Difficulties in tracking the long-term global trend in tropical forest area

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The long-term trend in tropical forest area receives less scrutiny than the tropical deforestation rate. We show that constructing a reliable trend is difficult and evidence for decline is unclear, within the limits of errors involved in making global estimates. A time series for all tropical forest area, using data from Forest Resources Assessments (FRAs) of the United Nations Food and Agriculture Organization, is dominated by three successively corrected declining trends. Inconsistencies between these trends raise questions about their reliability, especially because differences seem to result as much from errors as from changes in statistical design and use of new data. A second time series for tropical moist forest area shows no apparent decline. The latter may be masked by the errors involved, but a "forest return" effect may also be operating, in which forest regeneration in some areas offsets deforestation (but not biodiversity loss) elsewhere. A better monitoring program is needed to give a more reliable trend. Scientists who use FRA data should check how the accuracy of their findings depends on errors in the data.

global environmental monitoring | sustainability indicators | tropical deforestation

Widespread clearance of tropical forest has aroused concern for over forty years (1), with stress now being placed on the consequential reduction in biological diversity (biodiversity) (2), and emissions of carbon dioxide and other greenhouse gases that contribute to global climate change (3). Yet while the planet has been monitored by remote-sensing satellites since 1972, estimates of the annual deforestation rate are still inaccurate (4), and the appearance of each new estimate generates debate (5, 6). In contrast, the related long-term trend in tropical forest area has been neglected. It might become a major environmental indicator of global sustainability if it could be quantified with reasonable accuracy and frequency (7). This article examines available area data and finds that the evidence for decline is not as clear as commonly assumed, even since the 1970s, by which time as much as 300 million hectares (ha) of tropical forest may have already been cleared since 1860 alone (8).

Our main focus is on the trend in the area of tropical "Natural Forest," which includes all naturally occurring woody vegetation with a tree canopy cover of ≥10% but excludes forest (timber) plantations, shrubland, and other wooded land. Values for this statistic have been obtained from, or calculated by using, statistics in the Forest Resources Assessments (FRAs) for 1980, 1990, 2000, and 2005 of the United Nations Food and Agriculture Organization (FAO) (9–13). [Our calculations are described in supporting information (SI) *Text*]. This is the first article to construct a time series for this statistic by combining estimates from every FRA. FAO has, until recently, virtually monopolized global forest monitoring: its Department of Forestry reported on world forest resources every 5 years from 1948 until 1963, when it suspended publication because of poor tropical forest data (14); in 1981 it resumed activities by launching its series of FRAs, focusing initially on the tropics.

Another reason to analyze FRA statistics is that they are an important source of data for sustainability scientists (15): in land change studies (16) that use cross-sectional models to make international generalizations about the factors causing and controlling deforestation (17–19); and in global change research that monitors or forecasts trends in carbon stocks and emissions (3, 20) and biodiversity (21). Such studies rarely examine in depth the quality of FRA data on which their findings are based, so this article fills a gap here too.

FRA estimates of tropical forest areas and deforestation rates have been quoted in thousands of documents. We scanned >2,000 scientific publications that cite FRAs and found 159 in which FRA data make a substantial contribution (Table 1). Three-quarters of them are descriptive surveys or focus on land change modeling or climate change. However, climate change and biodiversity researchers have increasingly used estimates of forest areas and deforestation rates in the humid tropics based on independent satellite remote sensing surveys. Reports on the latter account for 14% of the total, because they routinely compare their findings with those of FRAs. Some of the papers that obtained FRA data from other compilations, e.g., the *World Resources* reports (22), may be missing from our list.

Values for the area of "Forests and Woodland"—which also includes plantations and other wooded land—were published annually until 1995 by another FAO department in its Production Yearbook series (23). This alternative statistic was used in 20% of the "first wave" of land change modeling exercises (24), including the very first (25). But it was less authoritative than FRA statistics, because its value for each country was only that reported—not measured—by governments each year, in contrast to the more discriminating FRA compilations. Despite cautionary statements (26) it is still used for modeling (27), revealing demand for an annual time series. Another justification is that it has fewer deficiencies than FRAs, e.g., population growth was used to estimate deforestation in FRAs 1980 and 1990, which confuses tests for statistical relationships between the two variables (28).

Results

Our time series for Natural Forest area consists of two estimates for 1980 and three trends (Fig. 1). The latter result from FAO revising estimates in previous FRAs to be consistent with the latest ones. According to FRA 1980 Natural Forest covered 1,970 million ha in 76 tropical countries in 1980 (9). This was corrected to 1,935 million ha in a 1982 summary (10). In FRA 1990 it was cut again, and forest area was said to decline from 1,910 to 1,756 million ha between 1980 and 1990 for 90 countries (11). According to FRA 2000, for the same countries forest area fell from 1,926 to 1,799 million ha between 1990 and 2000 (12). In FRA 2005 the 1990 estimate was raised again, and forest area

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Table 1. Scientific publications (no.) to which FAO Forest Resources Assessments (FRAs) make a substantial contribution, sorted by type and primary FRA reference

FRA, year	Surveys	Land change modeling	Climate change	Biodiversity	Remote sensing	Total
1980	12	10	8	2	4	36
1990	12	26	18	6	9	71
2000	12	9	7	10	9	47
2005	2	2	0	0	1	5
Total	38	47	33	18	23	159

All publications are listed in SI References.

shrank from 1,949 to 1,768 million ha between 1990 and 2005 (13) (Table 2). [FRAs 2000 and 2005 covered >90 countries, but, because those added contain little tropical forest, the full totals for 1990, 2000, and 2005 exceed those in Fig. 1 by just 0.3% (see SI Table 4).]

One way to interpret these trends is as an increasingly accurate portrait of the actual trend, as expected for successive "vintages" of statistics (29). Each shows the expected fall in forest area, and their slopes are remarkably consistent given the debates over deforestation rates. Yet owing to FAO's adjustments, they are less consistent in terms of area. Estimates for 1980 have fallen in successive FRAs; those for 1990 and 2000 have risen. The FRA 2000 trend was effectively a "rerun" of that in FRA 1990, the increase in the earlier 1990 estimate exceeding the area reported cleared in the 1980s (170 vs. 154 million ha). Although the FRA 1990 trend displays some continuity with FRA 1980 figures, the others do not. If the FRA 2005 trend is projected backwards linearly the inference is that there were actually ≈2,070 million ha of forest in our 90 countries in 1980, not 1,970 million ha as reported in FRA 1980 for 76 countries.

Such inconsistencies raise questions about the reliability of FRA trends and suggest that the results of studies in Table 1 will be affected by which FRA dataset they used. To address the first point—to do justice to the second requires another article—we now examine possible systemic and error-related reasons why estimates for the same year have changed from one FRA to the next.

Systemic Reasons for Differences Between Estimates

There are two main systemic reasons why estimates differ. First, changes in FRA design. In FRA 2000, for 11 of the countries whose 1990 estimates were raised—including Costa Rica, Ethiopia, and Kenya—FAO treated as Natural Forest some domestic vegetation categories it previously excluded. Estimates for two other countries, Guinea and Somalia, rose because smaller areas of vegetation were now counted as forest (12). The net increase in 1990 forest area in these 13 countries was 21.5 million ha, or 13% of the total adjustment. In contrast, all FRAs have used a tree canopy cover of ≥10% to class tropical vegetation as "forest," so changes in this threshold have not caused estimates of forest area in 1990 and 2000 to rise in successive FRAs. Nor have changes in geographical scope, because all three trends in Fig. 1 refer to the same 90 countries. Indeed, although the number of countries increased from 76 in FRA 1980 to 90 in FRA 1990, the estimate for 1980 declined.

Second, the use of different data. When FRA 1980's estimate of forest area in Latin America in 1980 was cut in 1982, FAO explained that better data had become available (10). In the other FRAs, later data have overall revealed more forest than previously identified while still showing a net decline over time. FAO justifies most of its adjustments, and specifically those made in FRA 2000 to FRA 1990 estimates for 63 of our 90 countries (30), on the grounds that the latest data are usually more reliable. The smaller adjustment in FRA 2005 appears to give credence to this justification and to the FRA 2000 trend. Estimates of already proven oil reserves also rise over time as more information is obtained, a phenomenon called estimate appreciation (31).

Care is needed when linking relationships between global aggregate trends to adjustments at subglobal levels (32), but support for estimate appreciation comes from regional trends for Asia-Pacific and Latin America. From FRA 1990 onwards, previous figures for both regions have been either raised or changed only slightly (Table 2). The African pattern is more erratic: FRA 1990 cut FRA 1980's estimate for 1980 by 19%; FRA 2000 increased FRA 1990's estimate for 1990 by 30%, but this was trimmed by 2% in FRA 2005. The correction in FRA 2000 was equivalent to 92% of the total upward adjustment to tropical forest area in 1990.

Evidence for a consistent improvement in data quality is less convincing at national level. For 54 of the 90 countries, FRA 1990 estimates for 1990 were raised in FRA 2000 and cut in FRA 2005 (or vice versa), and only in 32 was the second correction below the first in absolute value. Estimates for 1990 for the 12 countries with two-thirds of all tropical Natural Forest were changed by up to 209% in FRA 2000 and up to 38% in FRA 2005. Seven had less forest in 2005 than in 1980, but five had more forest (see SI Table 5). FRA 1990 estimates for 1990 changed by ≥33% for 27 countries in FRA 2000, and FRA 2000 estimates for 2000 changed by the same proportion for 22 countries in FRA 2005 (see SI Table 6). Most of these latter countries are in Africa and Central America and the Caribbean, where forest monitoring capacity is developing slowly. Eight are in both lists: Burundi, Costa Rica, El Salvador, Ethiopia, Kenya, Mozambique, St. Lucia, and St. Vincent. The wide variation in African estimates is consistent with the erratic regional trend.

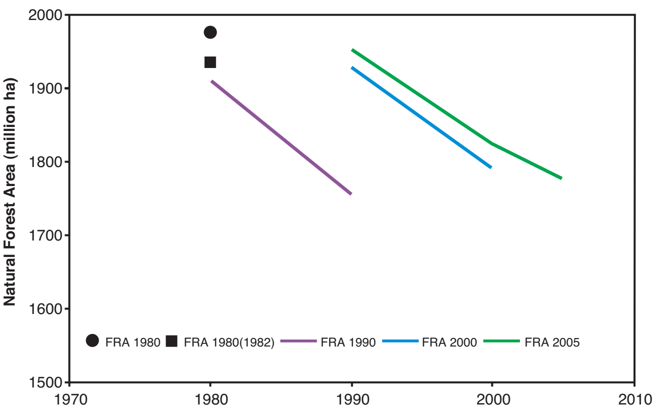

Fig. 1. Trends in Natural Forest area 1980–2005 in 90 tropical countries (10^6 ha) from data in Forest Resources Assessments (FRAs) 1990, 2000, and 2005, with estimates for 76 countries from FRA 1980 and its 1982 revision. (Sources: refs. 9–13.)

The Role of Errors

Are the latest survey data really the most accurate? Or are differences between revised estimates and those they replaced merely within the limits of errors involved in estimating national areas and combining them to give regional and global figures?

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Table 2. Natural Forest area (10^6 ha) 1980–2005 in 90 tropical countries* from data in Forest Resources Assessments (FRAs) 1980, 1980 (1982 revision), 1990, 2000, and 2005

	FRA1980	"FRA 1982"	FRA 1990		FRA 2000		FRA 2005		
Location	1980	1980	1980	1990	1990	2000	1990	2000	2005
Africa	703	703	569	528	684	629	672	628	607
Asia-Pacific	337	337	350	311	307	265	342	312	296
Latin America†	931	896	992	918	936	905	934	889	865
Totals‡	1,970	1,935	1,910	1,756	1,926	1,799	1,949	1,829	1,768
No. of countries	76	76	90	90	90	90	90	90	90

Sources: refs. 9–13.

*Except for FRA 1980 and "FRA 1982" (a summary of FRA 1980 containing revised estimates). The 76 and 90 countries are listed in SI Table 4. For continuity, East Timor is aggregated with Indonesia, and Eritrea is aggregated with Ethiopia throughout 1980–2005

†Includes the Caribbean, Central America, and South America.

‡Totals may not match subtotals due to rounding.

The size of FRA 2000's correction to the FRA 1990 estimate for 1990 shows how great such errors may be.

Variation in the Natural Forest Time Series. There are three main sources of errors. First, those incurred in undertaking national forest surveys. For instance, estimates were based on subjective expert assessments for 33% of our 90 countries in FRAs 2000 and 2005 and on maps derived from more accurate remote sensing data for only 59% of countries in FRA 2000 and 51% in FRA 2005 (12–13).

Second, projection errors. To estimate total tropical forest area, FAO must project the result of the last national forest survey for each country from the year it was carried out to a common reporting year for all countries, e.g., 2000 for FRA 2000. This usually involves linear projection and, preferably, extrapolating the line joining the areas found in the last two surveys (12). The longer the time since the last survey, however, the higher the errors may be. Projection "gaps" often extend to 10–20 years. In FRA 1990, estimates of forest areas for 1980 and 1990 were projected from surveys before 1980 for 29 of the 90 countries, and in FRA 2000 estimates for 1990 and 2000 were projected from outside the decade for 15 countries. This fell to 13 by FRA 2005, but for 4 countries estimates still relied on surveys from 1970 or earlier.

Errors may also occur when revising estimates in previous FRAs to form the three trends in Fig. 1. For some countries, the revisions result from FAO "projecting backwards" from the most recent survey finding on which the latest estimates are based. For the majority, however, there is interpolation between the areas found in that survey and the one before. Yet again, in both cases, the longer the gap since the last estimate, the greater the scope for errors. Confusion may also arise between estimate appreciation and net reforestation, which is becoming more common (see below). For example, in FRA 1990, the estimate of 45.7 million ha for Venezuela in 1990 was obtained by projecting forward 13 years from the 55.8 million ha of Natural Forest found in a 1977 survey. For FRA 2000, FAO had the luxury of a survey that found 49.9 million ha in 1995. So it projected forward from this to give 48.6 million ha for 2000, and by interpolation produced a new estimate of 51.3 million ha for 1990. This assumed, of course, that deforestation continued since 1977, but given the long gap this is not certain. In principle, forest area may have dropped as sharply as FRA 1990 reported, but then recovered to 49.9 million ha in 1995. Because a long gap obscures the current trajectory this can lead to errors in forward projection too. So if, hypothetically, forest area did indeed expand in Venezuela in the 1990s then the actual area in 2000 would be >49.9 million ha, not lower, as reported in FRA 2000.

Changes in projection methods give more scope for variation. FRAs 1980 and 2000 relied on linear projection and expert assessment. However, FRA 1990 switched to nonlinear models in which forest area declined with rising population density, and this may be why many African estimates, especially, were unduly depressed. In FRA 2005, FAO asked governments to make their own projections within a common framework (33), selecting the projection method they thought most appropriate (although most opted for the linear method). They could also choose the survey on which to base their estimates, and so could use data that FAO rejected in 2000 on quality grounds or (for 27% of countries) new data. They could even interpret differently the same data FAO used for FRA 2000: the Venezuelan government gave estimates of 52.0, 49.2, and 47.4 million ha for 1990, 2000, and 2005, respectively, by interpreting the 1995 survey mentioned above to reveal the presence of 50.6 million ha of forest in 1995, not 49.9 million ha (34). Such discretion may explain the contradictory adjustments to 1990 estimates for 60% of countries in FRAs 2000 and 2005. FAO admits that it often caused figures in the two FRAs to differ (35). So the FRA 2005 trend is probably best seen as an alternative to that in FRA 2000, not a consistent refinement of it and hence the third in a series of increasingly accurate trends.

Third, errors arise from the increasing aggregation of FRA statistics. Although FRA 1980 listed national areas of Closed Forest, which has a closed canopy, this was amalgamated with Open Forest (e.g., savanna woodland) in FRA 1990 as Natural Forest, which was combined with Forest Plantations in FRAs 2000 and 2005 as "Total Forest." (This is why for some years in these two FRAs we had to calculate Natural Forest area by subtracting Forest Plantations area from Total Forest area.) Open forest accounts for ≈40% of Natural Forest, but area estimates are far less accurate than for closed forest, because its boundaries are more diffuse and surveys infrequent (36). The locations and boundaries of forest plantations are better defined, but FAO routinely deducts 30% from official reports of their areas to correct for errors because of tree mortality (12). Most of these errors are removed here by focusing on Natural Forest, but those related to open forest remain. FAO has always placed great stress on identifying its data sources and assessing their reliability, but increasing aggregation of statistics makes the latter task more difficult.

Variation in a Tropical Moist Forest Time Series. To remove open forest errors, we constructed another time series for closed forest in the humid tropics only. Tropical moist forest accounts for ≈90% of tropical closed forest and comprises two main types: tropical rain forest and tropical moist deciduous forest (37). Our series comprises three sets of estimates. First, five expert assessments from before 1990, including one of our own based on FRA 1980 data (14, 38–41). Another, using Closed Broadleaved Forest data (FAOCB) from FRA 1990, was included too. Second, two estimates derived from areas of ecosystem types in

Table 3. Tropical moist forest area (10^6 ha) 1973–2000, with alternative totals for 63 countries (65 for Sommer)

Source	Date of estimate	No. of countries	Total	Total (63 countries)
Persson	1973	61	979	980
Sommer	1975	65	935	935
Myers	1980	51	973	982
Grainger	1980	63	1,081	1,081
Myers*	1989	34	778	801
FAOCB†	1990	53	1,136	1,180
FAOE‡	1990	85	1,510	1,434
TREES§	1990	56	1,150	1,152
TREES	1997	56	1,116	1,118
FAOE‡	2000	100	1,426	1,347
GLC¶	2000	42	1,123	1,181

The 63 countries are listed in SI Table 7. Sources: refs. 11, 12, 14, 38–42, and 44–47.
*Myers's own extrapolation for "all tropical moist forest" was 800 million ha.
†Based on FRA 1990 closed broadleaved forest area data.
‡From FAO ecosystem type estimates in FRAs 1990 and 2000.
§Updates an earlier, almost identical, estimate (43).
¶JRC's own aggregate GLC estimate for tropical moist forest (48) is 1,094 million ha, but the number of countries is not specified.

FRAs 1990 and 2000 (FAOE). FRA estimates of Natural Forest area were divided between major ecosystems, using proportions found in separate surveys, and from these we combined areas of Tropical Rain Forest, Tropical Moist Deciduous Forest, and Montane Forest (assumed to include high altitude forms of the other two types). Third, three estimates based on remote sensing surveys by the TREES Program of the European Commission's Joint Research Center (JRC) (42–43) and its successor, the Global Land Cover (GLC) Program (44–47) (Table 3).

Estimates for the same year vary, as for Natural Forest, but here because they draw on different sources, not revisions. Systemic differences arise because each source could choose its own methods, ecosystem classification systems, data, and geographical scope. We corrected for the latter in Fig. 2 by adjusting all estimates to cover 63 countries (based on ref. 38 and listed in SI Table 7) containing 95% of all tropical moist forest.

Errors for each estimate vary in scale and type, but differences between the remote sensing and FAOE estimates (20% for 1990 and 12% for 2000) may be linked to systematic errors in both sets. Using a single remote sensor to survey all tropical forest within a few years of the reporting year minimizes projection and other combination errors and reduces subjectivity, but relying on coarse resolution images limits accuracy. Errors for the FAOE estimates occur because of reliance on FRA data and misclassification, e.g., open forest being wrongly classed as Tropical Moist Deciduous Forest. In our view, the Köppen–Trewartha system (49–50) used in FRA 2000 misclassifies less forest than the Yangambi-United Nations Educational, Scientific, and Cultural Organization system (51–52) in FRA 1990 (53), so the lower figure for 2000 is expected. It should also be more accurate, because Natural Forest was allocated to ecosystem types by computer overlay of an ecosystem map and a global forest map based on satellite images, whereas in FRA 1990 allocation used various vegetation maps. The expert assessments are affected to varying degrees by subjectivity; Myers's innovative use of consultative appraisal may explain why his 1989 estimate was so low.

Variation Among Estimates for Different Years

Long-Term Trends. If errors do make a major contribution to variation in the Natural Forest time series (Fig. 1), then, regardless of internal consistency in each of the FRA trends, this raises questions about whether any of them offers a reliable guide to the long-term trajectory in tropical forest area. Indeed, if back projections to correct for changes between FRAs are ignored, the sequence of contemporary estimates only—1,970, 1,756, 1,799, and 1,768 million ha for 1980, 1990, 2000, and 2005, respectively—has no clear trajectory after 1990.

In contrast, the Tropical Moist Forest time series (Fig. 2) appears to show a long-term rising, not declining, trend. Yet here too errors must be taken into account. If the Myers (1989) and FAOE estimates are treated as outliers, owing to their fairly large systematic errors, then a more conservative interpretation is that tropical moist forest area has changed little since at least 1990, within the limits of errors generated when producing global estimates. The relative consistency between the remote sensing estimates and expert assessments—the TREES and FAOCB estimates for 1990 differ by just 28 million ha—is understandable given estimate appreciation resulting from greater use of satellite monitoring.

Of the remote sensing estimates between 1990 and 2000, only the GLC 2000 and TREES 1990 figures are based on comprehensive surveys. The GLC estimate (1,181 million ha) does exceed the TREES estimate (1,152 million ha), but errors will have been introduced by extrapolation to 63 countries, and by differences in ecosystem classification systems among the various GLC regional surveys, and between these and the TREES study. So inferring forest expansion from the two figures would be unwise. Equally, although the TREES 1997 estimate is below that for 1990 (1,118 vs. 1,152 million ha), it was estimated by

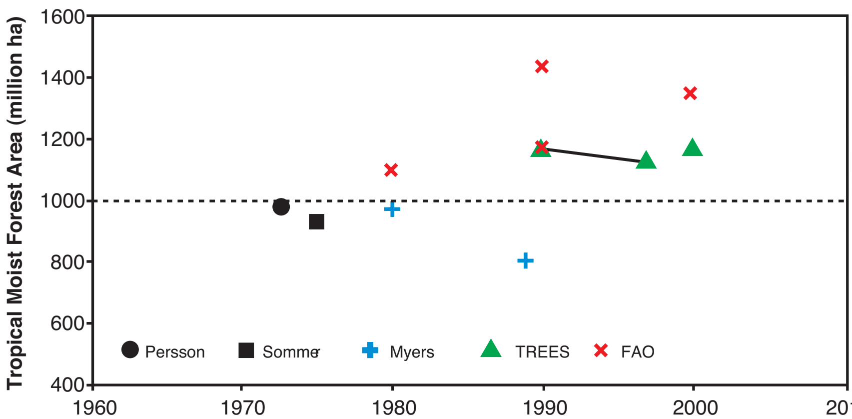

Fig. 2. Estimates of tropical moist forest area (10^6 ha) for 63 countries 1973–2000. For clarity, the Grainger (1980) estimate derived from FRA 1980 and the FAOCB 1990 estimate are both shown as FAO estimates, and the GLC estimate is shown as a TREES estimate. (Sources: refs. 11, 12, 14, 38–42, and 44–47.)

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subtracting from the 1990 area an estimate of subsequent deforestation, made by sampling clearance "hot spot" areas (42). Because questions have been raised about whether any sampling method gives reliable estimates of deforestation (54), they also extend to inferences of forest decline from the two TREES figures.

The Tropical Moist Forest time series, therefore, lends support to our sceptical view of the Natural Forest time series. This definitely does not mean there has been no decline in tropical forest area, just that present global monitoring systems are too imprecise to detect it convincingly.

Forest Return. If our interpretation of Fig. 2 is correct then it raises a further question: could something else, besides estimate appreciation, be raising tropical forest area over time? One possibility is that the continuing reduction in primary forest area [though not its biodiversity and carbon stocks (55)] is being offset by secondary forest expanding elsewhere, e.g., on abandoned farmland. We call this dual effect "forest return."

Secondary forest is receiving growing attention (56–59). Governments are promoting its rehabilitation (60), and its dynamics are being monitored by remote sensing studies (61–63). FRA 2005 was the first since FRA 1980 to include estimates of primary and secondary forest areas, but their quality is still limited. A remote sensing survey undertaken for FRA 2000 found that in the 1990s regeneration was equivalent to 10% of all deforestation in tropical closed forest and fallows (12) (see SI Table 8). TREES gave a higher proportion of 17%, even though its sample sites were confined to deforestation "hot spot" areas (42). These may be underestimates: secondary forest in the humid tropics is difficult to distinguish from mature forest on satellite images after a few years, so regrowth is easily overlooked by infrequent surveys.

The same applies to FRA statistics in which, as we argued above, forest regeneration may be confused with estimate appreciation. Six of our 90 countries—Bhutan, Cuba, Gambia, Puerto Rico, St. Vincent, and Vietnam—sustained net Natural Forest expansion between 1990 and 2005 (13), and so seem to have passed through their "forest transitions" (64–65), by switching from a net decline to a net rise as the reforestation rate exceeds the deforestation rate. Four more—Cape Verde, India, Ivory Coast, and Rwanda—did so based on the trend in the combined area of Natural Forest and Forest Plantations (see SI Table 9). But net reforestation in all 10 countries was only 4.6 million ha between 1990 and 2000, or just 3.6% of Natural Forest loss reported in FRA 2000 for that decade.

Because forest return is a logical precursor to forest transitions, estimating its true scale more accurately is vital for a better understanding of these. It will also shed light on trends in biodiversity and carbon stocks, e.g., forest return may help to explain the "missing carbon sink," an artifact of an accounting imbalance in the global carbon budget (20).

Deforestation Rates. This article has focused on analyzing estimates of forest area, not deforestation rates. In Fig. 1, the latter seem more consistent between FRAs than forest areas, but consistency does not mean accuracy. Because the accuracy of deforestation rate estimates is linked to that of forest area estimates in every FRA except the first, where deforestation was assessed independently by expert assessments or models, our reservations about FRA area estimates apply to those of deforestation rates too. Deforestation may well have occurred at the global rates published in FRAs, but we cannot be certain about this given the errors involved.

Although coarse resolution satellite images can clarify the forest area trend, they are as limited as official statistics for estimating deforestation rates, because they miss fine-scale processes. When the TREES Program used a sample of high resolution images to monitor the deforestation rate in the humid tropics in the 1990s its estimate was 23% below the corresponding FRA value (42). FAO arrived at an inflation figure of 17% when it carried out its own check for the 1990s, using high resolution images and another sampling design (12). But since any use of sampling to estimate deforestation rates has been queried (54), discrepancies between these two ways of monitoring deforestation may only be resolved satisfactorily by a "wall-to-wall" survey with high resolution images.

Discussion

Our analysis does not prove that tropical forest decline is not happening; it merely shows that it is difficult to demonstrate it convincingly using available tropical forest area data, despite the dedication of all who collected them. Global generalizations about tropical forest trends should therefore be more cautious until better global data are obtained. We also advise scientists who use FRA data to critically appraise how the accuracy of their findings may be affected by errors in the data. They should judge the accuracy of a particular dataset in the context of the sequence of FRAs of which it is part, so that correct comparisons may be drawn with studies using other datasets. Because FRA 1990 and FRA 2000 have been the source for 45% and 30%, respectively, of publications that use FRA data, the inconsistency shown in this article between the two datasets is a cause for concern.

We are not the first to challenge accepted thinking about forest change. Inconsistencies in tropical forest area trends contribute with those for temperate forests (66) to uncertainty about global forest trends (67). Supposed remnants of "virgin forest" in West Africa may have regrown naturally or been planted on previously deforested land (68).

Nor are we alone in recognizing the importance of uncertainty in global change research (69). We have highlighted the difficulties of estimating global environmental variables by combining large numbers of national statistics, produced by various measurement and estimation techniques. A similar (but more complex) situation prevails when estimating the long-term trend in mean global temperature (70).

How can matters be improved? Statistics have become so aggregated in recent FRAs that it would be impractical for "outsiders" to check and correct every national estimate. Constructing a trend line through the mean area for each year in Fig. 1 could not be justified either, if the size of FRA 2000's adjustment to the 1990 estimate in FRA 1990 represents the errors involved.

What is needed, in our view, to show which FRA trend is the more reliable, is a reconstruction of the tropical forest area trend since 1970, using all available empirical data and a rigorous scientific design. It should be "wall-to-wall" (54), rather than rely on sampling. Fortunately, the high resolution satellite image archive dates back to the mid-1970s. To allow validation by contemporary estimates and ground data and construction of Natural Forest and Tropical Moist Forest time series, it should have national resolution and distinguish closed from open forests. A more intensive study, which geo-references clearances when they occurred, could distinguish areas of secondary forest and show the true size of "forest return." FAO might wish another body to carry out this work, as obligations to member states prevented it from deriving national estimates of ecosystem type areas from the separate remote-sensing survey of the tropics undertaken for FRA 2000 (71).

So better techniques alone are not enough. By definition, an appropriate set of institutions, which are "enduring regularities of human action in situations structured by rules, norms and shared strategies, and by the physical world" (72), is essential to sustain regular monitoring of forests or other phenomena. Little attention was paid to institutions at the seminal meeting held at Tylney Hall in 1988 to discuss the global databases needed for global change research (73). Yet the institutions that allow FAO to collect data from its member states also constrain the quality of its statistics, owing to the need to respect national sovereignty. The sustainability science community, meanwhile, lacks suitable global forest monitoring institutions of its own, and has had to compromise by using coarse resolution satellite images for area assessment and high resolution images for sampling deforestation.

Raven was right to question whether current international institutions are adequate for "building a sustainable world" (74). Quantifying changes in tropical forest cover is crucial to modeling and monitoring global environmental change and assessing sustainability. So sustainability scientists must press for a global monitoring program compatible with the quality of global data they need to supply society with the reliable knowledge it demands.

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