Can a sample of Landsat sensor scenes reliably estimate the global extent of tropical deforestation?

R. L. CZAPLEWSKI

USDA Forest Service, Rocky Mountain Research Station, 2150 Centre, Ave. Bldg. A Fort Collins CO 80526, USA; e-mail: rczaplewski@fs.fed.us

Abstract. Tucker and Townshend (2000) conclude that 'wall-to-wall coverage is needed to avoid gross errors in estimations of deforestation rates' because tropical deforestation is concentrated along roads and rivers. They specifically question the reliability of the 10% sample of Landsat sensor scenes used in the global remote sensing survey conducted by the Food and Agricultural Organization (FAO) of the United Nations. They base their conclusion on simulations with data from Bolivia, Columbia and Peru, in which the size of a 10% sample is $4 \leqslant n \leqslant 6$ Landsat sensor scenes. However, their conclusion is not valid when extrapolated to larger sample sizes (e.g. $n \geqslant 40$), such as those employed by the FAO and the European Commission for global and pantropical assessments.

1. Introduction

The FAO uses a 10% stratified random sample of Landsat sensor scenes to estimate the global extent of tropical deforestation from 1980 to 1990, and 1990 to 2000 (FAO 1996, 2001). However, Tucker and Townshend (2000) question the reliability of a 10% sample. They conclude: 'Because tropical deforestation is spatially concentrated, it is very improbable that an accurate estimate of deforestation by random sampling of Landsat scenes will be achieved', and they believe their 'results clearly have significant implications on the advisability of methods reliant on the sampling of Landsat images, such as those formerly used by the FAO'. Tucker further concludes in *Science* that 'a small and random sample—such as the 10% sample used by FAO—will give you grossly inaccurate numbers' (Stokstad 2001).

Tucker and Townshend (2000) base this conclusion on a statistical simulation study. They began with full coverage of 41 Landsat images for lowland Bolivia, 61 for Columbia and 45 for Peru. Deforestation is highly concentrated along roads and rivers in this region. For example, 75% of all deforestation by 1986 was contained within five Landsat images for Bolivia. To evaluate the reliability of estimates from a 10% sample, they drew a simple random sample of Landsat sensor scenes from each county ($4 \leqslant n \leqslant 6$), made a statistical estimate of deforestation with each sample, and independently repeated this process 200 times for each

country with different random samples. They then compared the distributions of 200 independent estimates to the true amount of deforestation, which is known exactly from the full coverage of Landsat images in their study.

2. Methods and results

This Letter reports upon a replication and extension of Tucker and Townshend's simulation study. It uses their data for the 41 Landsat images of lowland Bolivia (data for Columbia and Peru were not published). The sample size is $n = 4$ for a 10% sampling fraction in Bolivia. The resulting approximation of the empirical sampling distribution is identified as the 'national scale' in figure 1A. Only 3% of the simulated samples produce estimates of deforestation that are within $\pm 10\%$ of the true value (68% of the samples produce smaller estimates, and the remaining 29% produce larger estimates). Therefore, Tucker and Townshend's conclusion is valid within the bounds of their experimental design: it is very improbable that a sample size of $n = 4$ Landsat sensor scenes will achieve an accurate estimate of deforestation for Bolivia. However, further simulations demonstrate that their conclusion is not valid when extrapolated to larger sample sizes, such as those used by the FAO for the continental and pantropical geographic domains.

Extensions of Tucker and Townshend's simulations use FAO definition of the sampled population (FAO 1996). Ten of the 41 Landsat sensor scenes from Bolivia were omitted from the sampled population because they include only small slivers of forestlands in Bolivia; the remaining 31 scenes cover over 95% of the forestlands, and over 98% of the deforestation. Then, these 31 scenes were replicated four times ($n = 124$). This simulates a geographic domain that is four times larger than Bolivia, in which tropical deforestation is concentrated along roads and rivers exactly as in Bolivia. These 124 Landsat sensor scenes mimic an area that is approximately the size of a 'sub-continental' region, such as Central Africa, which is the smallest sampling domain considered by the FAO with their remote sensing survey (FAO 1996, 2001). Then, the empirical sampling distribution was approximated
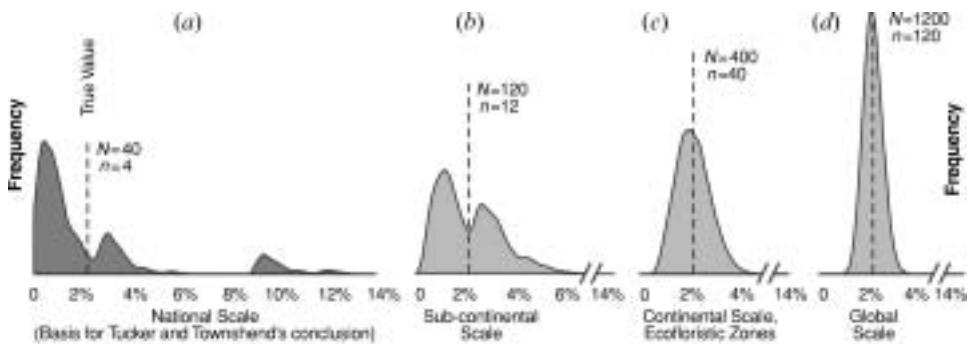

Figure 1. Empirical sampling distributions for deforestation estimates at different geographic scales. The horizontal *x*-axis is the estimated extent of deforestation, and the vertical *y*-axis is the expected frequency of that estimate over all possible samples. All simulations use a 10% sample of Landsat sensor scenes, and all have exactly the same spatial concentration of deforestation.

by drawing 100 000 independent random samples, each of which contained 10% of these 124 Landsat sensor scenes ($n=12$). The spread of the sampling distribution (see figure 1B) is reduced when the sample size increases from $n=4$ to $n=12$, even though the sampling fraction remains fixed at 10%. Therefore, any estimate from a sample size of 12 is much more likely to be near the true value than an estimate from a sample of four Landsat sensor scenes.

To evaluate FAO estimates for even larger geographic areas, Tucker and Townshend's data were replicated 13 times ($n=403$), which produces a simulation population approximately the size of all tropical forests within a single continent, or a pantropical ecofloristic zone, such as the moist tropics of the world (FAO 1996, 2001). One hundred thousand independent random samples were drawn, each with a sample size of $n=40$. The resulting sampling distribution is labelled as the 'continental scale' in figure 1C. Finally, Tucker and Townshend's data were replicated 40 times ($n=1240$), which produces a simulation population approximately equal in size to the entire tropical forest zone of the world. The corresponding sampling distribution is labelled as the 'global scale' in figure 1D.

Figure 1 shows that a sample estimate from the FAO global survey is more likely to be near its true value as the sample size increases, even when the sampling fraction is fixed at 10%. Deforestation in all of these simulation populations is spatially concentrated exactly as in lowland Bolivia, and all have the same sampling fraction of 10%. The only difference is the extent of the geographic area being analysed, and the resultant sample size.

3. Discussion

These simulations might understate the true accuracy of FAO estimates. The FAO uses stratified random sampling (FAO 1996), which is typically more efficient than simple random sampling. Those strata with higher expected rates of deforestation are sampled more intensively by the FAO. Furthermore, tropical deforestation in Central Africa and Southeast Asia is less spatially concentrated than Bolivia; therefore, the sampling error among Landsat sensor scenes in these simulations is higher than other parts of the global tropics.

The FAO also publishes official statistics on deforestation that are provided by each member nation (FAO 2001). However, national statistics have well known problems for global and multi-national assessments of tropical deforestation (Watson *et al.* 2000, Stokstad 2001). Each nation optimizes their own national forest inventory within their own funding constraints to address their own national issues; and the importance of international compatibility is too rarely considered. Few tropical nations regularly conduct national forest inventories, and many are incomplete and out of date. There is no universally accepted definition of forest cover, which has a major effect on national estimates for sparse forests in arid or cold regions. Funding disparities among nations cause differences in methods and data quality. Definitions and methods in each nation can change over time. Some national governments use expert opinion to adjust for these shortcomings, but expert opinion is difficult to validate and vulnerable to unknown biases. To partially compensate for these problems, the FAO uses an independent, scientific method to evaluate certain broad conclusions for large, multi-national regions. This method is a stratified random sample of 117 Landsat sensor scenes, objective measurements with globally consistent protocols and standards, consistent imagery

dates, and statistically valid estimation techniques (FAO 1996, 2001). This method allows statistical tests of hypotheses to make scientifically defensible inferences. The FAO does not use this method to make estimates for individual nations because the FAO sample size within most nations is too small for reliable estimates.

4. Conclusion

A sample of Landsat sensor scenes can provide reliable estimates of deforestation if the sample size is sufficiently large. In the results reported here, and in table 3 of Tucker and Townshend (2000), sufficient sample sizes range from 40 to 135 Landsat sensor scenes. Stratification and ratio estimators can increase efficiency and produce equally precise results with smaller sample sizes. These latter statistical methods are employed by the FAO (1996, 2001) and the TREES program at the Joint Research Centre of the European Commission (Achard *et al.* 2002).

Our knowledge of global rates and distribution of tropical deforestation is surprisingly limited, even though the need for scientifically reliable data is critically important in the study of the global carbon budget (Achard *et al.* 2002) and sustainable forestry. A sufficiently large sample of Landsat sensor scenes can be one valid and cost-effective method to rapidly produce such knowledge for global, pantropical, continental, and large sub-continental geographic areas.

References

ACHARD, F., EVA, H., STIBIG, H.-J., MAYAUX, P., GALLEGO, J., RICHARDS, T., and MALINGREAU, J-P., 2002, Determination of deforestation rates of the world's humid tropical forests. *Science*, **297**, 999–1002. http://www.gvm.sai.jrc.it/Forest/PublicationsForest.htm.

FAO, 1996, Forest Resources Assessment 1990: survey of tropical forest cover and study of change processes. Forestry Paper No. 130, Food and Agricultural Organization of the United Nations, Rome.

FAO, 2001, Global Forest Resources Assessment 2000: main report. Forestry Paper No. 140, Food and Agricultural Organization of the United Nations, Rome. http://www.fao.org/forestry/fo/fra/main/index.jsp.

STOKSTAD, E., 2001, UN Report suggests slowed forest losses. *Science*, **291**, 2294.

TUCKER, C. J., and TOWNSHEND, J. R. G., 2000, Strategies for monitoring tropical deforestation using satellite data. *International Journal of Remote Sensing*, **21**, 1461–1471.

WATSON, R. T., NOBLE, I. R., BOLIN, B., RAVINDRANATH, N. H., VERARDO, D. J., and DOKKEN, D. J., 2000, *Land Use, Land-Use Change and Forestry* (Cambridge: Cambridge University Press).