Mapping land use of tropical regions from space

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An alarming annual average deforestation rate of 22,500 km^2 in the Brazilian Amazon (1) from 2000 to 2005 has focused international attention on Brazil because of the destruction of this high-biodiversity biome (2) and its globally significant contribution to carbon emissions (3). Deforestation has already converted 680,000 km^2 of pristine forests to other land covers, accounting for 75% of Brazil's carbon emissions (1, 3). Satellite remote sensing is an indispensable tool for detecting and mapping deforestation over large areas in the region. For example, the Amazon Deforestation Monitoring Program (PRODES), conducted by the Brazilian National Institute for Space Research (INPE), has used Landsat images to map deforestation since 1988. Even though the extent and rate of deforestation are monitored, land-use changes after deforestation have not been systematically tracked. The few studies that have characterized and mapped land use after deforestation have done so only at local scales (4–6). Therefore, the amount and rates of land abandonment at regional scales are unknown. In this issue of PNAS, Morton *et al.* (7) present the results of a pioneering study that used remote sensing and field observations to characterize and map land use after deforestation in the Brazilian Amazon. Their work fills an important technological gap for understanding deforestation dynamics and land-use patterns in the Brazilian Amazon.

Morton *et al*. (7) mapped and followed individual deforestation clearings (>25 hectares) over time to track land-use history. Satellite-derived deforestation data, vegetation phenology information from MODIS (Moderate Resolution Imaging Spectroradiometer), and field observations were combined to classify all clearings as being pasture, cropland, or not in production. Their study was conducted in the state of Mato Grosso, the Amazon state that has most contributed to deforestation, from 2001 to 2004.

The approach developed by Morton *et al.* (7) represents a breakthrough in tropical remote-sensing studies in light of the difficulty in acquiring cloud-free optical imagery (8) for mapping tropical land cover. Additionally, no study that I am aware of has used the temporal domain of remote-sensing data to characterize land use in the Amazon region. To overcome the cloud limitation, these scientists took advantage of the high-frequency MODIS images that are acquired every 1–2 days (9). The advent of fast, inexpensive computer technology and advanced image-processing algorithms allowed Morton *et al.* to rapidly process a very large volume of remotely sensed data and assign land-use categories to each individual clearing after deforestation. The changing phenological temporal signature of deforestation clearings was used to determine whether each forest area had been converted to pasture or cropland or not put into production (7).

Morton *et al.* (7) point out that cropland is expanding at an unprecedented rate in Mato Grosso. The annual forest area directly converted to crop production ranged from 785 to 2,150 km^2 during 2001–2004, totaling 5,400 km^2 of the 33,200 km^2 in total area deforested in this period. The establishment of cropland directly from deforestation is rapid, with 90% of the converted area being put in production within 1 year. Although forest-to-pasture conversion was predominant in the region, Morton *et al.* detected a 12% decrease in forest-to-pasture conversion and a 10% increase in conversion of forest to cropland during 2002–2003. They also demonstrated that the pattern of cropland expansion has a strong correlation with the mean annual soybean price during 2001–2004. This finding implies that under favored economic conditions, continued cropland expansion in the Amazon is possible. Another important finding of the study was that clearings for cropland were, on average, more than twice the size of the clearings for pasture. Finally, the remote-sensing techniques developed by Morton *et al.* also allowed them to quantify other types of conversions to cropland. Planted pasture and natural grasslands converted to croplands accounted for 36% of the total cropland area, whereas conversion of *cerrado* savanna/woodland vegetation accounted for 30%. Their results warn of a rapid and very large-scale conversion process of forest to croplands in the Amazon region, a land-use pattern undocumented until now.

Cropland has become one of the major drivers of deforestation.

The results of Morton *et al.* (7) also confront those from previous works on deforestation dynamics and economic drivers of land use in the Brazilian Amazon. In other studies, cropland expansion has been found to be mostly associated with the conversion of previously deforested areas, not leading to new deforestation. This is not the case for the state of Mato Grosso. Morton *et al.* conclude that cropland has become one of the major drivers of deforestation and that the pattern of rapid forest conversion to cropland has the potential to spread to other parts of the Brazilian Amazon.

Potential Applications

Future research activities and land-use policy applications will be facilitated by the remote-sensing techniques developed by Morton *et al.* (7) for mapping and monitoring land use after deforestation.

Improving Carbon Flux Models. Morton *et al.* (7) highlight the importance of characterizing land use after deforestation to improve current carbon flux models. They point out that forest conversion to croplands is faster and removes a greater amount of aboveground biomass than forest-to-pasture conversion. Additionally, the methodology developed by Morton *et al.* also has the potential to detect land abandonment, pasture degradation, and forest recovery because these land-cover types have unique changing phenological temporal signatures, all of which are other sources of uncertainty in carbon flux models of the region (10).

Licensing, Command Control, and Law Enforcement. Land use after deforestation has not been tracked in federal and state deforestation monitoring programs. The remote-sensing techniques developed by Morton *et al.* (7) can be incorporated into the Rural Property Environmental Licensing system of the state of Mato Grosso (11). According to state environmental legislation, deforestation and land use within rural properties must be approved and authorized by the State Environmental Agency (12). Therefore, land-use information can be integrated into the state

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licensing system to facilitate monitoring, control, and environmental law enforcement. Although incorporation of this land-use mapping system into the Mato Grosso licensing system is technically viable, it requires capacity-building of the state environmental staff.

Agribusiness Market Regulation. Market regulation has the potential to help reduce deforestation in the Amazon region (13). Recently, the most important soybean buyers from the Amazon region have begun evaluating a proposal not to buy soybeans from newly deforested areas after 2006 (detailed information available at www.greenpeace.org.br/amazonia/?conteudo_id=2843&sub_campanha=0). The success of this market regulation program depends greatly on buyers' ability to monitor where the soybeans are coming from. The remote-sensing system developed by Morton *et al.* (7) has the potential to fulfill this demand.

Modeling Deforestation Dynamics. Understanding the drivers, rates, and patterns of deforestation is key for the successful implementation of models for predicting the future impacts of deforestation. Existing models have not incorporated the patterns and the potential impacts of cropland expansion on deforestation (14). The land-use patterns, rates and dynamics revealed by the work of Morton *et al.* (7) can greatly contribute to improving accuracy of such models.

An Integrated Forest Monitoring Program

Land use before and after deforestation is altering and converting the Amazon rainforests at unprecedented rates (Fig. 1). Cattle ranching is the most important land use after deforestation in the Amazon region (15), with smallholder agriculture, shifting cultivation, and gold mining making smaller contributions (16). Large-scale agriculture has recently become economically important in the region (13), contributing significantly to increased deforestation rates (7, 17). Other land-use activities that do not directly cause, but often precede, deforestation alter forest structure, composition, and biodiversity. Selective logging is the forest use with the highest impact (18) and facilitates the spread of anthropogenic agricultural fires into forested areas (19).

Understanding and quantifying the environmental impacts of land use in the Amazon region requires accurate mapping of all processes that cause forest degradation and deforestation, as well as land use after deforestation and land abandonment patterns (Fig. 1). The work of Morton *et al.* (7) provides the final technological approach necessary for building a fully integrated monitoring system for tracking total forest changes in tropical regions. For example, the remote-sensing community has recently developed tools for mapping and monitoring forest degradation caused by selective logging and forest fires (18, 20, 21) and land use after deforestation (7). The remote-sensing methodology developed by Morton *et al.* has the potential to track land abandonment and secondary growth changing phenological temporal signatures as well. If satellite data are available, a monitoring program to track all of these processes responsible for forest change can be implemented, contributing to a reduction in deforestation rates by providing ready information for market regulation, command and control, and forest law enforcement.

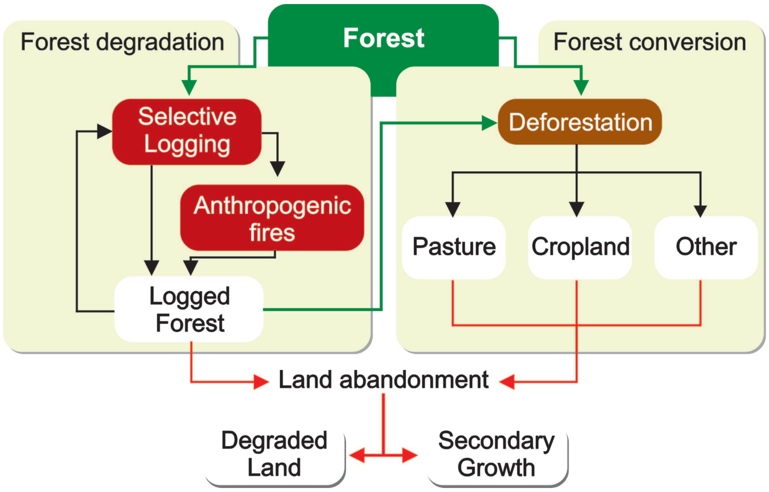

Fig. 1. Processes that lead to forest degradation and forest conversion in the Brazilian Amazon. Remote-sensing techniques were available for mapping deforestation and forest degradation, but until the work by Morton *et al.* (7), little was known about land use after deforestation in large areas of Amazon region. Land abandonment could also be monitored with this new remote-sensing methodology.

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