Sustainability science from space: Quantifying forest disturbance and land-use dynamics in the Amazon

Lisa M. Curran*† and Simon N. Trigg‡

*School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511; and ‡Department of Geography, University of Maryland, College Park, MD 20742

Tropical deforestation is occurring at unprecedented rates, contributing as much as a fifth of annual global carbon emissions and imparting significant impacts on biodiversity, ecosystem function, livelihoods, and climate (1–3). Selective logging, removal of 1–25 canopy trees per hectare with associated levels of harvesting damage, is predicted to greatly exceed tropical deforestation in extent worldwide, but it remains largely unquantified (4). However, selective logging is highly heterogeneous not only in time and space but also in intensity of forest disturbance. Quantifying how forests are degraded by selective logging has been one of the major technical challenges in remote sensing applications to forest cover assessment. Widely available satellite imagery used to monitor global vegetation cover has a much coarser grain than that of forest disturbance created by logging. These sensor constraints are exacerbated by rapid vegetation growth that reduces indicator signals measured by optical sensors and, thus, previously prevented reliable and consistent detection of logging, especially over several years. In this issue of PNAS, Asner *et al.* (5) present innovative high-resolution remote sensing analyses that have generated the first automated, large-scale assessments capable of discriminating logged forest condition across vast areas of the Amazon.

Asner *et al.* (5) develop a standardized canopy gap fraction metric for both unlogged and logged forests that quantifies spatially explicit logging intensity and canopy damage systematically and with high accuracy across a range of forest structural conditions. Even this baseline measurement of canopy gap fraction in unlogged forest across a diversity of Amazonian regions is a major contribution to our understanding of natural forest gap dynamics. Through a 5-year time series, Asner *et al.* (5) track the fates of these logged areas and find that selective logging significantly increases the probability of deforestation, rendering current management schemes unsustainable. This work advances large-area remote sensing capabilities; it both demonstrates the urgent need to improve forest management and provides an essential analytical tool that could be applied to enhancing governance across the tropics.

Technological Advances

Although the need to map logging impacts has long been recognized, previous research focused on relatively small areas, using best available cloud-free Landsat satellite images spanning many years (e.g., ref. 6). These studies often applied site-specific definitions of forest degradation. Several creative approaches used proxy data to circumvent sensor limitations; nested-scale analyses with multisensor imagery were often essential to address research questions (e.g., refs. 6–9). Such detailed time series classifications both uncovered synergistic interactions and identified social and economic drivers of land-use change. Although these studies involved extensive field work and validation, they largely lacked automation and transferability. None found a rapid and systematic method to quantify canopy cover change over large areas and through time. MODIS Vegetation Continuous Fields (VCF) products are now available to estimate percentage tree cover globally at a spatial resolution of 500 m and regionally at 250 m (10), but these products are too coarse to estimate the detailed pattern and intensity of selective logging.

To address this problem, Asner *et al.*'s (4, 5) Carnegie Landsat Analysis System (CLAS) probabilistic spectral mixture model (AutoMCU) derives subpixel fractional vegetation cover within each 30 × 30 m Landsat pixel, enabling the assessment of logging damage and other fine-grain ecosystem change. Although the general method of linear mixture modeling is not new, Asner *et al.* (4, 5) have improved its application in several novel ways. Importantly, their earlier work demonstrated how the visible to near-infrared wavelengths (generally used to determine fractional cover) introduce large errors due to inherent spectral variability; they further showed that such errors could be minimized by incorporating information from mid-infrared wavelengths. Asner *et al.* (5) also applied tremendous rigor to training their algorithm: their spectral unmixing is driven by a phenomenally comprehensive array of 130,000 field and space-borne spectrometer observations collected over a 5-year period.

Asner *et al.* (5) achieve a major breakthrough by executing this spectral unmixing both over a large area and at such a high level of detail. Although many remote sensing methods are available, the vast majority have only been applied to and tested rigorously within the area covered by a single image. Indeed, the ability to remotely map land cover consistently over large areas across many images is increasingly recognized as one of the discipline's "key frontiers" (11). By developing the means to calculate gap fraction reliably and consistently over 480 images of the Brazilian Amazon (2,030,637 km^2), Asner *et al.* (4, 5) have provided an important milestone toward the elusive goal of assessing forest condition across the globe.

CLAS has the potential to be a powerful tool for the management of tropical forests. Despite two-thirds of all tropical forests designated as permanent forests for conservation or the sustainable production of timber, the International Timber Trade Organization concedes that <5% of these "permanent" forests meet basic standards of sound management (www.itto.or.jp/live/PageDisplayHandler?pageId=270). Selective logging is the major source of tropical forest degradation worldwide, currently occupying a total estimated area of >1,084,000 km^2, especially in Southeast Asia (e.g., 80% of the lowlands of Borneo), the Congo basin (≈40% of land area), and across the Amazon basin (refs. 4, 5, 7–9 and www.itto.or.jp/live/PageDisplayHandler?pageId=270.). Asner *et al.*'s (5) annual time series of observations provides the first large-scale, spatially explicit assessment of the synergistic effects of logging, forest degradation, and conversion, demonstrating widespread interactions of logging and road access with an astounding forest conversion rate within just 4 years. These results highlight unforeseen linkages among social-economic drivers of land use change precipitated by logging.

Conflict of interest statement: No conflicts declared.

See companion article on page 12947.

†To whom correspondence should be addressed. E-mail: lisa.curran@yale.edu.

Logging typically occurs in remote frontier lands often characterized by contested land-use claims (12). Governmental agencies lack sufficient local field capacity and financial resources to enforce legislation. Across the tropics, the majority of logging operations are conducted with little independent quantitative assessment of their effects on forest damage. In many regions, powerful interests, corruption, and instability prevent transparent assessments and accountability of the areas harvested and resources extracted (13, 14). Thus, logging revenues and regulatory compliance remain grossly undercollected and unrealized.

Forest Management and Governance

The broad application of Asner *et al.*'s (4, 5) CLAS could potentially revolutionize monitoring of logging operations and improve land management (15), allowing rapid regional monitoring systems to provide essential data for resource managers. Such a remote sensing application has long been sought by both governmental and nongovernmental organizations to help ensure accountability and responsible logging operations, to prevent fire, and to assess payments for carbon credits (15).

This new detailed regional remote sensing capability would allow current management efforts to be more proactive because it would shift the burden of proof from company reporting and detecting infractions to independent monitoring of logging practices. Full environmental cost accounting could be applied to assess taxes and fees, thereby providing financial incentives to reduce harvesting damage and increasing revenues by capturing timber rents (16). Deploying a rapid means to detect logging activities is particularly important in the vast Amazon basin (e.g., Brazil, Peru, and Bolivia), where infrastructural expansion provides new access to remote regions (3), and countries such as Indonesia, where >70% of timber volume exported is extracted outside of government-sanctioned logging concessions. Indonesia loses an estimated one billion U.S. dollars annually in tax revenue from illegal logging.

Drought and Fire Vulnerability

Synergistic interactions of logging, El Niño Southern Oscillation (ENSO)-associated drought, and fires have been well documented across the Brazilian Amazon and Indonesian Borneo (6, 7). Given the functional relationships among logging degradation, proximity to roads, and spread of fire, forests can be assessed with a potential susceptibility to drought and fire based on integrating Asner *et al.*'s (5) canopy gap fraction measurements with plant available water and the forest flammability model (e.g., RISQUE) developed by Nepstad *et al.* (7, 17). Areas deemed highly susceptible to fire can then be targeted for intensive management interventions.

Carbon Emissions and Carbon Credits

With the ability to assess the condition and fate of degraded forests, major uncertainties in carbon accounting models could be addressed, particularly carbon loss from forest degradation coupled with carbon sequestration from forest regrowth after logging (18). Refined estimates of biomass loss would be a boon to process-based models of fire emissions from both deforestation and forest degradation (2). In addition, a better understanding of carbon dynamics could shape carbon payment incentives for forest management.

Given that Asner *et al.* (5) determined that >32% of the logged areas in the Brazilian Amazon were deforested within 4 years, management efforts could focus on increasing the economic value of these degraded forests through payments for carbon retained and sequestered. Moreover, such payments could be targeted to smallholders both to enhance livelihoods and to provide financial incentives to maintain forest cover. Such independent fine-scale monitoring of carbon sources and sinks on degraded forests can be incorporated into local, regional, and even national payment schemes (19).

Asner *et al.* (4, 5) and their long-term collaborators have generated and validated an innovative computational method based on several years of iterations derived from intensive, field-based empirical studies. This work represents significant technological advances with widespread applications in interdisciplinary sustainability science. Provided that high-resolution remote sensing data are available, we foresee enhanced governance capabilities, refined regional carbon emission estimates, and better understanding of the complex drivers of deforestation from logging and road access.

This work by Asner *et al.* (5) illustrates the major synergistic value of collaborative research efforts, notably the Brazilian–U.S. Large-Scale Biosphere–Atmosphere Experiment in Amazônia coupled with the Brazilian Institute for Space Research PRODES program and National Aeronautics and Space Administration's Landsat 7 ETM+ Mission for generating imagery with broad societal applications. Given this tremendous breakthrough of CLAS applications for tropical forest management, the availability, distribution, and continuity of high-resolution satellite imagery missions should be a top priority. If business-as-usual approaches continue without creative combinations of technical advances and research applications to promote effective governance, tropical forests will continue to be logged and then rapidly deforested with major, yet largely unforeseen, local, regional, and global consequences.

1. Achard, F., Eva, H. D., Stibig, H. J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J. P. (2002) *Science* **297,** 999–1002.
2. van der Werf, G. R., Randerson, J. T., Collatz, G. J., Giglio, L., Kasibhatla, P. S., Arellano, A. F., Olsen, S. C. & Kasischke, E. S. (2004) *Science* **303,** 73–76.
3. Soares, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., Voll, E., McDonald, A., Lefebvre, P. & Schlesinger, P. (2006) *Nature* **440,** 520–523.
4. Asner, G. P., Broadbent, E. N., Oliveira, P. J. C., Keller, M., Knapp, D. E. & Silva, J. N. M. (2005) *Science* **310,** 480–482.
5. Asner, G. P., Broadbent, E. N., Oliveira, P. J. C., Keller, M., Knapp, D. E. & Silva, J. N. M. (2006) *Proc. Natl. Acad. Sci. USA* **103,** 12947–12950.
6. Siegert, F., Ruecker, G., Hinrichs, A. & Hoffmann, A. A. (2001) *Nature* **414,** 437–440.
7. Nepstad, D. C., Verissimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., *et al.* (1999) *Nature* **398,** 505–508.
8. Curran, L. M., Trigg, S. N., McDonald, A. K., Astiani, D., Hardiono, Y. M., Siregar, P., Caniago, I. & Kasischke, E. (2004) *Science* **303,** 1000–1003.
9. Laporte, N. T. & Lin, T. S. (2003) *Proc. Int. Geo. Rem. Sens.* **4,** 2565–2567.
10. Hansen, M. C., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C. & Sohlberg, R. A. (2003) *Earth Int.* **7,** 1–15.
11. McDermid, G. J., Franklin, S. E. & LeDrew, E. F. (2005) *Prog. Phys. Geo.* **29,** 449–474.
12. Nepstad, D., McGrath, D., Alencar, A., Barros, A. C., Carvalho, G., Santilli, M. & Diaz, M. D. V. (2002) *Science* **295,** 629.
13. Smith, J., Colan, V., Sabogal, C. & Snook, L. (2006) *For. Pol. & Econ.* **8,** 458–469.
14. Smith, J., Obidzinski, K., Subarudi & Suramenggala, I. (2003) *Int. For. Rev.* **5,** 293–302.
15. Fuller, D. O. (2006) *Soc. J. Trop. Geo.* **27,** 15–29.
16. Conrad, R. E., Gillis, M. & Mercer, D. E. (2005) *Env. Dev. Econ.* **10,** 689–709.
17. Nepstad, D., Lefebvre, P., Da Silva, U. L., Tomasella, J., Schlesinger, P., Solorzano, L., Moutinho, P., Ray, D. & Benito, J. G. (2004) *Global Change Biol.* **10,** 704–717.
18. Hirsch, A. I., Little, W. S., Houghton, R. A., Scott, N. A. & White, J. D. (2004) *Global Change Biol.* **10,** 908–924.
19. Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D., Curran, L. & Nobre, C. (2005) *Clim. Change* **71,** 267–276.