Can a Forest/Nonforest Change Map Improve the Precision of Forest Area, Volume, Growth, Removals, and Mortality Estimates?

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Abstract.—In an extensive forest inventory, stratifications that use dual-date forest/nonforest classifications of Landsat Thematic Mapper data approximately 10 years apart are tested against similar classifications that use data from only one date. Alternative stratifications that further define edge strata as pixels adjacent to a forest/nonforest boundary are included in the test. The variance of stratified estimates of total forest area, volume, growth, removals, and mortality are used to compare results. The two classifications tested are the 1992 and 2001 National Land Cover Data (NLCD) maps, referred to as NLCD-92 and NLCD-01, respectively. The study area is the Minnesota portion of Mapping Zone 41, an area that covers 60 percent of Minnesota and contains 90 percent of the State's forest. Permanent plot data from nearly 6,500 samples measured over the period 1999 to 2002 are used to compare the alternatives that include four different edge stratifications at the forest/nonforest boundary: one 2-pixel wide stratum, one 4-pixel wide stratum, two 1-pixel wide strata, and two 2-pixel wide strata. Estimates that use stratifications based only on the NLCD-92 were found to be more precise than estimates that used only the more recent NLCD-01 for stratification. Change-based stratifications (those that incorporated the NLCD-92 and NLCD-01) produced estimates with lower variances than estimates based on either single-date stratification alone, with the largest differences observed for the forest area estimates and smaller differences observed for estimates of volume, mortality, growth, and removals.

The Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service has implemented an annual forest inventory system on a State-by-State basis in which a proportion of plots are measured in each State each year. The sampling design consists of rotating panels of permanent sample plots; the intent is to measure one complete panel each year. The time between inventories varies among States because of funding limitations and varying information needs. Population estimates and their sampling errors are calculated using stratified estimation with strata derived from classified satellite imagery. For the 11-State North Central region, stratifications derived from the 1992 National Land Cover Data data set (NLCD-92), developed by the Multi-Resolution Land Characterization Consortium (MRLC), have demonstrated that they can decrease forest area (FA) estimate variances by a factor exceeding 3.5 and volume (V) estimates by a smaller factor (Hansen and Wendt, 2000; McRoberts *et al*. 2002).

If the above stratifications derived from forest/nonforest classifications are effective in increasing the precision of estimates of forest attributes such as FA and V, analogy stratifications derived from forest change classifications may be effective in increasing the precision of estimates of forest change attributes such as growth (G), removals (R), and mortality (M). Completion of a final draft of a new National Land Cover Data data set (NLCD-01) by MRLC for most of Minnesota's forested area (fig. 1) provides the opportunity to construct such a land cover change classification. Our study's objective was to compare the precision of stratified FA, V, G, R, and M estimates using single-date stratifications derived from NLCD-92 and NLCD-01 and change-based classifications derived from NLCD-92 and NLCD-01 combined.

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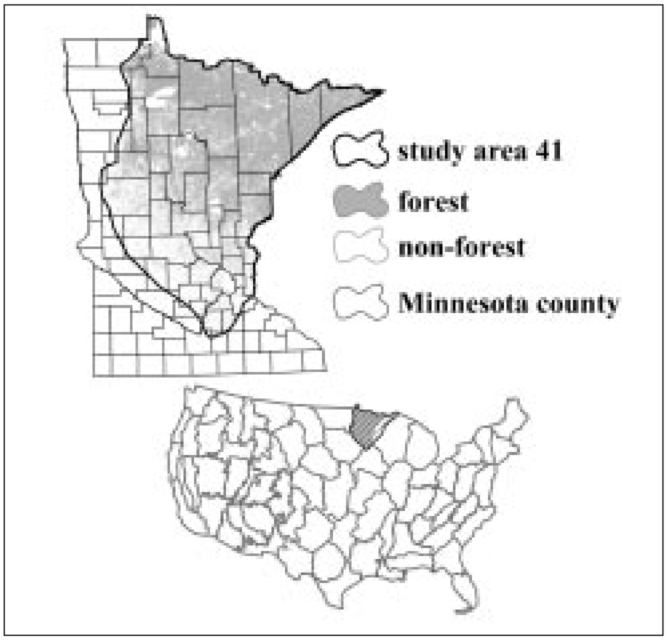
Figure 1.—*Mapping zones of the contiguous United States, with Minnesota study area.*



Data

Study Area

Our study was conducted for the Minnesota portion of the MRLC Mapping Zone 41 (fig. 1) for which the final draft of NLCD-01 is completed. Mapping Zone 41 encompasses 33,025,274 acres, including approximately 60 percent of Minnesota's total land area and about 90 percent of the State's forested land area.

Land Cover Classifications

NLCD-92 is a 21-class land cover map of the conterminous United States at 30 m x 30 m resolution. The U.S. Geological Survey developed NLCD-92 under the auspices of MRLC using nominal 1992 Landsat 5 Thematic Mapper (TM) imagery and ancillary data (Vogelmann *et al.* 2001). NLCD-01 has similar characteristics but is based on nominal year 2001 Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images (Homer *et al.* 2002).

FIA Plot Data

Inventory data were obtained from FIA plots in the study area that were measured between 1999 and 2002. Each FIA plot consists of a cluster of four 1/24-acre, fixed radius, circular subplots distributed over approximately 1 acre. FA and V estimates were based on observations of all 6,492 plots in the study area; G, R, and M estimates were based on observations from the 3,535 plots measured for the 1990 periodic inventory and the first four panels (1999–2002) of the annual inventory. Fewer plots were available for estimating G, R, and M because estimates for these change variables require measurements for two inventories; FA and V estimates, however, require measurements for only one inventory. The sample size decreased for two reasons: some plots were removed from the inventory during the transition from periodic to annual inventories, and other plots could not be relocated during the annual inventory. Each FIA plot is linked to the NLCD-92 and NLCD-01 pixels in which the plot center is located. Most plot center locations were obtained using global positioning system (GPS) receivers, although locations of plots that digital orthophoto quad analysis determined had no accessible forest land were obtained instead with digitization methods. The accuracy standard for FIA plot locations is ± 140 feet (43.7 m) of the true location for 99 percent of the plots. A USDA Forest Service study reported the accuracy of GPS receivers of the kind used by FIA field crews to average approximately 7.9 m with maximum errors of approximately 20 m (Karsky *et al.* 2001). Therefore, we were certain that plot centers were linked to the 30 m x 30 m TM pixel containing the plot center or an adjacent pixel.

Methods

Stratifications

All stratifications were based on aggregations of NLCD classes into two initial classes, forest and nonforest. For both NLCD classifications, the forest class was constructed by aggregating the three NLCD forest classes (41—deciduous forest, 42—evergreen forest, and 43—mixed forest), the woody wetlands class (91—woody wetlands), and the shrub land class (51—shrub land for NLCD-92 and 52—short shrub land for NLCD-01). In addition, the NLCD-92 transitional class representing land in transition to forest was also grouped in the NLCD-92 forest class. No comparable class was identified in NLCD-01. The aggregated forest classes were constructed to be consistent with

FIA forest land definitions. To conform to the FIA requirement that forest land be at least 1 acre, a clump and eliminate algorithm (ERDAS 1997) was applied to the initial forest/nonforest classifications to eliminate 1-acre and smaller areas in each class.

Five stratifications were derived from each of the two NLCD aggregated forest/nonforest classifications. Two single-date forest/nonforest stratifications were constructed, one obtained directly from the NLCD-92 aggregated forest/nonforest classification and designated SDS2-92 and the other obtained directly from the NLCD-01 aggregated forest/nonforest classification and designated SDS2-01. In stratification designations, SDS is a single-date stratification, 2 means two strata [forest (F) and nonforest (NF)], and 92 and 01 refer to the NLCD classifications the stratifications were based on. Two edge strata were derived from each single-date forest/nonforest stratification based on the recommendations of Hansen and Wendt (2002) and McRoberts *et al.* (2002). The forest edge stratum (FE) consisted of pixels in the F stratum within one pixel of a forest/nonforest boundary, and the nonforest edge stratum (NFE) consisted of pixels in the NF stratum within one pixel of a forest/nonforest boundary. These stratifications are designated SDS4-92-1P and SDS4-01-1P, where 4 refers to four strata and 1P to the one-pixel edge strata width. Similar stratifications were constructed using a two-pixel edge stratum width and were designated SDS4-92-2P and SDS4-01-2P. The two edge strata, FE and NFE, were also collapsed into a single transition (T) stratum. For stratifications with one-pixel edge strata widths, the T stratum was two pixels wide; for the stratifications with two-pixel edge strata widths, the T stratum was four pixels wide. These stratifications were designated SDS3-92-2T, SDS3-01-2T, SDS3-92-4T, and SDS3-01-4T. The five SDS classifications based on NLCD-01 are depicted in figure 2, where the white dot indicates an FIA plot center.

Five change-based stratifications were constructed by creating two-way classifications of comparable single-date stratifications derived from the NLCD-92 and NLCD-01 (fig. 3). The *n* main diagonal cells of the two-way classifications are strata for which the assignments of pixels to NLCD 92 and NLCD 01 strata are identical; n^2-n off diagonal cells are strata for which assignments of pixels to NLCD 92 and NLCD 01 strata changed. Thus, NF-NF defines the change-based stratum for which the NLCD 92 and NLCD 01 strata pixel assignments were NF; F-NF defines the change-based stratum for which the NLCD 92 and NLCD 01 strata pixels assignments changed from F to NF. However, we exercise caution in attributing actual ground change to pixels assigned to change strata, i.e., any strata off the diagonal in figure 3. Classification errors in NLCD-92, NLCD-01, or both will cause some erroneous pixel assignment to change strata even though no actual ground change occurs. In addition, error in image or NC-FIA plot registration will cause some erroneous pixel assignment to change strata. Although image misclassification and GPS plot location registration error reduces the effectiveness of the strata derived from classification by

Figure 2.—*GPS monumented FIA plot (white dot) that straddles two land use conditions on a 1992 digital orthophotograph subset (a). Also shown is the stratification mapping progression of the 1992 digital orthophotograph compared to the (b) SDS2-01 (c), SDS3-01-2T (d), SDS4-01-1P (e) SDS3-01-4T, and (f) SDS4-01-2P stratifications.*

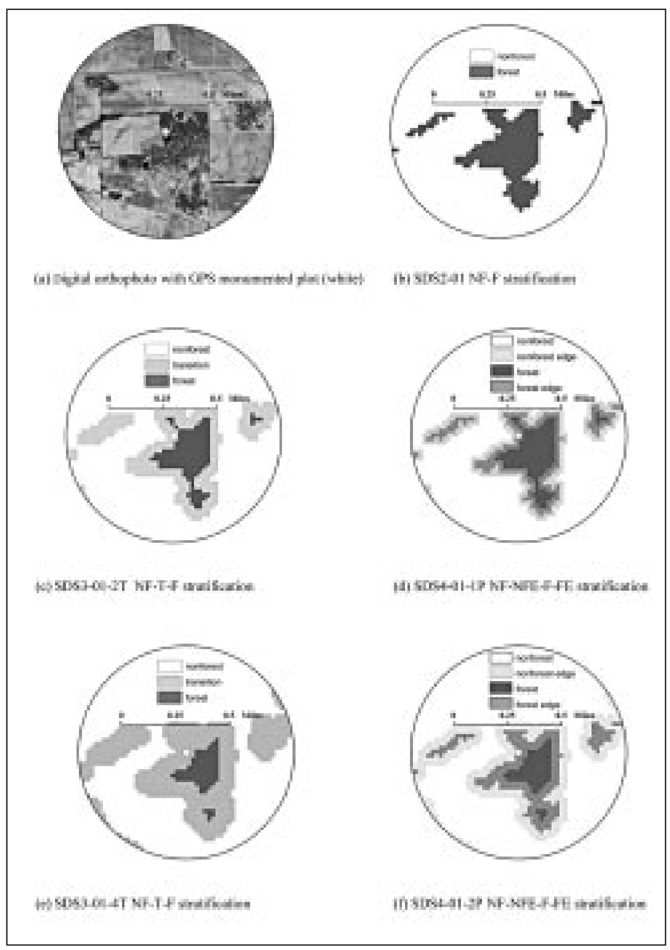
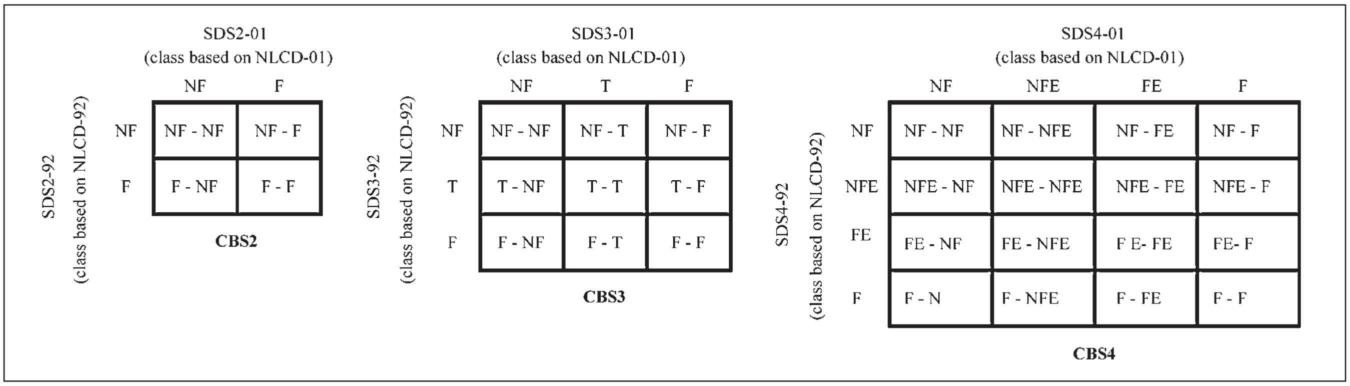


Figure 3.—*CBS2, CBS3, and CBS4 change-based stratifications. For change-based stratifications,* n^2 *classes are possible, where* n *is the number of classes and* $(n^2 - n)$ *off-diagonal possible change classes.*



decreasing precision, they will not produce bias in the estimates as long as the misclassifications are independent of ground sample plots. If using a consistent technique that does not incorporate the ground plot classification used later for estimation, the estimates will be unbiased.

The five change-based stratifications are designated using change-based stratification (CBS). CBS2 is based on SDS2-92 and SDS2-01, CBS3-2T on SDS3-92-2T and SDS3-01-2T, CBS3-4T on SDS3-92-4T and SDS3-01-4T, CBS4-1P on SDS4-92-1P and SDS4-01-1P, and CBS4-2P on SDS4-92-2P and SDS4-01-2P. Table 1 summarizes all stratifications.

Table 1.—*Stratification alternatives.*

Stratification	Description	Edge/transition strata	No. strata
No stratification			
SRS	Simple random sample	None	1
Single-date, NLCD-92			
SDS2–92	NLCD 92 F/NF	None	2
SDS3–92–2T	NLCD 92 F/T/NF	2 pixel transition	3
SDS3–92–4T	NLCD 92 F/T/NF	4 pixel transition	3
SDS4–92–1P	NLCD 92 F/FE/NFE/NF	1 pixel edge	4
SDS4–92–2P	NLCD 92 F/FE/NFE/NF	2 pixel edge	4
Single-date, NLCD-01			
SDS2–01	NLCD 01 F/NF	None	2
SDS3–01–2T	NLCD 01 F/T/NF	2 pixel transition	3
SDS3–01–4T	NLCD 01 F/T/NF	4 pixel transition	3
SDS4–01–1P	NLCD 01 F/FE/NFE/NF	1 pixel edge	4
SDS4–01–2P	NLCD 01 F/FE/NFE/NF	2 pixel edge	4
Change-based			
CBS2	NLCD 92-01 F/NF change	None	4
CBS3–2T	NLCD 92-01 F/T/NF change	2 pixel transition	9
CBS3–4T	NLCD 92-01 F/T/NF change	4 pixel transition	9
CBS4–1P	NLCD 92-01 F/FE/NFE/NF change	1 pixel edge	16
CBS4–2P	NLCD 92-01 F/FE/NFE/NF change	2 pixel edge	16

Stratified Estimation

Stratified estimates and sampling errors were calculated using post-stratification estimators (Cochran 1977) with finite population correction ignored. Estimates of population totals were calculated with this formula:

$$\hat{Y}_{Str} = A\sum_{h=1}^{L} W_h \bar{y}_h \quad (1)$$

Estimates of sampling errors were calculated as follows:

$$S_{\hat{Y}_{Str}} = A\sqrt{\frac{1}{n}\sum_{h=1}^{L} W_h^2 s_h^2} \quad (2)$$

where h denotes stratum, L is the number of strata, n is the total number of plot observations, $\bar{y}_h$ and s_h^2 are the observed sample mean and variance in stratum h, W_h is the weight for stratum h calculated as the proportion of pixels assigned the stratum, and A is the population area defined as the Minnesota portion of Mapping Zone 41.

Analyses

FA, V, G, R, and M estimates were calculated using [1] and [2] for the 15 stratifications and compared using two measures. The first measure, relative efficiency (RE), was calculated with this formula:

$$RE = S^2_{\hat{Y}_{SRS}} / S^2_{\hat{Y}_{Str}} \quad (3)$$

where $S^2_{\hat{Y}_{SRS}}$ is the variance of the estimate obtained under the assumption of simple random sampling (SRS) that uses no stratification, and $S^2_{\hat{Y}_{Str}}$ is the variance obtained using stratified estimation. RE values close to 1.0 indicate that the stratification has little use in increasing precision; RE values greater than 1.0 indicate increasing utility. RE is equivalent to the factor by which the sample size must be increased to obtain the same variance under SRS obtained using stratified estimation. The second measure was based on converting the observed sampling error to a percent per specified area or volume (Hansen 2001). This measure is reported in FIA publications as the sampling error per million acres for FA estimates and the sampling error per billion cubic feet for V, G, R, and M estimates. The percent sampling error per S, where S is 1 million acres or 1 billion cubic feet, is calculated as follows:

$$E_S = \frac{S_{\hat{Y}_{Str}}}{\sqrt{S}} 100\% \quad (4)$$

FIA guidelines are $E_s \leq 3.0$ for FA and $E_s \leq 5.0$ for V, G, and R.

Results

We noted several important results. First, the stratifications generally improved the precision of estimates (table 2). For FA, RE > 2.0 indicates that the stratifications were effective; however, for V, G, M, and R, RE only slightly greater than 1.0 indicates that the stratifications were less effective.

Second, FIA precision guidelines were satisfied or nearly satisfied for all variables except V. $E_s \approx 3.0$ indicates that the FIA precision guidelines were nearly satisfied for FA; $E_s < 5.0$ indicates that the guidelines were satisfied for G and R estimates; but E_s near 7.0 indicates that the precision guidelines were not satisfied for V.

Third, generally, the most precise estimates were obtained using one of the change-based stratifications, although RE with the change-based stratifications was often only slightly greater than with single-date stratifications. We attributed this result to the increased precision from more strata with the change-based stratifications.

Fourth, estimates obtained with single-date stratifications with three or four strata were more precise than estimates obtained with single-date stratifications with only two strata, although precision estimates for the stratifications with three and four strata were similar. Nevertheless, adding edge and/or transition strata increased precision.

Fifth, estimates were more precise when using single-date stratifications derived from NLCD-92 than those derived from NLCD-01 for all variables except V, for which the results were mixed. Although the differences were small, the trend is pronounced. The only apparent explanation for this phenomenon is that the aggregated forest and nonforest classes obtained from NLCD-92 conformed better to FIA definitions of forest land than did the classes obtained from NLCD-01, even with the nearly 10-year gap between the two sets of images. One possible reason is including the transition class in the NLCD-92 aggregated forest class.

Table 2.—*Estimates by stratification alternative.*

Stratification		Forest area (million ac)				Volume (billion ft³)				Growth (million ft³/yr)				Mortality (million ft³/yr)				Removals (million ft³/yr)			
	L	$\hat{Y}$	$S_{\hat{Y}}$	E_S	RE	$\hat{Y}$	$S_{\hat{Y}}$	E_S	RE	$\hat{Y}$	$S_{\hat{Y}}$	E_S	RE	$\hat{Y}$	$S_{\hat{Y}}$	E_S	RE	$\hat{Y}$	$S_{\hat{Y}}$	E_S	RE
SRS	1	14.72	0.195	5.08	1.00	16.36	0.325	8.04	1.00	306.8	17.06	3.08	1.00	336.1	13.32	2.30	1.00	305.3	20.75	3.75	1.00
SDS2–92	2	15.19	0.128	3.28	2.33	16.89	0.287	6.98	1.28	284.3	15.47	2.90	1.22	309.9	11.72	2.10	1.29	282.4	19.02	3.58	1.19
SDS2–01	2	15.25	0.131	3.36	2.20	16.97	0.288	6.99	1.28	286.0	15.54	2.91	1.21	312.6	11.85	2.12	1.26	291.9	20.02	3.71	1.07
SDS3–92–2T	3	15.16	0.122	3.12	2.57	16.86	0.283	6.90	1.32	279.4	15.21	2.88	1.26	305.0	11.52	2.09	1.34	277.6	18.79	3.57	1.22
SDS3–01–2T	3	15.17	0.125	3.20	2.45	16.86	0.285	6.94	1.30	281.8	15.35	2.89	1.24	308.0	11.70	2.11	1.30	288.7	19.81	3.69	1.10
SDS3–92–4T	3	15.14	0.128	3.28	2.33	16.82	0.288	7.02	1.27	282.5	15.39	2.90	1.23	307.7	11.65	2.10	1.31	279.8	18.80	3.55	1.22
SDS3–01–4T	3	15.05	0.131	3.39	2.20	16.73	0.287	7.02	1.28	282.4	15.43	2.90	1.22	308.9	11.80	2.12	1.27	289.1	19.81	3.68	1.10
SDS4–92–1P	4	15.19	0.120	3.08	2.64	16.89	0.283	6.88	1.32	279.7	15.24	2.88	1.25	305.0	11.52	2.09	1.34	278.0	18.83	3.57	1.21
SDS4–01–1P	4	15.22	0.123	3.15	2.52	16.94	0.284	6.90	1.31	282.2	15.38	2.89	1.23	308.5	11.70	2.11	1.30	289.1	19.82	3.69	1.10
SDS4–92–2P	4	15.20	0.121	3.09	2.61	16.90	0.284	6.91	1.31	281.4	15.28	2.88	1.25	306.6	11.54	2.08	1.33	279.0	18.73	3.55	1.23
SDS4–01–2P	4	15.19	0.124	3.19	2.46	16.91	0.284	6.91	1.31	282.3	15.37	2.89	1.23	308.7	11.69	2.10	1.30	288.9	19.76	3.68	1.10
CBS2	4	15.28	0.121	3.09	2.60	16.99	0.283	6.86	1.32	282.3	15.34	2.89	1.24	308.4	11.60	2.09	1.32	281.9	18.97	3.57	1.20
CBS3–2T	9	15.16	0.114	2.94	2.91	16.87	0.280	6.81	1.35	278.9	15.14	2.87	1.27	302.3	11.40	2.07	1.37	271.9	18.61	3.57	1.24
CBS3–4T	9	15.11	0.119	3.05	2.70	16.81	0.283	6.90	1.32	279.4	15.13	2.86	1.27	303.1	11.41	2.07	1.36	274.3	18.92	3.61	1.20
CBS4–1P	16	15.20	0.114	2.92	2.92	16.94	0.280	6.80	1.35	279.7	15.23	2.88	1.26	303.6	11.47	2.08	1.35	271.7	18.45	3.54	1.26
CBS4–2P	16	15.20	0.114	2.92	2.93	16.95	0.281	6.83	1.34	280.3	15.17	2.87	1.26	304.1	11.40	2.07	1.37	272.9	18.50	3.54	1.26

L = number of strata.
$\hat{Y}$ = estimated total.
$S_{\hat{Y}}$ = sampling error.
E_S = sampling error per million acres (area) or billion cubic feet (volume).
RE = relative efficiency.

Finally, stratified estimates of the mean were similar for all variables, but SRS estimates differed from the stratified estimates. This result is attributed to forested strata undersampling for two reasons: first, some private land owners refused to allow FIA crews to measure plots on their lands, and second, some forested plots could not be relocated at the time of the second inventory. The undersampling generally did not occur for nonforested strata because plots determined to have no accessible forest land based on digital orthophoto quad analyses were not visited by field crews; hence, land owner permission was not required, and plots did not have to be relocated. Stratified estimation compensates for this phenomenon by producing independent, within-stratum estimates. Although the SRS estimates are biased, their precision estimates are still useful to compute RE for comparison.

The observed values of $n_h, \bar{y}_h, s_h^2,$ and W_h for the CBS3-2T stratification provide additional information on the effectiveness of the change-based stratifications (table 3). Overall, this nine-strata, change-based stratification produced estimates with the same or higher precision than other strata. Precision estimates for CBS4-2P were comparable but required nearly twice as many strata.

Three salient points are noted. First, more than 80 percent of the population did not change stratum assignment from NLCD-92 to NLCD-01. The changed portion of the population was distributed over four strata with weights ranging from 0.004 to 0.042. The few plots in some strata corresponding to change in strata assignments indicates that change-based stratifications may not be useful for subpopulations such as counties. Second, the general trend of smaller strata having large within-stratum variances indicates that the stratifications are correctly grouping high-variance plots into strata with small weights that contributes to stratification effectiveness. Third, the within-stratum means tend to conform to expectations that strata corresponding to F for NLCD-01 have greater means. One exception is the estimate of the FA mean in the F-NF stratum that, although expected to be relatively small, was actually large. This result could be attributed to the clump and eliminate procedure that reclassified predicted forested areas of less than 1 acre into the nonforest class. Thus, some forested plots in small, isolated patches of forest land that were actually larger than 1 acre may have been classified in error as nonforest and assigned to a nonforest stratum.

Table 3.—*Observations and within-stratum estimates for CBS3-2T stratification.*

NLCD-92 Attribute[2] Stratum		NLCD-01 stratum														
		NF					T					F				
		p_f	v	g	m	r	p_f	v	g	m	r	p_f	v	g	m	r
NF	n_h	2261	2261	982	982	982	241	241	107	107	107	30	30	18	18	18
	W_h	0.328	0.328	0.328	0.328	0.328	0.035	0.035	0.035	0.035	0.035	0.006	0.006	0.006	0.006	0.006
	$\bar{y}_h$	0.007	5.1	0.21	0.04	0.29	0.099	99.4	2.88	1.42	3.93	0.3275	149.5	2.46	3.39	0.00
	s_h	0.072	82.4	3.03	0.79	7.10	0.2630	354.4	12.33	7.57	40.68	0.4472	280.3	10.82	8.13	0.00
T	n_h	236	236	117	117	117	656	656	366	366	366	268	268	177	177	177
	W_h	0.039	0.039	0.039	0.039	0.039	0.107	0.107	0.107	0.107	0.107	0.042	0.042	0.042	0.042	0.042
	$\bar{y}_h$	0.088	93.1	2.78	0.30	10.24	0.362	458.0	8.56	8.21	4.77	0.7139	697.5	10.15	12.63	8.81
	s_h	0.244	425.0	11.54	1.91	54.92	0.4071	740.0	30.92	22.94	20.75	0.3935	862.6	33.49	24.46	31.14
F	n_h	34	34	28	28	28	399	399	255	255	255	2367	2367	1485	1485	1485
	W_h	0.004	0.004	0.004	0.004	0.004	0.061	0.061	0.061	0.061	0.061	0.378	0.378	0.378	0.378	0.378
	$\bar{y}_h$	0.632	277.6	5.85	10.41	64.31	0.753	821.8	12.15	17.05	24.98	0.8752	983.7	16.00	17.38	13.00
	s_h	0.466	468.4	25.33	23.67	85.45	0.3746	903.7	36.12	29.34	54.92	0.3008	886.2	38.82	29.37	43.47

p_f =proportion of forest.
v=volume (ft^3/acre).
g=growth (ft^3/acre/yr).
m=mortality (ft^3/acre/yr).
r =removals (ft^3/acre/yr).
[2] n_h=sample size for stratum h.
W_h=weight for stratum h.
$\bar{y}_h$ =sample mean for stratum h.
n_h=sample standard deviation for stratum h.

Conclusions

Our study confirms two previous findings. First, stratifications derived from NLCD aggregated forest/nonforest classifications are effective in increasing the precision of forest attribute estimates. Second, creating transition or edge strata at forest/nonforest boundaries enhances the effectiveness of the stratifications.

Three primary conclusions can be drawn from our study: (1) change-based stratifications improved the precision of forest attribute estimates, even though increases in precision over single-date stratifications were not great; (2) differences among the precision estimates for stratifications using three and four strata and two- and four-pixel widths for edge or transition strata were minimal; and (3) stratifications were more effective in increasing the precision of FA estimates than V, G, M, and R estimates. A possible reason for the last conclusion is that the classification of land as forest is based on the presence of forest canopy, which is not necessarily a good indicator of below canopy forest attributes such as volume, growth, removals, and mortality.

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