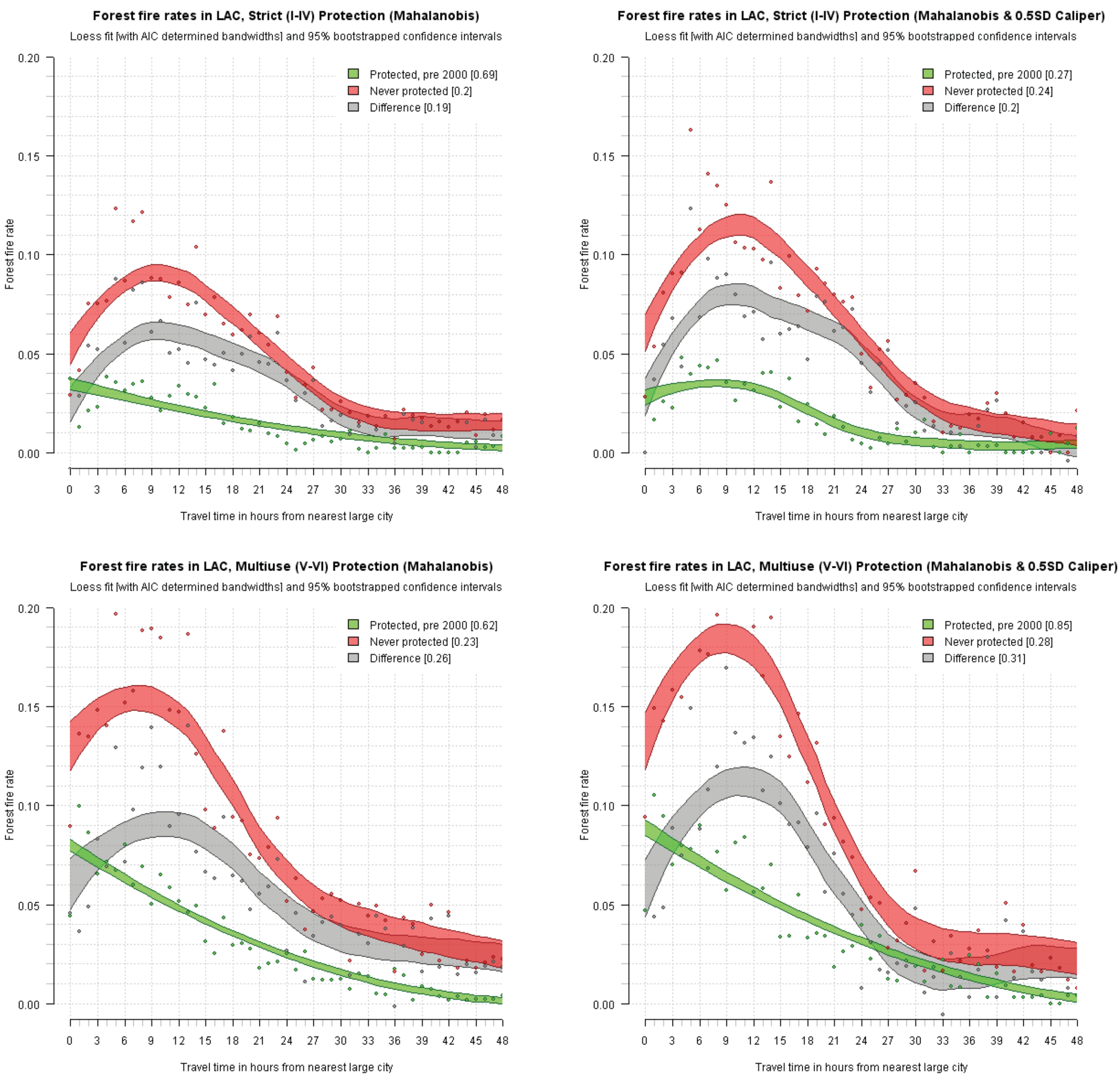
determine the best fitting smoothing factor or bandwidth. Furthermore, the loess estimator (1,000 repetitions) was bootstrapped to determine 95 percent confidence intervals around the curve. This was done for the fire rates from the matched control (never protected, red), and treatment data (protected pre-2000, green) and for the difference between the two (gray). This difference is essentially a disaggregated version of the estimates in Table 7 and provides an unbiased estimate of the avoided deforestation fires due to protection for different degrees of remoteness. The following figures (13, 14, and 15) show these confidence intervals around the loess curve as shaded polygons, as well as the points that they are fitted though. The results are reported for strict, multi-use, and indigenous areas for Latin America and the Caribbean, strict for Africa (there are insufficient pairs for multi-use to permit disaggregation), and strict and multi-use for Asia, although the number of pairs for multi-use in Asia is just acceptable. These estimates provide an unbiased and more realistic view than the naïve estimates in Figures 6 and 7.

Some strong regularities emerge. First, in almost all cases, fire activity inside protected areas declines with increasing remoteness. Although the same is generally true for areas outside protected areas, in some cases (strict and multi-use in Latin America and the Caribbean and strict in Asia) the outside rate and hence effectiveness of protection increases with remoteness reaching a maximum at around 9–12 hours. Second, except for strict protection in Africa, protected areas generally have significantly lower fire rates than comparable nonprotected areas. However, this differential declines as remoteness increases. Natural protection is often as effective as strict protection in remote areas—at least for the moment. Third, in both Latin America and the Caribbean and Asia, nonremote multi-use areas are located in areas of higher deforestation pressure than strict areas. For instance, at 1 hour from cities in Latin America and the Caribbean, the control for multi-use areas experience fire rates of about 16 percent whereas the controls for strict areas had fire rates of about 6 percent. Fourth, in Latin America and the Caribbean, fire rates are generally higher in multi-use than in strict protected areas, controlling for remoteness. Yet the absolute impact of multi-use areas is greater than that of strict areas. At 1–12 hours from cities, for instance, multi-use protected areas reduce fire rates by about 6–12 percentage points, and strict protected areas reduce rates by only about 5 or 8 percentage points. Indigenous areas also have a very high absolute impact.

In Asia, the pattern is different. Controlling for distance, deforestation rates are higher in strict than in multi-use protected areas. Strict protected areas appear to be ineffective at deterring fires in nonremote areas. Their effectiveness increases with remoteness, peaking at about 12 hours distance from the city and declining thereafter. In contrast, multi-use protected areas are most effective in regions proximate to population centers.

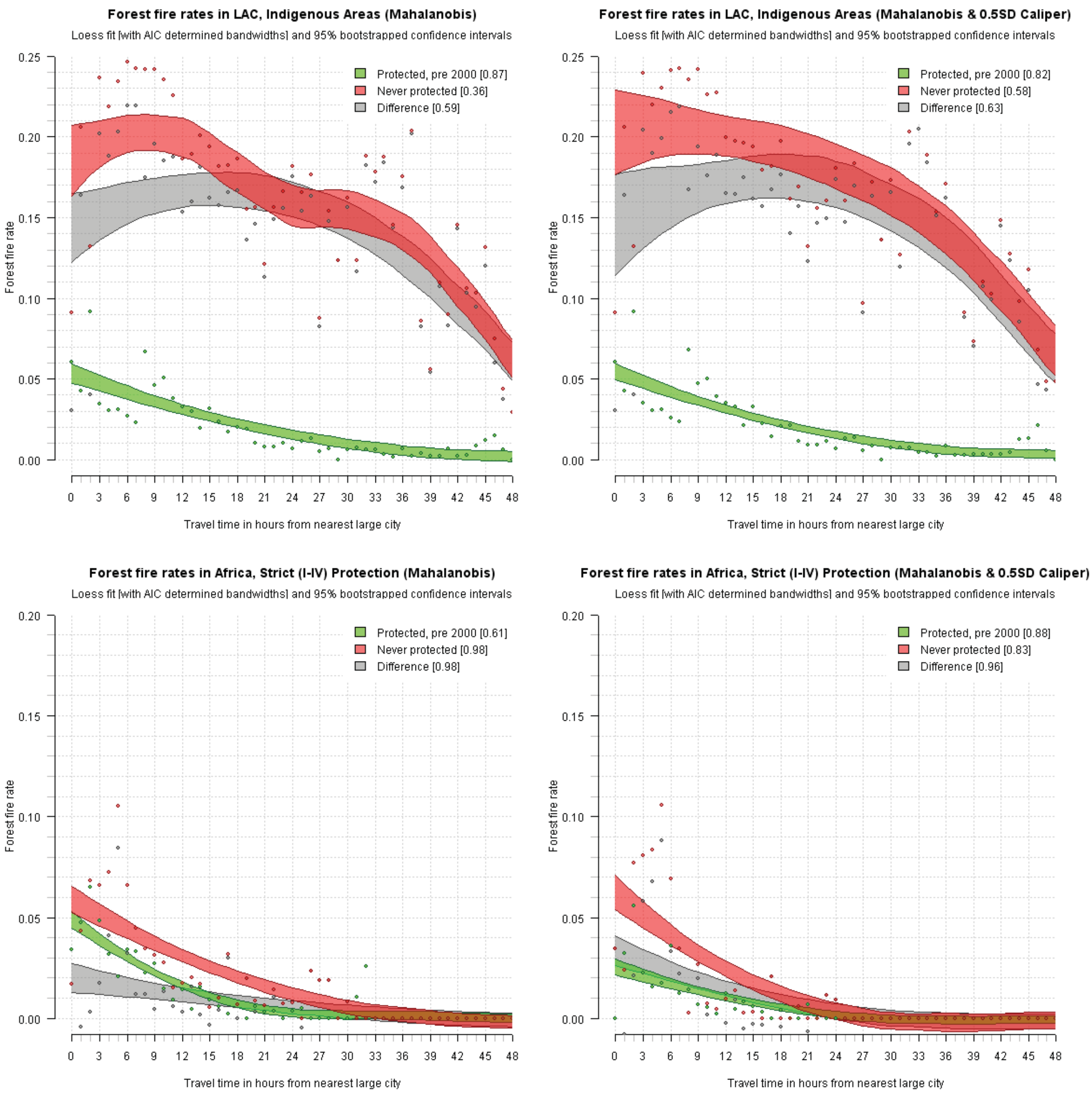
In Africa, strict protected areas appear to have a modest impact. Estimates of the impact of multi-use areas are limited by a small sample and are not robust.

Figure 13: Unbiased Estimated Fire Rates (red, never protected; green, protected; and grey, difference) for Tropical Forests in Latin America (with matching)



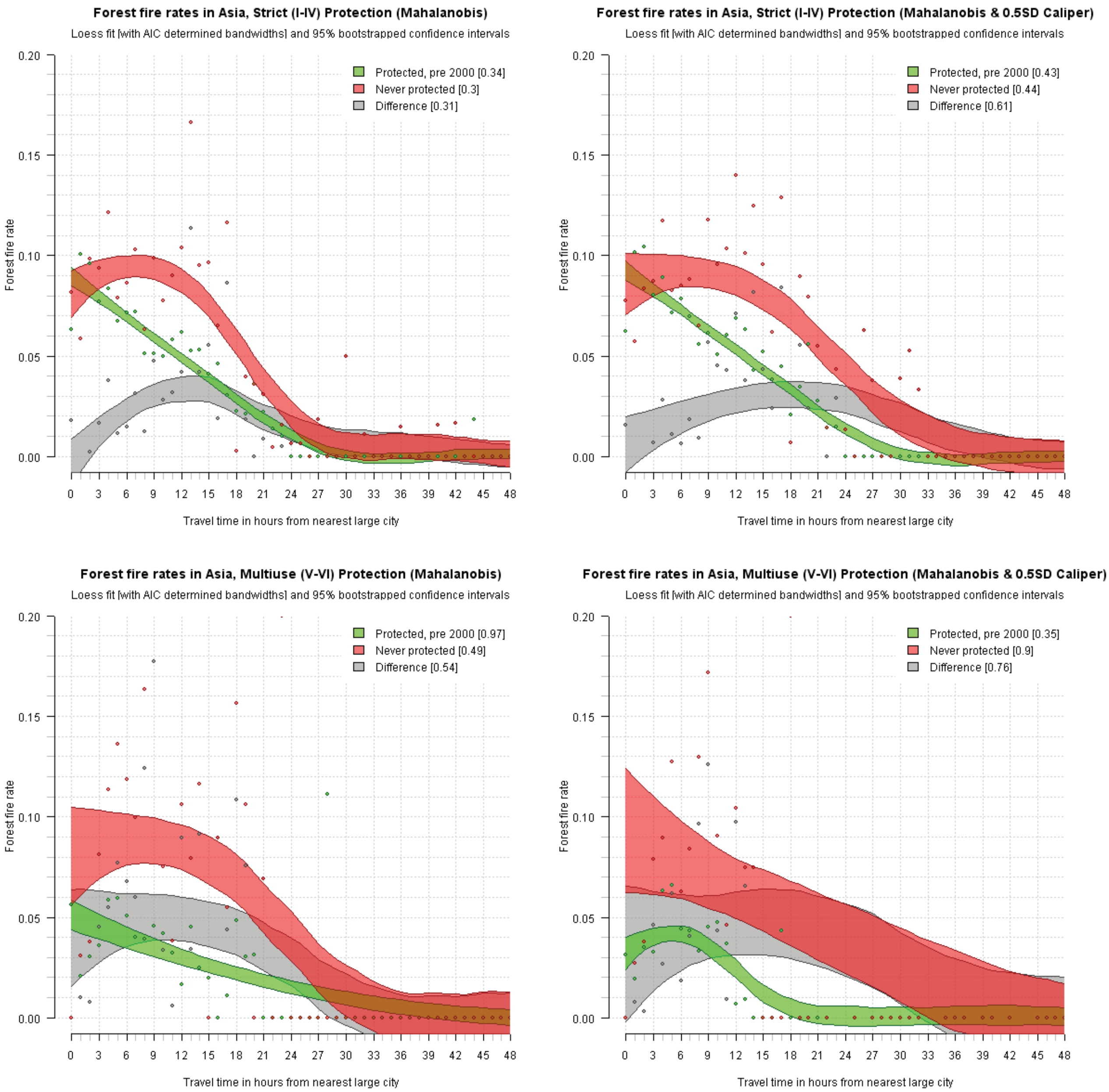
Note: Top – Strict protection in Latin America and the Caribbean, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right). Bottom – Multi-use protection in Africa, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right).

Figure 14: Unbiased Estimated Fire Rates (red, never protected; green, protected; and grey, difference) for Tropical Forests in Latin America and Africa (with matching)



Note: Top – Indigenous protection in Latin America and the Caribbean, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right). *Note the change in scale on y axes*. Bottom – Strict protection in Africa, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right).

Figure 15: Unbiased Estimated Fire Rates (red, never protected; green, protected; and grey, difference) for tropical forests in Asia (with matching)



Top – Strict protection, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right)
Bottom – Multi-use protection, with Mahalanobis matching (left) and Mahalanobis matching with calipers (right)

Note

1. In all cases the crude (comparing all protected pixels against all never protected pixels) and prematch rates (comparing an unmatched 10 percent sample of protected pixels against a similar proportion of never protected pixels) were

Chapter 5
Conclusions

This paper uses forest fires as a proxy for deforestation and associated carbon release. Using global data for the tropical forest biome, it is apparent that protected areas have a substantially and statistically significantly lower incidence of forest fires than nonprotected areas, even after controlling for terrain, climate, and remoteness. The protective effect is greatest in nonremote areas (for Latin America and Africa) and areas of intermediate remoteness (Asia). Very remote areas have low deforestation rates even if unprotected—at least for the moment.

Importantly, it is clear that mixed-use protected areas—where some degree of productive use is allowed—are generally as effective or more effective than strict protected areas, especially in less remote areas with greater pressure for agricultural conversion and timber extraction. In Latin America, where indigenous areas can be identified, they are found to have extremely large impacts on reducing deforestation—much larger than a naïve, uncontrolled comparison would suggest. These results suggest that mixed-use and indigenous areas are disproportionately located in areas of higher deforestation pressure. This is noteworthy, given increasing attention to indigenous land rights.

From a policy viewpoint, these findings suggest that some kinds of land use restrictions—variations of protection—can be effective contributors to biodiversity conservation and climate change mitigation goals. The results suggest that indigenous areas and multi-use protected areas can help accomplish these goals, also suggesting some compatibility between environmental goals (carbon storage and biodiversity conservation) and support for local livelihoods. Zoning for sustainable use may be more politically feasible and socially acceptable than designation of strict protection in areas of higher population density and less remoteness.

This analysis does not however attempt to measure "leakage"—the degree to which protection of one forest plot merely displaces conversion to another, unprotected plot. This is a more significant issue for carbon emissions than for biodiversity conservation, because the latter might be preferentially concerned with certain unique biodiversity locations whereas the former cares only about the density of carbon. Chomitz (2002) reviews theoretical and empirical studies of leakage and concludes that on both grounds leakage is far less than the 100 percent feared by critics. He points out that complementary policies (such as sponsoring crop intensification) could neutralize any leakage thought to arise from forest protection.

In addition, this analysis is unable to detect some kinds of forest degradation. Surreptitious removal of timber can result in biodiversity damage and lower carbon densities, but may not be detected through fire data.

Extension of this line of evaluation will be facilitated as better data become available. Improvements in remote sensing techniques and interpretation offer the prospect of more direct and precise measurement of deforestation and of forest carbon emissions. There is also a need to assemble, harmonize, and make public assessments of protected area management resources and practices in order to better understand the specific interventions that can contribute to reduced carbon emissions. Finally, there is a great need to complement land cover and land management measures with monitoring of human welfare and conditions in protected and unprotected forest areas.

It is important to stress that protected areas may be effective along other dimensions, even where there is little impact on current deforestation rates. This is especially true for protected areas established in remote regions with little current pressure for agricultural conversion. Such areas may already be effective in mitigating other threats, such as poaching of mammals and selective logging. Equally important, it is easier to reach consensus on the necessity and approach to protecting a forest before there are large economic pressures for conversion, often by people from outside the forest itself. A well-established protection regime may be better able to withstand pressures for unsustainable exploitation when the frontier arrives, as it eventually will in many currently remote places.

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