



Stratifying to Reduce Bias Caused by High Nonresponse Rates: A Case Study From New Mexico's Forest Inventory

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Abstract

The USDA Forest Service's Forest Inventory and Analysis (FIA) Program applies specific sampling and analysis procedures to estimate a variety of forest attributes. FIA's Interior West region uses post-stratification, where strata consist of forest/nonforest polygons based on MODIS imagery, and assumes that nonresponse plots are distributed at random across each stratum. The sample of New Mexico's forests during 2005-2013 did not meet this assumption due to a large number of private landowners who denied permission to access plots on their properties. We developed a modified stratification scheme to minimize bias in our estimates of forest attributes. The purpose of this paper is twofold: first, to document the customized stratification methods used for the New Mexico forest inventory of 2005-2013, and second, to provide sufficient instructions for application of this method to other states or inventories where high nonresponse rates occur.

Keywords: Forest inventory, FIA, stratification, nonresponse, bias, Interior West

Citation:

Goeking, Sara A.; Patterson, Paul L. 2013. Stratifying to reduce bias caused by high nonresponse rates: A case study from New Mexico's forest inventory. Res. Note RMRS-RN-59. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 22 p.

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The following revisions were made to the appendix:

- Step 1.3 was added. The Intermountain West FIA is developing a computer program to automate the process. This additional step is used with the program.
- The title of Step 1 has been modified to reflect the addition of Step 1.3
- Step 2.2: The citation Woudenberg and others, 2010, was replaced with Burrill and others, 2017. The new reference was added to the References section.

Introduction

The USDA Forest Service's Forest Inventory and Analysis (FIA) program is designed to produce timely, objective estimates of forest attributes on an ongoing basis (Gillespie 1999). A comprehensive set of statistical sampling and estimation procedures have been developed to meet this objective (Bechtold and Patterson 2005). The FIA sample design consists of an array of field plots distributed across the entire United States, where each plot represents roughly 6,000 acres, and the sample represents a variety of land cover types and ownership groups. Field measurements provide the basis for broad-scale estimation of forest attributes such as forest area, numbers of trees, volume, growth, and mortality. To reduce the variance of these estimates, FIA applies a stratification scheme on a state-by-state basis, where strata typically consist of forest, nonforest, and noncensus water, as determined by satellite imagery (Scott and others 2005).

FIA's stratification and estimation methods assume that nonresponse occurs at random within each stratum. Nonresponse is defined as the portion of the sample that cannot be measured, and it occurs because some plots are deemed too hazardous to survey safely or, more typically, permission to access plot locations cannot be obtained. We recognize that nonresponse may not occur randomly within strata for two reasons. First, past and current rates of nonresponse are higher on private lands, where landowners have the right to deny access to their property, than on non-private lands where FIA and the appropriate land managers have typically entered into memoranda of understanding that facilitate field sampling. Second, plots that are not designated for field sampling due to their obvious nonforest status have a different probability of nonresponse than plots that are designated for field sampling. Prior to field sampling, photo-interpreters examine each plot location using aerial photographs, and plots that are unquestionably nonforest are designated as non-field plots and are not included in the field sample. The purpose of this prefield discrimination between "field" and "non-field" plots is to decrease inventory costs by minimizing unnecessary field sampling at nonforest plot locations. However, non-field plots have zero probability of nonresponse, while field plots have a positive probability of nonresponse because they may be inaccessible due to hazardous conditions or lack of permission to access the plot. Therefore, the assumption of random nonresponse is violated in any stratum that has a combination of non-field plots, sampled field plots, and nonresponse field plots.

Recent work by Patterson and others (2012) demonstrates that forest estimates may be biased when the assumption of random nonresponse is not met. For example, in a state with a high rate of nonresponse, the estimated forest land area will be lower than the true forest land area. In order to reduce this bias, FIA must modify its approach to stratification such that nonresponse rates are homogeneous within each stratum (Patterson and others 2012). Because most nonresponse plots in the Interior West occur on private lands due to landowners' right to deny access to their property, a modified stratification protocol should distinguish private from non-private strata, in addition to the forest/nonforest distinction that is already used for variance reduction.

We applied a revised stratification approach to the New Mexico forest inventory, and the resulting estimates from the national FIA database (FIADB; see Woudenberg and others 2010) are available to the public at <http://www.fia.fs.fed.us/tools-data/default.asp>. The two purposes of this paper are (1) to provide documentation of the customized stratification methods used to estimate the publicly available population-level forest attributes in New Mexico, and (2) to provide a roadmap to other analysts faced with constructing such estimates in the face of high nonresponse. We also illustrate discrepancies in statewide estimates of forest land area based on the standard FIA stratification versus the modified approach used here.

Methods

Overview of FIA Sample Design

FIA's annual inventory system is designed to provide spatially and temporally balanced estimates of forest attributes via a sample plot grid that is subdivided into spatially interpenetrating panels, where each panel is scheduled for a specific inventory year. In the western United States, the entire sample grid is measured over a 10-year period and therefore each panel consists of 10% of the grid. Sample plots are pre-assigned to specific panels in the 10-year cycle, such that a plot scheduled for inventory year 2013 will be remeasured in 2023, 2033, etc.

FIA produces estimates at the scale of individual states, which can then be aggregated into regional estimates, as well as at smaller scales within each state. Within-state population estimates are constructed at two scales: survey units that are comprised of groups of counties, and smaller estimation units that typically represent individual counties. The eight states in FIA's Interior West region contain between one and five survey units per state. The number of estimation units is equal to the number of counties per state, except in cases where minimum sample size requirements necessitate lumping counties into larger estimation units.

Study Area

We developed and tested our modified stratification procedure using forest inventory data from the State of New Mexico. Four FIA survey units comprise all of New Mexico and are further subdivided into 33 estimation units corresponding to individual counties (Figure 1). After FIA began New Mexico's annual inventory in 2008, funding became available through the American Recovery and Reinvestment Act of 2009 to accelerate the inventory in that state. Under a compressed data collection schedule, plots that were scheduled for the 2005-2007 and 2009-2013 inventory years were measured during 2010-2012. Thus the inventory years for this analysis were 2005-2013, or 90% of the total sample grid, and actual measurement years were 2008-2012. The dataset used for our stratification is identical to that available from the public FIADB (Woudenberg and others 2010) as well as the forthcoming report on New Mexico's Forest Resources (Goeking and others, in preparation).

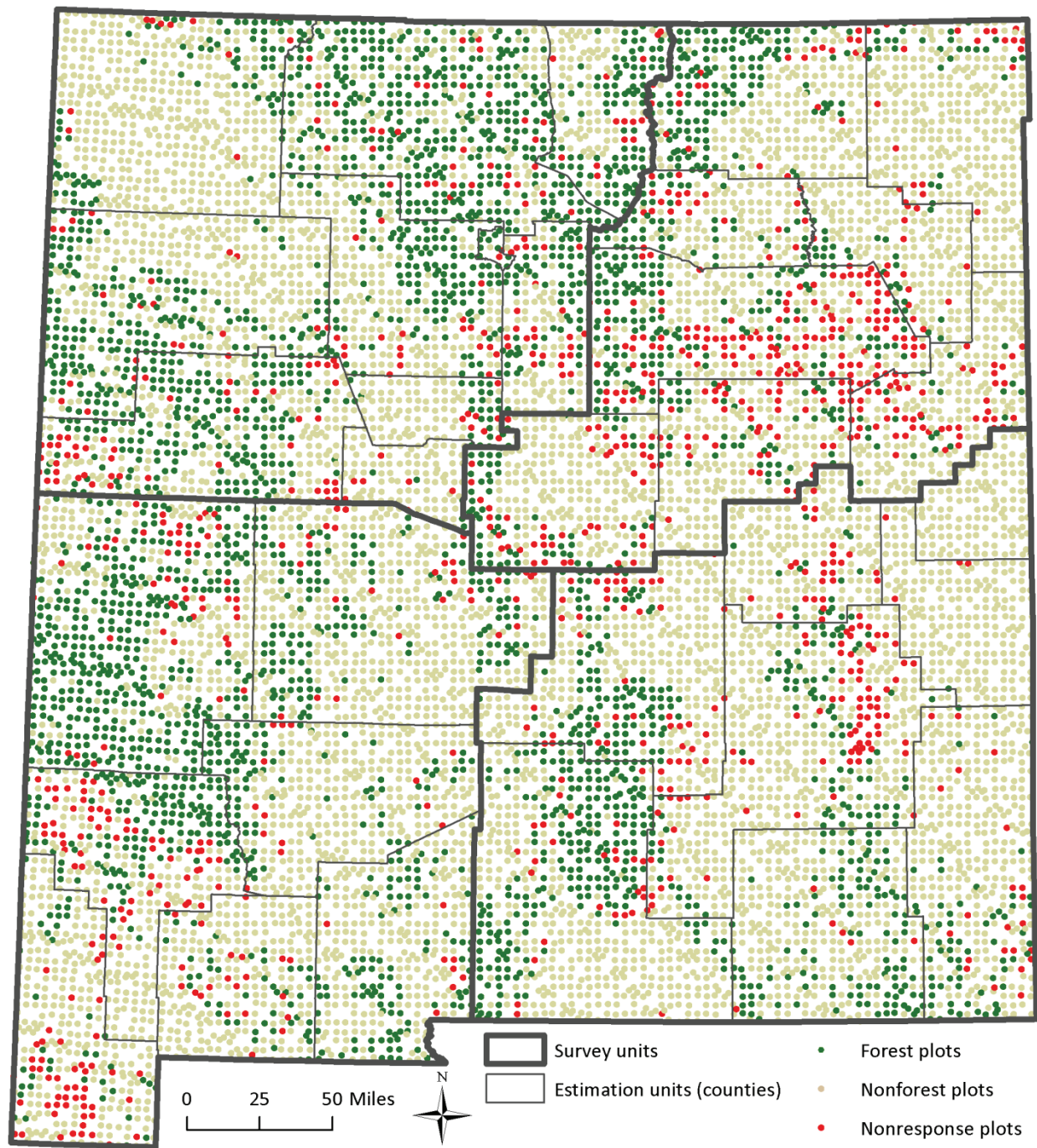


Figure 1—Map showing New Mexico's four FIA survey units and 33 estimation units, which correspond to individual counties. Dots show approximate FIA plot locations from the national Forest Inventory and Analysis Database (FIADB).

Preliminary analysis revealed high nonresponse rates in the private land category, which warranted customization of New Mexico's stratification procedures in an effort to better satisfy the assumption of random nonresponse. We focused on plots that were entirely nonresponse because only 32 plots, or less than 0.3% of all plots, contained a combination of response and nonresponse, and because FIA's estimators already adjust for partial nonresponse.

Statistical Principles

Our stratification was based on two statistical premises. First, a minimum sample size is required in each population or subpopulation of interest. Sample size equates to the number of plots that were sampled by either a prefield photo interpreter or a field crew, and therefore have been assigned a definitive status as either forest or nonforest. Nonresponse plots are not included in the sample size. The minimum sample size requirements apply to each estimation unit, or county, as well as the strata within each county. Although Scott and others (2005) recommended a minimum sample size of 4 response plots per stratum, recent work by Westfall and others (2011) revealed that fewer than 10 plots per stratum may yield a biased variance estimate. We followed the latter recommendation and used a minimum sample size of 10 response plots per stratum in our stratification scheme.

The second premise is that all plots in a stratum should have an equal likelihood of nonresponse. As mentioned above, FIA estimation uses stratification for variance reduction, with the assumption that nonresponse occurs at random within each stratum. If the assumption of random nonresponse within strata is not met, then estimates may be biased (Patterson and others 2012). Therefore the goal of our modified approach to stratification was to produce strata wherein each plot has an equal probability of nonresponse. We refer to this characteristic as response homogeneity, following the response homogeneity group (RHG) model of Särndal and others (1992). We approached the New Mexico stratification with the guiding principle that strata should be defined using predetermined stratification variables that are known to affect response probability, in addition to FIA's traditional stratification classes. Within our newly defined strata, we applied a threshold of 5% to distinguish high versus low nonresponse rates. Therefore strata with nonresponse rates of 5% or greater were examined for subdivision, while strata with less than 5% nonresponse were left intact and not split.

Stratification Steps

We developed a stratification guide (Appendix) to translate theoretical principles of minimum sample size and response homogeneity into practical application. The guide prescribes the order of operations for stratification and specifies the decision rules for each step. We tested the guide on the New Mexico data from 2005-2013, with the objective of producing a repeatable statewide stratification procedure wherein every stratum consists of at least 10 response plots that have similar response probabilities. The stratification process consisted of four distinct steps.

1. We selected classification variables to define our stratification such that final strata would have greater response homogeneity.

2. We combined populations and subpopulations that did not meet the minimum sample size requirement, with the constraint that nonresponse rates in the strata being combined should be uniformly high ($\geq 5\%$) or low ($< 5\%$) whenever possible.
3. We examined each stratum once again, by estimation unit, splitting strata with nonresponse rates greater than 5% into non-field/field substrata, provided that the resulting substrata had at least 10 response plots.
4. We calculated stratum weights for strata with spatially quantifiable areas, and estimated stratum weights for strata that had been subdivided into non-field and field plot substrata.

Each of these steps is described in more detail in the following sections.

Step 1: Selecting Stratification Variables—In the Interior West, traditional FIA stratification schemes distinguish predicted forest/nonforest classes developed from 250-m MODIS satellite imagery. We refer to these strata individually as green (predicted forest) and brown (predicted nonforest), and collectively as Phase 1 strata (Bechtold and Patterson 2005). We retained the Phase 1 classes and added ownership as a second stratification variable because preliminary analysis showed that nonresponse rates were higher on private lands than on any other ownership category (Figure 2). Classes for the ownership variable were non-private and private. Using geographic information system tools, we computed the spatial intersection of the Phase 1 green/brown layer with a statewide ownership layer (USDOI BLM 2012) to produce four initial strata: (1) green/non-private, (2) green/private, (3) brown/non-private, and (4) brown/private (Figure 3).

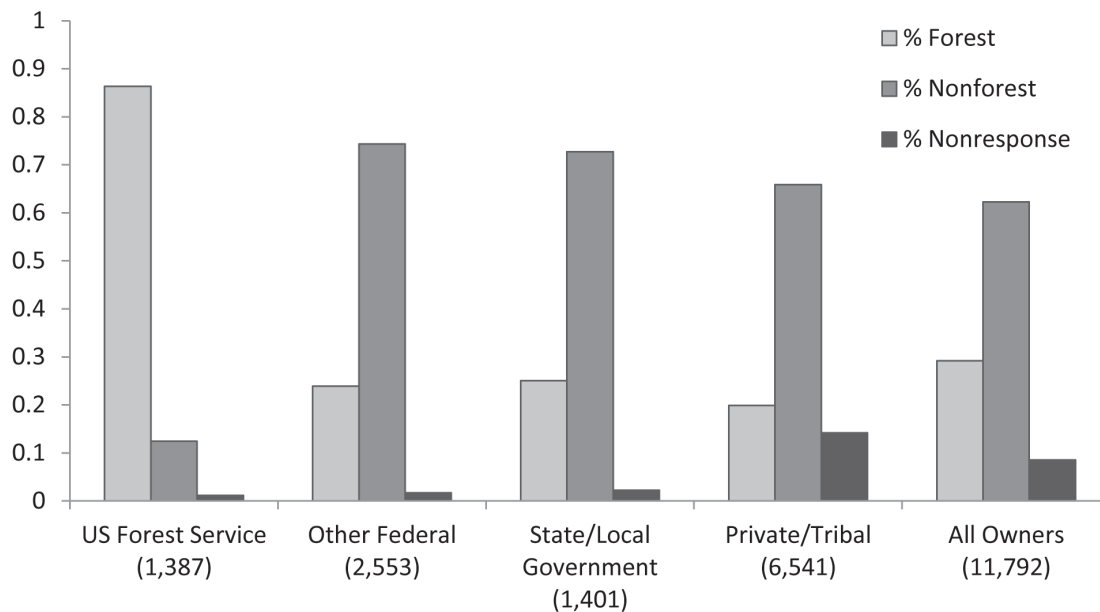


Figure 2—Proportion of plots recorded as forest, nonforest, and nonresponse, by owner group (number of plots in group).

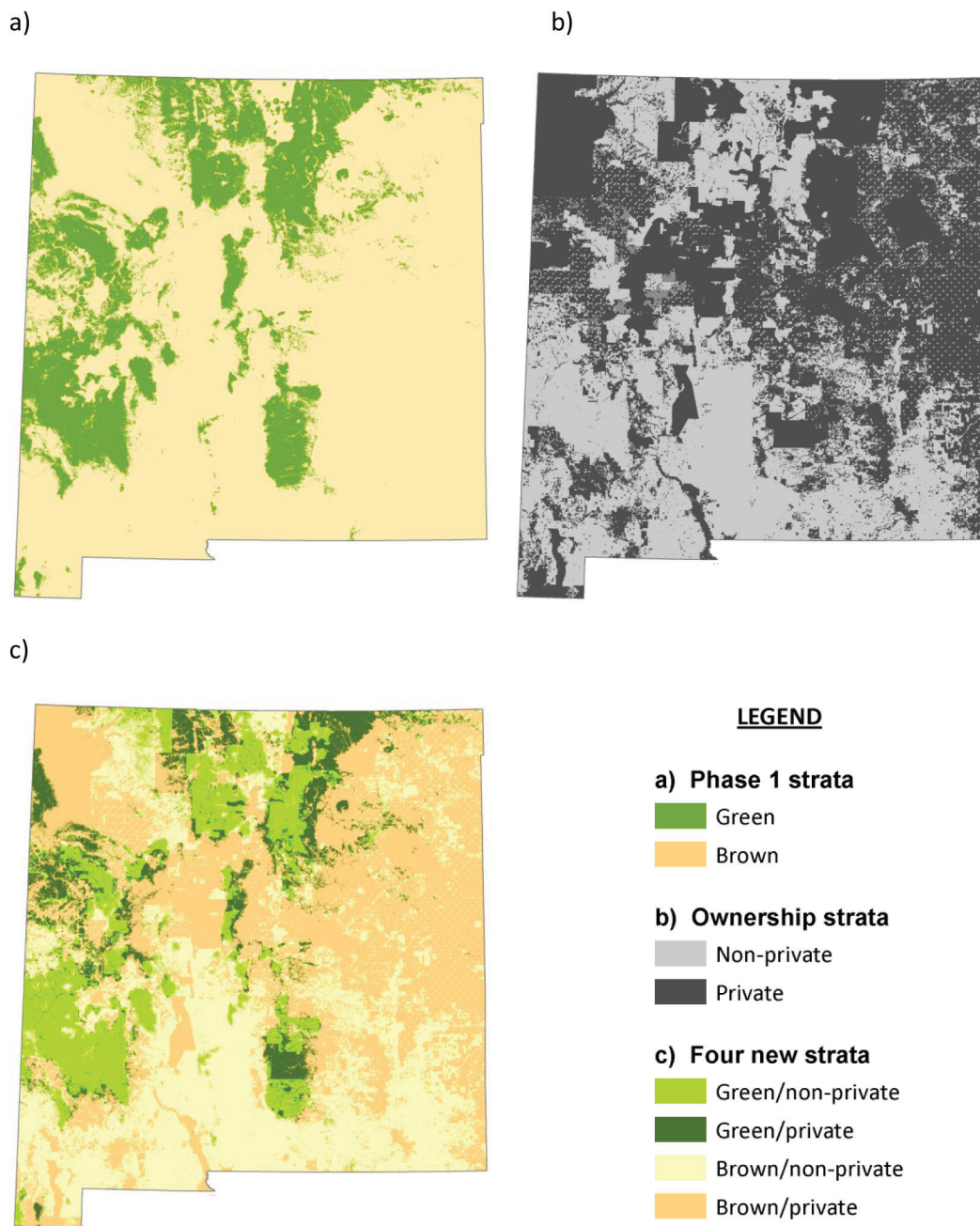


Figure 3—Maps showing (a) two Phase 1 strata, which were modeled based on MODIS imagery as green (predicted forest) and brown (predicted nonforest); (b) two ownership strata, recoded from a statewide ownership layer as non-private and private; and (c) the four strata resulting from the spatial intersection of Phase 1 strata and ownership strata.

Although this four-stratum scheme accounts for different nonresponse rates due to Phase 1 and ownership classes, it does not account for the unequal response probabilities between field plots versus non-field plots. Any stratum that has high nonresponse as well as large numbers of both non-field and field plots is likely to violate the assumption of random nonresponse. Because non-field plots have zero probability of nonresponse, splitting a high-nonresponse stratum into non-field/field substrata produces one substratum with zero nonresponse (i.e., the non-field substratum) and another substratum with higher nonresponse but greater response homogeneity than the initial stratum. Thus, given sufficient sample sizes, separating strata with high nonresponse rates into non-field and field substrata is necessary to increase response homogeneity within each substratum and thereby reduce bias. Unlike the stratification variables of green/brown and non-private/private, the field status variable was not considered until Step 3, where we examined only strata with high nonresponse. This is because Phase 1 classes and ownership classes are spatially continuous variables, whereas non-field/field status is known only for point locations. This difference has statistical implications for both strata weights, as described in Step 4, and variance estimators, which will be addressed in future research.

Step 2: Combining Strata to Achieve Minimum Sample Size—To meet the minimum sample size constraint, we first examined each estimation unit and then each stratum within each estimation unit. None of the estimation units in New Mexico had fewer than 10 response plots, so combining estimation units was not necessary. However, some estimation units would have had fewer than 10 response plots if our sample encompassed fewer than nine panels. FIA stratifications in the Interior West are done state by state, often using only five panels, so we developed rules for combining estimation units (see Step 2.1 of the Appendix). For example, if a very small county contained only nine response plots, combining all of that county's strata into a single stratum would not achieve the minimum sample size. In this case, the county must be lumped with the nearest county that falls within the same survey unit, where geographic distance is based on the counties' centroids, to create a new estimation unit. The rules regarding the minimum sample size per stratum then apply to the strata in the combined estimation unit.

Within each estimation unit, many strata had fewer than 10 response plots and were therefore combined with other strata in the same estimation unit. The following decision rules governed the pairing of strata that could be combined (see Step 2.2 of the Appendix for details). First, if a stratum had less than 10 response plots and nonresponse was less than 5%, then the stratum was combined with another stratum that also had less than 5% nonresponse. The first priority was to combine such a stratum with respect to its Phase 1 class (i.e., green/brown); if that was not possible or did not meet the minimum sample size requirement, then the second priority was to combine with respect to ownership status (i.e., non-private/private).

Examples of small strata, one with low nonresponse and the other with high nonresponse, illustrate the decision rules for combining strata. To demonstrate the situation of low nonresponse, let Stratum 1 be the green/non-private stratum. Stratum 1 has fewer than 10 response plots and a nonresponse rate of zero. We would first attempt to combine the green/non-private stratum with the green/private stratum in the same estimation unit, provided that the green/private stratum also has a nonresponse rate less than 5%. If these conditions are not met in their entirety, or if the combined stratum has fewer than 10 response plots, then we consider combining the green/non-private stratum with the brown/non-private stratum, where the same constraints apply. If the green/non-private stratum and the brown/non-private stratum do not have similar response levels, or if combining them does not create a stratum with at least 10 response plots, then all strata in the estimation unit are combined into a single stratum. In New Mexico, this situation occurred in only one estimation unit, where there was one nonresponse plot and each stratum had fewer than 10 response plots.

Similarly, if a stratum has high nonresponse and fewer than 10 response plots, then the stratum should be combined with another stratum with high nonresponse. For example, Stratum 2 is the green/private stratum, and if its nonresponse rate is high, then we would first attempt to combine it with the green/non-private stratum to obtain a combined green/non-private/private stratum. However, to combine these strata the green/non-private stratum must have more than 5% nonresponse and combining green/private and green/non-private strata must yield at least 10 response plots. If these criteria are not met, we would instead attempt to combine the green/private stratum with the brown/private stratum to create a green/brown/private stratum, provided that the brown/private stratum has high nonresponse and the combined green/brown/private stratum has at least 10 response plots.

Step 3: Splitting Strata to Achieve Response Homogeneity—After achieving minimum sample sizes based on the rules for combining strata, we examined the nonresponse rate of each stratum within each estimation unit. To account for different nonresponse probabilities among non-field versus field plots, we attempted to split strata with high nonresponse rates into non-field/field substrata. For any stratum with greater than 5% nonresponse, if there were at least 10 response plots in both non-field and field classes, then we split the stratum into non-field/field substrata. However, if either the non-field or field substratum was too small, then we retained the original stratum with high nonresponse because splitting the stratum would have resulted in substrata with less bias but also much less precision. Within any stratum in the green Phase 1 class, this concession was acceptable because nearly all plots in the green class (more than 95%) were designated as field plots.

Step 4: Calculating or Estimating Strata Weights—Strata weights are used to expand plot data to an area of interest such as an estimation unit. When strata are spatially continuous across the area of interest, the strata weights can be calculated as the proportion of the total area in each stratum. When strata are defined by point variables, however, their weights must be estimated as the product of the total area and the proportion of plots in that stratum's class. Therefore, we calculated strata weights for all strata defined by only Phase 1 and ownership status, because green/brown and non-private/private classes exist as spatially explicit, continuous statewide datasets (Figure 3). In contrast, the strata weights for non-field/field substrata were estimated as the initial stratum weight, prior to subdivision, multiplied by the proportion of non-field and field plots within that stratum. Therefore the sum of the non-field/field substrata weights is equal to the weight of the initial stratum from which they were split. Within each estimation unit, the sum of the weights for all strata, including the estimated weights for non-field/field substrata but not the weights of their initial strata, is equal to one.

Results

The New Mexico sample for inventory years 2005-2013 included 11,792 plots statewide, where 3,444 (29%) met FIA's definition of forest land, 7,340 (62%) were nonforest land, and 1,008 (9%) were nonsampled (i.e., nonresponse). Nonresponse plots were spatially dispersed throughout the state and among estimation units (Figure 1). Using the stratification guide in the Appendix, we did not encounter any ambiguous scenarios during the stratification process using the New Mexico 2005-2013 dataset. Thus we met the objective of developing repeatable decision rules for stratification that incorporated the principles of minimum sample size and response homogeneity.

Statewide Nonresponse Rates Among Strata

Table 1 presents the statewide sample size, proportion of field plots, and nonresponse rate, by each of the four initial strata as well as aggregated among green/brown and non-private/private classes. To assess the ability of a modified stratification scheme to meet the response homogeneity objective at a statewide scale, we compared the nonresponse rates within the traditional strata to those within our newly created strata. The green and brown groups showed similar nonresponse rates (10.6% and 8.0%, respectively), while the non-private and private groups showed a difference of more than 10 percentage points (2.1% and 13.9%). Strata 2 and 4 represent the private portions of Phase 1 green and brown classes, and both had nonresponse rates greater than 10%. Both Stratum 1 and Stratum 3 had nonresponse rates less than 5%. This signifies that including ownership class as a stratification variable produced strata with more internal response homogeneity than using green/brown classes alone.

Table 1—Statewide sample size, percentage of plots designated for field sampling, and percentage of plots that are nonresponse, by stratum, for New Mexico's Forest Inventory, 2005-2013.

		Ownership classes		
		Nonprivate	Private	
Phase 1 Classes	Green	<u>Stratum 1</u> 1,528 98.0% 2.9%	<u>Stratum 2</u> 1,041 97.8% 22.0%	<u>Green total</u> 2,569 97.9% 10.6%
	Brown	<u>Stratum 3</u> 3,811 48.6% 1.8%	<u>Stratum 4</u> 5,412 37.5% 12.3%	<u>Brown total</u> 9,223 42.0% 8.0%
		<u>Nonprivate total</u> 5,339 62.7% 2.1%	<u>Private total</u> 6,453 47.2% 13.9%	<u>Stratum</u> <u>Sample Size</u> <u>Field Plot %</u> <u>Nonresponse Plot %</u>

These results confirm that the factors affecting nonresponse are ownership status and non-field/field status; private plots clearly have a higher probability of nonresponse than non-private plots, and all non-field plots are designated as nonforest and therefore have zero nonresponse. Pairwise comparisons of the four initial strata illustrate the relative importance of these factors in each stratum. For example, Strata 1 and 2 respectively comprise the non-private and private segments of the Phase 1 green category, and both strata had 98% of plots included in the field survey but had very different nonresponse rates (2.9% and 22.0%). These two metrics collectively imply that nonresponse disparities between the two strata are due to ownership differences rather than their proportions of non-field/field plots. A comparison of Strata 3 and 4 (see Table 1) corroborates the influence of private ownership on nonresponse rates. In contrast, a similar comparison of Stratum 1 and Stratum 3 indicates that the small difference in their low nonresponse rates is due to the fact that (a) nonresponse is low on non-private lands, and (b) nonresponse was lower in the stratum with a smaller proportion of field plots (i.e., potential nonresponse plots). Similarly, while Stratum 2 and Stratum 4 both have high nonresponse rates, nonresponse is higher in the green stratum where the proportion of field plots is much larger.

Description of Final Strata Among Estimation Units

The final stratification scheme maintained the original 33 estimation units, which had total sample sizes ranging from 11 to 611 response plots. After the four initial strata were combined due to sample size constraints, and then split when necessary and possible for response homogeneity, there were 17 final strata (Table 2). Because Steps 2 and 3 were conducted independently for individual estimation units, not every stratum exists in every estimation unit. The number of final strata per estimation unit varied from one to five with strata sample sizes ranging from 10 to 423 response plots. The most common strata among estimation units were the original strata 1, 2, and 3, along with strata 41 and 42, which represent the non-field/field substrata of the original stratum 4. Eight of the final strata represent non-field/field substrata that were split from a previous stratum with high nonresponse; their final strata numbers are denoted with two digits (e.g., strata 31 and 32).

Table 2—List of final strata in the New Mexico 2005-2013 inventory. Estimation units contain between one and five strata; frequency indicates the number of estimation units that contain each stratum.

Final stratum	Description	Constituent initial strata	Substrata	Frequency
1	Green/Non-private	1	n/a	17
2	Green/Private	2	n/a	15
3	Brown/Non-private	3	n/a	22
4	Brown/Private	4	n/a	7
5	Green	1, 2	n/a	2
6	Brown	3, 4	n/a	1
7	Non-private	1, 3	n/a	7
8	Private	2, 4	n/a	1
9	Green/Brown	1, 2, 3, 4	n/a	1
31	Brown/Non-private/Non-field	3	non-field plots	1
32	Brown/Non-private/Field	3	field plots	1
41	Brown/Private/Non-field	4	non-field plots	16
42	Brown/Private/Field	4	field plots	16
71	Non-private/Non-field	1, 3	non-field plots	1
72	Non-private/Field	1, 3	field plots	1
81	Private/Non-field	2, 4	non-field plots	7
82	Private/Field	2, 4	field plots	7

Nonresponse rates in individual strata, by estimation unit, ranged from zero for several strata to a maximum of 59% for one private/field stratum with 91 total plots, which was formed after the initial green/private and brown/private strata (Strata 2 and 4, respectively) were combined during Step 2 for sample size reasons and then split during Step 3 into non-field/field categories to address high nonresponse. Of the 33 estimation units, 17 had high nonresponse in either Stratum 1 or Stratum 2, yet none of these could be sub-stratified into non-field/field substrata because they did not have 10 or more non-field plots. As mentioned above, this situation requires prioritizing practical sample size constraints over the statistical purity of response homogeneity. This is a reasonable concession for Strata 1 and 2 because having nearly 100% field plots equates to response homogeneity within the strata, at least with respect to the non-field/field distinction. To investigate whether this concession was also reasonable for the brown strata, we examined estimation units where Strata 3 and 4 had high nonresponse and could not be split into non-field/field substrata. There were only two of these situations, and the vast majority of plots in both cases were field plots. Therefore we concluded that when the small sample size of a potential substratum precluded splitting a high nonresponse stratum into non-field/field substrata, preserving the initial stratum with high nonresponse was acceptable.

Effects of Modified Stratification on Statewide Estimates of Forest Area

To gauge the effects of the new stratification on estimates of forest attributes, we contrasted estimated forest land area by ownership group and by forest type, based on the standard Phase 1 versus modified stratification procedures. The two stratification schemes produced estimates of total forest land area that differed by more than one million acres, where the smaller estimate resulted from the standard Phase 1 stratification (Figure 4a). This result is consistent with the findings of Patterson and others

(2012) regarding the bias, or underestimation of forest attributes, that can result when nonresponse is high. The private/tribal ownership group had the highest nonresponse rate of all ownership groups (Figure 2) and also exhibited the largest difference in the forest land area estimates produced by the two stratification methods (Figure 4a). Relative to the modified stratification, the standard stratification underestimated forest area on private/tribal lands by nearly two million acres, or 22% of the standard stratification's estimate, and overestimated forest area on non-private lands by an aggregate of roughly 830,000 acres.

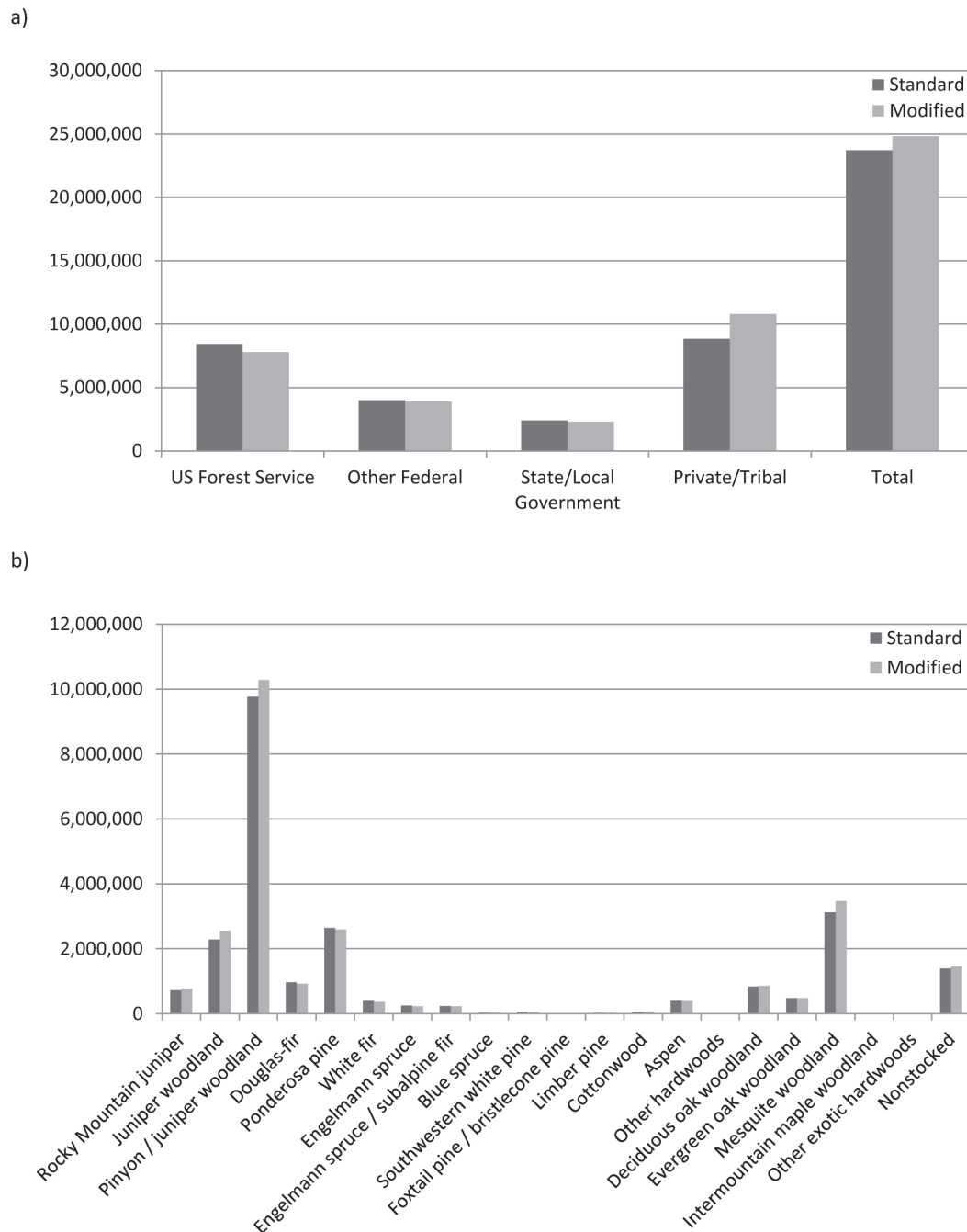


Figure 4—Graph showing the forest land area, in acres, estimated using standard versus modified stratification schemes, by (a) ownership group, and (b) forest type.

In general, the proportional differences between the two stratification schemes for lands categorized as National Forests, other Federal lands, and state/local government lands were inversely related to their nonresponse rates. This may be because plots in ownership groups with low nonresponse (e.g., National Forests) carried more weight in the standard stratification than in the modified scheme and therefore had more forest land area attributed to them when high nonresponse occurred on private lands. By including ownership status as a stratification variable, the modified stratification reduced the expansion factor of each non-private plot.

The two stratifications produced different estimates of forest land area not only by ownership group but also by forest type (Figure 4b). Forest land area was underestimated by the standard stratification, relative to the modified scheme, within the following forest types: the three types representing various juniper and pinyon/juniper woodlands, deciduous oak woodlands, mesquite woodlands, and nonstocked stands. These forest types occur most frequently on either private lands or Federal lands other than National Forests (Table 3). The forest types that were overestimated were Douglas-fir, ponderosa pine, white fir, and Engelmann spruce, all of which occur most frequently on National Forest lands. However, the differences in forest types that were overestimated, as well as in the underestimated deciduous oak woodland and nonstocked stands, were very small.

The magnitude of the nonresponse bias shown by the standard stratification highlights the potential ambiguity of FIA's standard statewide summary tables. Every FIA state report contains several prescribed tables that report on particular variables and categories within the state of interest. The first of these tables reports the

Table 3—Number of plots in each forest type, by ownership group.

Forest type	National Forest	Other Federal	State/local government	Private/tribal	Total
Rocky Mountain juniper	21	7	11	77	116
Juniper woodland	68	75	40	175	358
Pinyon / juniper woodland	498	203	127	616	1,444
Douglas-fir	104	0	5	38	147
Ponderosa pine	268	14	12	111	405
White fir	49	0	2	8	59
Engelmann spruce	30	0	0	8	38
Engelmann spruce / subalpine fir	22	0	0	10	32
Blue spruce	6	0	0	1	7
Southwestern white pine	9	0	0	1	10
Foxtail pine / bristlecone pine	1	0	0	2	3
Limber pine	2	0	0	3	5
Cottonwood	1	0	2	8	11
Aspen	49	0	1	14	64
Other hardwoods	0	0	1	0	1
Deciduous oak woodland	63	0	4	69	136
Evergreen oak woodland	62	4	1	11	78
Mesquite woodland	2	204	123	136	465
Intermountain maple woodland	1	0	0	0	1
Other exotic hardwoods	0	0	0	2	2
Nonstocked	33	109	27	54	223
Nonforest	305	2,086	1,134	5,467	8,992
Total	1,594	2,702	1,490	6,811	12,597

“percentage of area by land status” for specific inventory years within the state, along with the total land area of the state. Land status categories include accessible forest land; nonforest and other land; and nonsampled land (i.e., nonresponse). However, the percentages reported in the table actually refer to the percentage of sample plot area rather than the percentage of statewide land area in each class. Presenting them alongside the total state land area may be misleading to FIA data users, as this implies that the statewide forest land area, for example, is the product of the total state land area and the ostensible percentage of forest land area. For New Mexico’s 2005-2013 forest inventory, this table lists percentages of 27.4, 63.9, and 8.7 for forest, nonforest, and nonsampled land areas, respectively, and a total state land area of 77,817,000 acres (Goeking and others, in preparation). A casual observer may conclude that the estimated forest land area for New Mexico is 27.4% of this land area, or 21.3 million acres, despite the unstated implication that over 6.7 million acres are neither forest nor nonforest (i.e., nonsampled). This is obviously erroneous; the estimated forest land area, based on stratification for variance reduction and bias reduction, is over 24.8 million acres. Indeed, the latter estimate is reported in several other standard summary tables. This discrepancy may cause confusion, or worse, misinterpretation of FIA’s estimates, and therefore should be remedied to remove ambiguity regarding sample plot area versus state land area.

Conclusions

The modified stratification methods presented here improved our ability to meet the assumption that nonresponse occurs randomly within each stratum and therefore minimized nonresponse bias in the New Mexico forest inventory of 2005-2013. We developed a stratification guide based on the statistical principles of minimum sample size and response homogeneity, and then applied that guide to generate a stratification scheme where no stratum had fewer than 10 response plots and individual strata were defined based on similarity of nonresponse rates. No ambiguous situations were encountered throughout the four steps stipulated in the guide, implying that the stratification’s decision rules are objective and repeatable. This modified stratification was used to generate FIA’s publicly available estimates of forest attributes in New Mexico for 2005-2013.

Under the modified stratification, estimates of forest land area were over one million acres higher than the estimated area under the standard green/brown stratification. This considerable difference can be attributed to the inclusion of ownership status, which is a major determinant of each plot’s likelihood of nonresponse, as a stratification variable in the modified scheme. New Mexico’s forest inventory had a statewide nonresponse rate for private lands of 13.9%, while non-private lands had only 2.1% nonresponse. The fact that non-private versus private strata had very different rates of nonresponse, whereas green versus brown strata did not, underscores the importance of incorporating ownership as a stratification variable in situations where high nonresponse occurs on certain ownership categories. The large range of nonresponse rates among our final strata (0-59%) signified that including ownership status increased response homogeneity within strata.

The differences in estimated forest land area from the two stratification schemes reinforces the recommendations of Patterson and others (2012) to increase response homogeneity within strata and thus reduce bias caused by nonrandom nonresponse. In states where nonresponse rates are related to factors other than Phase 1 strata, forest estimates based only on green/brown status may underestimate attributes such as forest land area, volume, growth, and mortality. Several states, including all of those within the Interior West region, have recently exhibited more than 10% nonresponse on private lands (Patterson and others 2012). Thus, to minimize nonresponse bias in forest estimates, these states should be stratified based on ownership groups in addition to existing Phase 1 classes.

The factors affecting nonresponse rates should be identified and included in modified stratification schemes whenever possible, and they may include land ownership status or other variables such as non-field/field status, topographic classes, or other variables. For example, extremely steep topography, such as that on the Hawaiian island of Kauai or the rugged karst region of Puerto Rico, may encompass a high proportion of physically inaccessible plots. Given an adequate sample size, plots in these areas could be stratified using slope, where slope values would be classified as either greater than a critical threshold or lower than that threshold. Selection of stratification categories should favor variables that exist as spatially continuous datasets so that stratum weights can be calculated directly, based on raster and/or polygon datasets, rather than estimated from sample points.

Future Research about Nonresponse and Stratification

Future research will investigate the sensitivity of forest estimates to our thresholds for sample size and nonresponse rate. First, we need to verify that a sample size threshold of at least 10 response plots per stratum is adequate and does not produce an unacceptably large variance. For strata that were not split into non-field/field substrata, the variance is calculated as described in Bechtold and Patterson (2005). However, an estimated variance must be derived for strata that use estimated rather than known strata weights (i.e., those that were split into non-field/field substrata). If the estimated variance is unacceptably large for small strata, then we may need to reconsider the minimum sample size as described in Westfall and others (2011). Second, we plan to simulate various levels of nonresponse to assess our definition of “high nonresponse.” Although we suspect 5% is a reasonable threshold for categorizing high-nonresponse versus low-nonresponse strata, we will compare estimates of forest attributes produced under other simulated nonresponse thresholds to evaluate this definition.

Finally, customized stratification methods can be implemented on a trial basis using the Forest Inventory Estimation for Analysis (FIESTA) software package currently in development (Frescino and others 2012). FIESTA will enable forest analysts to perform custom analyses on forest inventory data, including the ability to simulate alternative stratification schemes with user-defined stratification variables, minimum sample sizes, and nonresponse thresholds. The ability to simulate the consequences of modifying FIA's stratification schemes will surely prove useful as we incorporate the concept of response homogeneity in other states with high nonresponse.

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Appendix—Guide to Stratification Based on Response Homogeneity Groups.

Procedures for creating custom stratification schemes in states with high nonresponse

When Applied:	In any state inventory that has $\geq 5\%$ nonresponse among all plots within any discernible group (e.g., private plots)
Procedure Overview:	Acquire green/brown spatial data layer (forest/nonforest strata) and statewide surface management layer (or other layer that allows discerning the group(s) of high nonresponse); then follow the steps below, in order, to produce initial strata, combine strata to achieve the minimum sample size, and split strata with high nonresponse to achieve response homogeneity.

Step 1: Select stratification variables, cross-tabulate with the standard Phase 1 strata, and calculate strata weights

- 1.1 Acquire the spatial layer representing the standard stratification scheme of green/brown/blue stratification, where strata represent potential forest/nonforest/census water. (In the Interior West FIA region, blue is typically lumped with brown to yield a green/brown stratification.)
- 1.2 Identify a classification variable that is an important determinant of response probability. In New Mexico, that variable was ownership (non-private/private). Spatially intersect the Phase 1 green/brown strata with a statewide surface management GIS layer. Recode all non-private, non-tribal ownerships into a single stratum; recode all private ownership classes (including tribal) into another single stratum. This creates four initial strata:
 - 1) green/nonprivate,
 - 2) green/private,
 - 3) brown/nonprivate, and
 - 4) brown/private.

From the resulting spatial layer, we can calculate stratum weights and produce plot stratum assignments.

- 1.3 Absorb strata with zero plots. The purpose of this step is to eliminate strata with zero plots, but with non-zero strata weights, by combining them with the appropriate strata. For descriptive purposes, when strata are combined we define the stratum with 0 sampled plots as the “source” stratum; the stratum into which we combine the source stratum is referred to as the “target” stratum. The initial stratum assignment for the target stratum is referred to below as the “target stratum index.”

Begin with the first estimation unit (ESTN_UNIT=1; see Burrill and others 2017). Consider each stratum separately within the estimation unit, in order of the stratum numbers, and complete Step 1.3 for each stratum. When all strata in the estimation unit have been examined, proceed to the next sequential estimation unit and repeat Step 1.3 for all strata; continue until all estimation units and strata have been examined.

(A) Is the number of sampled plots in the stratum = 0?

No: The original stratum stands. Proceed to Step 1.3 for the next stratum.

Yes: Is there another stratum with >0 plots in the same green/brown category?

Yes: Combine weights based on green/brown (e.g., combine green/private with green/nonprivate) and keep the target stratum index. Proceed to the next stratum and repeat Step 1.3.

No: Is there another stratum with >0 plots in the same ownership category?

Yes: Combine weights based on ownership (e.g., combine green/private with brown/private) and keep the target stratum index. Proceed to the next stratum and repeat Step 1.3.

No: At this stage combine weights based on opposite green/brown category and opposite ownership category, and keep the target stratum index. Proceed to the next stratum and repeat Step 1.3.

Step 2: Combine estimation units and/or strata where the sample size is too small

- 2.1 For any estimation unit with less than 10 response plots, combine the estimation unit with another estimation unit, where the target estimation unit is the one whose centroid is nearest the centroid of the source estimation unit and is in the same survey unit as the source estimation unit. Maintain the initial strata from both source and target estimation units. Combine the strata of the two estimation units and then proceed to Step 2.2 to consider each combined stratum's sample size and nonresponse rate.

For example, if one estimation unit has plots in strata 1, 3, and 4, and another estimation unit has plots in strata 1, 2, and 3, the combined estimation unit will have all four strata, and strata 1 and 3 will include plots from both estimation units. Each of the four strata will be examined in Step 2.2.

- 2.2 The purpose of this step is to eliminate strata with small sample sizes by combining them with the appropriate strata. For descriptive purposes, when strata are combined we define the stratum with <10 sampled plots as the "source" stratum; the stratum into which we combine the source stratum is referred to as the "target" stratum.

Begin with the first estimation unit (ESTN_UNIT=1; see Burrill and others 2017). Consider each stratum separately within the estimation unit, in order of

the stratum numbers, and complete Step 2.2 for each stratum. When all strata in the estimation unit have been examined, proceed to the next sequential estimation unit and repeat Step 2.2 for all strata; continue until all estimation units and strata have been examined. .

(A) Is the number of sampled plots in the stratum <10 ?

No: The original stratum stands. Proceed to Step 2.2 for the next stratum.

Yes: Is the level of nonresponse in the stratum $<5\%$?

No: Go to Step 2.2(B).

Yes: Is there another stratum with $<5\%$ nonresponse in the same green/brown category, and if so, will combining by green or brown yield ≥ 10 response plots?

Yes: Combine based on green/brown (e.g., combine green/private with green/nonprivate). Proceed to the next stratum and repeat Step 2.2.

No: Is there another stratum with $<5\%$ nonresponse in the same ownership category, and if so, will combining by ownership yield ≥ 10 response plots?

Yes: Combine based on ownership (e.g., combine green/private with brown/private). Proceed to the next stratum and repeat Step 2.2.

No: Does combining based on green/brown, regardless of nonresponse levels, result in ≥ 10 sampled plots in the new stratum?

Yes: Combine based on green/brown. Proceed to the next stratum and repeat Step 2.2.

No: Does combining based on ownership, regardless of nonresponse levels, result in ≥ 10 sampled plots in the new stratum?

Yes: Combine based on ownership. Proceed to the next stratum and repeat Step 2.2.

No: Does combining all strata in the estimation unit result in ≥ 10 sampled plots in the estimation unit?

Yes: Combine all strata in the estimation unit. Proceed to the first stratum in the next estimation unit and repeat Step 2.2.

No: The estimation unit should have been combined with another estimation unit. Return to Step 2.1.

(B) The number of sampled plots in the source stratum is <10 and nonresponse is $\geq 5\%$. Is there is another stratum with $\geq 5\%$ nonresponse in the same green/brown category, and if so, does combining by green or brown yield ≥ 10 response plots?

Yes: Combine based on green/brown (e.g., combine green/private with green/nonprivate). Proceed to the next stratum and repeat Step 2.2.

No: Is there another stratum with $\geq 5\%$ nonresponse in the same ownership category, and if so, will combining by green/brown yield ≥ 10 response plots?

Yes: Combine based on ownership (e.g., combine green/private with brown/private). Proceed to the next stratum and repeat Step 2.2.

No: Does combining based on green/brown, regardless of nonresponse levels, result in ≥ 10 sampled plots in the new stratum?

Yes: Combine based on green/brown. Proceed to the next stratum and repeat Step 2.2.

No: Does combining based on ownership, regardless of nonresponse levels, result in ≥ 10 sampled plots in the new stratum?

Yes: Combine based on ownership. Proceed to the next stratum and repeat Step 2.2.

No: Does combining all strata in the estimation unit result in ≥ 10 sampled plots in the estimation unit?

Yes: Combine all strata in the estimation unit. Proceed to the first stratum in the next estimation unit and repeat Step 2.2.

No: The estimation unit should have been combined with another estimation unit. Return to Step 2.1.

Step 3: Split strata that have high nonresponse

After completing this step for each stratum within each estimation unit, complete Step 4. Again, consider each stratum within each estimation unit separately, and proceed through estimation units and strata in ascending numerical order.

(A) Is nonresponse in the stratum $\geq 5\%$?

No: Do not split the stratum. Proceed to Step 3 for the next stratum.

Yes: If the stratum is split into visit/nonvisit groups, will there be ≥ 10 sampled plots in both the visit and nonvisit strata?

- No: Do not split the stratum. Proceed to Step 3 for the next stratum.
- Yes: Split the stratum further into visit and nonvisit strata (e.g., split brown/private into brown/private/visit and brown/private/nonvisit). Proceed to Step 3 for the next stratum.

Step 4: Calculate and/or estimate stratum weights

Consider each estimation unit separately.

- 4.1 Calculate strata weights for strata that were not split into visit/non-visit substrata. Calculate the weights as the proportion of the estimation unit's area that occurs within each stratum (i.e., divide the stratum's area by the estimation unit's area).
- 4.2 Estimate strata weights for strata that were split into visit/non-visit substrata. First calculate the hypothetical stratum weight for the two substrata in aggregate, as though they had not been subdivided, as described in Step 4.1. Then calculate the proportion of plots in the aggregate stratum that are in the visit and non-visit substrata. Multiply these two proportions by the calculated aggregate stratum weight to obtain the estimated strata weights for the respective non-visit/visit substrata.



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