Sampling strategies for estimating accuracy and area in a long-term land-cover monitoring program

Stephen V. Stehman
State University of New York (SUNY)
College of Environmental Science and Forestry
320 Bray Hall, 1 Forestry Drive
Syracuse, NY 13210 USA
svstehma@syr.edu

Abstract

Accuracy assessment of land-cover change products creates challenging problems of sampling design and analysis particularly because change is typically rare, and in a detailed land-cover monitoring program specific types of change may be exceedingly rare. Stratified sampling is often implemented to increase the sample size from rare classes, but how to define strata and allocate the sample to these strata has not been investigated when a time series of land-cover products must be assessed. An evaluation of different options for implementing stratified sampling for a multiple date accuracy assessment will be conducted and results used to provide recommendations on the design and analysis of such studies.

Keywords: sampling design, model-assisted estimation, accuracy assessment, stratification, area estimation

1. Introduction

Global, continental, and national land-cover monitoring programs have been established on the basis of using remote sensing to construct complete coverage maps. These mapping efforts typically include collection of a sample of “reference data” (i.e., high quality information on ground condition) that is used to estimate various measures quantifying accuracy of the map and also used as the basis for estimating area of land-cover at a given point in time (i.e., status) and area of change in land-cover (i.e., trends). A primary goal of accuracy assessment is to obtain precise estimates of accuracy for each class, where a class may be a particular type of land cover or a type of land-cover change. These class-specific measures include user’s and producer’s accuracies, or their complementary measures commission and omission errors. Typically some classes occupy only a small proportion of area of the landscape. Unless the overall sample size for the accuracy assessment is very large, these rare classes will be represented by small sample sizes if equal probability designs such as simple random or systematic sampling are implemented. The small sample size often results in relatively large standard errors for the class-specific accuracy estimates. Land-cover change is a typical example of a rare class, but change is one of the key features that a land-cover monitoring strategy must be able to address. Accordingly, stratified sampling is often recommended to increase the sample size from a rare class for the purpose of reducing standard errors of the estimates.

A second use of the sample of reference data obtained from an accuracy assessment is to estimate area. In the basic approach to estimating area, a complete coverage map is viewed as a source of auxiliary information that can be incorporated in a model-assisted estimator. That is, the map data are the not the basis of the estimate of area, but instead the map contributes to reducing the standard error of an area estimator that is based on the reference classification of the sample units. Model-assisted estimation is a strategy that takes advantage of auxiliary information to reduce standard errors of estimates of key parameters. Although a model is used in model-assisted estimation, the goodness of fit of the data to the model affects the reduction in standard error achieved by the estimator, but the basic properties of the estimator (e.g., approximate unbiasedness and validity of variance formulas) are not dependent on whether the model is a good representation of reality (Särndal et al. 1992, p. 227). The inference is "assisted" by the model but not dependent on the model. Poststratified estimation is a commonly used example of model-assisted estimation of area (Stehman 2009). Olofsson et al. (2013) advocated for use of such estimators to enhance precision of land change area estimates and Stehman (2013) evaluated the performance of several model-assisted area estimators associated with the error matrix analyses typically conducted with accuracy data.

The sample of reference data can thus address two important objectives, estimating accuracy and estimating area. The question of how to construct a sampling strategy that effectively achieves both objectives is addressed by this research. Stehman (2012) investigated how to allocate sample size to strata to accommodate the dual objectives of accuracy estimation and area estimation for the case of two classes (e.g., change and no change) for a single change period. However, it is necessary to extend these studies to determine recommended sample allocations when more than two classes are of interest, as for example when four classes are mapped such as persistent forest, deforestation, forest degradation, and forest gain. Moreover, in the case of a long-term monitoring program (e.g., monitoring forest change), the temporal dimension of monitoring becomes critical as questions related to stratification over time are introduced. For example, for estimating accuracy and area for 5-year time intervals in a long-term monitoring program, is it better to employ a single stratification or to revise strata for different change periods? Given that model-assisted estimation can incorporate the same information that is used to construct strata, perhaps a better strategy is to forego stratification entirely and instead use the map information via a model-assisted estimator for each time interval.

The objectives are to: 1) develop guidelines for sample size allocation to strata and total sample size to produce precise estimates of proportion of area for more than two classes; 2) develop recommendations for defining strata and allocating sample size when accuracy and area estimates are required for multiple land change types and multiple time periods; and 3) compare precision of stratified random sampling estimators (including different sample allocations to strata) relative to model-assisted estimators used with simple random sampling to evaluate whether map information is more effectively incorporated in the sampling design or in a model-assisted estimator. The technical approach is founded on comparing standard errors of the area estimators. All estimators considered are design-unbiased estimators, so the goal is to provide recommendations on sample allocation and sample size based on standard errors of these estimators.

2. Methods

Standard errors for accuracy and area estimators will be computed for different choices of strata (including the option of not using stratification in the sampling design), sample size and sample allocation for a wide variety of scenarios (i.e., different population error matrices) in which the characteristics of the error matrix are varied to mimic anticipated outcomes of real-world applications. The evaluation of the different sampling strategies will examine the case where land-cover monitoring includes at least five time intervals. The key characteristics to vary are overall accuracy, class-specific accuracy, and the proportional distribution of different classes (e.g., the proportion of a relatively rare class representing a change such as deforestation could be varied from 0.001 to 0.15 per time interval). Once a hypothetical population error matrix with the specified features is created, the standard errors can be computed for the target estimates of area and for estimates of class-specific accuracy.

3. Results

Table 1 shows an example of empirical results that can be used to compare different options for choosing strata and allocating the sample to strata. In Table 1, three stratification options are identified for estimating percent area of forest loss for different time periods (3 years and 12 years). The stratification options listed as ST1, ST2, and ST3 are based on different auxiliary information used to create the strata, where in each case the auxiliary information is a prediction of change for each block in the population. The sample size allocations to strata are optimal (opt), proportional (prop), and equal, with the standard error of simple random sampling (SRS) included as a baseline for comparison to the stratified sampling options.

Table 1 illustrates one of the important features of an investigation of designs used for estimation at multiple time periods, which is how well strata work for different estimates (in this case 3 year and 12 year change). ST3 with optimal allocation yields the smallest standard errors for both the 3 year and 12 year change intervals, but the standard errors for the 3 year estimates are much smaller than the standard errors for the 12 year estimates. If a particular stratification proves beneficial when proportional allocation is implemented, this stratification offers potential for use in a poststratified estimation strategy because poststratified estimation has precision nearly the same as the estimator from stratified sampling with proportional allocation. ST2 performs well for proportional allocation so there would be some potential advantage to choosing ST2. In a multi-objective accuracy assessment, optimization the sampling design for one objective may be detrimental to the precision for other accuracy or area estimates, so poststratified estimation with an equal probability sampling design is an appealing option.

Table 1. Comparison of standard errors for estimating percent forest cover loss over a 3 year and a 12 year time period under different stratification options and sample allocations to strata (number below each stratum label represent number of blocks in the stratum, and numbers below "Opt" are sample sizes for optimal allocation based on a total sample of 100 blocks).

ST1	Opt	ST2	Opt	ST3	Opt
12276	1	6987	35	19147	14
7992	53	3115	30	15534	56
16721	45	27387	35	2808	31

Standard errors (best stratification for each allocation underlined)

	3 year			12 year		
	ST1	ST2	ST3	ST1	ST2	ST3
Optimal	.153	.135	.122	.508	.394	.338
Prop	.205	.186	.175	.644	.539	.471
Equal	.186	.135	.138	.621	.399	.402
SRS	.230	.230	.230	.761	.761	.761

4. Conclusions

Improvements in satellite remote sensing will continue to generate new statistical challenges because better technology will create more opportunities for enhanced monitoring of land cover. The availability of very high resolution imagery for collecting reference data has enhanced the quality of reference data used to validate land-cover products, and the development of methods to process dense time series of Landsat images has opened up the possibility of more frequent temporal monitoring. Sampling and estimation protocols will need to keep pace with these developments in remote sensing technology. In particular, statistical challenges related to sampling design and estimation for validation of annual land-cover products will need to be addressed. The work reported in this article is one small step in the process of developing the necessary tools.

References

Olofsson, P., Foody, G. M., Stehman, S. V., and Woodcock, C. E. (2013). Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation, *Remote Sensing of Environment*, 129, 122-131.

Särndal, C. E., Swensson, B., and Wretman, J. (1992). Model-Assisted Survey Sampling. Springer-Verlag, New York.

Stehman, S. V. (2009), Model-assisted estimation as a unifying framework for estimating the area of land cover and land-cover change from remote sensing, *Remote Sensing of Environment* 113: 2455-2462.

Stehman, S. V. (2012). Impact of sample size allocation when using stratified random sampling to estimate accuracy and area of land-cover change. *Remote Sensing Letters* 3, 111-120.

Stehman, S. V. (2013). Estimating area from an accuracy assessment error matrix, *Remote Sensing of Environment* 132, 202-211.