Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s

H. K. Gibbs[a,1], A. S. Ruesch[b], F. Achard[c], M. K. Clayton[d], P. Holmgren[e], N. Ramankutty[f], and J. A. Foley[g]

[a]Program on Food Security and the Environment, Stanford University, Stanford CA 94305; [b]College of the Environment, School of Forest Resources, University of Washington, WA 98195; [c]Global Forest Resource Monitoring Project (TREES-3), Institute for Environment and Sustainability, Joint Research Centre of the European Commission, I-21027 Ispra (VA), Italy; [d]Department of Plant Pathology, Department of Statistics, University of Wisconsin, Madison, WI 53506; [e]Environment, Climate Change and Bioenergy Division, United Nations Food and Agricultural Organization, Rome 00100, Italy; [f]Department of Geography and Earth System Science Program, McGill University, Montreal, QC, Canada H3A 2K6; and [g]Institute on the Environment, University of Minnesota, St. Paul, MN 55108

Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved July 30, 2010 (received for review September 22, 2009)

Global demand for agricultural products such as food, feed, and fuel is now a major driver of cropland and pasture expansion across much of the developing world. Whether these new agricultural lands replace forests, degraded forests, or grasslands greatly influences the environmental consequences of expansion. Although the general pattern is known, there still is no definitive quantification of these land-cover changes. Here we analyze the rich, pan-tropical database of classified Landsat scenes created by the Food and Agricultural Organization of the United Nations to examine pathways of agricultural expansion across the major tropical forest regions in the 1980s and 1990s and use this information to highlight the future land conversions that probably will be needed to meet mounting demand for agricultural products. Across the tropics, we find that between 1980 and 2000 more than 55% of new agricultural land came at the expense of intact forests, and another 28% came from disturbed forests. This study underscores the potential consequences of unabated agricultural expansion for forest conservation and carbon emissions.

deforestation | expansion pathways | cropland | biofuels | carbon emissions

Global demand for food, feed, and fuel is increasing at unprecedented rates, but the agricultural land base needed for production is shrinking in many parts of the world (1–3). Population increases and rapidly rising meat consumption were forecasted to increase global agricultural demands dramatically (3, 4), even before the spike in the use of crop-based biofuels.

This situation raises the question: How will the increasing demand for agricultural products be met? Increases in crop yield will be a critical component in meeting these needs, but the projected ∼1–2% annual increases probably will not be enough to match the rapidly mounting demand for agricultural commodities (5). Some studies consider these projected yield increases overly optimistic (6) and expect they will decline over the next 10 y to less than 1% per y in some regions (7). Even with yield increases and intensification, we will see net expansion in agricultural area (8).

Consequently, much of the world is looking toward the remaining areas of arable land in the tropics to meet increasing agricultural demands (2, 4, 9–11). Lower production costs and fewer environmental regulations have helped forest-rich tropical countries such as Brazil, Indonesia, and Malaysia respond quickly to increased demand for crops such as sugarcane, soybeans, and oil palm (12–14). Indeed, the expansion of the global agricultural land area during the 1980s and 1990s occurred primarily in developing countries where total agricultural land (croplands, pastures, and temporary agriculture) increased by 629 million ha while developed countries lost 335 million ha (4, 14). For example, soybeans now cover more than 21 million ha in Brazil, up from just 13 million ha at the turn of the century (14). Similarly, Indonesia's oil palm production nearly tripled during the 1990s, with the harvested area expanding from 2 million ha in 2000 to 5 million ha in 2008 (14, 15). Brazil, Indonesia, and Malaysia combined now produce more than 40% of the world's sugarcane, soybeans, and oil palm (14), and this proportion is expected to increase.

Total cultivated land area undoubtedly will expand across the tropics, and some estimate that as many as 10 billion new ha of agricultural land will be needed to sustain global demands by 2050, more than doubling the current agricultural land base (3, 4, 14). Demands for animal fodder and biofuels alone have been projected to drive increases in soy and sugarcane acreage in Brazil from 28 million ha today to 88–128 million ha by 2020 (16). Similarly, oil palm estates in Indonesia are estimated to grow from 6.5 million ha to 16.5–26 million ha during this period (16).

The environmental impacts of this unprecedented expansion of tropical croplands and pastures will vary widely, depending on the types of land being cleared and cultivated. Agricultural expansion is a major driver of tropical deforestation (17–20), but not all expansion results in the loss of intact forests: shrublands, pasture, logged or regrowing forests, degraded land, and shifting cultivation fields are all sources for new permanent agriculture (21–23). It is critical to understand the geographic and temporal differences in expansion pathways to quantify the impacts on all ecosystems services, including carbon storage, wildlife habitat, and watershed benefits.

Scientific descriptions of these expanding agricultural lands—and whether they arise from new deforestation or from previously cleared lands—are surprisingly absent and remain largely undocumented for the tropics as a whole. Progress in environmental governance and policy decisions (e.g., domestic and international standards for renewable fuel) is hindered by sparse information on land sources for newly expanded croplands. Indeed, debate continues to mount about the landscape origins of global agricultural commodities such as oil palm, sugarcane, and soybeans. Agroindustrialists and some scientists suggest that expansion is occurring largely on degraded or previously cleared land (23–25), but others posit that agriculture is expanding into rainforests (22, 26–28). This debate became even more pressing with the surge in the demand for biofuel, because recent studies have argued that expansion of biofuel crops into rainforests may substantially increase rather than decrease net carbon emissions (29–31).

Most studies have focused on net expansion in agricultural area, and those that identify land sources often are limited to local and regional scales. For example, Morton et al. (21) tracked the origins of expanding soybean fields in Brazil using a combination of remote sensing and field verification in the state of Mato Grosso along the Amazon basin's agricultural frontier. Similarly, Brown et al. (23) examined soy expansion in a portion of Rondônia, Brazil. Brink and Eva (32) used a sample of Landsat imagery to quantify land-cover dynamics across sub-Saharan Africa between 1975 and 2000. Others have postulated land sources from the United Nations Food and Agricultural Organization's (FAO) national-level agriculture and forestry statistics for broad regions (22, 30), but these data are highly aggregated, have been described as unreliable (33), and do not provide the spatially detailed information

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Author contributions: H.K.G., N.R., and J.A.F. designed research; H.K.G. and A.S.R. performed research; H.K.G., F.A., P.H., N.R., and J.A.F. contributed new reagents/analytic tools; H.K.G., A.S.R., F.A., and M.K.C. analyzed data; and H.K.G., A.S.R., F.A., M.K.C., and J.A.F. wrote the paper.

The authors declare no conflict of interest.

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This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: hgibbs@stanford.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.0910275107/-/DCSupplemental.

needed for an accurate identification of land sources for new agricultural landscapes.

To describe the pathways of agricultural expansion across the tropics systematically, we analyzed a library of satellite-based, high-resolution land-cover maps and change statistics for the 1980s and 1990s also compiled by the FAO (Fig. 1). This remotely sensed database is distinct from the FAO country statistics and offers dramatic improvements over other information sources.

The FAO conducted a statistical survey of tropical land cover, consisting of 117 sampling units across the tropics: 47 in Africa, 30 in Asia, and 40 in Latin America (34). Each sampling unit was comprised of three separate Landsat satellite images acquired in approximately 1980, 1990, and 2000 and statistically standardized to those years. The survey includes all tropical forest types in wet, moist, and dry conditions and covers 63% of the total tropics and 87% of tropical forests (34, 35). Nonforest tropical areas (e.g., deserts) were excluded.

Unlike most satellite-based studies that identify only locations of land-cover conversions, the interdependent visual method of detecting change used by the FAO tracks land parcel transitions from one land-cover class to another. This method involves manual interpretation of both images (historical and recent) at the same time, reducing errors associated with change detection (34) and offering major advantages over single-period analysis or compilations of different sources of imagery (17, 33, 35, 36). Typically such detailed imagery processing is reserved for a single Landsat scene or small areas; by contrast, the FAO database provides a major advance by combining high-resolution analysis with a pan-tropical scale over a 20-y period. The resulting library of images provides the only detailed and reliable information about land-cover transition spanning the tropical forest belt for this time period.

Here we analyze this rich satellite library to explore the pathways of agricultural expansion across the tropics during the 1980s and 1990s. We organized the tropical belt into seven broad regions with similar trends in land use (20). For each region we map and document the sources for newly expanded agricultural land and tree plantations and test for changes in expansion pathways between the decades at each sampling location using paired t tests. We use weighted averages to aggregate the results from each Landsat scene up to the regional level.

We consider the expansion of agricultural land (permanent croplands and pastures) into intact forests (open and closed forests), disturbed forests (fragmented forests, e.g., those affected by long-fallow shifting cultivation, logging, and fuel wood collection), shrublands (cerrado, savannas, woodlands, shrublands, and grasslands) and tree-plantation crops (Table 1). We also consider the expansion of tree-plantation crops into the same land sources in Southeast Asia, the only region with substantial expansion of plantation crops during 1980–2000.

We refer to combined pasture and cropland as "agricultural land." However, we also describe separate cropland and pasture area trends using FAO national statistics (14). These statistics are of dubious accuracy for some regions but remain the only consistent source of information available across the tropics. The data describe new agricultural expansion occurring within each decade and do not address expansion before 1980 or after 2000.

Results

Sources for Newly Expanded Agricultural Lands. Across the tropical regions, the total net increase in agricultural area was more than 100 million ha during the 1980s and 1990s (14). Cropland expansion was faster in the 1980s than in the 1990s, whereas pasture showed the opposite trend (14). Crop types were highly diverse throughout the tropics, but rice, maize, soybeans, and oil palm exhibited the most dramatic increases over these two decades, and the area devoted to millet, cassava, groundnuts, and beans remained steady (14).

Our results reveal that, overall, more than 55% of this new agricultural land came from intact forests (Fig. 2). This finding confirms that agricultural expansion did not arise largely from previously cleared land and indeed has been a major driver of deforestation and the associated carbon emissions (31). An additional 28% of new agricultural land came from disturbed forests that previously had been affected by shifting cultivation, logging, fuel wood collection, or other forms of gradual degradation (Fig. 2). Shrubland conversion provided most of the remaining 8% of expansion.

The sources for new agricultural land varied greatly among the major tropical regions, depending largely on the dominant type of ecosystem. For example, shrublands were substantial sources of new cropland in South America and East Africa. Disturbed forests were most frequently converted in the forest-poor areas of the tropics, particularly West Africa and South Asia, where most of the intact forests had been cleared many years ago. However, expansion in forest-rich regions of Latin America, Central Africa, and Southeast Asia relied predominately on clearing intact forests for new agricultural land.

Intact forests had become a more dominant source of new agricultural land by 2000. For instance, the relative amount of agricultural expansion from clearing of intact forest increased by 6% between the 1980s and 1990s, whereas clearing of disturbed forest and shrubland decreased by 4% and 2% respectively (Table S1). Thus, if these trends continue, we can expect even larger areas of intact forest to be felled for new crop and pasturelands.

Latin America. The greatest expansion of agricultural land in Latin America occurred for cattle pastures, which increased by ~35 million ha in South America and ~7 million ha in Central America (14). Cropland areas increased by ~5 million ha in South America between 1980 and 2000, more than double the increase in Central America. Sugarcane and soybeans are responsible for the majority of the increase in South America, whereas there were few changes in crop types across maize-dominated Central America (14).

Most new agricultural land was established from intact and disturbed forests in Latin America, but strong geographic variation exists (Fig. 3). For example, although forest conversion dominated in the dense humid rainforest regions, shrubland (i.e., cerrado) became increasingly important in more sparsely forested areas. Eastern Pará and Northern Tocantins in the Amazon basin converted notably more disturbed forests and shrublands than did other Brazilian states. Conversely, dramatic increases in soybeans and pasture have driven the relatively higher rate of intact forest clearing in Mato Grosso and Rondônia along the "arc of deforestation" in southeastern Brazil. In fact, soy is the principle crop in this deforestation hotspot, whereas a mixture of maize, cassava, rice, and sugarcane dominate throughout the rest of South America (37). Moreover,

Table 1. Definitions of potential land sources for newly expanded agricultural land

Aggregated land-cover classes	FAO land-cover classes	Definition
Intact forest	Closed forest	Continuous tree cover of natural origin, canopy cover >40%
	Open forest	Continuous tree cover of natural origin, canopy cover 10–40%
Disturbed forest	Long fallow	Forest affected by shifting cultivation; predominately forested
	Fragmented forest	Mosaic of forest and nonforest; on average 1/3 forested and 2/3 nonforested
Shrubland	Shrubland	Low woody vegetation of natural origin; includes cerrado, savanna, woodland, shrubland, and grassland
Agricultural land	Short fallow	Agricultural area with short fallow period; predominately nonforested
	Other land cover	Agricultural and urban area with <10% woody vegetation cover; the vast majority of this class is comprised of cropland and pasture
Plantation	Plantation	Agricultural and forestry plantation; man-made woody vegetation

The FAO land-cover classes were aggregated to increase reliability of results.

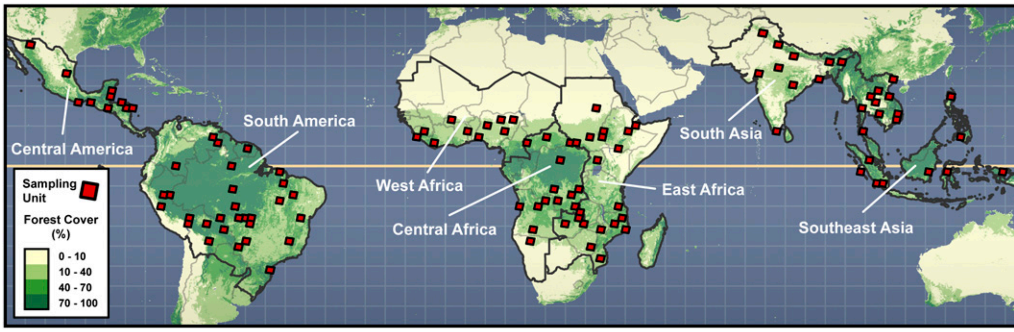

Fig. 1. Map of major tropical regions with locations of the 117 randomly sampled Landsat sites shown as red squares. (All Landsat sites were used except in four cases where inherent errors or missing data could not be corrected.) Each Landsat sampling unit is ∼3 million hectares in size, comparable to a district or province, and is shown to scale. Percent forest cover estimated from moderate-resolution imaging spectroradiometer (MODIS) data for the year 2000 is shown by background shading.

a much higher proportion of available forest was cleared in this soy-producing area than elsewhere. A detailed study using field and remote-sensing observations by Morton et al. (21) identified roughly equal shares of forest, pasture, and shrubland as the sources for expanding soy fields in Mato Grosso between 2000 and 2004.

The area of agricultural land coming from intact rainforests in South America was 13% higher in the 1990s than the 1980s (Fig. 3). Shrublands and disturbed forests each provided a quarter of the new cropland in the 1980s but only 13% and 20%, respectively, by the 1990s (Table S1). Conversely, the role of clearing intact forests in expanding agricultural area decreased from 73% to 67% in Central America, and that of disturbed forests had become more important by 2000. Shrubland conversion declined slightly from 7% to 4% between 1980–1990 and 1990–2000.

Africa. Africa has less cropland than the other regions, comprising only 13% of the global harvested area (38). However, between 1980 and 2000 cropland area increased by ∼50% in East Africa and by ∼25% in West Africa. In Central Africa the total cropland area declined during this period (14) despite favorable biophysical conditions for large-scale expansion (9). The major crops often are produced in subsistence farming systems with small plots and include sorghum, maize, millet, cassava, groundnuts, rice, coffee, and yams (14).

Throughout Africa as a whole, nearly 60% of new agricultural land was derived from intact forests, and another 35% came from disturbed forests. The remaining 5% of new agricultural land was taken from shrublands (Table S1). Another Landsat-based study in sub-Saharan Africa (1975–2000) confirms this general trend, estimating that 58% of new agriculture came from forests (32). However, land sources varied considerably across the continent (Fig. 4). For example, in Central Africa agricultural land was taken largely from intact forests, whereas East and West Africa used roughly equal amounts of intact and disturbed forests. Shrublands were converted primarily in regions with little forest cover and constituted a significant source of expanding agricultural land only in East Africa (Fig. 4).

In Central Africa, 75% of new agricultural land came from forests in the 1980s, but this percentage decreased by ∼10% during the 1990s as disturbed forests became more important sources (Table S1). Less densely forested East and West Africa had very divergent trends. East Africa increased clearing of intact forests by ∼20%, and conversion of disturbed forests decreased by the same amount. The opposite trend prevailed in West Africa: 20% less agricultural land came from intact forests, and 20% more came from disturbed forests in the 1990s than in the 1980s.

Asia. Asia has the smallest total land area and highest population densities in forested areas (39). This region has a long agricultural history dominated by rice production. Cultivation of wheat, millet, and sorghum also is important in South Asia and has remained largely consistent over time (14). Southeast Asia is the only region where tree plantations occupy a large portion of total agricultural land, and the area of tree plantations increased from roughly 11 million ha to 17.4 million ha between 1980 and 2000 (14). In the 1980s, the increase came from a range of plantation crops. However, oil palm was responsible for more than 80% of the expansion in plantation area by the 1990s (14). Rice and rubber tree plantations dominate overall cultivation in continental Southeast Asia, whereas insular Southeast Asia has highly diverse areas of row crops, along with coconut, rubber, and oil palm tree plantations (37). The area used to grow annual crops also increased in Southeast Asia during the last few decades but at a much more moderate rate than that of perennial tree crops (14).

Southeast Asia relied on intact forests for nearly 60% of new agricultural land and on disturbed forests for more than 30%. Southern Asia depended on disturbed forests for ∼60% of new land and on intact forests for only 35% (Fig. 5). However, geographic patterns of land conversion were highly variable throughout the region, with new agricultural land coming from several sources in most sampling locations. Mainland Asia and the Philippines are the only regions where shrublands were primary sources of agricultural land.

The sources for new agricultural land remained very stable in both Southeast and South Asia from 1980 to 2000 (Table S1). Tree plantations in Southeast Asia, however, had highly varied origins. During the 1980s, roughly half of new plantations were carved from forests; most of the remaining area came from conversion of agricultural land. By the end of the 1990s, conversion of agricultural land accounted for nearly 70% of new plantations, indicating a reduction in forest clearing for this purpose. However, this particular result does not agree with other analyses. For example, a recent analysis of national agricultural and deforestation statistics for 1990–2005 by Pin Koh and Wilcove (22) found that more than half the area of new plantations was carved from forests. Furthermore, our own analysis of a related Landsat database developed by the Tropical Resources and Environment monitoring by Satellites project (TREES) (36) identified intact and disturbed forests as the sources for ∼90% of new plantations between 1990 and 1997. Although the TREES sampling scheme focused on deforestation "hotspots" rather than on broader forest ecoregions, as did the FAO analysis, all of insular Southeast Asia was identified as a "hotspot," so the region was fully covered by the TREES analysis. It is unclear why our analysis of the FAO database shows a decrease in forest clearing for plantations between 1980–1990 and 1990–

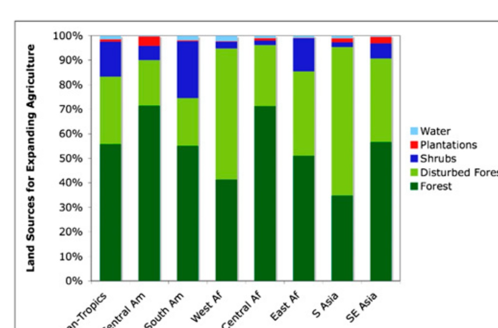

Fig. 2. The origins of new agricultural land, 1980–2000. Bars show the average proportion of land sources comprising new agricultural land in major tropical regions.

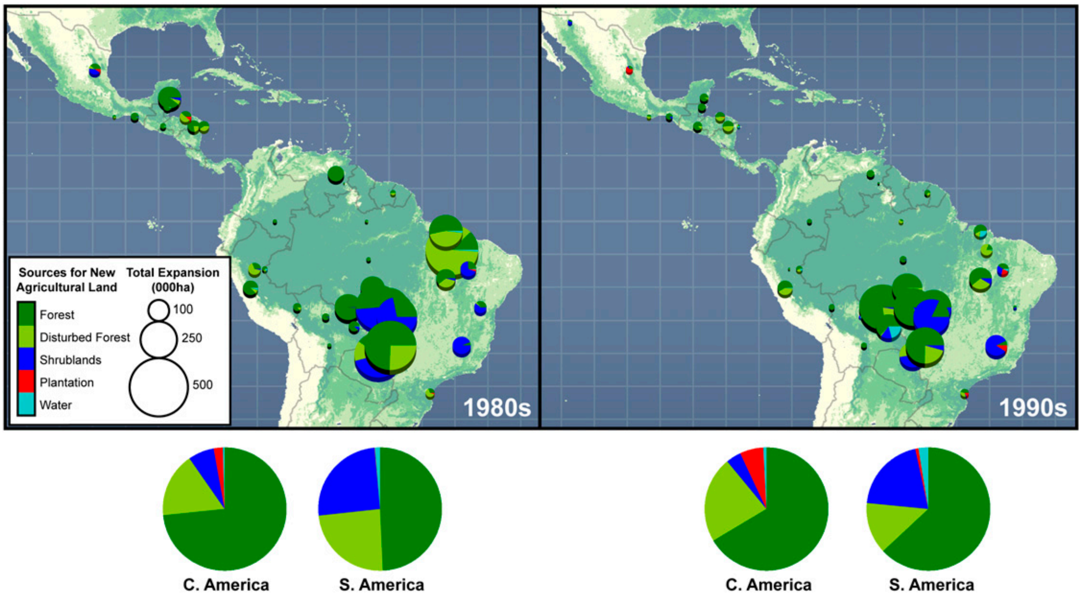

Fig. 3. Sources for newly expanded agricultural land in tropical America during the 1980s and 1990s. The pie charts show the relative proportions of land sources across broad regions and for individual Landsat sites, which are scaled according to the size of the agricultural land expansion (Fig. S1 shows unscaled pie charts).

2000, when these other analyses indicate a marked increase. Additional study is needed to explore and confirm the landscape origins of new plantations in this critically important region.

Potential Sources of Uncertainty. The FAO Landsat database provides major advances in data for assessing land sources for agricultural lands but does have inherent uncertainties and weaknesses. For example, the FAO sampling scheme excluded nonforest areas such as desert zones and areas with negligible forest cover (34, 35). This omission potentially could lead to a bias toward forests as the land sources in some cases. However, in recent decades most expansion in agricultural area occurred in or near forest frontiers, and very little occurred in dry zones, so excluding areas with <10% forest cover should not affect the results substantially. In continental Africa, for example, only the very dry zones were excluded, so the FAO sampling scheme captured the great majority of newly expanded agricultural areas occurring in more fertile zones (14, 32, 34). Continental and insular Southeast Asia were largely unaffected because they contain almost no area with <10% forest cover according to the FAO land-cover map used to design the sampling scheme (34). Only India's dry zones, where there is very limited agricultural expansion, were excluded from South Asia. Parts of the cerrado in South America were excluded from the analysis, but most agricultural changes in this region were crop type or pasture substitution rather than increases in total agricultural land. In addition, we evaluated the state-level agricultural expansion across Brazil and found that the majority of expansion occurring in the 1980s and 1990s was in the mid and northern regions of the country, indicating that we captured most agricultural expansion in this region (40).

Because these land-use/land-cover changes were assessed at 10-y intervals, the results are intended to describe decadal trends in land-cover change and therefore can mask short-term, year-to-year variations in land use. Land sources may have had intermediate uses within a decade, but our investigation captured only the two end points. For example, agricultural land may have been abandoned temporarily early in the decade but replanted several years later. Over the longer term, however, agricultural land rarely was abandoned long enough to enable forest regeneration. We estimate that less than 5% of previously agricultural land later supported natural vegetation during the 1980s and 1990s.

The aggregated agriculture categories also may mask shifts between agricultural land types, such as between pasture and cropland and different crop types. Substantial cropland expansion into pasture is found only in Latin America where trends of soy and sugarcane replacing pasture are well documented (21, 23, 40). However, the total net increases in cropland are larger than the reduction in pasture areas (40), showing that cropland unquestionably expanded into natural ecosystems. Outside Latin

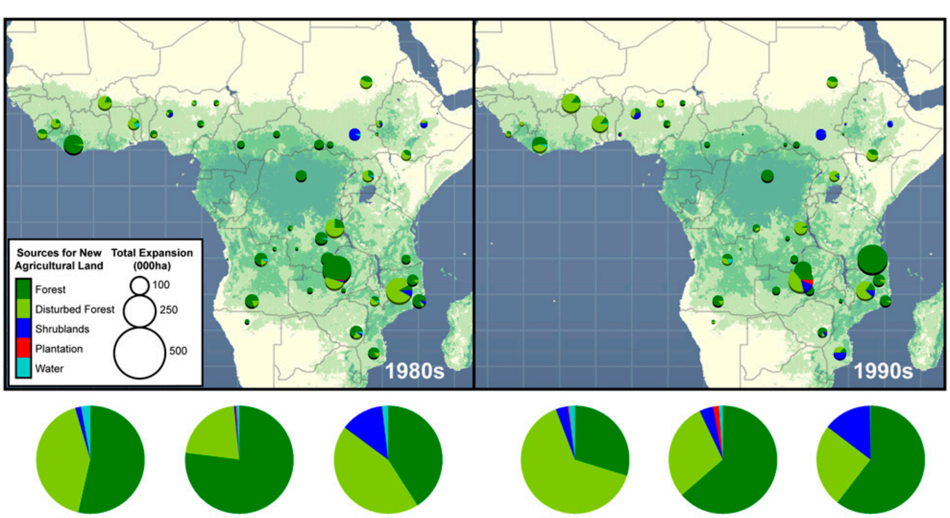

Fig. 4. Sources for newly expanded agricultural land in tropical Africa during the 1980s and 1990s. The pie charts show the relative proportions of land sources across broad regions and for individual Landsat sites, which are scaled according to the size of the agricultural land expansion (Fig. S2 shows unscaled pie charts).

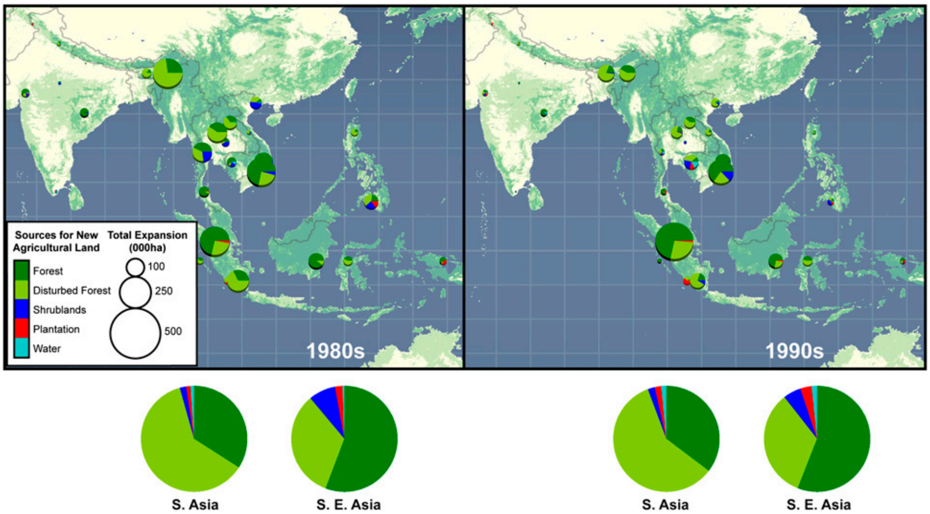

Fig. 5. Sources for newly expanded agricultural land in tropical Asia during the 1980s and 1990s. The pie charts show the relative proportions of land sources across broad regions and for individual Landsat sites, which are scaled according to the size of the agricultural land expansion (Fig. S3 shows unscaled pie charts).

America, the pasture area has remained relatively constant (14), and thus most agricultural expansion is for croplands.

A formal accuracy assessment of the results was not feasible, given the historical nature of the study and the pan-tropical scale, which make field verification extremely difficult (17, 34–36). However, the FAO does provide indications of measurement and sampling errors. Measurement error was assessed using a reliability ranking. This ranking indicated that transitions between forests and agricultural land were highly reliable, a finding that has been confirmed by others who estimate the measurement accuracy of forest-to-nonforest transitions as 90–95% accurate (41). However, transitions between similar classes, such as fragmented forests and forests affected by shifting cultivation, were ranked as less reliable. Our study maximized the reliability by aggregating the similar classes that were challenging to discern from one another, such as open and closed forest and small-scale and large-scale agriculture (Table 1) (17, 34, 35). The FAO estimated sampling error for forest cover as ±3.6% for the pan-tropics, ±8.0% for Africa, ±4.7% for Latin America, and ±8.2% for Asia (34). We did not have adequate information to assess fully the sampling error for agricultural land transitions in our study regions.

Conclusions

This study confirms that rainforests were the primary source for new agricultural land throughout the tropics during the 1980s and 1990s. More than 80% of new agricultural land came from intact and disturbed forests. Although differences occur across the tropical forest belt, the basic pattern is the same: The majority of the land for agricultural and tree plantation expansion comes from forests, woodlands, and savannas, not from previously cleared lands.

Worldwide demand for agricultural products is expected to increase by ∼50% by 2050, and evidence suggests that tropical countries will be called on to meet much of this demand. Consider, for example, that in developed countries the agricultural land area, including pastures and permanent croplands, decreased by more than 412 million ha (34%) between 1995 and 2007, whereas developing countries saw increases of nearly 400 million ha (17.1%) (14, 42). Moreover, developing countries expanded their permanent croplands by 10.1% during the current decade alone, while permanent cropland areas in developed countries remained generally stable (14). If the agricultural expansion trends documented here for 1980–2000 persist, we can expect major clearing of intact and disturbed forest to continue and increase across the tropics to help meet swelling demands for food, fodder, and fuel.

Indeed, recent studies confirm that large-scale agro-industrial expansion is the dominant driver of deforestation in this decade (e.g., 26, 28, 42, 43), showing that forests fall as commodity markets boom (44). Rising commodity prices have been implicated in the destruction of Amazonian rainforests for soy production (21, 28) and peat swamp forests for oil palm production in Southeast Asia (22, 28). Drivers of cropland expansion may impact forests directly through local or regional demand or indirectly through more globalized demand that may occur via market-mediated effects (30). Although this study does not specifically assess displacement or indirect land use changes, it does highlight the likelihood that intact and degraded forests will be replaced by agricultural land when such changes occur. Regardless of the mechanism, concern continues to mount about the large emissions of carbon dioxide that result when tropical forests are felled and often burned to make room for new agricultural land (31).

The results presented here emphasize the critical need to enact economic mechanisms to value standing forests, such as the Reducing Emissions from Deforestation (REDD) initiative currently being considered by the United Nations framework convention for inclusion in the post-2012 commitment period (44). Without such provisions, lucrative and increasingly large-scale agriculture will continue to clear forests in the path of expansion. However, with policies such as REDD in place, farmers and large-scale producers would have greater incentives to improve management of previously cleared land and receive carbon payments for avoiding carbon release from further deforestation (45, 46).

As we have demonstrated here, expansion of the global agricultural land base inevitably means clearing tropical forest and shrubland ecosystems. These natural ecosystems provide locally and globally important services including storing of much of Earth's biomass carbon, serving as habitats for endangered plants and animals, preserving major elements of the global hydrological cycle, and protecting massive watersheds (34, 44, 47, 48). The tradeoffs between the value of commodities obtained from expanding agricultural area and the services provided by intact ecosystems need to be considered carefully as we move forward in an increasingly integrated world.

Methods

We analyzed the library of classified Landsat scenes originally processed by the FAO as part of the Forest Resources Assessments (17, 34, 35). This database consists of 117 randomly selected sample locations stratified by dry, moist, and humid tropical forest and covers 10% of the tropical forest belt (Fig. 1). There were 47 sampling units in Africa, 30 in Asia, and 40 in Latin America. The survey included all tropical forest types and covered 63% of the entire tropics and 87% of tropical forests (34). Nonforest tropical areas (e.g., deserts) were excluded. Each sampling unit was comprised of three Landsat satellite images acquired approximately for 1980, 1990, and 2000 and statistically standardized to those years. The average years for the imagery were 1977, 1989, and 1998. The spatial resolution of the Landsat imagery ranged from 30 m to 60 m.

The FAO used a detailed land-cover classification scheme to account for major changes in land-cover type throughout the tropics (e.g., from closed forests to agriculture) (Table 1). When estimating changes within one period at each sampling unit, the FAO used interdependent visual interpretation of two satellite images acquired at different dates (17, 34, 35). This procedure consists of visual interpretation of both images (historical and recent) at the same time

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using a single interpretation process and provides significant advantages over single-period analysis or compilation of different sources of imagery (17, 33–36). The FAO approach assures a high level of consistency and reduces errors associated with change detection (34). It also allows direct tracking of all decadal class-to-class land-cover transitions.

We quantified and documented the sources for newly expanded agricultural lands at each sampling location, as well as their geographic and temporal patterns, by analyzing the FAO Landsat database and change matrices. We organized the tropical belt into seven broad regions, each with broadly similar socioeconomic and ecological conditions expected to lead to common pathways of land-use change (20). These regions are Central and South America; West, Central, and East Africa; and South and Southeast Asia. We performed paired *t* tests between each Landsat scene location to determine whether changes at the sampling unit level between 1980–1990 and 1990–2000 were statistically significant within the regions. Assumptions of normality were assessed by examining histograms of data distribution within regions and changes between decades; no obvious deviations from normality were found. Spatial patterns of residuals and Moran's Index indicated no evidence of spatial auto-correlation (49). The width of the confidence intervals indicated that sampling within each of the seven regions was adequate.

A formal accuracy assessment of the imagery was not feasible, given the historical nature and pan-tropical scale of the study (17, 34–36). However, the FAO did assess measurement and sampling errors. Measurement error, which is extremely difficult to quantify without field verification, was assessed using a reliability ranking, similar to fuzzy set theory (50), based on assumptions about the study areas and classification method used. This reliability ranking indicated that transitions between forests and nonforests were highly reliable, but transitions between more similar classes, such as fragmented forests and forests affected by shifting cultivation, were less reliable. Others have assessed the identification of forest-to-nonforest transitions as 90–95% accurate (41). Our study maximized the reliability of the FAO Landsat analysis by aggregating similar classes that are challenging to discern from one another, such as open and closed forest and small-scale and large-scale agriculture (Table 1) (17, 34, 35).

Sampling error, determined by the sampling design and variation within the population, was estimated for forest cover by the FAO as $\pm3.6\%$ for the pantropics, $\pm8.0\%$ for Africa, $\pm4.7\%$ for Latin America, and $\pm8.2\%$ for Asia (34). However, we did not have adequate information to assess fully the sampling error for agricultural transitions in our study regions.

ACKNOWLEDGMENTS. This paper benefited from suggestions by G. Allez, S. Foley, C. Monfreda, and two anonymous reviewers. Funding for this study was provided by a US Department of Energy Global Change Education Program doctoral fellowship (to H.K.G.), a David H. Smith Conservation Research Fellowship (to H.K.G.), and a Terrestrial Ecology Research grant from the National Aeronautics and Space Agency.

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