

STRATEGIES FOR GLOBAL MONITORING OF TROPICAL FORESTS

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INTRODUCTION

The Food and Agricultural Organization (FAO) of the United Nations is conducting a global assessment of tropical forest resources, which will be accomplished by mid-1992. This assessment requires, in part, estimates of the total area of tropical forest cover in 1990 and the rate of change in forest cover between 1980 and 1990. The following are described here: (1) the strategic process used to select the statistical and remote sensing methods that accomplish this objective, (2) general details and expected precision of the selected method, and (3) recommendations for monitoring and assessment actions after mid-1992. The following is a summary of Czaplewski (1991) which is a consultation report on this subject submitted to FAO in February 1991.

DESIGN ALTERNATIVES CONSIDERED

Four fundamentally different design alternatives were considered:

1. Collection of existing data, primarily national forest inventories, supplemented with regression models that predict forest extent and rates of deforestation as functions of eco-floristic classifications and human population density.
2. Digital classification of coarse-resolution satellite scenes from 1990 that completely image the world's Tropics. All terrestrial 1.1 km² AVHRR pixels for the world's Tropics are classified into two categories: forest or nonforest. Regression models from the first alternative would be used to estimate rate of deforestation between 1980 and 1990.
3. Visual interpretation of a randomized sample of high-resolution satellite

images (which are treated as permanent plots) for two dates (1980 and 1990), with a sampling intensity of 5 to 40 percent of the world's Tropics. All 30 m² pixels within each sample scene are classified into 7 to 14 different categories of terrestrial cover.

4. Visually interpreted classification of high-resolution satellite images that completely cover the world's Tropics.

FAO has already accomplished the first alternative, the second and third alternatives can be accomplished before mid-1992, and the fourth alternative would require 5 to 10 years to complete.

EVALUATION CRITERIA

These 4 alternatives were compared using 12 evaluation criteria that reflect FAO objectives, which are presented in more detail by Dr. K.D. Singh elsewhere in these workshop proceedings. These criteria are summarized in this section, including supporting rationale. More details are available in Czaplewski (1991a).

Given the controversial nature of tropical deforestation and the contradictions among existing global estimates, FAO must produce scientifically objective and credible estimates that can be trusted by various national and international institutions. If estimates used to support policy considerations are suspect, then technical methods used to produce the estimates become a central issue, diverting attention from more important issues and hindering development of consensus among institutions. Therefore, the FAO design should use statistically acceptable methods. Estimates should be reasonably precise and include a quantitative and objective measure of reliability to evaluate precision. Estimates should be

statistically unbiased, or nearly unbiased, relative to the precision of the estimates.

The FAO assessment requires more than a description of the current status and trends in the global condition of tropical forests. The assessment also requires an understanding of the processes that have caused the current condition and the effects of current policies. Therefore, the FAO statistical design should help institutions better understand the causes and effects of deforestation, and eventually afforestation and reforestation practices. This can be accomplished, in part, by development of quantitative models that predict the expected rate of deforestation based on social, technological, and environmental variables. Model predictions can be scientifically compared to observed rates of deforestation. Where the expected and observed rates agree, the predominant causal factors are likely included in the model, and there is more confidence that the major processes are reasonably well understood. Where the agreement is poor, additional study is required to hypothesize the cause of the disagreement and to incorporate additional predictor variables in the model. Reliable models are necessary to analyze future policy issues. The monitoring design should support this evolution of understanding.

Global monitoring is a massive task that requires effective cooperation among FAO, several other international institutions, and many national institutions. This requires logical motivation for each cooperating institution to contribute to joint efforts. Therefore, the FAO design should have utility to developing nations, which often require better mapping, inventory, and assessment of their national forest resources, including a stable institutional base to support these activities. For similar reasons, the design should have utility to international institutions. One of the implications of this is the ability to address global environmental issues, such as biomass, biodiversity, and opportunities for reforestation and afforestation.

The FAO design must have a high probability of success to support its global tropical forest resource assessment due by mid-1992. In the longer term, global monitoring should be conducted on a regular cycle to support assessments of existing and future policies. This requires a design that is adaptable to changing funding levels, both increases and decreases.

As will be discussed later, none of the 4 design alternatives is clearly superior relative to all 12 evaluation criteria. The short-term selection of one alternative necessitates compromises among FAO objectives, and their associated evaluation criteria. However, in the longer term, components of all four alternatives might be combined into a global monitoring system that adequately satisfies all objectives. This would preserve the value of investments in a design that is specialized for short-term objectives.

STATISTICAL ISSUES

Any system for credible global monitoring of tropical forests will have certain complexities that involve many statistical issues. Many of these issues are discussed in detail in Czaplewski (1991a). However, some of the more important issues are summarized in this section.

Sampling error is a well-known source of uncertainty in sample surveys. This primarily affects the third design alternative, which uses a sample of high-resolution satellite scenes and is briefly described above. However, all four alternatives are affected by substantial sources of nonsampling error.

Land uses are rapidly changing in many tropical regions. The informational value of past data is slowly lost because of changes in land use, such as conversion of forests to agricultural uses. In statistical terms, these changes introduce bias when past data are used to estimate current conditions. The magnitude

of this bias shifts with time, at different rates depending on the rate of change in land use. The magnitude of this bias can be estimated with models that predict the expected rate of change, and the bias can be corrected with these expectations. However, models introduce an additional component of uncertainty, known as prediction error.

The last three design alternatives use satellite data; many of the existing national inventories used in the first alternative also use satellite data. Missing data is a chronic problem with satellite images. Most images have some small cloud patches that are largely distributed randomly. Many tropical regions are dominated by clouds at most times, but adequate satellite images with minimal cloud cover are usually available during a 1-to-3-year interval. However, some areas have perpetual cloud cover, especially in equatorial Africa. In addition, many historical satellite scenes have not been archived and are not available, especially coarse-resolution satellite data.

Classification of land cover and land uses with satellite data is not a perfect process, and many sites are misclassified. This causes misclassification error in estimates of the percentage of a region occupied by different cover categories. For example, let Y equal the remotely sensed percentage of deforestation in a region, and X equal the true percentage of deforestation. The remotely sensed percentage is the following mathematical function of the true percentage:

$$Y = [H_A X] + [(1-H_B) (100\% - X)]$$

where H_A is the proportion of sites classified as deforested that are truly deforested, and H_B is the proportion of sites classified as forest that are truly forest. The equation shows that misclassification will bias area estimates from remote sensing; the remotely sensed percentage (Y) will not equal the true percentage (X) unless there are no omission errors; i.e., $H_A = H_B = 1$, or effects of omission errors exactly compensate; i.e., $(1 - H_B) (100\% - X) = (1 - H_A) X$. Assume

classification accuracies are high for all cover types (e.g., $H_A = H_B = 0.95$). If deforested areas truly cover 10 percent of a region, then the remotely sensed estimate will be 14 percent (see equation 1). In this example, the remotely sensed percentage will be 40 percent larger than the true value. If a small percentage of a common cover type is misclassified as a rare cover type, then the area occupied by the rare type will be overestimated, unless there is a high rate of omission error in classifying the rare type. The magnitude of misclassification bias is discussed in more detail by Czaplewski (1991b). Misclassification bias might explain some of the disturbing discrepancies between current estimates of deforested areas made with coarse-resolution satellite data by several international institutions and independent estimates made with photointerpretation of high-resolution satellite data by national institutions. Unexplained discrepancies reduce the credibility of all estimates.

Statistical calibration techniques can be used to remove the bias caused by misclassification. Calibration cannot identify misclassified pixels. Rather, calibration is a probabilistic technique; it uses proportions of imperfectly classified pixels in a sample of reference plots to estimate conditional probabilities of various types of misclassification, and these estimated probabilities are then used to predict the true percentage of each cover type given the remotely sensed percentages. For example, equation (1) can be solved for the true percentage of deforestation (X), given the remotely sensed percentage (Y) and the estimated conditional probabilities of correct classification (H_A and H_B). Since a sample of reference data is used to estimate these conditional probabilities, the estimates of H_A and H_B will contain sampling errors, and the estimated percentage of deforestation will include propagated errors from the calibration model. A sample of high-resolution satellite scenes is well suited as reference data to calibrate coarse-resolution satellite estimates. Hay (1988) discusses this general situation in more detail.

Statistical calibration requires accurate estimates of misclassification probabilities using reference plots from the region, and this requires accurate registration of high-resolution reference plots onto the lower resolution imagery. Registration error will cause error in the estimates of the conditional probabilities of correct classification (H_A and H_B) in equation (1). This error will be propagated through the calibration model and cause error in calibrated area estimates. Accurate registration can be difficult in certain landscapes, and effective quality control is required to minimize this source of error.

Classification of land cover into multiple categories presents a multivariate estimation situation. The sum of all cover categories equals exactly 100 percent of a region. Independent univariate estimates for each category will not necessarily add to 100 percent, which can reduce credibility. In addition, the estimation error variance for the sum of all cover categories equals exactly zero (because the sum of all cover types equals exactly 100 percent), even though area estimates for each category will have a nonzero variance caused by random sampling, prediction, or propagated errors. Therefore, the estimation error covariance matrix should have many negative covariance terms off the diagonal. For assessment purposes, different cover categories are often combined into less specific categories, and the estimation error variance for a combined category will be reduced if the negative covariance terms are properly considered. Also, the additivity constraint can make multivariate estimators more precise than independent application of univariate estimators to each category. However, the statistical methods for multivariate estimation are less developed than those for univariate estimation.

A systematic sample might improve statistical efficiency. However, systematic sampling might unknowingly align with systematic features within strata, and variance estimates for systematic sampling are more problematic than for random sampling. These

factors reduce credibility somewhat. It is also easier to intensify future random sampling if funding levels increase, but this is more geometrically difficult with systematic sampling.

The statistical efficiency of a sample of high-resolution satellite data scenes might be increased by sampling with probability proportional to size (PPS). The "size" of each possible sample unit could be defined as the expected rate of deforestation, or the expected extent of forests, within each potential sample scene. These expectations are available from existing FAO models and geographic information systems, which contain continental-scale maps. However, a PPS sample will cause inefficiencies if the FAO sample is used as permanent plots in a long-term monitoring program. For example, a sample unit with a high rate of deforestation between 1980 and 1990 might have a low rate between 1991 and 2000 because the forest resource in that sample unit might be depleted by 1990. Also, PPS requires proper consideration of the unequal probabilities of sample unit selection when fitting regression models, which might be used in future calibration estimators or deforestation models; weighted regression should be used, with weights inversely proportional to probability of selection. PPS will produce unbiased estimates. However, sample units with high rates of expected deforestation are selected with higher probabilities than sample units with low expected rates of deforestation. This fosters a misperception among non-statisticians that PPS will produce overestimates. Even though this perception is not based on statistical theory, this perception can reduce credibility of PPS estimates.

Other statistical issues are discussed by Czaplewski (1991a), which are summarized here. Several alternative sampling frames can be used for high-resolution satellite data, or calibration for misclassification bias with coarse-resolution satellite data: subnational geopolitical units, high-resolution satellite scenes, map sheets, aerial photographs, and field plots. Each

potential frame has advantages and disadvantages. Efficiency of sampling designs for high-resolution satellite data, or calibration of coarse-resolution satellite data, can be improved with stratification; there are numerous criteria that can be used with available data to stratify, and each potential set of criteria have advantages and disadvantages.

EVALUATION OF ALTERNATIVE STATISTICAL DESIGNS

None of the four design alternatives listed at the beginning of this paper are clearly superior given the evaluation criteria; this implies that some objectives will be satisfactorily served, while other objectives will not be fulfilled, at least in the short term. Therefore, selection of a design implies judgments regarding the priority of evaluation criteria.

The most important short-term objective is production of credible global estimates of deforestation rate (ha/yr) between 1980 and 1990, and secondarily on credible global estimates of the area extent (status) of tropical forests in 1990. To be credible, the estimates must be scientifically sound, unbiased, and reasonably precise. Without credible estimates, it is impossible to objectively defend their validity. Some degree of consensus is required among national and international institutions in order to implement policies that affect management of tropical forests. Consensus is best nurtured by credible information, and FAO is one of the few institutions capable of providing this information in a timely fashion. Until some consensus is achieved, changes in the current management of tropical forests are unlikely. Therefore, high priority should be placed on production of credible information in the near future.

The first design alternative is use of existing national inventories and deforestation models. It uses ad hoc methods similar to those used by FAO in 1980 for its previous assessment of tropical forest resources. This alternative produces estimates of unknown precision that

include unknown levels of bias. The expectation is that these estimates will be reasonably precise and unbiased, but this expectation cannot be scientifically defended. In fact, this alternative has already been implemented by FAO. However, FAO has decided to continue its progress by pursuing a complementary alternative that provides more defensible information.

The existing FAO data base has great value in that it can be used to more efficiently implement other design alternatives that are more credible to other institutions. This data base has also been used to model the rate of deforestation using empirical data on deforestation from existing national forest inventories, estimates of human population for subnational units, and maps of eco-floristic zones. This model is one initial step to better understand factors affecting the process of deforestation, which can help assess effects of policies on tropical forests. Therefore, past FAO efforts on this alternative serve an extremely useful purpose, and the value of these past efforts can be enhanced by progressing to a more scientifically credible design.

The second design alternative uses coarse-resolution satellite data to estimate the status of tropical forest cover in 1990. However, classification of 1.1 km² AVHRR pixels into a forest or nonforest category is not considered a reasonable definition of truth by national institutions; therefore, the credibility of data produced by this alternative is suspect.

This alternative cannot estimate the rate of deforestation between 1980 and 1990 because historical images near 1980 were not acquired or archived. This alternative might be used to make biased estimates of total deforestation to date for regions in which the past extent of forests is known. However, a deforestation model is required to estimate deforestation between 1980 and 1990, as in the previous alternative. Since the precision and bias of this model are not known, this alternative is not recommended for estimating deforestation.

Misclassification errors will bias coarse-resolution satellite estimates of tropical forest cover in 1991. Without a sample of higher resolution data, the magnitude of misclassification bias is cannot be scientifically estimated. Therefore, uncalibrated coarse-resolution satellite estimates lack credibility. Coarse-resolution satellite estimates can be calibrated for misclassification error, using existing forest inventories of subnational units. However, this requires a nonrandom sample of subnational units to build the statistical calibration model. There will be differences in dates of subnational inventories, and probably differences in definitions and measurement protocols. Therefore, the scientific credibility is suspect, and cannot be recommended for FAO objectives.

Coarse-resolution satellite data can be calibrated for misclassification error, using a sample of high-resolution satellite scenes. Presently, no institutional base has provided the necessary high-resolution satellite data that are needed to calibrate for misclassification bias. Therefore, this alternative is not recommended for implementation by FAO, although this decision could change if the accurately classified calibration plots were available in the future.

This alternative does have several short-term benefits. It provides a description of the geographic distribution of land uses that have caused deforestation and areas where tropical forest cover and current land uses are compatible. This is valuable to better focus national and international assessments and policy concerns in specific geographic areas. It also provides a picture of the current situation that can be rapidly and effectively communicated to policy makers and concerned publics. Furthermore, the present extent of tropical forest cover is one of several important predictors of deforestation in the FAO deforestation model. Even biased estimates of forest extent will improve application of the FAO deforestation model to relatively small geographic areas (e.g., subnational units) where current data on forest extent is not available.

Several international institutions are in the process of implementing this alternative, and results for the world's tropical forests are expected in the near future. FAO has attempted to assist these other institutions by facilitating archival of 1990 AVHRR digital images for the entire Tropics.

The third design alternative is a statistical sample using high-resolution satellite data. It emphasizes a scientifically credible, design-based statistical sample of high-resolution satellite data scenes for estimating area extent of tropical forests in 1990 and the rate of deforestation between 1980 and 1990.

This alternative does not use the FAO deforestation model to estimate deforestation between 1980 and 1990. Rather, it uses a randomized sample of high-resolution satellite data scenes (i.e., permanent plots) for which 1980 and 1990 images are available (although the FAO deforestation model can serve as stratification criteria to make this alternative more efficient). This alternative assumes that credible estimates of change in forest extent for each sample unit between 1980 and 1990 can be visually interpreted by comparing images for the same sample unit at two dates. This assumption is considered reasonable because many international institutions consider interpretations of coarse-resolution satellite data as truth, and many national institutions currently map their forest resources with visual interpretation of high-resolution satellite data.

This alternative prescribes a randomized sample of high-resolution satellite data scenes, which is expected to have high scientific credibility. However, the precision of this alternative depends on the sample size of plots used to estimate forest extent in 1990, and the rate of deforestation between 1980 and 1990. If this sample size is too small for a given region, then this alternative will not be credible because the precision of the estimates will be unacceptable. Preliminary estimates of sampling error have been made using the current FAO data base, and acceptable levels of precision

are expected using 100 high-resolution satellite data scenes for a global estimate; however, more intensive sampling is needed for higher spatial resolution, such as continents or multinational subregions. This alternative is discussed in more detail in the next section.

The fourth design alternative is complete mapping of the Tropics with high-resolution satellite data. This alternative emphasizes national objectives, but it also produces data for international objectives. A nonrandom sequence of cartographic units (i.e., map sheets) are visually interpreted by national institutions, using high-resolution satellite scenes, until entire nations are completely mapped. This will take 2 to 10 years for any single nation. Then, map sheets are reinterpreted using more recent imagery to estimate rates of area change such as hectares of deforestation.

This alternative requires complex statistical methods to produce relatively unbiased estimates of known precision. The nonrandom sequence requires a deforestation model to update area estimates for older map sheets. However, the bias and precision of model predictions can be objectively quantified using remeasurements of some map sheets each year for multinational subregions.

Although this alternative has desirable features for long-range FAO objectives, this alternative requires functional national institutions that do not currently exist in most tropical nations, and it will take years to develop such institutions in many nations. Complex model-based statistical methods are vulnerable to legitimate scientific criticism, which reduces the international credibility of this alternative. However, the FAO selection of the third alternative (i.e., randomized sample of high-resolution satellite data) facilitates an evolution toward this fourth design, which better serves national objectives. This is required for national and international policies that are based on credible, compatible, and mutually accepted information.

STATISTICAL DESIGN SELECTED BY FAO

All four alternatives except one lack the credibility that is needed to improve the current situation that faces FAO and the international community. Therefore, FAO has chosen a design based on a randomized sample of high-resolution satellite data scenes for estimating the extent of tropical forests in 1990 and the rate of deforestation between 1980 and 1990. This alternative places highest priority on credible estimates of tropical forest extent in 1990 and rates of deforestation between 1980 and 1990. This alternative produces the most credible estimates in the short term, assuming a sufficiently large sample of satellite scenes can be purchased and interpreted.

The first alternative, i.e., accumulation of existing data, has already been implemented by FAO, but the sample of high-resolution satellite scenes is required to improve credibility of existing estimates. Other international institutions are implementing the third alternative, i.e., coarse-resolution satellite data, but these institutions will not likely produce credible estimates of deforestation between 1980 and 1990. The fourth alternative, i.e., complete land cover and land use mapping of the global Tropics, has many desirable features in the long-term, but this alternative cannot be completed in time for the FAO assessment, due in mid-1992. However, the selected FAO alternative is a short-term design that will serve more long-term objectives, which will be discussed later.

The principal weakness of the high-resolution satellite data alternative is the potential lack of precision from a small sample size of high-resolution satellite data scenes, which is caused by cost and logistical requirements. Based on preliminary data in the current FAO data base, it appears that reasonable continental estimates of the status of tropical forest cover in 1990 can be estimated from a global sample size of 117 high-resolution satellite scenes, as shown in the following table.

Current estimate of sampling precision + x% at 95% probability level

Region/stratum	Confidence interval (%)	Landsat sample scenes
Central America and Mexico	+ 13	10
Tropical South America	+ 8	13
Brazil	+ 7	17
Latin America	+ 5	40
Africa	+ 8	47
Asia	+ 8	30

However, the confidence intervals for rate of deforestation between 1980 and 1990 are expected to be 1.5 to 2.0 times larger than confidence intervals for status in 1990. Also, confidence intervals for more detailed classifications of land cover and type of change will be greater. These factors will limit the spatial detail of the initial FAO assessment in mid-1992; reasonable precision might only exist for the global estimates, which would preclude detailed assessments for continental or subcontinental regions. More spatial detail is needed for global assessments, and opportunities to improve precision by building upon the FAO system are briefly discussed in the final section.

FUTURE GLOBAL MONITORING EFFORTS FOR TROPICAL FORESTS

Although a statistical sample of high-resolution satellite scenes appears best for short-term FAO objectives, the other three alternatives have certain advantages for midterm and long-term objectives. A far better course of action would be the eventual combination of the strengths of each alternative into a single, continuous system for monitoring and assessing tropical forest conditions. Without a continuous system, policy decisions are based on information that loses credibility over time. The selected FAO design should be considered as a

short-term step toward achieving a continuous system that combines the desirable features of many alternative monitoring procedures. Some of the opportunities for evolution toward better monitoring systems of the future are discussed in this section.

In cooperation with other international institutions, FAO's sample of high-resolution satellite data should be used to calibrate coarse-resolution satellite data estimates of tropical forest extent, which are now being developed by other international institutions. Calibration is required to correct for misclassification bias. Calibration for misclassification bias would reconcile inconsistencies and increase credibility of estimates from all participating institutions. The advantages of the spatial detail in coarse-resolution satellite data estimates could be combined with the advantages of unbiased FAO global estimates for all subnational units, even those for which high-resolution satellite data sample estimates were not available. This would greatly enhance the spatial resolution for unbiased FAO estimates of deforestation.

The sample size of high-resolution satellite data scenes should be increased after the initial FAO assessment is produced in mid-1992. High resolution satellite data imagery for 1980 and 1990 would be used to produce more precise estimates of deforestation between 1980 and

1990, and its status in 1990. For example, the global assessment might be based on 100 high-resolution satellite data scenes, but another 100 sample scenes might be interpreted in 1992, another 100 sample scenes in 1993, and another 100 sample scenes in 1994. This will continually improve the precision of the statistical estimates over the next few years for global estimates and estimates for subregions.

The sample of high-resolution satellite scenes should be continuously monitored after the initial FAO results are produced in 1992. This is one step towards achieving the FAO objective for continuous monitoring of tropical forests. For example, high-resolution satellite data scenes imaged in 1994 might be acquired for a portion of high-resolution satellite data sample scenes for which 1980 and 1990 high-resolution satellite data imagery was interpreted. Changes in forest cover and land uses between 1990 and 1994 would then be interpreted to produce a statistical estimate of deforestation between 1990 and 1994. The following year, high-resolution satellite data scenes imaged in 1995 might be acquired for a different portion of high-resolution satellite data sample scenes to produce a statistical estimate of deforestation between 1990 and 1995. An interpenetrating cycle of remeasurements of high-resolution satellite data would permit annual estimates of deforestation. The details of this progressive development of a continuous monitoring design require considerable thought and planning, but this might be deferred until the immediate FAO objectives are met in 1992. This would require more complex statistical estimators that incorporate a deforestation model in order to correctly treat a time series of remeasurements for high-resolution satellite data permanent plots. Also, a time series of high-resolution satellite data will permit calibration of future coarse-resolution satellite data estimates of deforestation.

Coarse-resolution satellite data estimates should be combined with model predictions of deforestation. If the other actions given previously are accomplished, unbiased

estimates of deforestation for all subnational units will be available from calibrated coarse-resolution satellite data estimates and calibrated predictions from the FAO deforestation model. Both types of estimates for each subnational unit will be unbiased with known precision, but the two estimates for each subnational unit will be different because of errors propagated from the statistical calibration models. However, the two estimates for each subnational unit can be combined into a single, more precise estimate with a multivariate composite estimator.

In cooperation with many institutions, FAO should maintain the data base for existing data for subnational units. This includes summary results of future forest inventories conducted by individual nations, and other estimates of forest extent, deforestation, reforestation, afforestation, and human population density. The FAO geographic information system that contains subnational unit boundaries and thematic maps of forest status should also be maintained. This data base has already been built by FAO and has been essential in the development of the FAO deforestation model. Improvements in the deforestation model require maintenance of the FAO data base. The deforestation model is essential for several of the actions above; also, the deforestation model is expected to be an important tool in future policy analyses for tropical forests. Additional tabular and geographic data should be acquired and maintained, such as road densities.

Forest mapping by national institutions should be supported. This is important for development of forest resource monitoring, assessment, and management at the national level. This can also benefit international monitoring and assessment activities. If national and international institutions can share the same information base, then credibility and successful coordination are more likely. The first step in this process is developing or strengthening national institutions that can consistently perform these functions, and transferring the necessary technologies to these institutions.

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