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measurement

Methods for Estimating Private Forest Ownership Statistics: Revised Methods for the USDA Forest Service's National Woodland Owner Survey

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The USDA Forest Service's National Woodland Owner Survey (NWOS) is conducted to better understand the attitudes and behaviors of private forest ownerships, which control more than half of US forestland. Inferences about the populations of interest should be based on theoretically sound estimation procedures. A recent review of the procedures disclosed an error in the application of estimation used in the NWOS. These issues are addressed and resolved in this article. The NWOS is administered to ownerships that contain a sample point determined to be forested and privately owned. The random selection of the sample points results in selection of ownerships with probability proportional to area of forestland owned. Inferences from survey results, including numbers of ownerships, area of forestland and associated variances, can be made using appropriate techniques, such as the Hansen-Hurwitz Estimator.

Keywords: private forest owners, sampling design, probability proportional to size, Hansen-Hurwitz estimator, family forest owners

To understand the forests of the United States, what has influenced them in the past, and what will influence them in the future, it is imperative to understand who owns the forests. Fifty-six percent of the 751 million acres (304 million ha) of forestland in the United States is privately owned. Private ownerships can include corporations, families, individuals, Native American tribes, nongovernmental organizations, clubs, associations, and others (Smith et al. 2009).

Surveys of private forest ownerships in the United States have been conducted since at least the 1940s (Barraclough and Rettie 1950), and the first publication with national-level forest ownership estimates was authored by Josephson and McGuire (1958). The US Department of Agriculture (USDA) Forest Service began to institutionalize forest ownership surveys in the 1970s (Kingsley and Finley 1975) with national-level reports published for 1978 (Birch et al. 1982), 1993 (Birch 1996), and 2006 (Butler 2008), referred to here as the National Woodland Owner Survey (NWOS). This first national publication (Josephson and McGuire 1958) reported only numbers of ownerships and area of forestland by size of forest holdings by region. Subsequent national reports included finer spatial resolution, either subregion or state, and more detailed information such as reasons for owning, management practices, owner demographics, and many other attributes. This information is used by policy analysts, federal and state agencies, educators, private consultants, nongovernmental organizations, and others to help design and implement policies, programs, and services aimed at private forest ownerships.

The theoretical basis for estimators used in the reports published to date has not been fully established. Metcalf et al. (2012) raised this point, but they too failed to establish a theoretical basis for their proposed estimation approach. Their critique is not theoretically justified and contains errors. They correctly point out that NWOS estimators, as presented in the past, have ignored the with-replacement aspect of the sampling design. However, they assert empirically rather than theoretically, and despite well-estab-

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lished proofs from the sampling literature, that the Hansen-Hurwitz estimator (HHE) used with the NWOS is asymptotically biased. This empirical assessment is based on one case study of eight counties in one state, using sampling intensities that are not comparable to that used by the NWOS. Metcalf et al. (2012) do suggest that although the previous estimation approaches need updating, NWOS point estimates probably will not change much after accounting for the with-replacement design because of the low sampling intensity.

This article provides a theoretical justification for estimation of population parameters related to the USDA Forest Service, NWOS. After a brief review of sampling literature, details of the NWOS sampling procedures are presented. An overview of the estimation approach is then presented along with the revised estimators and their justification. Finally, the new approach is compared with the older approaches, the findings of Metcalf et al. (2012) are explored further, and the implications of the differences are discussed.

Background

There are four sources of error associated with surveys: sampling error, nonresponse, measurement, and data editing/coding/tabulation (Cochran 1977). The first, sampling error, is a result of random sampling variation and is minimized through adequate sample size. The other errors are minimized through careful survey planning, implementation, and data processing.

The NWOS uses a probability proportional to size (PPS) sampling design; the probability of an ownership being included is directly proportional to its acreage. There are two basic families of estimators generally used with PPS sample designs: the HHE (Hansen and Hurwitz 1943) and the Horvitz-Thompson Estimator (HTE) (Horvitz and Thompson 1952). The HTE can be used unbiasedly for with- or without-replacement designs, but the HHE can only be applied unbiasedly to with-replacement designs (Thompson 1992).

A sampling procedure can be described as with-replacement when a unique sampling unit may be selected more than once (Jessen 1978), as is the case with the NWOS.[1] Thus, either the HHE or HTE can be used. However, Thompson (1992) and others point out that unbiasedly estimating the variance associated with the HTE for the NWOS sampling design requires calculation of joint inclusion probabilities, which can be prohibitively complicated. The HHE variance estimator can be used as a biased but conservative estimate of HTE variance, but the point estimates from the two estimators do not differ substantially at low sampling intensities anyway (Murthy 1967). Either the HHE or HTE point estimators can be used, but only the HHE variance estimator is feasible.

NWOS Sampling Procedures

The NWOS is part of the USDA Forest Service Forest Inventory and Analysis (FIA) program and is built on the FIA forest inventory sampling system. FIA samples land to estimate forest attributes, such as tree species composition, volumes of trees, and growth, removals, and mortality of trees, along with other variables, such as type of ownership. The FIA forest inventory uses a three-phase sampling system: stratification to increase precision; field measurements of forest mensuration and related variables; and field measurements of forest health variables (Bechtold and Patterson 2005). Only the second sampling phase, measurement of traditional forest inventory variables, has relevance to the NWOS and is the only phase discussed here.

A hexagonal grid was randomly placed over the United States with each hexagon having an area of 5,937 acres (2,403 ha) or roughly 1 sample point per 6,000 acres (2,428 ha) (Bechtold and Patterson 2005). Within each hexagon, one random sample point was selected using methods presented in Bechtold and Patterson (2005) such that all areas of any given unit have an equal probability of containing a sample point (within a stratum). These sample points are the primary sampling units (PSUs)[2] for the FIA forest inventory. The tessellation (i.e., spreading out the sampling points using the hexagons) prevents clustering of sample points and improves precision compared with a true simple random sample of points (Bechtold and Patterson 2005). Periodicity problems normally associated with systematic sampling are less of an issue here because the sampling points are randomly offset from hexagon centers.

At each sample point, FIA superimposes a sample *plot* with a sampling area of 0.17 acres (0.07 ha) spread across four equal area subplots and determines whether there is forestland on any portion of a subplot. Forestland is defined as being at least 10% stocked with trees, at least 1 acre (0.4 ha) in area and at least 120 feet (37 m) wide; further details of the classification rules are available in the FIA forest inventory field guide (USDA Forest Service 2010). For the sample points that are associated with plots that have one or more forested conditions, the ownership is determined from public tax records.

The NWOS sample consists of ownerships on which FIA forest inventory sample points fall. The only attributes recorded by the FIA forest inventory used for the NWOS are the forest cover indicator and ownership category variables. All other attributes used in NWOS analyses are collected from the survey. The ownerships are selected with probability proportional to size because points on the ground are located at random (within a systematic framework) and ownerships have different areas (for agricultural applications relevant to the NWOS, see Sukhatme 1954, Murthy 1967, and Som 1973).

Revised NWOS Estimation Procedures

Forest ownership statistics can be reported in terms of ownerships or units of area. An ownership is a legal entity that owns land and can be an individual person, fam-

Management and Policy Implications

The results of this article have direct implications for the USDA Forest Service National Woodland Owner Survey (NWOS) and consequently for any researchers or policymakers who have made use of NWOS-based inferences about private forest ownerships and acres in the United States. Estimation procedures for the NWOS and its precursors have had several theoretical problems for many decades. This article updates those procedures accordingly and provides a theoretical foundation for the new estimators.

Because of low sampling intensity for the NWOS, the new estimators are not expected to give point estimates substantially different from those given by the old estimators. The implication is that historical estimates made over the last several decades should be generally reliable. More importantly, the policies, programs, and services that have used such estimates should not be affected by these changes.

ily, or business partnership, corporation, nonprofit organization, trust, or other entity. Area owned is the number of acres, or equivalent units, owned by that entity. The proper unit of analysis depends on the needs of the end-user, but often it is important to examine both ownership- and area-based estimates. Ownership-based inference is more relevant to issues concerning the people who own the forests, whereas area-based inference relates better to issues concerning the landscape itself.

The key terms used to discuss estimation of forest ownership statistics are population, stratum, and domain of interest. The population sampled by the NWOS is all land in the United States, the same as the population sampled for the FIA forest inventory. However, the populations of interest for the NWOS are either private forest ownerships or private forest area. The strata in the NWOS are individual states. The NWOS is administered with various sampling intensities in different states due mainly to budgetary issues. The domain of interest refers to a subset of private forest ownerships or area with a particular characteristic, either within or across strata.

NWOS estimation must be conducted first at the state level. Estimates for domains of interest that cross state boundaries require combining estimates. Estimates of totals and their associated variances are additive because the strata are independent and mutually exclusive, but combining means and their variances across strata requires weighting (Lohr 2010).

The PSUs identified by the FIA to fall on private forest ownerships comprise the part of the sample to be surveyed (Butler et al. 2005). Other PSUs that do not fall on private forestland (they fall either on forestlands owned by the public or on nonforest land of any ownership) are still part of the sample; however, these do not require a survey. NWOS procedures are documented in Butler et al. (2005) and Butler (2008). Sampling is with-replacement and so attribute information from an ownership is used in estimation as many times as the ownership is selected.

Only the total estimators and associated variance estimators for a single stratum are presented here. Estimators for means, quantiles, and proportions can be derived from the total estimators (Särndal et al. 1992). Expanding estimates to multiple strata is a matter of adding for totals and their variances but is more complicated for the other statistics (Lohr 2010).

Sidebar 1. Definitions of Variables Used in Estimating Private Forest Ownership Statistics

A_{hd}: estimated total area of land in stratum, or state, h within domain d.
$\bar{a}_{hd}$: estimated average ownership size for stratum h within domain d, in acres.
a_{hi}: area (acres) associated with ownership i in stratum h.
d_{hi}: an indicator taking the value 1 if ownership i in stratum h is in domain d.
n_h: full intended sample size for stratum h, including ownerships as many times as they are selected.
N_{hd}: the estimated number of ownerships in stratum h within domain d.
P_{hd}: the sample proportion of ownerships in stratum h that fall in domain d.
p_{hi}: the selection probability for ownership i in stratum h.
Y_{hd}: the estimated total for attribute y in stratum h within domain d.
y_{hi}: the value of attribute y for ownership i in stratum h.

The Hansen-Hurwitz Estimator

The population total for an attribute in a given stratum is (Lohr 2010)

$$Y_{hd} = \sum_{i=1}^{N_h} y_{hi} d_{hi} \qquad (1)$$

where Y_{hd} is the population total for attribute y in stratum h and domain d, N_h is the total number of ownerships in stratum h; y_{hi} is the attribute value for ownership i, and d_{hi} is an indicator variable taking the value of 1 if ownership i is in domain d (e.g., the sample point is owned by a private forest ownership) and 0 otherwise. We define the population of interest as all private forest ownerships or private forest area and domains of interest as subsets thereof. However, because of the sampling design, an unbiased estimator must account for all sample points regardless of whether they are in our population of interest; the domain variable is set to 0 for all sample points not within the population of interest.

The HHE is well-suited for estimating population totals, given the criteria of unbiasedness of point and variance estimators and ease of calculation. Appropriate selection probabilities therefore need to be incorporated. As pointed out by Metcalf et al. (2012), selection and inclusion probabilities have been confused in previous publications. To be clear, selection probability refers to the probability of an ownership being selected on any given draw, whereas inclusion probability means the overall chance of being included in the sample at least once (Thompson 1992). The selection probability within stratum h is equal to an ownership's area in the stratum divided by total area of the stratum (Jessen 1978)

$$p_{hi} = \frac{a_{hi}}{A_h} \qquad (2)$$

where p_{hi} is ownership i's probability of selection in stratum h, a_{hi} is the area of forestland owned by ownership i in stratum h, and A_h is the total area of land in stratum h.

The unbiased Hansen-Hurwitz (HH) estimator of population total Y_{hd} is the weighted sum of ownership attributes (Lohr 2010)

$$\hat{Y}_{hd} = \frac{1}{n_h} \sum_{i=1}^{n_h} \frac{y_{hi} d_{hi}}{p_{hi}} = \frac{A_h}{n_h} \sum_{i=1}^{n_h} \frac{y_{hi} d_{hi}}{a_{hi}} \qquad (3)$$

where $\hat{Y}_{hd}$ is the estimated population total, n_h is the sample size in the stratum, and the other variables are as defined above. The term n_h, in contrast to past NWOS estimators (Butler et al. 2005), refers to the total number of FIA sample points in the stratum. This includes sample points not on private forest ownerships and multiple points on a common ownership. For example, if in stratum 1 there are 5 sample points on nonforest land, 5 sample points on public forest ownerships, and 10 sample points on private forest ownerships then $n_1 = 5 + 5 + 10 = 20$. This holds even if 6 of the sample points on private forestland fell on the same ownership, meaning that only 5 ownerships were surveyed. In previous presentations of NWOS estimators (Butler et al. 2005 and others), n_1 is the number of unique private forest ownerships that are sampled, so that it would have been 5 in this case. The term A_h also differs from previous NWOS estimators; here it refers to the total area land in the stratum, not just private forestland as in past NWOS estimators.

The variance of the HHE is equal to the probability-weighted sum of squared deviations of individually weighted attribute values from the population total (Lohr 2010)

$$var(\hat{Y}_{hd}) = \sum_{i=1}^{N_h} p_{hi} \left(\frac{y_{hi} d_{hi}}{p_{hi}} - Y_{hd} \right)^2. \quad (4)$$

An unbiased[3] estimator of this variance is given by Lohr (2010):

$$\widehat{\text{var}}(\hat{Y}_{hd}) = \frac{1}{n_h(n_h - 1)} \sum_{i=1}^{n_h} \left(\frac{y_{hi} d_{hi}}{p_{hi}} - \hat{Y}_{hd} \right)^2 \quad (5)$$

where all terms are as defined above. This new variance estimator is simpler than that presented by Butler et al. (2005) because A_h (a component of p_h; see Equation 2) is a known constant. Before, the FIA-estimated area of private forestland was incorporated into the variance of the total estimate because FIA-estimated area is a random variable.

The old NWOS point estimator of total, used in place of Equation 3, is presented in Equation 6. This corresponds to Equation 5 in Butler et al. (2005), although the estimator has been generalized, and terms have been changed to match those in Equation 3 of this article

$$\hat{Y}_{hd} = \frac{1}{n_o} \sum_{i=1}^{n_o} \frac{y_{hi} d_{hi}}{p_{hi}} = \frac{\hat{A}_f}{n_o} \sum_{i=1}^{n_o} \frac{y_{hi} d_{hi}}{a_{hi}}. \quad (6)$$

The term n_o represents the number of unique private forest ownerships selected. FIA-estimated private forest area, $\hat{A}_f$, is used in place of the known constant A_h. The old variance estimator is presented in Equation 7, corresponding to Equation 6 from Butler et al. (2005)

$$\widehat{\text{var}}(\hat{Y}_{hd}) = \hat{A}_f^2 \frac{1}{n_o(n_o - 1)} \sum_{i=1}^{n_o} \left(\frac{y_{hi} d_{hi}}{a_{hi}} - \frac{1}{n_o} \sum_{i=1}^{n_o} \frac{y_{hi} d_{hi}}{a_{hi}} \right)^2 + \widehat{\text{var}}(\hat{A}_f) \times \left(\frac{1}{n_o} \sum_{i=1}^{n_o} \frac{y_{hi} d_{hi}}{a_{hi}} \right)^2. \quad (7)$$

The extra term accounts for the variance of $\hat{A}_f$. It follows from a Taylor series linearization method of approximating the variance of a product of two random variables, although it is missing covariance terms (Lohr 2010).

Ownership Totals

An important application of the estimators in Equations 3 and 5 is to estimate the total number of ownerships in a stratum and domain of interest. In that case, the attribute of interest y_{hi} in Equation 3 is existence itself and so equals 1 for all ownerships. The equation then simplifies to (Lohr 2010)

$$\hat{N}_{hd} = \frac{A_h}{n_h} \sum_{i=1}^{n_h} \frac{d_{hi}}{a_{hi}}. \quad (8)$$

The variance of $\hat{N}_{hd}$, based on Equation 5, can be estimated with

$$\widehat{\text{var}}\left(\hat{N}_{hd} = \frac{1}{n_h(n_h - 1)} \sum_{i=1}^{n_h} \left(\frac{d_{hi}}{p_{hi}} - \hat{N}_{hd} \right)^2. \right. \quad (9)$$

The point and variance estimators presented in previous publications (Equations 6 and 7) are *only* for estimating area and number of ownerships (although we generalize them here). We began with the more general HHE for attribute total (Equation 3) to derive Equation 8 because it is needed to derive estimators for total acres and for attribute means, proportions, and quantiles.

Area Totals

Equation 3 can be used to estimate the total area (e.g., number of acres) in a domain of interest within the population of all private forest area. FIA provides estimates for total private forest area and family forest area with greater precision and so NWOS estimates are only needed for domains that are subsets of FIA domains. The variable of interest is now area of forestland in a stratum and domain of interest, so Equation 3 simplifies to

$$\hat{A}_{hd} = A_h \frac{1}{n_h} \sum_{n_h} \frac{a_{hi} d_{hi}}{a_{hi}} = A_h \frac{1}{n_h} \sum_{i=1}^{n_h} d_{hi} = A_h \hat{p}_{dh} \quad (10)$$

where $\hat{p}_{dh}$ is the sample proportion of points on ownerships in the domain of interest and the other variables are as defined above. Note that in this case, the equation simplifies to an estimator of population size generally used with simple random sampling (Cochran 1977).

The variance of this total estimator can be estimated unbiasedly[4] with

$$\widehat{\text{var}}(\hat{A}_{hd}) = A_h^2 \widehat{\text{var}}(\hat{P}_{dh}) = A_h^2 \times \frac{\hat{p}_{dh} \times (1 - \hat{p}_{dh})}{n_h - 1}. \quad (11)$$

The point and variance estimators in Equations 3 and 5 comprise the foundation from which all other NWOS estimators are derived. These include estimators of means, proportions, and quantiles. For example, an estimate of average ownership size can be obtained with the ratio

$$\bar{a}_{hd} = \frac{\hat{A}_{hd}}{\hat{N}_{hd}} \quad (12)$$

and its variance can be approximated using Taylor series linearization (Särndal et al. 1992). Cross-stratum mean estimators are obtained by summing the total estimators contained in the numerator and denominator across strata. These additional estimators are not presented here due to space constraints; however, they will be detailed in a forthcoming USDA Forest Service General Technical Report.

An assumption behind the new estimators outlined thus far is full response; that is, all ownerships contacted fill out all items (full item response) on the survey and return it (full unit response). This is far from reality, with NWOS unit response rates being around 50% (Butler et al. 2005). For reasons too complex to detail here, nonresponse could be ignored in past NWOS estimation with implicit assumptions about the nature of nonresponse. However, the new estimators do not allow this because all sampled points are used. Proceeding as before would skew the sample toward nonprivate forest ownerships. That would entail assigning a domain indicator value of 0 to nonresponding private forest ownerships, which we know have the value 1. The result would be a systematic and severe downward bias for all estimators of total (except for Equation 10 applied to the case of estimating total private or total family forest acres, because these indicators are supplied by FIA).

There is a way to adjust the new estimators to explicitly incorporate the old approach to nonresponse, but a better strategy is needed. The old approach requires stringent assumptions such as all ownerships in the population having an equal probability of response and is commonly referred to in the sampling literature as the "naive" approach (Särndal et al. 1992, Lohr 2010). Better methods of addressing nonresponse are currently being investigated. The method chosen for the NWOS will be published in the forthcoming USDA Forest Service General Technical Report.

Discussion

Metcalf et al. (2012) and Metcalf (2010) raised some important issues with NWOS estimators as presented by Butler et al. (2005) and used in various ownership surveys over the past 30 years. They pointed out a misuse of sampling terminology (selection versus inclusion probabilities: HHE versus HTE) and the unjustified discarding of multiple draws of the same ownership when estimating with the HHE. Indeed, the NWOS estimators use selection probabilities, not inclusion probabilities, and use the HHE rather than the HTE. Furthermore, the HHE was not applied properly because ownerships need to be included in estimation as many times as they are selected, not just once.[5]

Another problem with past NWOS estimation was not addressed by Metcalf et al. (2012). All sample points, regardless of whether they are private forest, other forest, or nonforest, should be accounted for in estimation. The total area of stratum rather than the area of private forest in stratum should be used in calculating selection probabilities.

Other "issues" raised by Metcalf et al. (2012) lack theoretical support or otherwise do not apply to NWOS estimation. Metcalf et al. (2012) made three principle claims: that discarding duplicate ownerships from estimators will give increasingly and upwardly biased estimates of population total as sampling intensity increases; that even proper use of the HHE will lead to increasingly and downwardly biased estimates; and that the solution is to use the HTE, or "π estimator" (Särndal et al. 1992). We address these three assertions in order below.

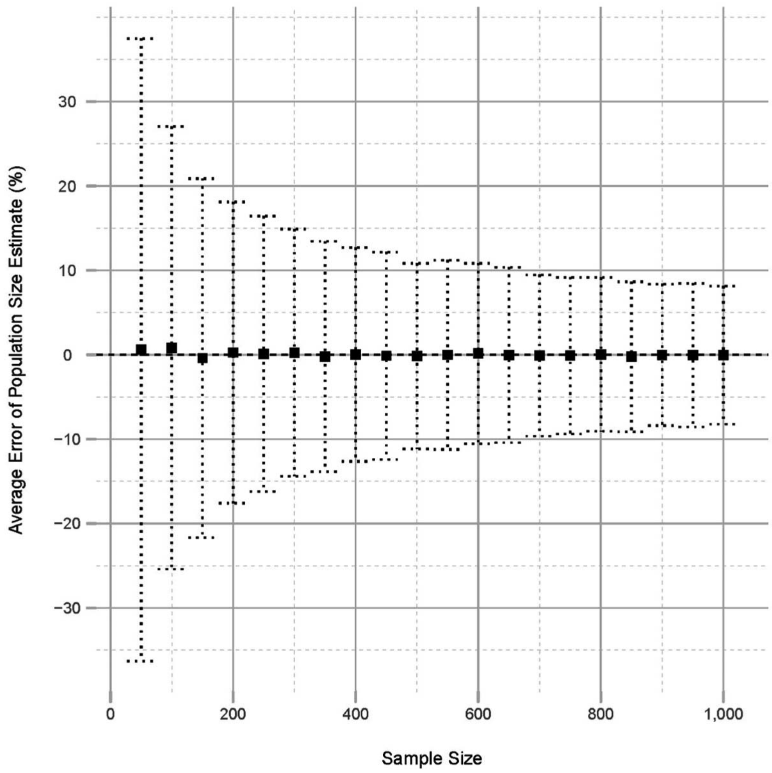

Figure 1. Simulated performance of the HHE for a population with an exponential distribution (rate = 1/20) as sample size increases from n = 50 to n = 1,000 with data points representing mean error of estimates and bars showing ±1.96 times the SD of estimates across 1,000 samples at each sample size.

Metcalf et al. (2012) base their conclusions on an empirical analysis of eight Pennsylvania counties for which they had electronic parcel maps. The authors selected 1,000 samples of ownerships using with-replacement PPS sampling, at various sample sizes from $n = 50$ to $n = 1{,}000$. At each sample size, three types of estimators were used to estimate population size: the incorrectly implemented HHE as in Butler et al. (2005), a correctly implemented HHE, and the HTE. Estimates of population size for each type of estimator were calculated and averaged across the 1,000 samples. The authors then compared the average estimates across sample sizes for each estimator.

Their first conclusion is that ignoring duplicates with a HHE (i.e., the previous NWOS estimator) gives increasingly and upwardly biased estimates beyond a certain sampling intensity. The authors do not discuss the sampling intensity threshold at which confidence intervals around the biased estimates do not contain the true population value. They do acknowledge that the bias is negligible at NWOS-level sampling intensity. Thus, whereas Metcalf et al. (2012) are correct that duplicate ownerships need to be included in estimation, the relatively low sampling intensity of the NWOS means that practical differences are probably minimal.

The authors' second conclusion, that even the correctly implemented HHE is biased at high sampling intensities (and that this is because the size of private forest ownerships is distributed non-normally), contradicts the estimator's well-established theoretical properties (Hansen and Hurwitz 1943, Särndal et al. 1992, Thompson 1992, Lohr 2010). Thompson (1992) and others prove that the HHE is unbiased. Differences in sampling intensity or shape of population distribution are simply unrelated to this property.

The authors' counter-theoretical results suggest an error in their approach. A simulation approach was used in an attempt to replicate the Metcalf et al. (2012) findings, with starkly different results. An exponentially distributed population of size $N = 17{,}000$ and rate $= 1/20$[6] was simulated. Samples were drawn with replacement using probability proportional to size at a sequence of sample sizes. For 1,000 samples at each sample size, the HHE was used to estimate population size. All data simulation was done in the R statistical package (R Development Core Team 2005). Figure 1 displays the results graphically, with average estimate error at each sample size presented as a percentage of the true population value. Bars are shown around each average at ±1.96 times the SD (in percent form) of the 1,000 estimates. This approximates the range of the sampling distribution in which 95% of all possible estimates will fall for each sample size. The increasingly downward bias purported by Metcalf et al. (2012) does not appear. If the number of samples is increased

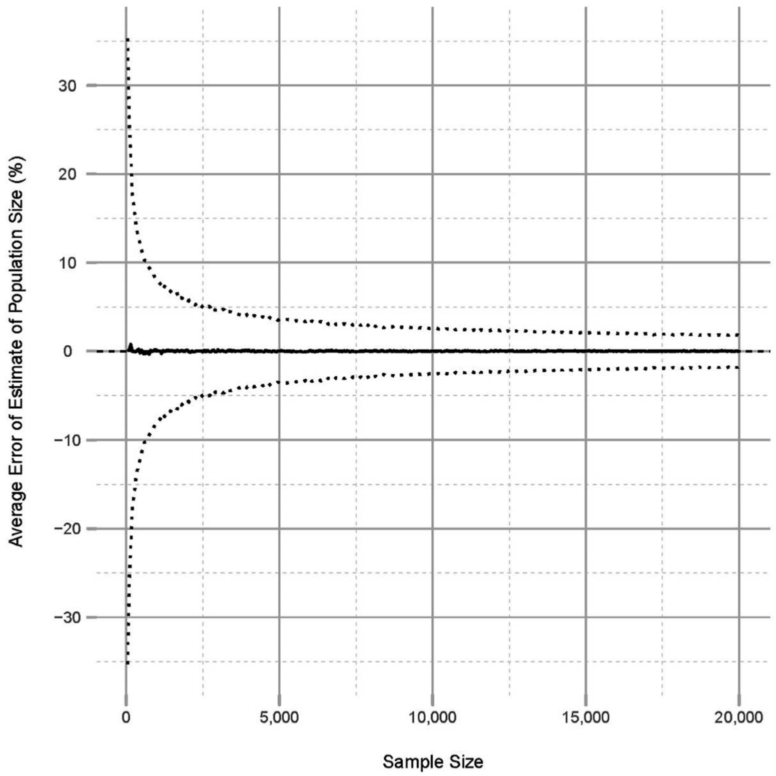

Figure 2. Simulated performance of the HHE for a population with an exponential distribution (rate = 1/20) as sample size increases from *n* = 50 to *n* = 20,000 with center line representing mean error of estimates and lines above and below showing ±1.96 times the SD of estimates across 1,000 samples at each sample size.

beyond 1,000, the average error of the estimate at any sample size approaches zero as the number of samples approaches infinity.

To further explore the performance of the HHE, sample sizes up to 20,000 were examined, thereby exceeding the population size itself (only possible for with-replacement sampling). As expected, Figure 2 supports the well-established properties of the HHE: unbiased with asymptotic variance approaching zero as sample size increases. The lines above and below the averages follow the same pattern as the bars in Figure 1; that is, they show the approximated range in which 95% of all estimates at that sample size will fall.

The third conclusion of Metcalf et al. (2012), that the HTE is a preferable solution, is unsupported beyond an erroneous critique of the HHE's statistical properties. Metcalf et al. (2012) mention variance estimates for each type of point estimate, but they do not indicate how these were calculated. We do not dispute that the Horvitz-Thompson (HT) point estimator is a viable alternative to the HH point estimator. However, Metcalf et al. (2012) do not address how to estimate the HT variance.

To estimate the HTE's variance without bias requires computing exact joint inclusion probabilities for all pairs of ownerships in the NWOS sample. Thompson (1992) presents a general formula for doing just that, but calculating these probabilities is not feasible, given the NWOS sampling design. The HH variance estimator may be a biased but reasonable approximation to the HT variance estimator (Murthy 1967, Wolter 1985). Regardless of the choice of estimator (HHE or HTE), additional investigation of the performance of the variance approximations for the HHE and HTE is needed.

Conclusions

The population of interest for the NWOS is private forest ownerships or private forest area in the United States. The NWOS is administered for ownerships that contain a point identified by the FIA forest inventory to be forested and privately owned. The country is divided into strata comprising states and the sampling intensity can differ among states. The random selection of FIA forest inventory PSUs results in selection of ownerships with probability proportional to area of forestland owned.

The NWOS sampling design can be described as spatially tessellated and temporally systematic, disproportionately stratified, with-replacement, and probability proportional to size. Every unit area of land and also of forested land has the same probability of selection. Ownerships cover differing amounts of land/forest area; thus, ownerships are selected with probability proportional to size. The HHE is unbiased and asymptotically normal.

Several important issues are not addressed in this article because of space constraints. Unit and item nonresponse needs to be fully addressed. This topic is ignored or given only glancing reference in previous efforts. The implications of the NWOS sampling design for analysis topics such as hypothesis testing and proper adjustments for regression analyses need to be elaborated as well.

Future research will assess the specific changes to historical data for comparisons across time.

Endnotes

1. The traditional with-replacement sampling design involves *n* independent selections, so that a sampling unit may theoretically be selected as many as *n* times. However, the NWOS uses points that are selected systematically across a hexagonal grid, so that an ownership can only be selected as many times as the number of hexagons it occupies. Although the properties of the HHE presented here are based on the traditional with-replacement sampling design, we use them to approximate unbiased estimators for the systematic-based NWOS sampling design. It can be shown that the HHE point estimator is unbiased for this systematic design; every area of a given unit has an equal probability of selection because the hexagonal grid is randomly placed. The spreading of points across a systematic grid will make this estimator more precise than a traditional with-replacement estimator (Bechtold and Patterson 2005), so that the HHE variance estimator is an upwardly biased and therefore conservative estimator of the true systematic variance.
2. The term "primary sampling unit" is ordinarily reserved for cluster sampling. The NWOS does not use cluster sampling; the term refers here to these zero-dimensional points used to select ownerships. We use the term here to be consistent with Bechtold and Patterson (2005).

3. As mentioned in footnote 1, the HHE variance estimator is only unbiased for a traditional with-replacement design; it will be an upwardly biased and so conservative estimate of the variance because of the systematic nature of the NWOS sampling design.
4. See footnote 3.
5. Refer to Equations 6 and 7; selection probabilities are $a_{h_i}/\hat{A}_f$. The term n_o is *effective sample size*, meaning each ownership is counted only once.
6. Rate is the parameter used to generate the exponential distribution. It represents the inverse of its mean value. That gives an average size of 20 acres, close to the Pennsylvania state average (Butler 2008).

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