ARTICLE IN PRESS

ELSEVIER

Update

TRENDS in Ecology and Evolution Vol.xx No.xx Monthxxxx

Full text provided by www.sciencedirect.com

SCIENCE DIRECT

Research Focus

Detecting anthropogenic disturbance in tropical forests

Carlos A. Peres[1], Jos Barlow[1] and William F. Laurance[2]

[1]Centre for Ecology, Evolution and Conservation, School of Environmental Sciences, University of East Anglia, Norwich, UK, NR4 7TJ
[2]Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Republic of Panamá

Tropical forests are beleaguered by an array of threats driven by different scales of anthropogenic perturbations, which vary in the degree to which they can be detected by remote sensing. The extent of different patterns of cryptic disturbance often far exceeds the total area deforested, as shown by two recent studies on selective logging in Amazonia. Here, we discuss different forms of disturbance in Amazonian forests and question how much of the apparently intact forest in this region remains relatively undisturbed.

Detecting forest disturbance

Several mapping exercises have attempted to quantify the extent of relatively intact forest-wilderness regions remaining worldwide [1,2]. In tropical forests, most of this effort has been based on widely available imagery, such as Landsat, which can be used to quantify threats at large spatial scales.

Unfortunately, many anthropogenic perturbations are obscured by the rainforest canopy and subtle changes in canopy structure can be difficult, if not impossible, to detect or distinguish unambiguously from natural disturbance. In fact, current threats to tropical forests are a consequence of different scales of co-occurring structural and non-structural human disturbances that often operate synergistically [3]. These range from conspicuous land-cover changes, such as deforestation, forest fragmentation and slash-and-burn agriculture, to less apparent changes in canopy structure driven by selective logging and surface wildfires, to perturbations that are almost undetectable using remote-sensing techniques (Table 1). Such subtle patterns of disturbance include invasions by non-forest and alien species, the proliferation of exotic pathogens, defaunation from large vertebrate overhunting, other unsustainable forms of non-timber resource extraction, and many ecosystem-level responses to climatic change.

Despite the proliferation of cryptic disturbances, rainforests that appear to be structurally undisturbed on the basis of conventional remote sensing are often assumed to be intact and fully functional ecosystems. Here, we discuss some of these hidden threats while focusing primarily on the Brazilian Amazon, which is experiencing the highest absolute rate of forest loss worldwide (>26 230 km^2 during 2004 [4]). In addition, two recent remote-sensing studies [5,6] indicate that less-detectable patterns of human-induced perturbation to the forest biota have been underestimated.

Corresponding author: Peres, C.A. (C.Peres@uea.ac.uk).

Logging disturbance

In Brazilian Amazonia, the extent of canopy and subcanopy disturbance has been underestimated in earlier studies and often exceeds the total area deforested. Selective logging in tropical forests is a vast and spatially diffuse activity, involving the perforation and fracture of the canopy through large-tree thinning. It is difficult to distinguish with remote sensing against the background of natural treefall–gap dynamics. In a recent study, Asner and colleagues [5] used an automated, high-resolution remote-sensing technique (spectral mixture analysis; SMA [5]) to map logged areas from 1999 to 2002 in the top five timber-producing states of Brazilian Amazonia. Their analysis of 480 Landsat ETM+ scenes, which detected small logging gaps (<0.5 ha) and associated understorey disturbance caused along skid trails and logging decks, shows that an area of 12 075–19 823 km^2 was selectively logged each year. This represents an area of forest degradation that is 60–123% greater than that deforested in the same states over the same period [4]. Field validation of their study suggests a combined uncertainty of 11–14% in a logged area of >47 000 km^2. These estimates echo those of previous studies indicating that selective logging affects an area that is comparable or greater than that completely clear-cut every year [7,8].

In another recent study in a smaller forest area of southern Amazonia surrounded by the recent expansion of soybean agriculture, Souza, Jr and collaborators [6] field tested another image-processing technique that holds great promise as a tool to map logging and fire-induced canopy damage. The technique relies on a gap fraction index (the Normalized Difference Fraction Index, NDFI) that combines the green and non-photosynthetic vegetation, soil and shade fractions derived from SMA to enhance the detection of log landings and skid trails, the spatial signature of selective logging [9]. An assessment of their method based on aerial digital videography yielded a high level of mapping classification accuracy (94%) of forest canopy damage. In their study area of 30 000 km^2, 65% was classified as intact forest, 22% as non-forest and 13% as canopy areas that had been damaged by logging and burning.

Yet, these enhanced techniques might still underestimate logging disturbance. Furthermore, because of the rapid regrowth of logging gaps, logging-induced canopy disturbance can be detected with either Landsat

www.sciencedirect.com 0169-5347/$ - see front matter doi:10.1016/j.tree.2006.03.007

Table 1. Intrinsic detectability of different threats to tropical forests using conventional remote-sensing techniques[a]

Highly detectable	Marginally detectable[b]	Almost undetectable
Deforestation	Recent mechanized selective logging	Hunting and exploitation of animal products
Forest fragmentation	Surface fires	Harvest of most non-timber plant products
Recent slash-and-burn agriculture	A range of edge-effects	'Old' mechanized selective logging
Major canopy fires	'Old' slash-and-burn agriculture	Small-scale non-mechanized logging
Major highways	Small-scale gold mining	Narrow subcanopy roads (<6-m wide)
Conversion to tree monocultures	Unpaved secondary roads (6–20-m wide)	Understorey thinning and clear cutting
Hydroelectric dams and other forms of flood disturbance	Selective thinning of canopy trees	Invasions of exotic species
		Spread of pathogens
Large-scale mining		Changes in net primary productivity
		Community-wide shifts in plant species composition
		Other cryptic effects of climate change
		Most higher-order effects (e.g. dispersal and pollinator limitation owing to extinction of mutualists)

[a]Modified with permission from [22].

[b]Threats that can be detected, at least partially, using high-resolution methods or specialized detection algorithms that are expensive, technically challenging to implement and available only for limited or specific areas.

or SPOT images (20–30-m pixel size) for at most 24–42 months after logging [10,11] and these 'scars' can become undetectable to even higher-resolution IKONOS images (1-m pixel size) that are more expensive and cover smaller areas [12]. This severely obscures cumulative estimates of the total logging-disturbed area over longer time frames.

Surface fire disturbance

Logging disturbance often paves the way for surface fires, which have affected millions of hectares of Amazonian forests in recent years [7,13] with devastating effects on the flora and fauna (e.g. [14]). Although the frequency and coverage of ground fires are difficult to monitor remotely [15], they have increased markedly in recent years (Figure 1). A new report indicates that 27.5% of the 4.1 million km^2 of Brazilian Amazonia are within 10 km of forest 'hot pixels' mapped by AVHRR/NOAA sensors [16]. In addition to surface fires and logging, these areas are facing various patterns of incipient human pressure, including unpaved roads, goldmining, small-scale agriculture and hunting, all of which are ignored in conventional mapping of anthropogenic disturbance. The alarming propagation of fire disturbance under closed-canopy forest can also be seen by the almost tripling of fire pixels across the region, from 16 000 to 42 000 y^{-1} from 2000 to 2002 [16].

The extent to which logging and fire disturbance are underestimated by traditional land-cover mapping was recently shown for a southern Amazonian landscape of 4547 km^2 in the State of Mato Grosso [17]. A conventional forest threshold would indicate that only 27% of this area had been deforested by 1999. However, of the 73% of forest that apparently remained intact, 68% had already been logged, burned or heavily fragmented, indicating that 77% of the landscape had been altered and had entered a new disturbance regime.

Canopy versus subcanopy disturbance

Although the extent of structural changes in Amazonian forests can be monitored with an increasing degree of confidence as remote-sensing techniques improve (Figure 2), many more subtle threats that do not involve canopy fracture remain undetectable with even the most sophisticated, high-resolution sensors. Yet these threats also spell the difference between intact and degraded forests, and their extent can far exceed the total area affected by canopy disturbance. For example, an unknown but much larger proportion of Amazonia has already succumbed to non-timber forest resource depletion, such as game hunting, with profound consequences on ecosystem functioning. Persistently overhunted areas that no longer retain a full complement of harvest-sensitive vertebrate species comprise a large fraction of the forestlands that appear to be intact [18]. For example, only 1.2% of the Brazilian Amazon basin is both strictly protected on paper and reasonably inaccessible (>9 km from the nearest access point) to subsistence hunting and extraction of other valuable nontimber products [19]. Detecting the effects of game harvest and many other nonstructural forms of forest disturbance still relies heavily on hard-won field studies that are unavoidably limited in scale. For example, labor-intensive plot-based studies suggest that

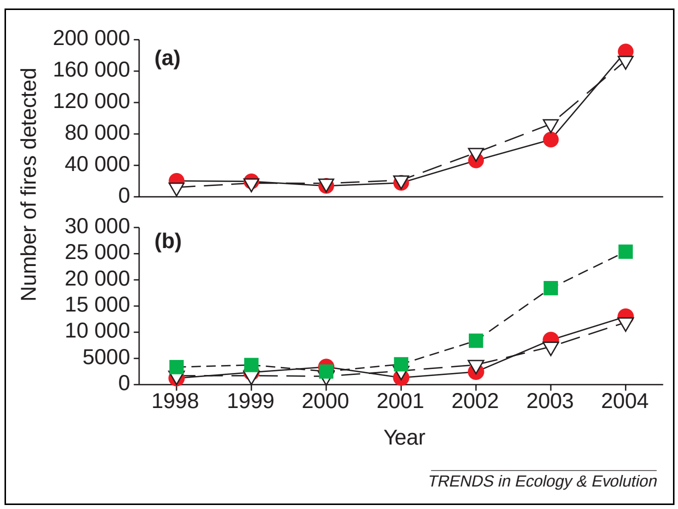

Figure 1. Proliferating fires. **(a)** The number of 'hot pixels' (1.1×1.1 km) detected by NOAA satellites in dense closed-canopy forest (open triangles) and more open-canopy forests (red circles) in Brazilian Amazonia have increased relentlessly over the past seven years. **(b)** Although many of these fire events occurred in non-forest and unprotected forest areas, there has been a similar increase in the number of surface fires detected in different types of indigenous forest reserves (green squares) and biological reserves managed by state (red circles) or federal (open triangles) government agencies. Only six months of data are shown for 1998. Modified with permission from [23].

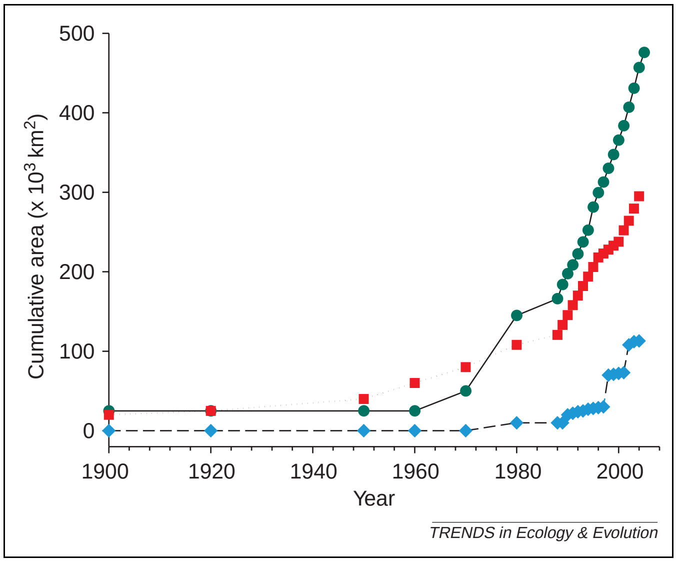

Figure 2. Total area affected by deforestation (red circles), selective logging (green squares) and surface fires (blue diamonds) throughout Brazilian Amazonia during the past century. These estimates are based on a range of sources, including the annual deforestation statistics made available by INPE [5]; a conservative estimate of basin-wide logging disturbance [5,8,16]; and a conservative estimate of the area affected by surface wildfires [7,17].

Amazonian forests have increased in productivity in recent decades [20], possibly in response to more CO_2 fertilization. However, other sources of disturbance can and should be accurately mapped using highly efficient remote sensors. For instance, a recently developed application of airborne imaging spectroscopy has been used to map changes in canopy nitrogen biogeochemistry caused by two plant invaders in Hawaiian montane forests [21].

Conclusions

As shown by Asner *et al.* [5] and Souza *et al.* [6], detecting cryptic forms of tropical forest degradation is a key challenge for researchers that will hopefully be overcome as new techniques and high-resolution imagery become more readily available as monitoring tools. Further progress, however, is yet to be made in quantifying the extent and intensity of less-visible forms of nonstructural habitat disturbance underneath the forest canopy. For now, we should not be misled into thinking that all is well when we see an apparently unperturbed forest from above: the subtle but sinister threats to tropical forests are far more extensive than we often realize.

Acknowledgements

We thank Carlos Souza, Jr for discussing this topic, and Greg Asner, Doug Sheil and an anonymous referee for comments on the article, which was written during a study leave granted by the Gordon and Betty Moore Foundation to C.A.P.

References

1 Bryant, D. *et al*. (1997) *The Last Frontier Forests: Ecosystems and Economies on the Edge*, World Resources Institute
2 Sanderson, E.W. *et al*. (2002) The human footprint and the last of the wild. *BioScience* 52, 891–904
3 Laurance, W.F. and C.A. Peres, eds *Emerging Threats to Tropical Forests*, University of Chicago Press (in press)
4 INPE (2005) *Monitoramento da Floresta Amazônica Brasileira por Satélite*, Brazilian Space Agency (http://www.obt.inpe.br/prodes/)
5 Asner, G.P. *et al*. (2005) Selective logging in the Brazilian Amazon. *Science* 310, 480–482
6 Souza, C.M., Jr. *et al*. (2005) Combining spectral and spatial information to map canopy damage from selective logging and forest fires. *Remote Sens. Environ.* 98, 329–343
7 Nepstad, D.C. *et al*. (1999) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398, 505–508
8 Matricardi, E.A.T. *et al.* (2001) *Multi-temporal Detection and Measurement of Selective Logging in the Brazilian Amazon using Landsat Data*, Document No. CGCEO/RA03-01, Michigan State University
9 De Wasseige, C. and Defourny, P. (2004) Remote sensing of selective logging impact for tropical forest management. *For. Ecol. Manage.* 188, 161–173
10 Souza, C.M., Jr, Multi-temporal analysis of degraded forests in the southern Brazilian Amazon. *Earth Interact.* (in press)
11 Asner, G.P. *et al*. (2004) Canopy damage and recovery after selective logging in Amazonia: field and satellite studies. *Ecol. Appl.* 14, S280–S298
12 Souza, C.M., Jr. and Roberts, D.A. (2005) Mapping forest degradation in the Amazon with Ikonos images. *Int. J. Remote Sens.* 26, 425–429
13 Cochrane, M.A. *et al*. (1999) Positive feedbacks in the fire dynamic of closed-canopy tropical forests. *Science* 284, 1832–1835
14 Barlow, J. and Peres, C.A. (2004) Ecological responses to El Niño-induced surface fires in central Amazonia: management implications for flammable tropical forests. *Phil. Trans. R. Soc. B* 359, 367–380
15 Cochrane, M.A. (2003) Fire science for rainforests. *Nature* 421, 913–919
16 Barreto, P. *et al.* (2005) *Human Pressure in the Brazilian Amazon*, Imazon (http://www.imazon.org.br/upload/ea_3e.pdf)
17 Cochrane, M.A. *et al*. (2004) Selective logging, forest fragmentation, and fire disturbance: implications of interaction and synergy. In *Working Forests in the Neotropics: Conservation through Sustainable Development* (Zarin, D.J. *et al*., eds), pp. 310–324, Columbia University Press
18 Peres, C.A. (2000) Effects of subsistence hunting on vertebrate community structure in Amazonian forests. *Conserv. Biol.* 14, 240–253
19 Peres, C.A. and Lake, I.R. (2003) Extent of nontimber resource extraction in tropical forests: accessibility to game vertebrates by hunters in the Amazon basin. *Conserv. Biol.* 17, 521–535
20 Lewis, S.L. *et al*. (2004) Concerted changes in tropical forest structure and dynamics: evidence from 50 South American long-term plots. *Phil. Trans. R. Soc. B.* 359, 421–436
21 Asner, G.P. and Vitousek, P.M. (2005) Remote analysis of biological invasion and biogeochemical change. *Proc. Natl. Acad. Sci. U. S. A.* 102, 4383–4386
22 Laurance, W.F. *et al.* Emerging threats to tropical forests: what we know and don't know. In *Emerging Threats to Tropical Forests* (Laurance, W.F. and Peres, C.A., eds), University of Chicago Press (in press)
23 INPE (2005) *Monitoramento de Queimadas*, Brazilian Space Agency (http://www.cptec.inpe.br/queimadas/)