Disturbance and deforestation have profound ecological and socioeconomic effects on tropical forests, but their diffuse patterns are difficult to detect and quantify at regional scales. We expanded the Carnegie forest damage detection system to show that, between 1999 and 2005, disturbance and deforestation rates throughout the Peruvian Amazon averaged 632 square kilometers per year and 645 square kilometers per year, respectively. However, only 1 to 2% occurred within natural protected areas, indigenous territories contained only 11% of the forest disturbances and 9% of the deforestation, and recent forest concessions effectively protected against clear-cutting. Although the region shows recent increases in disturbance and deforestation rates and leakage into forests surrounding concession areas, land-use policy and remoteness are serving to protect the Peruvian Amazon.

Tropical forests play essential roles in ecological, climate, and biogeochemical processes and in the lives of human populations (1–4), but anthropogenic disturbances can disrupt forest structure, function, and composition (5–7). Because of its large, relatively contiguous area of primary rainforest, the Peruvian Amazon has major conservation value and is considered a priority in nearly all global biodiversity inventories (8). Despite the internationally recognized uniqueness and importance of Peruvian rainforest ecosystems, the impacts of human activities throughout the region remain poorly understood.

Increasing rates of large-scale forest damage in the neighboring Brazilian Amazon have been linked to modern road building and government policies supporting resource extraction and settlement (9, 10). Peru’s 661,000 km² of Amazon tropical forest are also subject to elevated human impacts that have not been well documented at the landscape level: The paving of the Inter-Oceanic Highway and the spreading road network throughout the Pucallpa region have brought migrants mostly from the Peruvian Andes, along with largely undocumented impacts on forest cover and structure. However, in recent years the Peruvian government has also established or extended large natural protected areas and indigenous territories in the Peruvian Amazon, and forest management legislation has placed 31% of its forests into permanent resource production status (table S9), 104,970 km² of which went into long-term, timber-producing, commercial concessions by 2005 (11). Small-scale studies have noted an increase in forest damage within some protected areas, mostly as a result of land conversion to agriculture and pasture near human settlements and river valleys (12) associated with proximity to roads, rural credit programs, and access to markets (13), as well as inadequate land-use planning and governance (14). However, a synoptic assessment of forest disturbance and deforestation has not been derived for Peruvian forests.

Large-scale assessments of forest disturbance in the Peruvian Amazon, typically diffuse and difficult to detect, require complex detection algorithms for the analysis of high-resolution satellite imagery (15, 16), but these methods are just now proving critical for land management, conservation analysis, and land-use policy assessments in tropical forest regions (17). We adapted a satellite-based forest disturbance detection system, originally designed for industrial-grade timber extraction monitoring in Brazil, to Peru’s generally smaller-scale forest disturbance regimes. We present an updated version of the Carnegie Landsat Analysis System (CLAS, http://asnerlab.stanford.edu) and applied it to a study area covering 79% of the Peruvian Amazon (I8) from 1999 to 2005. The core technology of the CLAS change-detection algorithm (15, 19, 20) was improved with optimized, automated versions of the atmospheric and haze correction and the water- and/or cloud-masking processes of the Monte Carlo unmixing (AutoMCU) approach (21). We also added an automated deforestation-detection component to provide an integrated analysis of both diffuse forest disturbance and clear-cutting. We used 101 Landsat 5 TM (Thematic Mapper) and Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) satellite images at a spatial resolution of 30 m by 30 m to derive annual incremental damage maps for most of the human-impacted, timber-producing regions—up to 24 images per year, with each nonoverlapping footprint covering 26,000 km². The satellite detection results were validated via a large field survey in the Pachitea and Ucayali watershed regions and regionally evaluated against available land use, land cover, and conservation maps.

We found that 632 ± 230 km² year⁻¹ and 645 ± 325 km² year⁻¹ of Peruvian Amazon forests were subjected to new forest disturbances and deforestation.
deforestation, respectively, between 1999 and 2005 (Fig. 1 and Table 1). Our forest disturbance values represent previously unaccounted human impacts throughout the region. The deforestation portion of our analysis is in agreement with Food and Agriculture Organization (FAO) deforestation estimates (table S1) but are lower than those reported by the Peruvian government (21–23).

Between 1999 and 2001, we found that 86% of all forest damage was concentrated in only two regions. In this period, the four satellite scenes covering the area around the Ucayali logging center of Pucallpa, and along the road network that emanates from it (Fig. 2), had the highest rates of forest disturbance and deforestation, contributing 64% of the total Peruvian Amazon damage. This was followed by the four satellite images covering the corridor centered in the eastern Madre de Dios capital city of Puerto Maldonado, which extended along the Inter-Oceanic Highway, showing 23% of the total damage (Fig. 1). We therefore concentrated on a five-satellite-scene subset for more detailed analyses from 1999 to 2005. Within this subset, forest damage rates remained relatively constant between 1999 and 2003, with average forest disturbances and deforestation rates of 340 ± 44 km² year⁻¹ and 469 ± 35 km² year⁻¹, respectively (table S7). Total forest damage rates then increased substantially between 2003 and 2005, particularly in the last year of our analysis, when disturbance and deforestation rates of 995 km² year⁻¹ and 1140 km² year⁻¹ were 2.9 and 2.4 times higher than the average for the initial 4 years, respectively (21). In particular, forest disturbance greatly increased east of Pucallpa in 2004 and west of the Iberia area of Madre de Dios in 2005, in regions where forest concessions had recently been granted.

Forest disturbances and deforestation were detected in other areas to the north near the Loreto capital of Iquitos, where early indications of small-scale damage were seen in 1999, but these increased in intensity over the years of analysis, spreading to nearby forest areas on both sides of the Amazon River (Fig. 1). The northern Loreto forests close to the Colombian border, which maintained relatively low damage rates between 1999 and 2002, mostly in and around native communities’ lands along rivers, showed only a slight increase in forest disturbances by 2004–05. The remote Napo moist forests of western Loreto showed very little damage between 1999 and 2002, which was concentrated on river edges (17). The concentration of forest damage along the Iquitos-to-Nauta road is a clear indication that road access could be the most important control over forest disturbance and deforestation rates in the remote Peruvian Amazon, where sheer distance and the intricate hydrologic network of the Amazon and Marañón rivers likely prevent high damage intensities and where timber extraction may be limited by current road access to markets (9).

Overall, only 2% of the forest disturbances and 1% of the deforestation detected in the entire study area occurred within the boundaries of natural protected areas. Furthermore, territories occupied by indigenous communities contained 11% and 9% of the total forest disturbance and deforestation, respectively (Table 2). These results show that these two forms of land-use allocation can provide effective protection against forest damage. However, a few exceptions occurring on indigenous community lands in the Oxapampa and Puerto Inca provinces and, to a lesser extent, in the El Sira natural protected area

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**Fig. 1.** Cumulative spatial distribution of forest disturbance (blue) and deforestation (red) in the Peruvian Amazon between 1999 and 2005. **(Left)** Light gray areas show the extent of native territories, and dark gray areas show natural protected areas. **(Right)** Orange lines show road distribution, magenta lines show 20-km road buffers, and green areas show the extent of forest concessions allocated by 2005; letters A and B denote the Pucallpa and Inter-Oceanic Highway regions, respectively. LOR indicates Loreto; SMT, San Martín; HUA, Huánuco; PAS, PASCO; UCA, Ucayali; and MAD, Madre de Dios.
appear to be related to proximity to roads, indicating that the protection afforded by their legal status may not be sufficient when the land is highly accessible to markets (6). In fact, an estimated 75% of the total Peruvian Amazon forest damage, including 66% of disturbances and 83% of deforestation, was detected within a 20-km distance from the nearest roads (Fig. 1). However, even within that 20-km buffer, forests within conservation units were more than four times better protected against deforestation than unprotected forests (21). Even after compensating for differences in the geographic extent of each land-use type, forest damage was about 18 and 10 times more likely in undesignated and indigenous territories, respectively, than in natural protected areas (21).

We also evaluated the impacts of recent timber harvest legislation on rates of forest disturbance and deforestation, before and after their enactment (11). Within all permanent production forests allocated to long-term concessions between 2002 and 2004, deforestation rates were up to two orders of magnitude smaller than forest disturbance resulting from the logging operations (table S5). However, outside the concession areas granted in 2004 in the remote northern Iquitos region, disturbance and deforestation rates increased by 468% and 304%, respectively. This leakage effect was also prevalent in the central Pucallpa logging region, where deforestation and forest disturbances outside concessions rose almost 400% to a combined rate of 1086 km² in 2005. Furthermore, the Madre de Dios logging region observed an increase within and outside concessions but still at relatively low rates. These results suggest that sanctioned forest extraction activities may be an effective deterrent against forest clear-cutting, but closer monitoring of neighboring nonconcession lands is critical to prevent leakage around concession forests. A time-series analysis of our data shows that the rate of clear-cutting previously disturbed forest was 1.8%, 7.2%, and 13.8% at 1, 3, and 5 years, respectively, after the initial disturbance (table S10). These relatively low values suggest that forest disturbances in the Peruvian Amazon are not simply a precursor to deforestation.

Our field validation studies showed that the CLAS methodology is precise and accurate in detecting forest disturbance and deforestation in the Peruvian Amazon. Our uncertainty was 10.5% for forest disturbances and 0.5% for deforestation (table S6). Atmospheric correction, cloud cover, and annualization errors in the satellite analyses were found to be very low and had been proven nearly negligible compared with manual audit uncertainty (15, 21).

The establishment of protected natural areas, the titling of native territories, and the sanctioning of selective logging activities have combined with the Peruvian Amazon’s traditional conservation allies—its remoteness and a complex hydrological network—to ensure a moderate level of success in the conservation of its forest eco-

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**Table 2. Percentage of detected forest disturbances and deforestation that falls within the boundaries of natural protected areas and indigenous territories of the Peruvian Amazon.** Geographic information system (GIS) spatial layers obtained from the Peru 2000 Forest Map, INRENA. Spatial layers of titled indigenous territories have their basis in unpublished data collected and prepared by the Instituto del Bien Común for an ongoing study, in which territories of 80% of titled indigenous groups had been mapped. Analysis also included Madre de Dios State Reserve (Indigenous Peoples in Voluntary Isolation) spatial layer from Centro de Información Forestal—INRENA, 2005.

<table>
<thead>
<tr>
<th>Year</th>
<th>Damage within natural protected areas (%)</th>
<th>Damage within indigenous territories (%)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>Deforested</td>
</tr>
<tr>
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<td>1</td>
</tr>
<tr>
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<tr>
<td>1999–2005</td>
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</tbody>
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**Fig. 2.** Two high-resolution examples of forest disturbance and deforestation detection from CLAS overlaid on satellite imagery, showing impacted forest (A) near Pucallpa (left), where damage is more extensive in nonprotected areas accessible from roads or rivers, and (B) near the remote area of Iquitos (right) with small damage (see fig. S1 for location).
Economic development of the forest sector, which employed 279,000 people nationally in 2001 (24), is essential for the well-being of human populations, but poorly monitored logging concessions, along with the challenges of uncontrolled road access, may hinder efforts to maintain ecological function and diversity in Peruvian rainforests in the future. Deforestation pressures, along with rising rates of forest disturbance, in many tropical countries are often at odds with increasing conservation efforts


turbance, in many tropical countries are often at odds with increasing conservation efforts. A balanced portfolio of forest use and protection, along with substantive law enforcement, could be used to sustain the services provided by tropical forests to society while also protecting those forests. Increased satellite monitoring of logging and other forest disturbances will thus be essential to conservation, management, and resource policy development efforts in Peru and other rainforest nations.

References and Notes

21. Materials and methods are available as supporting material on Science Online.

Supporting Online Material

www.sciencemag.org/cgi/content/full/1146324/DC1

Materials and Methods

Fig. S1

Tables S1 to S10

References

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