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Integrating urban and national forest inventory data in support of rural–urban assessments

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Due to the interest in status and trends in forest resources, many countries conduct a national forest inventory (NFI). To better understand the characteristics of woody vegetation in areas that are typically not forested, there is an increasing emphasis on urban inventory efforts where all trees both within and outside forest areas are measured. Often, these two inventories are entirely independent endeavours from data collection through analytical reporting. To holistically explore landscape-scale phenomena across the rural–urban gradient, there is a need to combine information from both sources. In this paper, methods for combining these two data sources are examined using data from an urban inventory conducted in Austin, Texas, USA, and NFI data collected in the same and surrounding areas. Approaches to aggregating areas based on sampling intensity and plot design combinations are of considerable importance for the validity of the estimation. An additional complexity can also arise due to temporal discrepancies between the two data sources. Thus, it is imperative to accurately identify all the existing sampling intensity/plot design combinations within the population of interest. Once this difficulty is surmounted, there still exist aggregation methods that will produce erroneous results. Statistically valid variance estimation arises from maintaining independence of the two samples. This approach satisfies both the proportional allocation among strata requirement as well as the necessary partitioning of the two plot designs. Difficulty in interpretation of results can also be encountered due to differences in measurement protocols across aggregated areas. Thus, analysts should have an in-depth understanding of data sources and the differences between them to avoid unintended errors. The need for rural–urban assessments are expected to increase dramatically as urban areas expand and issues such as land conversion, wildland fire and invasive species spread become of further importance.

Introduction

It is common in many countries to implement a national forest inventory (NFI) due to the importance of renewable wood resources and other amenities attributable to forested areas (Tomppo *et al.*, 2010). NFI data provide a wealth of information that are used at various spatial and temporal scales for forest management, planning and policy decisions. In the last few decades, the importance of inventorying vegetation in other areas has been increasingly recognized, particularly in urban environments (Nowak *et al.*, 2001). Konijnendijk (2003) notes that urban forestry first gained acceptance in North America in the 1970s, with the concept gradually spreading to Europe a decade later. However, it was not until the 1990s that all-land urban inventories were initiated in some US cities (Nowak and Crane, 2002). As the value of these inventories became increasingly visible, more urban inventory efforts were undertaken in cities around the globe (Thaiutsa et al., 2008; Nagendra and Gopal, 2010; Nowak et al., 2013; Gardi *et al.*, 2016).

In the broader context of landscape-scale monitoring, it seems desirable that urban inventory efforts would be integrated into existing NFI programmes (Riemann, 2003; Schnell *et al.*, 2015a). Integration could accrue considerable benefits, such as consistent information on urban-relevant attributes across large areas (Corona, 2016) and seamless analyses of status and trends in resource characteristics across the rural–urban gradient (Corona *et al.*, 2012). Despite the clear need and value, an integrated solution has generally not come to fruition for various reasons, including NFI and urban inventory efforts (1) being under the purview of different government entities, (2) having inconsistent information needs and (3) differing in practical aspects of implementation. Examples of these differences include (1) some tree species encountered in urban settings generally are not found in forests (Blood *et al.*, 2016), (2) tree attributes of interest are often not the same, e.g. merchantable volume in forests as compared to crown size for urban environments (Donovan and Butry, 2009) and (3) more compact sample plot designs and increased sample intensities for urban inventories (Nowak *et al.*, 2008). Another difficulty is that often NFIs are well established and thus considerable work is required to integrate urban inventory components into existing field guides, databases and analytical software. Despite the lack of integration, assessments that take advantage of both urban and forest inventory data are needed to better understand trends in resource characteristics across the rural–urban gradient.

An impediment to conducting such assessments arises when NFI and urban data reside in independent databases and must be appropriately combined to make valid estimations. To our knowledge, there has been no assessment published that combines these data to produce population-level estimates. There are numerous methods that might be devised, although many of these ad hoc approaches can produce incorrect results. Only the most data-savvy analysts or scientists might be able to combine these data successfully and produce valid estimates. This situation limits the potential for important science and resource management advances on issues affecting rural–urban landscapes, such as land conversion/peri-urban forest preservation, wildland fire and invasive species spread. The objective of this paper is to identify valid estimation methods that combine NFI and urban inventory data. We identify important differences between the two inventories and present methods to address those differences. This is done using data from an urban inventory conducted in Austin, TX, USA and NFI data from the surrounding area. We focus estimation on tree biomass and forest area as representations of the two most prevalent types of variables, that being tree- and area-based, respectively. Findings should be of interest to scientists and analysts desiring population estimates of a number of possible inventory variables in the rural–urban landscape. The methods developed here should also prove useful in efforts to develop data retrieval and estimation tools that combine the two datasets, which will promote access and use of the data.

Methods

Data

Two data sources were used for this study, both of which originate within the forest inventory and analysis (FIA) programme of the US Forest Service. The first dataset is from the measurement of sample plots that are a part of the FIA's ongoing NFI effort. The NFI employs a panelized design where a portion of the plots are measured each year, generally corresponding to 5-, 7- or 10-year cycle lengths. The data were collected using the annualized FIA sample and plot design, where the sampling intensity is approximately one plot for every 2400 ha of area (Reams *et al.*, 2005). Each sample plot contains four 7.31-m (24 ft) radius subplots (Bechtold and Scott, 2005). On these subplots, trees within a forested condition having a diameter at breast-height (dbh) of 12.70 cm (5.0 in.) and larger were measured for various attributes such as species, dbh, total tree height, crown ratio and crown class (U.S. Forest Service, 2010). The proportion of each subplot that is forested is also recorded. Each subplot also contains a 2.07-m (6.8 ft) microplot in which saplings (2.54 cm ≤ dbh < 12.70 cm) are assessed. The biomass of each tree and sapling is predicted using the methods described by Woodall *et al.* (2011). For this study, a full inventory cycle of plots measured between 2004 and 2013 in 14 counties including and surrounding the city of Austin, Texas (TX) were used (Figure 1). Various subsets of these data will be used for analysis and will be referred to as Area(NFI) where Area will be either, red, blue or grey to indicate the area of interest and the data that reflect the NFI measurement protocol.

The second dataset was collected as a part of the FIA urban inventory in the vicinity of Austin, TX (Figure 1). The urban inventory was implemented using a systematic unaligned sampling design which is similar to the NFI sample that is based on a hexagonal grid (Reams *et al.*, 2005). For Austin, an intensified hexagonal grid was used, wherein existing FIA plot locations were retained for the grid cells in which they occurred and new plots were chosen for empty grid cells. The sampling intensity was approximately one plot for every 354 ha of area – which is approximately a sevenfold intensification of the base sample grid (Blackard and Patterson, 2014). In the urban areas outside Austin city limits (urban areas and urban clusters; Figure 1), there is no intensification of the urban sample and the urban inventory protocol is applied to existing NFI plot locations, i.e. the urban and NFI plots are co-located.

The urban inventory plot design is a circular 14.63-m (48.0 ft) radius plot, within which are four microplots having radii of 2.07 m (6.8 ft) with centre points being offset 3.66 m (12.0 ft) horizontally from plot centre in each cardinal direction (Nowak *et al.*, 2016). Tree measurement protocols are very similar to the NFI conventions, i.e. trees having dbh 12.70 cm and larger are measured on the entire area, whereas saplings (2.54 cm ≤ dbh < 12.70 cm) are only recorded on microplots. Two key differences in the urban inventory are as follows: (1) an expanded list of species considered to be a tree (and thus recorded in the data) in comparison to the NFI and (2) all listed trees on the plot are recorded, including areas that are not forested. Tree biomass is estimated using the methods described by McPherson *et al.* (1994, Ch. 6). As with the NFI plots, the portion of the plot that is forested is also recorded (U.S. Forest Service, 2014). In the analysis, these data will be noted as Area (U) to indicate the area of interest and the urban plot design and measurement protocol.

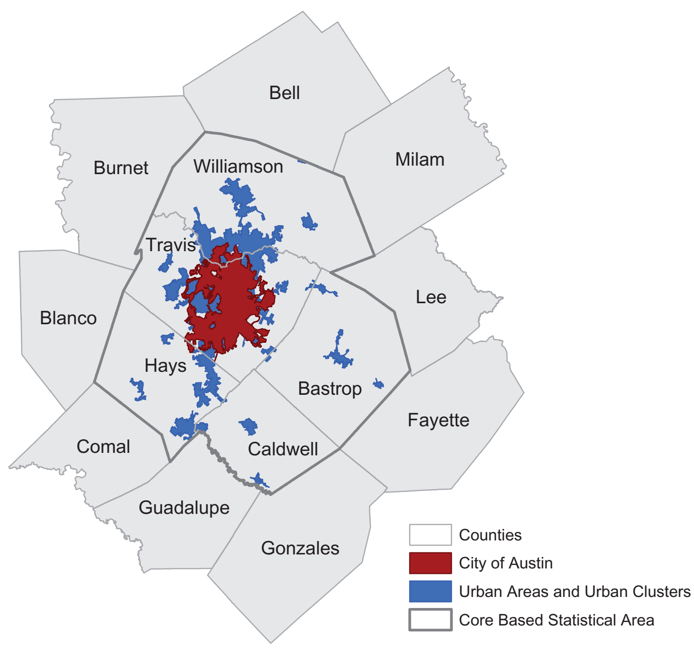

Figure 1 Map of the 14 counties' study area in the vicinity of Austin, TX, USA.

Both the NFI and urban inventories are implemented as autonomous efforts, in the sense that each has its own field guide, data compilation process, database, etc.; however, plot locations are shared when possible to facilitate field work efficiency. For example, within the Austin city limits defined by 2010 US Census (red area; Figure 1) there are 27 co-located NFI/urban plots. However, the NFI measurements on these plots are only taken when scheduled within the regular NFI inventory cycle. Outside the city limits, but within the urban zone defined by US Census urban areas and urban clusters (blue area; Figure 1), the urban and NFI sample intensity is the same and thus all plots are co-located plots. In this area, both the NFI and urban measurements are taken when the plot is scheduled according to regular inventory cycle. Thus, all co-located plots will eventually have observations based on both the urban and NFI protocols when the entire cycle is completed. However, at this time there are few co-located plots outside Austin having urban data due to the recent establishment of the urban inventory. To assist in conducting analyses where the entire set of co-located plots in the blue area have been measured, blue(U) data were created to mimic this scenario. For simplicity, it was assumed the observed proportion of forest on each NFI plot would be the same for the co-located urban plot (although in reality they may differ due dissimilar plot configurations). To predict the amount of biomass on blue(U) plots, a statistical model was developed using the urban data collected in the city of Austin. Due to the number of zeros in the data, a zero-inflated gamma model (El-Shaarawi and Piegorsch, 2002) was chosen and the predictor variable was crown cover assigned to each plot from the NLCD map product (Homer *et al.*, 2015). If the predicted probability for a plot to have zero biomass was >0.5, the plot was assigned zero; otherwise, the plot biomass was predicted from the gamma model. To approximate the variability in the population, these values were perturbed by adding the product of an N(0,1) random variate multiplied by the standard deviation of the model residuals. In this study, these values were treated as observations without error and these data are referred to as blue(U). The remaining area (grey area; Figure 1) not associated with red or blue areas will be called grey(NFI). There is further delineation of the study defined by the boundary of the core-based statistical area (CBSA; Figure 1), which is considered to be socioeconomically associated with Austin (Nowak *et al.*, 2016). Summary statistics for each dataset are given in Table 1.

Statistical analysis

As one of the primary motivations of this study is to examine various analytical possibilities encountered when making population estimates, there are several primary considerations to address. First, in all cases, the red, blue and grey zones are non-overlapping, mutually exclusive area designations for which stratification schemes have been independently developed for estimation purposes by area and protocol combination (e.g. strata differ between red(U) and red(NFI) designations). Estimates for combinations of areas will build upon the existing strata. Second, different sampling intensities must be recognized and accounted for. There are numerous scenarios where this may occur, including (1) combining red(U) plots and blue(U) plots, (2) combining the red(U) plots and the blue(NFI) plots prior to the completion of the blue(U) plots and (3) combining blue(U) and grey(NFI) plots when only a partial cycle of blue plots are available, but a full cycle of grey(NFI) plots are complete. Other related considerations include defining population boundaries and the use of domain estimation (Scott *et al.*, 2005). To briefly describe domain estimation, consider a defined population where an estimate for a certain attribute is desired, e.g. area of forest type A. In the estimation process, all plot observations not in forest type A are set to zero such that the sum over all plots results in a total for forest type A only. This often creates a number of observations of zero in the data. The alternative, when possible, would be to redefine the population to only include the area of interest. This primarily is only possible for administrative boundaries but has relevance to this study in the context of the boundaries shown in Figure 1.

The issues described above were studied by developing various scenarios and evaluating the estimation outcomes. In the NFI and urban inventories, the plot represents the primary sampling unit. For each plot, the tree biomass values are summed and expressed on a per-hectare basis and the proportion of the plot that contains forest area is calculated from field crew measurements. To create strata, the distribution of the NLCD crown cover per cent (Homer *et al.*, 2015) was examined and crown cover classes were delineated based on natural breaks in the distribution and to ensure a minimum of 10 plots per stratum (Westfall *et al.*, 2011). Plots were assigned to strata using plot centre latitude and longitude to obtain the crown cover per cent at that location on the NLCD map. Estimation was then conducted using the standard FIA procedures when post-stratification is employed (Scott *et al.*, 2005). The general estimator forms are presented to provide a basis for subsequent more in-depth application and discussion. First, the observed plot values are modified based on the domain indicator and partially non-sampled plot adjustment factor:

$$y_{hid} = \frac{y^*_{hi}\delta_{hid}}{\bar{p}_h} \tag{1}$$

where y^*_{hi} = observed value for plot i in stratum h; $\delta_{hid} = 1$ if plot i in stratum h is in the domain of interest d, 0 otherwise; $\bar{p}_h$ = non-sampled adjustment factor for stratum h and y_{hid} = adjusted value for plot i in stratum h and domain d. The non-sampled adjustment factor accounts for portions of plots that are inaccessible for measurement due to various circumstances (Scott *et al.*, 2005). Subsequently, compute the attribute mean for each stratum h,

Table 1 Summary statistics for various geographic areas and inventory protocols.

					Biomass (tonnes/ha)		Forest proportion	
Area(protocol)	Area (ha)	n	Biomass = 0	Forest = 0	Mean	SD	Mean	SD
Red(U)	79 037.65	203	53	144	45.66	63.92	0.262	0.430
Blue(U)	93 780.97	39	11	34	41.15	42.46	0.066	0.191
Red(NFI)	79 037.65	27	24	24	3.59	16.13	0.055	0.187
Blue(NFI)	93 780.97	39	34	34	2.07	7.22	0.066	0.191
Grey(NFI) within CBSA	936 114.98	361	249	245	10.51	21.27	0.243	0.387
Grey(NFI) outside CBSA	2 020 648.58	840	555	544	9.44	18.43	0.274	0.413

$$\bar{Y}_{hd} = \frac{\sum_{i}^{n_h} y_{hid}}{n_h} \tag{2}$$

where $\bar{Y}_{hd}$ is the domain mean and n_h is the number of plots for stratum h, respectively. Obtain the estimated total for the domain, $\hat{Y}_d$, by summing the weighted (by stratum weight W_h) means and multiplying by the area (ha) in the population (A_T):

$$\hat{Y}_d = A_T \sum_{h}^{H} W_h \bar{Y}_{hd} \tag{3}$$

To calculate the per cent sampling error for the estimate, the within-stratum variances $v(\bar{Y}_{hd})$ must be obtained:

$$v(\bar{Y}_{hd}) = \frac{\sum_{i}^{n_h} y_{hid}^2 - n_h \bar{Y}_{hd}^2}{n_h(n_h - 1)} \tag{4}$$

The within-stratum variances are then used to calculate the overall variance $v(\hat{Y}_d)$:

$$v(\hat{Y}_d) = \frac{A_T^2}{n}\left[\sum_{h}^{H} W_h n_h v(\bar{Y}_{hd}) + \sum_{h}^{H} (1 - W_h)\frac{n_h}{n} v(\bar{Y}_{hd})\right] \tag{5}$$

Finally, the per cent sampling error is expressed as:

$$SE(\%) = \frac{\sqrt{v(\hat{Y}_d)}}{\hat{Y}_d} 100 \tag{6}$$

The attributes of interest in this study are total tree biomass and forest area; however, the methods are applicable to any tree- or area-based variable. Initially, estimates were calculated for the red area (Austin city limits) and subsequently for larger regions that include blue and grey areas up to the entire study area. An estimation issue is whether to create a single population and stratify as necessary (designated the one-population method) or to treat the areas as separate populations and sum the results across populations (hereafter the hierarchical method). In this study, populations are defined based on areal boundaries as shown in Figure 1. Evaluation of these two approaches was performed by selecting various combinations of areas and calculating estimates for each method. Subsequently, an area subset of interest (Travis County; Figure 1) was defined to assess domain estimation *vs* redefining population boundaries (and the requisite reformulation of areas and strata).

Hierarchical method

Partition the red(U) area, with total area in hectares denoted A_R, into H strata having areas expressed as A_h. Let y_{hi} be the observed value for the ith plot in the hth strata, which can either be a proportion if estimating area or a per-hectare value if estimating a tree attribute such as biomass. Using the ^ designation for the hierarchical method, the estimate of the population total for red(U) is:

$$A_R * \hat{Y}_R = A_R \sum_{h=1}^{H} W_h \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi} \tag{7}$$

with $W_h = A_h / A_R$ and n_h the number of sample plots in the hth strata (note $\sum_h n_h = n_R$). Next, the blue(NFI) area is stratified into H' strata. These strata are defined independently of the stratification scheme for red(U). The estimate for the blue(NFI) and red(U) combined is a sum of the estimates for the two areas:

$$A_B * \hat{Y}_B + A_R * \hat{Y}_R = A_B\left(\sum_{h'=1}^{H'} W_{h'} \frac{1}{n_{h'}} \sum_{i=1}^{n_{h'}} y_{h'i}\right) + A_R\left(\sum_{h=1}^{H} W_h \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}\right) \tag{8}$$

with $W_{h'} = A_{h'} / A_B$ and $n_{h'}$ is the number of sample plots in the h'th strata (note $\sum_{h'} n_{h'} = n_B$).

One-population method

First, the red and blue areas (as defined above) are considered as one population (A_{BR}), but are stratified into the two sampling intensity zones. The estimators for the one-population method use the ~ designation:

$$A_{BR} * \tilde{Y}_{BR} = A_{BR} * (W_B \tilde{Y}_B + W_R \tilde{Y}_R) \tag{9}$$

Since $W_B = A_B / A_{BR}$ and $W_R = A_R / A_{BR}$,

$$A_{BR} * \tilde{Y}_{BR} = A_B * \tilde{Y}_B + A_R * \tilde{Y}_R \tag{10}$$

in which if the same stratification scheme developed for the blue and red areas in the hierarchical approach was used, we have equality between the two estimators.

Estimated variances

As noted above, the samples of the red and blue areas are independent, so the variance of $A_{BR} * \tilde{Y}_{BR}$ is the sum of the variances of estimators for the red area and the blue area. Using equation (10) as the form of the estimator $A_{BR} * \tilde{Y}_{BR}$, the estimated variance is

$$v(A_{BR} * \tilde{Y}_{BR}) = A_B^2 * v(\tilde{Y}_B) + A_R^2 * v(\tilde{Y}_R) \tag{11}$$

If the same stratification scheme for red and blue areas are used in both the hierarchical and the one-population methods, there will be equality of the estimated variances. Also, note that although the sampling design is systematic unaligned, the variance estimators being employed are those for a simple random sample and tend to overestimate the variance for systematic samples.

Combining weights

It is natural to consider multiplying the estimators on the right-hand side of equation (9) by the weights, as being shown more explicitly in the context of the stratification scheme within each area:

$$A_{BR} * (W_B \tilde{Y}_B + W_R \tilde{Y}_R) = A_{BR} * \left[\left(\sum_{h'=1}^{H'} W_B W_{h'} \frac{1}{n_{h'}} \sum_{i=1}^{n_{h'}} y_{h'i}\right) + \left(\sum_{h=1}^{H} W_R W_h \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}\right)\right] \tag{12}$$

Since $W_B W_{h'} = A_{h'} / A_{BR}$ and $W_R W_h = A_h / A_{BR}$, new weights could be defined as $W_{\tilde{h}}$, where $W_{\tilde{h}} = \begin{cases} A_h / A_{BR} & \text{for } h = 1, \ldots, H \\ A_{(h-H)'} / A_{BR} & \text{for } h' = H + 1, \ldots, H + H' \end{cases}$

and new within-stratum sample sizes are given by $n_{\tilde{h}}$. Equation (12) can then be expressed as:

$$A_{BR} * (W_B \tilde{Y}_B + W_R \tilde{Y}_R) = A_{BR} * \left(\sum_{\tilde{h}=1}^{H+H'} W_{\tilde{h}} \frac{1}{n_{\tilde{h}}} \sum_{i=1}^{n_{\tilde{h}}} y_{hi}\right) \tag{13}$$

Using equation (5) to calculate the estimated variance of equation (13) produces the following for the one-population approach:

$$v(A_{BR}{*}\breve{Y}_{BR}) = A_{BR}^{2}{*}v\left(\sum_{h=1}^{H+H'} W_{\tilde{h}}\frac{1}{n_{\tilde{h}}}\sum_{i=1}^{n_{\tilde{h}}} y_{hi}\right) \quad (14)$$

While using the same equation (5) to estimate the variance for the hierarchical approach from equation (11) yields:

$$v(A_{BR}{*}\breve{Y}_{BR}) = A_{B}^{2}{*}v(\breve{Y}_{B}) + A_{R}^{2}{*}v(\breve{Y}_{R}) \quad (11)$$

It appears the two estimated variances shown in (14) and (15) could produce different outcomes and an empirical calculation verifies this. The issue is that using equation (5) as the basis for variance estimation in equation (14) assumes that the combined blue and red areas (BR) are sampled by a single simple random sample, which is not a correct assumption, if there are different sampling intensities between the red and blue areas. Thus, equation (14) is an incorrect estimator of the variance and implies that when combining areas having different sample intensities, the appropriate method is to define each area as an independent population and sum the area-weighted estimates and estimated variances for the populations. The sample intensity issue will arise again in the next section when estimates are extended to a larger area that partially includes the blue area.

Extending to the grey area (CBSA)

The grey area is defined as all the area that is neither blue nor red. Depending on the analytical objective, the grey area may be constrained by the CBSA boundary or also extended to counties outside the CBSA (Figure 1). The notation is extended to A_G, $\widehat{Y}_G$ and n_G; with the grey area partitioned into H'' strata. In the hierarchical method, a third summand $A_G{*}(\sum_{h''=1}^{H''} W_{h''}\frac{1}{n_{h''}}\sum_{i=1}^{n_{h''}} y_{h''i}) = A_G{*}\hat{Y}_G$ would be added to equation (8) yielding

$$\begin{aligned} A_G{*}\hat{Y}_G + A_B{*}\hat{Y}_B + A_R{*}\hat{Y}_R &= A_G{*}\left(\sum_{h''=1}^{H''} W_{h''}\frac{1}{n_{h''}}\sum_{i=1}^{n_{h''}} y_{h''i}\right) \\ &+ A_B{*}\left(\sum_{h'=1}^{H'} W_{h'}\frac{1}{n_{h'}}\sum_{i=1}^{n_{h'}} y_{h'i}\right) \\ &+ A_R{*}\left(\sum_{h=1}^{H} W_h\frac{1}{n_h}\sum_{i=1}^{n_h} y_{hi}\right) \end{aligned} \quad (16)$$

In the one-population method, there are two possibilities: (1) the grey area has been sampled independently from either the blue or red areas or (2) the grey area was not sampled independently of the blue area. The first case includes the obvious situation where the sampling intensities are different, but can also include a situation where political boundaries define separately the grey, blue and red areas and the sampling is considered independent. Another situation is where non-response (unmeasured plots due to denied access, hazardous conditions, etc.) rates are different between the grey and blue areas.

When the grey area has been sampled separately from either the blue or red areas, equation (9) is replaced with,

$$A_{GBR}{*}\breve{Y}_{GBR} = A_{GBR}{*}\left(\breve{W}_G\breve{Y}_G + \breve{W}_B\breve{Y}_B + \breve{W}_R\breve{Y}_R\right) \quad (17)$$

and the stratum weights are defined by $\breve{W}_{*} = A_{*}/A_{GBR}$ ($\breve{W}$ denotes the weights relative to combined grey, blue and red areas indicated by the GBR subscript). A similar calculation as in equation (10) would show that the estimates are the same providing the stratification schemes are the same for the hierarchical and one-population methods.

Still considering the case where each area is considered to be independently sampled, an argument similar to that given in the section 'Estimated variances' shows the estimated variance of the hierarchical and one-population methods are the same and given by,

$$\begin{aligned} v(A_G\hat{Y}_G + A_B{*}\hat{Y}_B + A_R{*}\hat{Y}_R) &= v(A_{GBR}{*}\breve{Y}_{GBR}) \\ &= A_G^2 v(\hat{Y}_G) + A_B^2 v(\hat{Y}_B) + A_R^2 v(\hat{Y}_R) \end{aligned} \quad (18)$$

where the estimated variances are based on equation (5).

If the grey and blue areas were not sampled independently, then the combined grey/blue(NFI) area can act as a single stratum that was sampled independently of the red area. The estimate of the attribute for the combined area is

$$A_{GBR}{*}\breve{Y}_{GBR} = A_{GBR}{*}\left(\breve{W}_{GB}\tilde{Y}_{GB} + \breve{W}_R\tilde{Y}_R\right) \quad (19)$$

where $\tilde{Y}_{GB}$ is the estimate for the grey/blue(NFI) area. If the grey/blue (NFI) area is post-stratified using the same stratification as was used in the hierarchical method for the grey and blue areas, then

$$\tilde{Y}_{GB} = \left(\sum_{h''=1}^{H''} V_{h''}\frac{1}{n_{h''}}\sum_{i=1}^{n_{h''}} y_{h''i}\right) + \left(\sum_{h'=1}^{H'} V_{h'}\frac{1}{n_{h'}}\sum_{i=1}^{n_{h'}} y_{h'i}\right) \quad (20)$$

where the stratum weights are now given as $V_{h'} = A_{h'}/A_{GB}$ and $V_{h''} = A_{h''}/A_{GB}$, with $\sum_{h''=1}^{H''} V_{h''} + \sum_{h'=1}^{H'} V_{h'} = 1$ and the total sample size is $n_{GB} = \sum_{h'} n_{h'} + \sum_{h''} n_{h''}$.

The estimated variance of the left-hand side of equation (19) is given by

$$v\left(A_{GBR}{*}\breve{Y}_{GBR}\right) = A_{GB}^2 v(\tilde{Y}_{GB}) + A_R^2 v(\tilde{Y}_R) \quad (21)$$

where the estimated variance is calculated using equation (5) formulation. The estimates given by equations (16), (17) and (19) will be the same, but the estimated variances given by equations (18) and (21) will often be slightly different.

Results/discussion

Estimates calculated for various area and protocol combinations revealed important considerations for analytical outcomes. For red(U), the larger sample size produced a substantially smaller sampling error in comparison to red(NFI) for both area and biomass (Table 2). Due to the measurement of trees outside of forest land, the red(U) estimate of total biomass was much larger, providing an indication of the magnitude of biomass present in non-forest areas. Also, the estimated forest area was much larger for red(U) than for red(NFI). This was unanticipated as forest land is defined identically in both samples and the expected value of the estimate over many samples should be the same (unbiased); although a much wider range of estimates is expected as sample sizes decrease, i.e. the considerable increase in sampling error for red(NFI). This is a good reminder that, despite the use of statistically unbiased designs and estimators, the realization of a single random sample may provide results that differ greatly from the true (unknown) population value, e.g. 5 per cent of 95 per cent confidence intervals are expected to not contain the true value.

Similar outcomes are found when making estimates where the population is defined by the combined red and blue areas. The discrepancy in forest area estimates for the urban and NFI protocols is still notable and the biomass estimates are much larger when using the urban protocol. While the total area of these subdivisions are similar, the sampling errors are largely controlled by red(U) due to the increased sample intensity

(Table 2). When the smaller red(NFI) sample is used instead, the sampling errors increase dramatically. Expanding the population to larger areas (CBSA and Study area) results in considerably larger estimates for both biomass and forest area. A notable outcome is that the substantial increase in sample size for NFI plots as a result of including the grey area is necessary to produce sampling errors that are smaller than those of the red (U) analysis.

A conundrum in interpretation is created when combining the NFI and urban protocols. Specifically, the population estimate includes trees measured on all land for a portion of the sample (U) and trees measured only on forest land for the remaining portion (NFI), where co-located plots exist (red and blue), analysts are also faced with choosing an estimation paradigm. Two approaches are possible (1) use the urban protocol to estimate both biomass (all trees or just forested) and forest area and (2) use the NFI protocol to estimate biomass on forest land and forest area. Within Austin, the choice should be clear to use the much larger sample size of the red(U) data; however, in blue the number of plots is the same. It is suggested for consistency purposes that option #1 is preferred when possible, i.e. all estimates arise from the same set of measurement protocols. When the population of interest includes areas where only (or mostly) NFI plots exist, then option #2 seems preferable; although the total biomass may be considerably underestimated due to the exclusion of urban trees (Schnell *et al.*, 2015b).

In the context of the above options, it may be possible to implement methods that would generate predicted observations of tree biomass for non-forest portions of NFI plots. This would make the NFI plots similar to urban plots where all trees are measured regardless of land use. In such a scenario, estimates of biomass on all land could be made for the blue and grey areas. Such approaches should be used cautiously, however, as there would be an implicit assumption that non-forest biomass predictions developed from red(U) plot data would be accurate for NFI plots in grey and blue, which likely tend to be in more rural settings and potentially have different species compositions and altered tree size distributions. Proper variance estimation would also need to account for the fact that these values are predictions that bring additional uncertainty into the estimation process. Because forest area has the same definition regardless of measurement protocol, the observed data already exist for that attribute on all NFI plots (although it should be noted that the proportion of forest area may differ on urban *vs* NFI co-located plots due to the difference in plot design).

Another issue analysts need to consider is defining the population in the context of domain estimation. Two approaches were examined to obtain estimates of biomass and forest area for Travis County (Figure 1), which includes red, blue and grey areas. Under the standard areas developed earlier, domain estimation would be used with the CBSA as the total combined area. All plots in the CBSA are included in the sample, but all those outside the Travis County domain are set to zero for biomass and forest proportion (equation (1)). An alternative approach would be to define the population as Travis County and thus only plots within the county are used for estimation. In this case, the area of red, blue and grey would be redefined based on the Travis County boundaries. The results show the sampling errors for the CBSA (Travis domain) approach can be ~5–10 per cent larger than those obtained when reducing the population to Travis County exclusively (Table 3). This

Table 2 Stratum weights, estimates and sampling errors for total biomass and forest land area by area and inventory protocol combinations using the hierarchical method.

Area(protocol)	Red				Blue		Grey			Biomass (tonnes)	Biomass SE%	Forest area (ha)	Forest SE%
	W_1	W_2	W_3	W_4	W_1	W_2	W_1	W_2	W_3				
Red(U)	0.408	0.194	0.251	0.147						3 563 869	7.91	20 187	9.07
Red(NFI)	0.736	0.264								202 244	106.36	3128	76.66
Red(U) and blue(U)	0.408	0.194	0.251	0.147	0.566	0.434				7 330 927	9.58	26 003	12.72
Red(U) and blue(NFI)	0.408	0.194	0.251	0.147	0.566	0.434				3 744 624	8.03	26 003	12.72
Red(NFI) and blue(NFI)	0.736	0.264			0.566	0.434				382 999	62.46	8943	40.83
CBSA – red(U); blue(NFI) and grey(NFI)	0.408	0.194	0.251	0.147	0.566	0.434	0.540	0.460		13 990 032	7.24	261 164	6.80
Study area – red(U); blue(NFI) and grey(NFI)	0.408	0.194	0.251	0.147	0.566	0.434	0.554	0.182	0.264	32 826 034	4.48	810 118	3.87

Table 3 Estimates for Travis County using the CBSA population with domain estimation and using Travis County as a stand-alone population.

Area(protocol)	Red				Blue		Grey		Biomass (tonnes)	Biomass SE%	Forest area (ha)	Forest SE%
	W_1	W_2	W_3	W_4	W_1	W_2	W_1	W_2				
CBSA (Travis) – red(U); blue(NFI) and grey(NFI)	0.408	0.194	0.251	0.147	0.566	0.434	0.540	0.460	3 918 484	9.30	35 134	15.81
Travis – red(U);blue(NFI) and grey (NFI)	0.404	0.192	0.251	0.153	0.512	0.488	0.682	0.318	3 977 980	8.86	35 332	14.53

Table 4 Comparisons of hierarchical method estimates that treat blue(NFI) and grey(NFI) as independent areas and treating blue(NFI)/grey(NFI) as a single area. Also shown are differences between hierarchical and one-population methods where the assumption of proportional allocation among strata is not satisfied in the one-population approach.

Area(protocol)	Biomass (tonnes)	Biomass SE%	Forest area (ha)	Forest SE%
Hierarchical method				
Red(U) and blue(NFI)	3 744 624	8.03	26 003	12.72
CBSA – red(U); blue(NFI) and grey(NFI)	13 990 032	7.24[a]	261 164	6.80[a]
CBSA – red(U) and blue/grey(NFI)	13 990 032	7.22[b]	261 164	6.79[b]
One-population method				
Red(U) and blue(NFI)	3 744 624	10.41[c]	26 003	11.19[c]
CBSA – red(U); blue(NFI) and grey(NFI)	13 990 032	7.43[c]	261 164	5.91[c]

[a]Variances estimated with equation (18).
[b]Variances estimated with equation (21).
[c]Variances incorrectly estimated with equation (14).

analysis and other similar investigations show that the domain approach results in higher sampling errors due to the creation of zeros in the data. The estimates themselves will also differ slightly as the stratifications will be revised and thus the relative weight assigned to each plot will change, as well as the non-sampled adjustment factor (equation (1)) for each stratum. To this latter point, non-sampled plots outside Travis County play a role in adjusting plot values within the county in CBSA (Travis domain) estimation, whereas only non-sampled plots within the county are used when Travis is defined as the population. Thus, analysts should endeavour to define populations as succinctly as possible to their area of interest. Often, especially in user-friendly analytical tools (Miles, 2017), populations and stratifications are predefined and recasting them differently would require substantial knowledge and effort. In most cases, therefore, domain estimation must be employed when using these tools.

There were two instances where exceptions to equality of results between the hierarchical and one-population methods were encountered. The estimates for total biomass and forest area were the same in both cases, but the variances were not. First, there were slight differences in the calculated variances depending on how blue(NFI) and grey(NFI) areas were identified, i.e. as independent areas or as a combined area. The results suggest the sampling error is slightly smaller when adopting the combined area interpretation and using equation (21) for variance calculation (Table 4). The second exception was that variances calculated using equation (14) for the one-population method were incorrect when combining the red(U) sample with blue(NFI) or grey(NFI) samples that resulted in mixed sampling intensities among strata. It is shown in Table 4 that use of the incorrect variance formula overestimates the variance for total biomass, while underestimating the variance for forest area. Thus, it is difficult to provide guidance on expected outcomes of magnitude and direction in bias of variance estimates should analysts fail to avoid this pitfall.

The proposed estimation methods should also be useful in other situations where rural–urban analyses require integration of inventory data lacking common bases of sampling intensity and response design. More broadly, the estimation concepts may generally apply when disparate data sources having overlapping areal coverage need to be combined to facilitate desired estimations. It is likely that some aspects of the inventories are different than the example presented here; requiring some thought on how populations/strata are defined such that construction of the estimators corresponds to the underlying designs.

Conclusion

The availability of both rural and urban inventory data offers a unique analytical opportunity across a continuous rural–urban spatial gradient; however, this opportunity comes at the cost of increased complexity in estimation and interpretation of results. In this paper, a number of factors associated with combining urban and rural forest inventory data were examined. From a statistical standpoint, the primary considerations were the sampling intensity and plot design differences which necessitated maintaining independence of the two samples and summing the estimates from each sample. The variance estimators required that proportional allocation among strata be maintained, which precluded treating the combined data as a single population and using strata to differentiate between the two plot designs. From an interpretation standpoint, analysts need to be aware of divergences in measurement protocols such as tree species list differences and recording of trees on non-forest land in the urban inventory. There are likely other differences that were not identified in this paper; therefore, analysts are encouraged to have a full appreciation of measurement and sampling protocols from each inventory to avoid unintended misinterpretation of results.

Combining data from two different samples is often fraught with technical intricacy and the acceptance of various assumptions. Thus, the ability to take advantage of both data sources simultaneously is limited to those analysts having appropriate technical capabilities. To further the value and use of combined NFI and urban inventory data, fully integrating these efforts into a unified programme is proposed. In particular, the establishment of a common database would greatly facilitate development of analytical tools that allow for comparisons between urban and rural domains in a single-analysis query and for analyses that span the urban–rural gradient (e.g. biodiversity, susceptible species) for policy or management decisions applicable within administrative boundaries such as a county. This approach would decrease the burden on analysts to make correct estimations and would reduce the likelihood of making mistakes in interpretation of results. Future efforts should focus on standardization (or harmonization) across inventories to make integration less onerous. The ultimate resolution of these issues would be to use identical sampling paradigms and measurement protocols across all land; however, the practicality of doing so may make this outcome elusive.

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Conflict of interest statement

None declared.

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