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A primer for nonresponse in the US forest inventory and analysis program

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Abstract Nonresponse caused by denied access and hazardous conditions are a concern for the USDA Forest Service, Forest Inventory and Analysis (FIA) program, whose mission is to quantify status and trends in forest resources across the USA. Any appreciable amount of non-response can cause bias in FIA's estimates of population parameters. This paper will quantify the magnitude of nonresponse and describe the mechanisms that result in nonresponse, describe and qualitatively evaluate FIA's assumptions regarding nonresponse, provide a recommendation concerning plot replacement strategies, and identify appropriate strategies to pursue that minimize bias. The nonresponse rates ranged from 0% to 21% and differed by land owner group; with denied access to private land the leading cause of nonresponse. Current FIA estimators assume that nonresponse occurs at random. Although in most cases this assumption appears tenable, a qualitative assessment indicates a few situations where the assumption is not tenable. In the short-term, we recommend that FIA use stratification schemes that make the missing at random assumption tenable. We recommend the examination of alternative estimation techniques that use appropriate weighting and auxiliary information to mitigate the effects of nonresponse. We recommend the replacement of nonresponse sample locations not be used.

Keywords Missing data · Post-stratification · Non-sampling error · Replacement procedure · Bias

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Introduction

The Forest Inventory and Analysis Program (FIA) of the US Forest Service is a forest inventory and monitoring system designed to meet the requirements for national assessments mandated by the Forest and Rangeland Planning Act of 1974 and the 1998 Farm Bill. The FIA monitoring system employs a statistically based sample from which status and trends in forest resources across all ownerships can be assessed and the information is used for strategic planning at the state, regional, or national level. Additionally, the data are used to address a suite of broad-scale environmental issues such as climate change, carbon flux, forest health, and sustainability (see for example Woodall et al. 2009, 2010; Heath et al. 2010; Van Deusen and Roesch 2009). The FIA sample is designed to meet national standards for precision in state and regional estimates of forest attributes and the target sampling intensity is approximately one sample location every 2,390 ha. As with many broad-scale environmental surveys, a portion of the sample cannot be observed due to inaccessibility. This can lead to non-sampling errors and influence the ability to make inferences about population parameters (Lesser and Kalsbeek 1999).

For simplicity, we will refer to missing data as nonresponse. While the ideal situation is to quantify the bias caused by nonresponse, this typically cannot be accomplished outside a simulation environment since bias is the difference between the true and unknown population parameter and the expected value of the estimator. We will consider nonresponse only when all data are missing from an entire sample unit. In the case of FIA, this is nonresponse on field inventory plots rather than missing data from individual trees. There are many analogies that could be drawn from the concept of the distinction between unit and item nonresponse for which there is an extensive body of literature. However, most of this literature pertains to social surveys rather than environmental inventory and monitoring programs, and the theoretical development has generally been in a finite population sampling context. Regardless, the literature does provide a general framework to manage and/or adapt to nonresponse. The basic steps for determining an appropriate approach for nonresponse are to quantify the amount of nonresponse, understand the properties of the nonresponse elements, understand the mechanisms behind the nonresponse, and then develop an appropriate strategy for addressing nonresponse (Lohr 1999; Little and Rubin 2002; Rubin 1987; Särndal et al. 1992). For example, with respect to the properties of the nonresponse element, one might pose the following questions: are the elements missing at random or concentrated within a subpopulation? If the nonresponse is concentrated within some subpopulation, what is the mechanism that has led to the differential nonresponse? The answers to these questions help form the basis for choosing a technique to handle and manage the nonresponse (which in some cases may be to ignore the issue).

Clearly, the goal is to observe all selected sample units and several of the basic strategies for nonresponse focus on "call-backs" and respondent incentives as mechanisms to minimize nonresponse (Cochran 1977; Kish 1965). Inevitably though, some sample units are not observed or perhaps cannot be observed. Based on the available literature, one technique for dealing with nonresponse is multiple imputation (Rubin 1996). This involves modeling the relationship of responders to nonresponders and is particularly suited to public use files where the public user has only complete data methods at his or her disposal and some limit to information on the reasons for nonresponse. Another approach is to ignore the nonresponse, which is an appropriate technique in some situations as it has a solid inferential basis in probability theory under the assumption of missing at random. When this assumption is tenable, one simply uses the usual complete data methods on the observed portion of the sample. Finally, Kish and Hess (1959) and Kish (1965) describe a replacement procedure for samples where responses were not obtained.

Strategies for nonresponse can differ by survey design and the appropriateness of any strategy is estimator dependent. Bechtold and Patterson (2005) describe the survey design and current estimation procedures for FIA program. Based on their description, nonresponse of entire plots is assumed to occur at random. The objectives of this manuscript are to (1) quantify the magnitude of nonresponse and describe the mechanisms that result in nonresponse within the FIA sample; (2) describe and qualitatively evaluate FIA's assumptions regarding nonresponse; (3) provide a recommendation concerning plot replacement strategies; and (4) identify appropriate strategies to pursue that minimize bias.

Quantification of nonresponse within FIA

To appropriately quantify nonresponse within the FIA program, we must first describe how the FIA monitoring program is implemented and the methods under which a sample location is determined to be field visited. White et al. (1992) provide the basis for the FIA sampling frame which is divided into temporally defined panels. The sampling frame for the eastern USA is divided into five panels and the sampling frame in the western USA is divided into 10 panels. In both cases, one panel is measured each year. Reams et al. (2005) describe the manner in which the sampling frame was populated. FIA is a partnership between states and the US Forest Service. This leads to state-level implementation coordinated through four regional FIA programs (Fig. 1) working under the umbrella of the national FIA program. For this reason, nonresponse is quantified by state within each FIA region.

The FIA sample is assumed to be an equal probability sample (McRoberts and Hansen 1999) and a certain portion of the sample locations fall in, for example, agricultural fields, high-density urban centers, and census water. Because it is not cost-effective to send field crews to these clearly non-forest areas, an initial screening of sample locations is performed. High-resolution (1 m) digital aerial photography available through the National Agriculture Imagery Program (USDA 2009) is used to determine whether each sample location potentially meets the FIA definition of forest. If the interpreter determines a sample location is obviously non-forest in its entirety, the sample location is not scheduled for visitation by a field crew. If the sample location has been visited

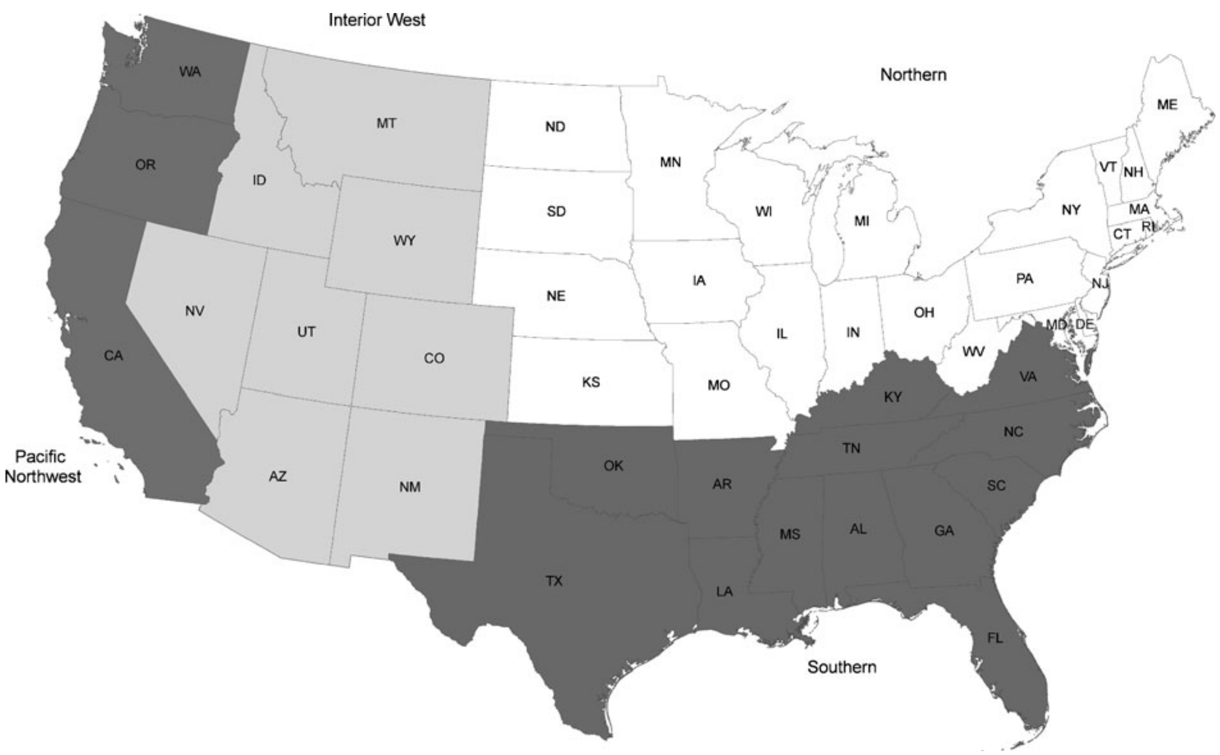

Fig. 1 The forest inventory and analysis regions

previously, old field notes will be used in conjunction with the high-resolution photography to determine whether a field visit is warranted. If there is any possibility that the sample location meets the FIA definition of forested lands, or if the interpreter cannot make such a determination, then the location is selected for a field visit. For our purposes, we quantify nonresponse as the portion of sample locations which were sent to the field for data collection and data collection did not occur.

There are primarily two mechanisms behind nonresponse of field-visited sample locations (field inventory plots). First, the field crew is denied access to a plot or part of a plot by the land owner. Second, a dangerous condition is present which precludes collecting the data from the plot. Because access to private land requires the permission of the landowner, denied access to private land is the most common reason for nonresponse (Fig. 2). In most cases, it eclipses other causes by an order of magnitude or more.

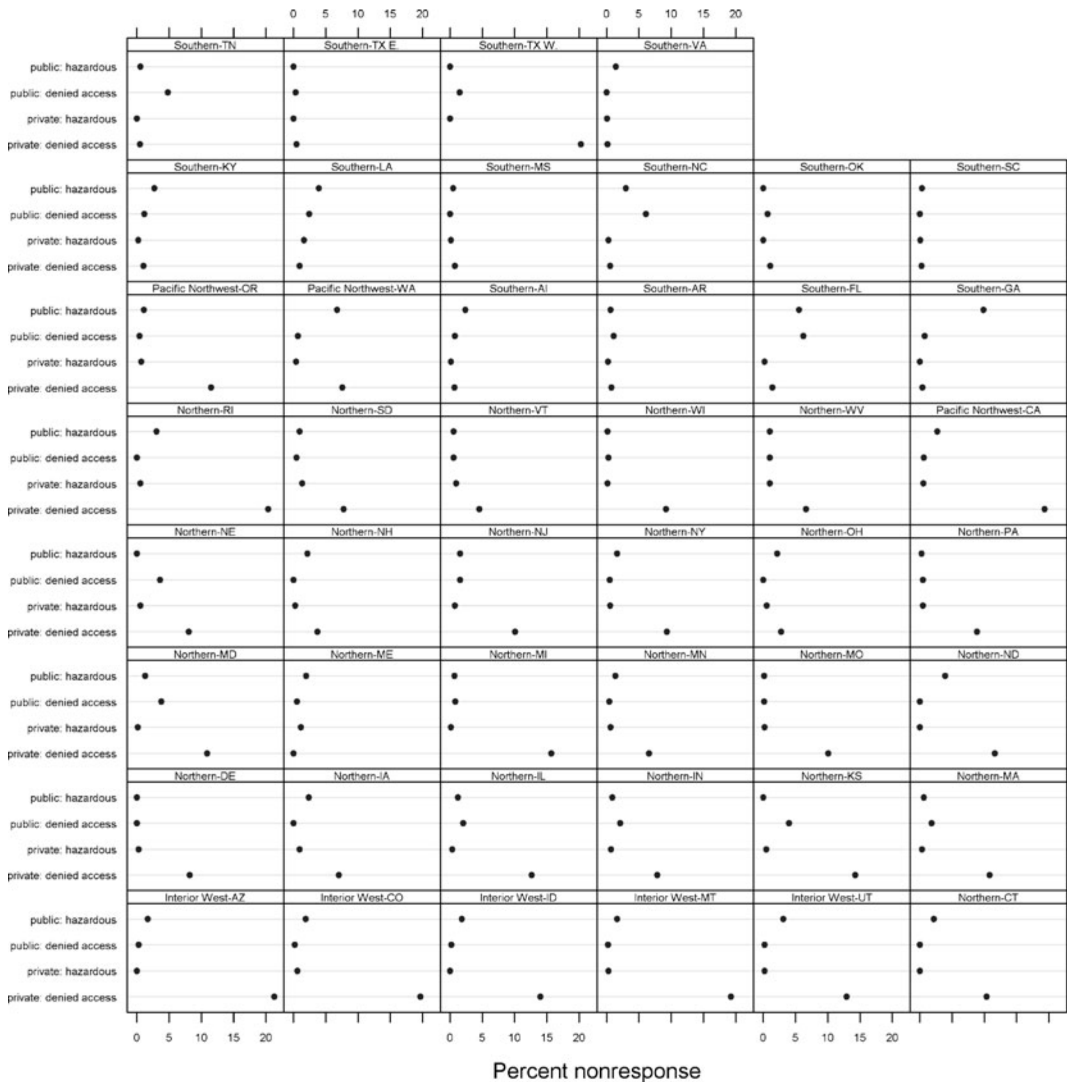

Fig. 2 Nonresponse rates by ownership and type for each state. The figure is arranged alphabetically (*bottom left to top right*) by region and state. East and West Texas are separated to reflect a five-panel system in the east and a 10-panel system in the west. Results for Nevada, New Mexico, and Wyoming are not shown because the current inventory and monitoring design has only recently been implemented in these states

With the exception of most of the Southern region and Maine, New Hampshire, and Ohio in the Northern region, the denied access rates for private lands range from 6% to 21%. In the Southern region, West Texas had a denied access rate of 20%. In Interior West and Pacific Northwest regions, the majority of the denied access to private lands is from individual owners as opposed to corporations, associations, and organizations. With the exception of Washington, Georgia, and Florida, the rate of nonresponse on public lands due to hazardous conditions is below 3%; with many states below 1%. The rates for Washington, Georgia, and Florida are 7%, 6%, and 10%, respectively. The notably lower rates of nonresponse in the Southern region (excluding West Texas) likely arose for two reasons. First, field crews visit each property owner where a field inventory plot is located to obtain access permission in person. This differs from other regions where mailed form letters may be used to obtain permission for access. Second, a small number of replacement plots were established after two successive denied access occasions. Given the five panel design in the eastern USA, this means that a sample location that could not be observed at year 1 may be replaced in year 16. However, only 113 of the approximately 96,000 plots in the South were replaced from 2002–2008 and the overall impact of this practice was considered minimal.

Nonresponse assumptions

Post-stratified estimator

FIA uses post-stratified estimation (Cochran 1977) to estimate population totals of area and other attributes of interest. Typically, the National Land Cover Database (Homer et al. 2004) or similar Forest Service databases (Ruefenacht et al. 2008) are used to assign plots to strata and determine strata weights. The overall estimate is given by

$$\hat{Y} = A_T \sum_h W_h \bar{y}_h \tag{3.1.1}$$

where W_h is the stratum weight for stratum h and A_T is the total area of the population. Typically nonresponse plots are ignored and an adjustment factor is used to compensate for partial nonresponse plots and partially out-of-population plots. The stratum level estimate is given by

$$\bar{y}_h = \frac{\sum_i^{n_h} y_{hi} / \bar{p}_{oh}}{a_o n_h}, \tag{3.1.2}$$

where y_{hi} is the plot level value for the attribute of interest for plot i in stratum h, n_h is the number of plots in stratum h excluding the nonresponse plots, and $\bar{p}_{oh}$ is the mean plot area sampled, which is the adjustment factor used to compensate for partial nonresponse plots and partially out-of-population. The formulation of the adjustment factor is

$$\bar{p}_{oh} = \frac{\sum_i^{n_h} a_{ohi}}{a_o n_h}, \tag{3.1.3}$$

where a_{ohi} is the area sampled for plot i in stratum h, and a_o is the plot area. FIA treats $\bar{p}_{oh}$ as a constant, that is, ignores the contribution of the variability in $\bar{p}_{oh}$ to the sampling variance. If there are no partial nonresponse plots and all plots are totally in the population, then $\bar{p}_{oh} = 1$. Plots that are partially out of population usually occur for two reasons, straddling an international boundary or straddling a national forest boundary and the population of interest is the national forest. With few exceptions, partially out of population situations occur relatively infrequently and the variation is expected to be small enough to ignore. Although the above is a slightly simplified version of the FIA estimator, it captures all the salient details related to nonresponse; for complete details, see Scott et al. (2005).

Ignoring the nonresponse plots assumes that the nonresponse occur at random within each stratum. The missing at random within a stratum (or group) assumption is common in the nonresponse literature (Särndal et al. 1992). One critical aspect not addressed by Bechtold and Patterson (2005) is that a subset of the sample locations are observed remotely and these locations are not affected by denied access or hazardous conditions. The number of "not sent to the field" plots varies widely among the states and is dictated by how much non-forest land can be identified from high-resolution photos in conjunction with old field notes (Fig. 3). The prairie and plain states have the

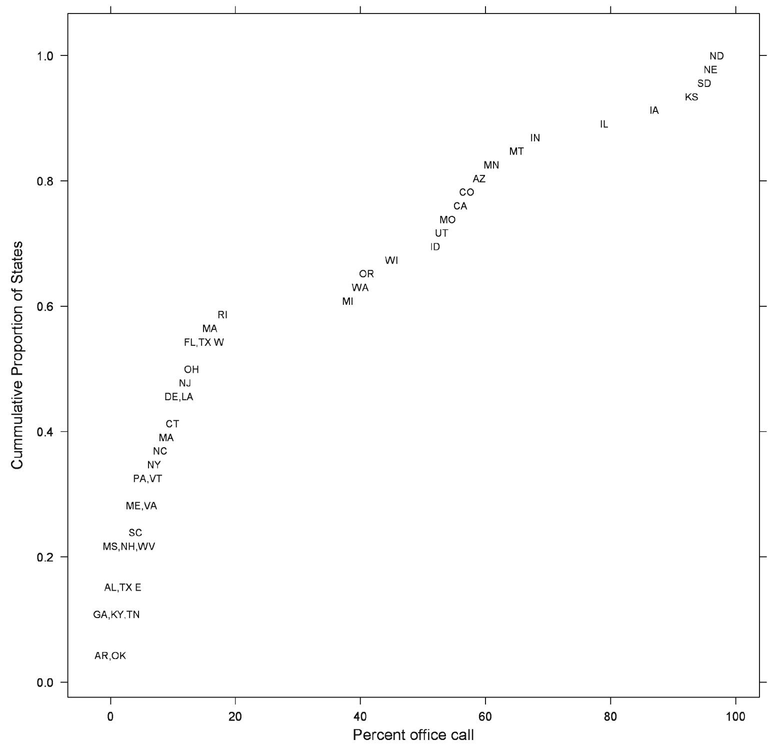

Fig. 3 The percentage of sample locations for each state which are determined using high-resolution photos to be non-forested and so are "not sent to the field"

largest percentage of "not sent to the field" plots; from 80% in Illinois to 98% in North Dakota. The heavily treed states in the east have the lowest percentage; from near 0% to 20%. The PNW-FIA and IW-FIA states and the states bordering the prairie range from 40% to near 70%. Based on this situation, there is a need to look more closely at the underlying assumption of missing at random within the strata.

Validity of the missing at random within strata assumption

There are three underlying components to the validity of assuming the observations are missing at random within strata. The first component is due to the fact that the sample is first observed remotely where there is no possibility of non-response. As mentioned in the previous section, this step determines whether each sample element will undergo further observation (i.e., each sample element is deemed either "sent to field" or "not sent to field"); those sample elements which are classified as "not sent to field" are non-forest and do not undergo further observation. This "not sent to field" group has a response probability of one that is likely distinct from response probability of the "sent to the field" of the sample. The second component is the accuracy of the post-stratification. The third component is the attribute for which an estimate is being made.

As an example of the first two components, suppose we want to estimate forest area using two strata; green (potential forest) and brown (potential non-forest). In the rare event when the post-stratification is in "perfect" agreement with the prefield classification, (i.e., all "sent to field" plots fall within the green stratum and all "not sent to field" plots fall in the brown stratum) the effect of nonresponse is that the green stratum is estimated based on a smaller number of plots. The equal (and higher) estimation weights of the "sent to the field" plots appropriately accounts for the lower realized sample intensity in the green stratum. Suppose instead that we have the usual situation in which the strata do not correspond to the prefield classification. This occurs because the stratification maps have modeling errors, registration errors, and there is often temporal error arising because the map products are derived from different points in time than the plot data were collected. When the "sent to field" and "not sent to field" plots are co-mingled within strata, the realized sample is more intense for the "not sent to the field" group (which are non-forest) than for the "sent to the field" group (which contains forest and possible non-forest plots). This causes an underestimate of forest area in the population.

Now consider the third component (the validity of the missing at random assumption might be specific to the attribute being estimated). Suppose that 10% of the "sent to field" plots in the forest stratum were non-sampled. Additionally assume all (or a large proportion) of the non-sampled plots were actually from a unique vegetation type. This result could have been obtained either through a random or a non-random mechanism. If the former is the case, then nonresponse is disproportionately affecting the estimates for that particular vegetation type in the same way that a reduced sample size would. This would also affect a variable that crosses vegetation types if the unique vegetation type contributes disproportionately to that variable. If the latter is the case, i.e., if the disproportionate allocation arose through a non-random event, the same effects on estimation would occur. However, this latter case would more obviously warrant a reaction because the FIA estimators can only be unbiased when all samples have been observed or when the unobserved samples are missing at random. From a sampling perspective, there is really only one way to recover from a violation of a missing at random assumption and that is to partition the population into subpopulations in such a way as to assure that the missing at random assumption applies within subpopulations. In this example, if the offending vegetation type was identifiable, it could be split out as a separate subpopulation, under the assumption that missing observations occur at random within each subpopulation.

Separating the population into groups where the missing at random assumption is valid is called the response homogeneity (RHG) model (Särndal et al. 1992). The RHG model has three basic assumptions: (1) the response probabilities are constant within each group; (2) although the number and composition of the groups may be dependent on the sample, it is assumed that if the population is sampled again and the same sample is drawn, then the number and composition of the groups is same; and (3) the sample elements are assumed to respond independently of each other. This last assumption is questionable for large landowners with multiple plots on their property.

For strata where there are both "not sent to the field" plots and "sent to the field" plots and the response probabilities are constant for the "sent to the field" plots (i.e., the RHG model holds), the direct weighting estimator (Särndal et al. 1992, result 15.6.1) applied to the stratum compensates for the differing response probabilities and is unbiased. Let $\bar{y}_{DWh}$ denote the direct weighting estimate for strata that contain both "not sent to the field" plots and "sent to the field" plots. If the response probability is equal to 1 (i.e., measurements are obtained for all "sent to the field" plots), then $\bar{y}_{DWh}$ is equal to $\bar{y}_h$. In order to gauge the practical implications of compensating for the differing response rates between "not sent to the field" plots and "sent to the field" plots, we calculated the difference between the estimate of proportion of forest using the current FIA estimator (Eq. 3.1.1) and estimate of proportion of forest obtained by substituting $\bar{y}_{DWh}$ for $\bar{y}_h$ in Eq. 3.1.1; for both estimates the proportion of forest is obtained by deleting multiplication by A_T in Eq. 3.1.1. We accepted the current stratification scheme and excluded from the analysis any plot with partial nonresponse. In addition, to simplify the calculation, any partially forested plot was deemed completely forested if the percentage of forest was greater than 0.5 and completely non-forested otherwise. In FIA, the smallest geographic area that estimates are calculated for are referred to as estimation units. The difference of the two estimates was calculated for each estimation unit in the IW, NRS, and SRS regions (Fig. 4). In SRS, where the nonresponse rates are low, the differences are close to zero. For IW the two estimation units with the largest difference have (1) a large number of "not sent to the field" plots, (2) a large percentage of nonresponse for the "sent to the field" plots, and (3) an equal number of forested and non-

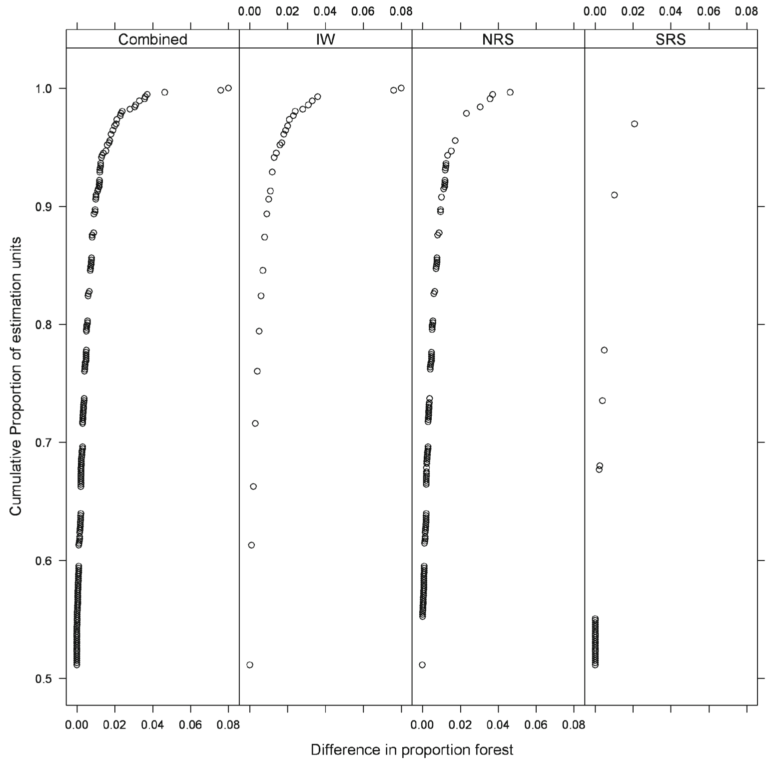

Fig. 4 Cumulative distribution of the difference between the direct weighting estimates of the proportion of forest and the current FIA estimates of the proportion of forest. The cumulative distribution is for estimation units in the IW, SRS, and NRS

forested plots for the measured “sent to the field plots”. This analysis indicates that not compensating for differing response probabilities within strata can lead to substantial under-estimation of the proportion of forest. Depending on the size of the estimation unit, even small differences in the proportion of forest can lead to large under estimates of the total hectares of forest.

Plot replacement strategies

One approach to deal with nonresponse that seems favorable among practitioners is to replace a plot location with an alternate location, possibly after some number of attempts at observation. Kish and Hess (1959) describe a replacement procedure that relies on being able to identify new samples with similar characteristics to the samples for which no information could be collected. However, Kish (1965) provides several cautions when considering replacements. The primary caution revolves around the argument that if one replaces samples, he or she is likely to replace it with something similar to what was already observed rather than what should have been observed based on the design. A small portion of plots within the Southern FIA region were replaced by selecting a new random location within the vicinity of the original location and although replacing individual missing observations does seem efficient and practical, we recommend that individual plots not be replaced in this manner. Rather, when it is determined that the sample has been sufficiently degraded due to nonresponse, we recommend that a new auxiliary probability sample should be drawn. We make this recommendation for a number of reasons; one being that an analysis performed in the Northern FIA region found that less than 2% of the land owners deny access on three consecutive occasions. Additionally, if a certain identifiable subpopulation is more likely to have nonresponse, then as plots are replaced the sample will become skewed away from that subpopulation. For example, individual private owners often have a higher rate of nonresponse than other owners do. Randomly replacing plots without regard to the private owner subpopulation would skew the sample toward other owner types, such as public owners and corporate private owners. Finally, if a large landowner denies access to land that contains a mixture of non-forest and forest plots, any plots identified in the office as non-forest are not sent to the field but remain in the sample, while plots sent to field and not observed would be replaced. The resulting set of plots would be either non-forested plots on the large landowner's land or plots off the large landowner's land, leading to a skewed sample.

Plausible strategies

Nonresponse, in the form of denied access, hazardous conditions, and missing data are a concern for the FIA program. Depending on the estimator used, nonresponse may increase sampling error and may lead to non-sampling errors (Särndal et al. 1992). In addition, an otherwise unbiased estimator may become a biased estimator in the presence of nonresponse. The best way to deal with nonresponse is to eliminate it; extra efforts should be made to reduce nonresponse due to denied access. Some nonresponse cannot be eliminated (e.g., certain hazardous conditions). Hazardous conditions are of two forms, permanent (e.g., cliffs and large swamps) or temporary (e.g., fires and animals). Every effort should be made to measure plots with temporary hazardous conditions. We also recommend that the FIA program continue to improve relationships with large land owners (e.g., Native American, National Park Service, King Ranch in Texas) so that field crews have continuous access to these areas.

Ignoring the nonresponse results in a decreased sample size but, as mentioned previously, may be appropriate in some situations as it has a solid inferential basis in probability theory under the assumption of missing at random. When this assumption is tenable, one simply uses the usual complete data methods on the sample actually observed. However, two criteria should be considered to keep bias at a minimum. First, the data that arise from office calls must be constrained within a separate stratum to avoid unequal inclusion probabilities within strata. Second, the set of plots sent to the field should be stratified such that an assumption of missing at random is tenable within strata. However, other difficulties related to number of strata and minimum within-stratum sample sizes may also be encountered in such an endeavor.

Multiple imputation techniques can be effectively employed to deal with missing data (Rubin 1987). This involves modeling the relationship of responders to nonresponders and is particularly suited to public use files where the user has only complete data methods at his or her disposal and some limit to information on the reasons for nonresponse (Rubin 1996). The model may rely on either previous measurements (if available) or ancillary data derived from digital aerial photos, Landsat Thematic Mapper imagery, digital elevation models, and public/private ownership GIS maps, for example to identify a set of observations that are candidate values for each nonresponse. The set of candidate observations are drawn from to impute values for the missing observations to form a "complete" data set. The "complete" data set is analyzed using the usual procedures. This entire process is repeated enough times to estimate the ranges of inferences that might have been obtained had there been no nonresponse under the assumed model. The most obvious way to effect a multiple imputation strategy is to construct and maintain multiple "complete" data sets to provide to users. A disadvantage to multiple imputation is the necessity of construction, storage, and maintenance of numerous data sets. This task potentially represents a large commitment of resources, which does not dissipate over time. Also, there is more complexity in understanding the methodologies needed to properly analyze the data and make appropriate interpretations of the results. Multiple imputation may be a viable solution in certain situations, e.g., periodic inventories, but may be impractical for a national forest inventory database where data are continually updated. While it is true that more robust change estimation could be achieved through multiple imputation, data management complexity may lead to a system that proves to be cost prohibitive.

The use of estimators that appropriately account for nonresponse is perhaps the most appealing solution when nonresponse is non-ignorable. If the RHG model is applicable, that is, the sample can be divided into response groups where the missing at random assumption holds, then Särndal et al. (1992) presents two alternatives, one method is the direct weighting used in "Nonresponse assumptions" to gage the practical implication of compensating for differing response rates and the other method uses auxiliary variables in addition to weighting. In the direct weighting method, the estimates for each response group are weighted based on the number of sample elements in the response group and number of respondents in the response group; whereas in the "ignore the nonresponse" method described above only the number of respondents in the response group is used. If additionally auxiliary information is available, Särndal et al. (1992, section 15.6.4) suggests the use of a regression estimator that is weighted to compensate for nonresponse. For both methods the set of plots sent to the field needs to be divided into response groups that the missing at random assumption is tenable within each group; at the same time taking into consideration minimum with-in group samples sizes.

There are regions that contain nonresponse plots that are clearly not missing at random. For example, South Florida survey unit contains the Big Cypress National Preserve and the Everglades National Park both of which contain large amounts of swamp; out of the 381 sent to the field plots in Everglades and Big Cypress 139 were deemed hazardous. Due to the unique characteristics, the Everglades and Big Cypress need to be handled separately from the rest of the South Florida survey unit. The nonresponse plots are clearly not missing at random and the areas where nonresponse occurs are by their nature different from the observed samples. There are alternative estimators which deal with nonresponse when the missing at random assumption is not tenable, such as the use of a Polya posterior (Meeden and Bryan 1996).

Defensible statistical treatment of data in conjunction with results that are easily understood are necessary in order to provide the most credibility to any national forest inventory and monitoring program. However, additional programmatic concerns must also be factored into any decision regarding the use of alternative estimators and strategies for nonresponse. These concerns include consistent public database construction across multiple legacy survey designs, consistency with previous estimates, and cost and timing of modifications to the national compilation system. Programmatic concerns must be considered jointly with statistical concerns in order to affect change and increase the overall efficiency of the FIA program.

Conclusions

Traditionally, FIA has viewed stratification as a method for variance reduction; however, since forest plots have higher probability of nonresponse, FIA should also take nonresponse into account when constructing strata. In the short-term, we recommend that FIA examine its stratification schemes and modify those approaches to more adequately stratify differing sampling intensities (caused by nonresponse) and different sampling mechanisms (field observed vs. office call). In the longer term we recommend that FIA investigate the properties and technical feasibility of alternative estimators that use appropriate weighting and auxiliary information to mitigate the effects of nonresponse. Permanently hazardous plots that occupy large and unique geographic areas are likely to be different from visited plots and may require techniques that do not rely on the missing at random hypothesis. Additionally, the plot replacement strategy previously used in the Southern FIA region warrants some concern and is not recommended. However, given the proportion (113 plot, approximately 0.1% of the sample) and the spatial distribution of the replacements (i.e., there is no clustering of replacements plots) the effects on the sample are considered negligible. Regardless, we recommend that the South revert to original sampling locations for those 113 replacement plots.

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