



A cover-based method to assess forest characteristics using inventory data and GIS



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ARTICLE INFO

Article history:

Received 30 November 2012
Received in revised form 27 February 2013
Accepted 28 February 2013
Available online 2 April 2013

Keywords:

Tree crown
Forest inventory
Canopy gap
Canopy cover
Wildlife habitat
Forest health

ABSTRACT

In most forest inventory data, it is not feasible to estimate the canopy coverage of trees having certain characteristics due to the lack of information on crown size. In this study, data from the Forest Inventory and Analysis (FIA) program were used to assign crown sizes to individual trees using published crown width models. This process effectively links trees to crown area such that estimates of canopy cover and changes therein can be made using domains that include tree-level attributes (e.g., dbh, total height, etc.). Advantages of implementing this approach are (1) estimation can proceed as with any other estimate of area derived from forest inventory data, and (2) canopy cover estimates provide different information than classical indicators such as number of trees. A disadvantage is the need to dissolve overlapping crowns after the tree-level domain is selected. Examples related to forest health, wildlife habitat, and old growth attributes are provided to illustrate applications of the method.

Published by Elsevier B.V.

1. Introduction

Tree canopy cover plays a critical role in defining forest characteristics. Canopy cover impacts understory species composition and structure by influencing light availability and soil properties (Canham et al., 1990; Beatty, 1984). Canopy cover also plays a role in assessments of wildfire risk and behavior of both modeled and actual wildfires (Pollet and Omi, 2002; Agee and Skinner, 2005). Additionally, amounts and types of canopy cover and structure influence habitat suitability for many forest-dwelling vertebrate species (Radford et al., 2005; Massé and Côté, 2009). A key factor in studies of the aforementioned relationships between canopy cover and forest-related phenomena is that relevant analyses often focus on specific aspects of canopy cover, e.g., cover of trees related to characteristics such as species, diameter at breast-height (dbh), and total height (Gabbe et al., 2002; Abrahamson and Gohn, 2004). Thus, expansion of research results to landscape-scale assessments can be difficult (Mitchell et al., 2001). A commonly employed methodology of estimating canopy cover has been to assign area to individual trees based on crown size delineation using remotely-sensed information (Solberg et al., 2006; Leckie et al., 2003). A limitation to this technique is that often only dominant/co-dominant trees are quantifiable. A more appealing approach would be to utilize comprehensive, large-area forest inventory data in order to account for the contribution to canopy cover from trees below the main canopy.

In forest inventory and monitoring programs, area estimates are often made for stand-level attributes such as forest type, and stand size. Estimates derived from tree-level variables are also commonly calculated, such as volume and number of trees per unit area. However, area coverage of tree-level attributes is usually difficult to estimate due to the lack of information on how much areal coverage is represented by an individual tree. The area occupied by each inventory tree can be approximated from the plot data using techniques such as Thiessen polygons (Lowell, 1997; Kenkel et al., 1989) or crown width models (Bechtold, 2003; Gill et al., 2000). Applying crown width models to forest inventory data, when mapped tree locations are available, allows for spatial representation of canopy cover as well as gaps between trees. However, tree-level estimates of canopy area are usually aggregated to estimate total amount of canopy cover without regard to individual tree attributes such as species, size, and canopy position. (Coulston et al., 2010; Toney et al., 2009). Because the crown-width approach is specific to individual trees, there is an explicit relationship that links canopy coverage to tree-level attributes. The objective of this paper is to show that canopy cover of trees with specific attributes can be estimated by combining forest inventory data and GIS (Geographic Information System). Applications of this methodology are presented in examples related to wildlife habitat, forest health, and old growth attributes.

2. Methods

In the US, a three-phase forest inventory and monitoring effort is implemented by the Forest Inventory and Analysis (FIA) program

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within the U.S. Forest Service (Bechtold and Patterson, 2005). Phase 1 (P1) is the development of a post-stratification scheme using remotely-sensed data in order to reduce variance in the estimates. Under the current FIA sampling design where plot locations are fixed over time, stratification occurs after the plot locations are selected, thus the term post-stratification. The second phase (P2) of data collection entails measuring sample plots on the ground for the usual suite of forest mensuration variables such as tree species, dbh, height, site index, forest type, and stand age. For each sample plot, trees having dbh of 12.70 cm or larger are measured on 4 subplots having a 7.32 m radius; saplings with dbh of 2.54–12.69 cm are measured on 4 microplots having 2.07 m radius (Bechtold and Scott, 2005). Phase three (P3) data collection occurs on a 1/16th subset of the P2 plots. On P3 plots, additional data on forest health indicators are collected (e.g., down woody material and crown condition information). To evaluate the efficacy of the methods presented below, two full cycles of data from Pennsylvania were used. Data for the first cycle (T1) were collected over the period 2001–2005; while the second cycle (T2) data were collected 2006–2010 (Table 1). Each cycle represents a measurement of all plots (4871) in the inventory and plots were re-measured at an interval of approximately 5 years.

To estimate the amount of canopy cover provided by each tree measured in the inventory, the crown width models described by Bechtold (2003) were used. In cases where species were encountered that were not listed in Bechtold (2003), coefficients for species of similar form were used. For this analysis, the model using dbh and crown ratio as input variables was used and predicted values in feet were converted to meters.

$$\widehat{CW} = \hat{\beta}_0 + \hat{\beta}_1 D + \hat{\beta}_2 D^2 + \hat{\beta}_3 CR \quad (1)$$

where $\widehat{CW}$ is the estimated crown width (ft; 1 ft = 0.3048 m); D is diameter at breast height (in.; 1 in. = 2.54 cm); CR is crown ratio (%). $\hat{\beta}_{0-3}$ are the species-specific coefficients.

Spatial representation of subplot canopy cover was accomplished by centering circles of estimated crown width at the tree location recorded during the subplot visit. To assess cover of overstory trees (dbh 12.70+ cm), overlapping crowns from neighboring trees were combined such that crown overlap was accounted for, i.e., the cover as it would appear as viewed from above the canopy. A GIS was employed to dissolve the boundaries between individual tree crowns in order to create polygons of non-overlapping crown cover for each FIA plot condition (Fig. 1). A key point in the analytical method is that crowns extending beyond the sample plot boundary are included in the total canopy cover for the plot. It is surmised that, on average, this will account for crown areas of non-sampled trees extending into the plot but not explicitly accounted for.

To quantify the crown cover associated with saplings (dbh 2.54–12.69 cm), the same methodology was applied using the microplot area as the basis. There are thus canopy cover estimates at two levels: (1) overstory canopy cover estimated at the subplot level, and (2) sapling canopy cover estimated at the microplot level. These estimates cannot simply be summed to obtain the total

cover as (1) overstory trees may partially/wholly obscure sapling cover, and (2) the overstory and sapling cover estimates are on a different area basis. To estimate total canopy cover at the subplot level, we assumed that, on average, the overstory:sapling cover relationships found on the microplot would be similar across the subplot area. The following steps were taken using GIS: (1) the canopy cover of saplings was mapped, (2) the overstory cover for trees whose stems occur within the microplot was overlaid on the sapling cover, and (3) the area of sapling cover remaining visible once overstory trees were accounted for was quantified (Fig. 2). The ratio of unobscured sapling cover to overstory microplot cover was used to estimate the amount of total cover that would be present if saplings were measured over the entire subplot area. For example, if the overstory subplot canopy area was 0.01 ha, the overstory microplot canopy area was 0.0005 ha, and the unobscured sapling canopy area was 0.0001 ha, the ratio would be $0.0001/0.0005 = 0.2$. The estimate of cover for all trees and saplings combined would be $0.01 + 0.01 \times 0.2 = 0.012$ ha. Due to the use of crown area occurring outside subplot boundaries and the method of estimating the contribution of saplings, the area of crown cover exceeded the forested area of the subplot in some cases. When this phenomenon occurred, the canopy cover estimate was constrained to the forested area expecting that these plots are, in actuality, those having continuous crown cover over the entire plot. As the plot is the primary sampling unit, plot-level cover estimates were obtained by summing over subplots.

Under standard FIA protocols, the total height of saplings is only measured on P3 plots. To facilitate analyses related to vertical structure, tree heights for saplings on non-P3 plots were predicted from models developed using observed sapling height data obtained on P3 plots. Due to the relatively small amount of model fitting data available, coefficients were estimated for hardwood and softwood species categories.

$$\hat{H}_S = \hat{\theta}_0 + \hat{\theta}_1 D \quad (2)$$

where $\hat{H}_S$ is the estimated sapling height (m); D is diameter at breast height (cm) and $\hat{\theta}_{0-1}$ are the coefficients estimated from the data.

Estimated coefficients and model fit statistics are presented in Table 2.

Estimation of area of forestland, area of canopy cover within forestland, and the proportion of forestland area having canopy cover was accomplished using the standard FIA methods documented in Scott et al. (2005). Specifically, the proportion was calculated using a ratio-of-means estimator,

$$\hat{R} = \frac{\sum_{j=1}^n y_j / n}{\sum_{j=1}^n x_j / n} = \frac{\bar{y}}{\bar{x}} \quad (3)$$

where $\hat{R}$ is the proportion of forestland having tree cover; y_j is proportion of plot j that is forested and has canopy cover; x_j is proportion of plot j that is forested and n is the sample size (P2 plots).

Because FIA samples all lands, some of the data collected include how much of the plot is composed of forest land. Thus, the

Table 1
Summary of individual tree attributes dbh (cm), height (m), crown ratio (%), and crown width (m) by time period and tree size group.

Time period	Size group	n	Dbh				Height				Crown ratio				Crown width			
			Min.	Mean	Max.	IQR	Min.	Mean	Max.	IQR	Min.	Mean	Max.	IQR	Min.	Mean	Max.	IQR
T1	Sapling	12,714	2.5	5.8	12.4	4.1	1.8	6.4	17.1	3.4	1	32	100	20	0.4	2.8	5.9	1.0
	Tree	70,286	12.7	24.1	119.9	13.0	1.5	17.1	42.7	7.6	1	32	100	25	0.6	5.4	21.3	2.0
T2	Sapling	11,268	2.5	5.8	12.4	4.1	1.5	6.7	16.2	3.4	1	37	100	23	0.3	3.0	6.1	1.0
	Tree	63,990	12.7	24.6	111.5	13.5	1.5	17.4	44.5	7.6	1	34	100	15	1.7	5.5	21.6	2.0

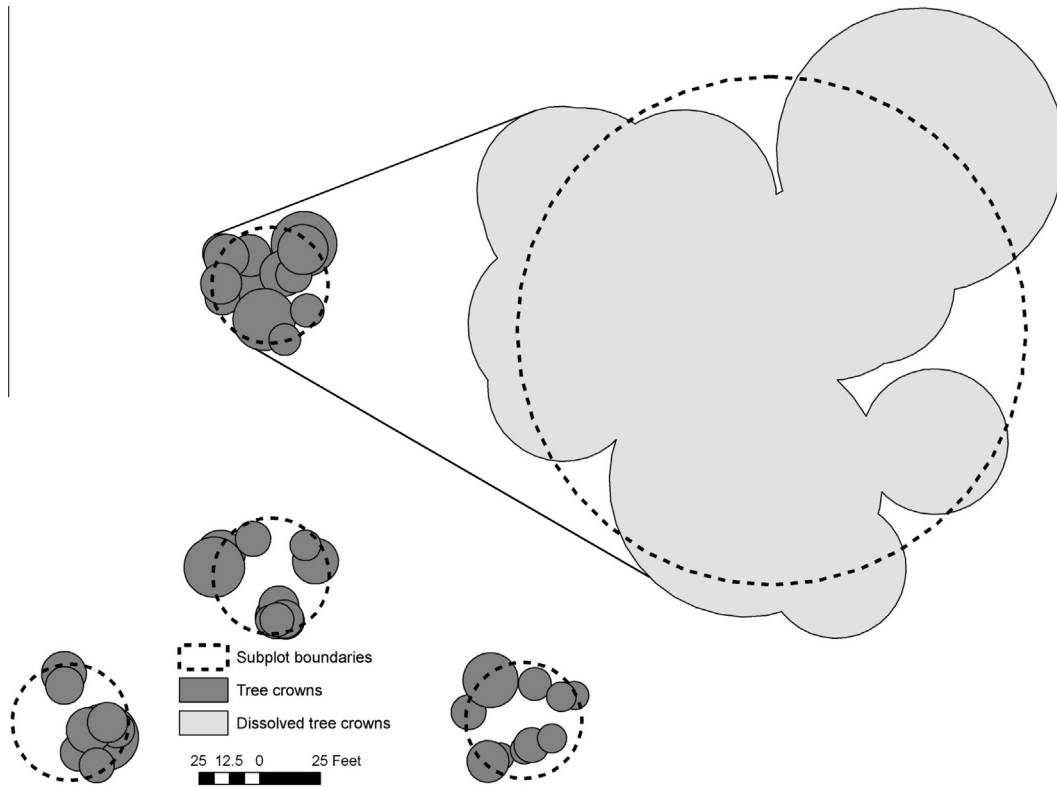


Fig. 1. Map of individual tree crowns on an FIA plot. Inset shows an expanded view of dissolved polygons of non-overlapping tree crown cover.

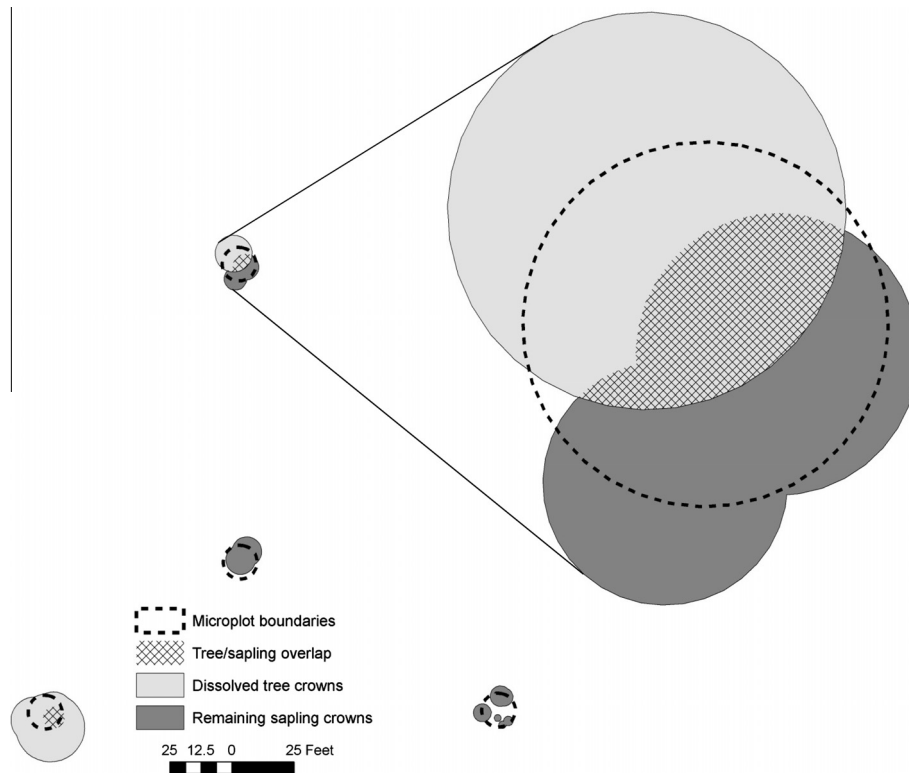


Fig. 2. Map of dissolved polygons of non-overlapping microplot tree crown cover of trees, crown overlap between microplot trees and saplings, and remaining dissolved sapling cover with no microplot tree cover above. Inset shows an expanded view of tree/sapling overlap.

Table 2

Estimated coefficients and fit statistics for sapling height model (2) by major species group.

Spp. group	n	$\hat{\theta}_0$ (std. error)	$\hat{\theta}_1$ (std. error)	R^2	RMSE
Hardwood	1481	2.8364 (0.1044)	0.6543 (0.0160)	0.53	1.7
Softwood	33	0.6351 (0.4622)	0.6468 (0.0660)	0.76	1.0

proportions alluded to above are obtained directly from the data. To better describe the estimator in the context of this paper, it is rewritten as a ratio of two area estimates by multiplying the average proportions by the total land area:

$$\hat{R} = \frac{A_T \bar{y}}{A_T \bar{x}} = \frac{\hat{A}_{F_C}}{\hat{A}_F} \quad (4)$$

The variance of (4) is calculated as

$$V(\hat{R}) = \frac{1}{n\hat{A}_F^2} V(\hat{A}_{F_C}) + \hat{R}^2 V(\hat{A}_F) - 2\hat{R} Cov(\hat{A}_{F_C}, \hat{A}_F) \quad (5)$$

where A_T is the total land area (ha), $\hat{A}_{F_C}$ is estimated area of forestland having canopy cover (ha); $\hat{A}_F$ is estimated area of forestland (ha); $V(\cdot)$ is variance of estimated parameter and $Cov(\hat{A}_F, \hat{A}_{F_C})$ is the covariance between $\hat{A}_F$ and $\hat{A}_{F_C}$.

To estimate the change in proportion of forested area having canopy cover, measurements at two points in time on the same sample plots are used. With the estimation procedures outlined above, the proportion of forestland having canopy cover at each time can be calculated ($\hat{R}_1$ and $\hat{R}_2$, respectively), and the change over the time period is,

$$\hat{R}_\Delta = \hat{R}_2 - \hat{R}_1 \quad (6)$$

The variance estimator for (6) accounts for the correlation due to using the same sample plots at each time (Cochran, 1977),

$$V(\hat{R}_\Delta) = V(\hat{R}_2) + V(\hat{R}_1) - 2Cov(\hat{R}_2, \hat{R}_1) \quad (7)$$

The standard error of the estimates was calculated from $SE(\cdot) = \sqrt{V(\cdot)}$. Estimates not within $\pm 2SE(\cdot)$ of zero were considered statistically different from zero at the 95% confidence level.

The estimators described above are applicable to a simple random sample. In practice, these estimators were implemented within the stratified estimation framework employed by FIA (Scott et al., 2005). Specifically, five strata were constructed based on percent canopy cover classes (0–5%, 6–50%, 51–65%, 66–80%, 81–100%). The plots were assigned to strata using plot center locations and the National Land Cover Database (NLCD) canopy cover map (Homer et al., 2004).

Three example analyses are presented in order to illustrate the utility of the canopy cover estimation method for assessing contemporary forestry issues like forest health, wildlife habitat, and old growth attributes. In each example, canopy cover is estimated for trees presenting a given set of attributes. Canopy cover estimates calculated for specific conditions may be particularly appli-

cable for issues such as prediction of the expected loss of host trees due to a forest pest. Such information may be more useful to a manager if that prediction reveals the potential loss of crown cover rather than the predicted number or biomass of lost trees.

In the first example, we estimate the amount of canopy cover susceptible to mortality by an exotic forest pathogen that kills a tree species that is important for mast production. Beech bark disease, also known as beech scale-*Neonectria* canker, is an insect-fungus complex involving the beech scale insect (*Cryptococcus fagisuga* Lind.) and the exotic canker fungus *Neonectria coccinea* var. *faginata* Lohm. or the native *Neonectria galligena* Bres. (Rossman and Samuels, 1999). The disease kills or injures American beech (*Fagus grandifolia* Ehrh.) when these fungi invade bark altered by the feeding activity of the beech scale insects. Trees of 20.3 cm dbh and higher are more susceptible to mortality (Houston and O'Brien, 1983). To evaluate the potential loss of crown cover due to the disease, the proportion of canopy area of American beech trees having dbh ≥ 20.3 cm was estimated.

In the second example, we assess habitat availability for the Cerulean warbler (*Dendroica cerulea*), a bird species that has been variously listed as threatened, rare, or of special concern in the United States (Stoleson and Sechler, 2010). Jones and Robertson (2001) found that successful nesting of Cerulean warblers most often occurred where crown cover occurred at 6–12 m, with additional high cover above 18 m. In the absence of crown shape models, estimates of canopy cover were calculated for trees having height of 6–12 m where there also existed trees having height of 18 m or greater on the same subplot.

In the third example, we estimate the canopy cover of trees having old growth attributes. The diversity of tree ages and sizes in late-successional (e.g., old growth) forests provides a broad range of habitats for flora and fauna while making them more dynamic and resilient to disturbance. One major characteristic of late-successional forests is the abundance of living trees greater than or equal 56 cm diameter (McGee et al., 1999). There are other features that could be included in an assessment of late-successional forests (e.g., large standing dead trees and large pieces of coarse woody debris), but since the focus of this study is crown cover, our estimates include live trees having dbh of at least 56 cm. A site-level characteristic was also added to the domain to represent late-successional forests – in addition to the tree-level dbh criterion, the trees must also be in stands 100 years in age or older.

3. Results

3.1. Total canopy cover

A preliminary analysis was conducted to estimate the current (T2) proportion of forest area having tree cover (Table 3). The area of forestland was estimated to be 6,670,566.0 ha ($SE = 63,323.3$) with the area of tree cover being estimated as 5,998,241.1 ha ($SE = 61,037.3$). The resultant proportion of forest area having tree cover, $\hat{R}_2$ was 0.899 ($SE = 0.007$). Thus, about 90% of forestland in

Table 3

Estimates of canopy cover area (ha) and the associated proportion of forestland area $\hat{R}$ (with standard errors) for total and for four different scenarios examining use of crown cover data.

Attribute	Time 1 (2001–2005)				Time 2 (2006–2010)				Change		
	Area	(SE)	$\hat{R}_1$	(SE)	Area	(SE)	$\hat{R}_2$	(SE)	$\hat{R}_\Delta$	(SE)	$Pr(T> t)$
Total canopy cover	5,852,283.5	(50,810.9)	0.880	(0.0066)	5,998,241.1	(61,037.3)	0.899	(0.0070)	0.0192	(0.0099)	0.0516
Beech bark disease	161,755.2	(9,396.2)	0.024	(0.0014)	171,142.7	(10,375.3)	0.026	(0.0015)	0.0013	(0.0008)	0.1140
C. warbler habitat	1,593,606.4	(33,143.7)	0.240	(0.0049)	1,679,232.5	(37,434.8)	0.252	(0.0054)	0.0113	(0.0069)	0.0999
Old trees – public	13,053.6	(3,590.0)	0.009	(0.0018)	40,233.9	(5,782.8)	0.015	(0.0026)	0.0094	(0.0019)	<0.0001
Old trees – private	19,729.6	(4,922.9)	0.004	(0.0011)	33,405.4	(6,267.8)	0.007	(0.0014)	0.0032	(0.0013)	0.0112

Pennsylvania is covered by canopy of trees having dbh of 2.5 cm and larger.

To compute estimates of change, the area of tree cover on forestland was also calculated for the previous cycle (T1). For this time period, forestland area was estimated to be 6,650,094.3 ha ($SE = 50,901.2$) with an estimated 5,852,283.5 ha ($SE = 50,810.9$) of tree cover (Table 3). The proportion of forestland having tree cover, $\hat{R}_1$ was 0.880 ($SE = 0.007$). The estimated change in proportion of area having tree cover between T1 and T2 was $\hat{R}_\Delta = 0.019$ ($SE = 0.10$). This estimate was not statistically different from zero at the 95% ($\alpha = 0.05$) confidence level ($p = 0.05$).

3.2. Beech bark disease

The most recent data (T2) indicate the area of canopy cover of American beech susceptible to beech bark disease was 171,142.7 ha ($SE = 10,375.3$). Using the total forest area reported above, the proportion of canopy area that could potentially be lost would be $\hat{R}_2 = 0.0257$ ($SE = 0.0015$).

Canopy cover area of American beech at T1 was smaller with an estimate of 161,765.2 ha ($SE = 9,396.2$). The corresponding canopy area proportion was $\hat{R}_1 = 0.0244$ ($SE = 0.0014$). The estimated change in canopy area proportion for American beech having dbh ≥ 20.3 cm was $\hat{R}_\Delta = 0.0013$ ($SE = 0.0008$). Although the estimated canopy area proportion did increase from T1 to T2, the result was not significantly different from zero ($p = 0.11$) at the 95% confidence level.

3.3. Cerulean warbler habitat

The current (T2) area of desirable Cerulean warbler habitat was estimated to be 1,679,232.5 ha ($SE = 37,434.8$). The associated $\hat{R}_2$ statistic is 0.252 ($SE = 0.005$) of the estimated forestland area – suggesting that more than 25% of Pennsylvania forestland may be suitable for Cerulean warblers.

A slightly smaller estimate for the T1 time period was obtained, with habitat area being estimated as 1,598,606.4 ha ($SE = 33,143.7$). This area as a proportion of forestland, $\hat{R}_1$, was 0.240 ($SE = 0.005$). Using both the T1 and T2 results, the estimated change in proportion, $\hat{R}_\Delta$, of forestland containing Cerulean warbler habitat was 0.0113 ($SE = 0.0069$). The change in proportion for warbler habitat was not statistically different from zero ($p = 0.10$).

3.4. Old growth attributes

The most recent estimate of canopy cover area on public land for trees having dbh of 56 cm and larger in stands whose age is at least 100 years was 40,288.9 ha ($SE = 5,782.8$). Using the same domain for private lands resulted in an estimated 33,405.4 ha ($SE = 6,267.8$) of canopy cover. As a proportion of forestland area within the corresponding ownerships, these $\hat{R}_2$ estimates translate to 0.018 ($SE = 0.0026$) and 0.007 ($SE = 0.0014$), respectively.

To evaluate change in canopy cover area for these trees, the same estimates were computed for the previous measurement cycle (T1), which produced estimates of 18,053.6 ha ($SE = 3590.0$) and 19,729.6 ha ($SE = 4922.9$) for public and private ownerships, respectively. The corresponding estimates described as a proportion of forestland area, $\hat{R}_1$, were 0.009 ($SE = 0.0018$) and 0.004 ($SE = 0.0011$). The change from T1 to T2 ($\hat{R}_\Delta$) in proportion of publically-owned forestland area having old growth attributes was 0.0094 ($SE = 0.0019$). On privately-owned forestland, the proportional change was 0.0032 ($SE = 0.0013$). Using a 95% confidence level, the changes on both public and private lands were statistically different from zero ($p < 0.01$ and $p = 0.01$, respectively).

4. Discussion

Pennsylvania's forests are largely composed of mature, closed-canopy stands (McWilliams et al., in press). Thus, it was expected the proportion of tree cover would be relatively large (0.90). The 10% of forestland area without tree cover primarily is due to gaps between tree canopies (9.0%), with a modest contribution (1.0%) from contiguous forested areas having no tree cover (e.g., clearcut). The change in total cover was not statistically significant, although it was nearly so with a p -value only slightly larger than 0.05. However, the result may be of practical importance as a nearly 2% increase in forest cover is indicated. A small part of this increase may be attributable to an increase in forestland area of 0.3%; however the relative proportions of canopy gaps and open areas remained nearly identical from T1 to T2. This result is consistent with the general trend in Pennsylvania of increasing amounts of mature stands (few canopy gaps) and decreasing area of younger stands (McWilliams et al., in press).

Over the last four decades, beech bark disease has spread from northeastern Pennsylvania to most of the remainder of the state except the south central and far southeastern regions (Morin et al., 2007). Fig. 3 shows the spatial distribution of plots containing beech having dbh ≥ 20.3 cm. Clearly, there is a propensity for larger-sized beech in the northern part of the state. The analysis showed that about 2.5% of the forestland in Pennsylvania has canopy cover that is at risk to the disease. Over the time period evaluated, there was a slight, non-significant increase in canopy cover proportion. While the population of American beech may be reduced in comparison to pre-infestation levels (Houston, 1994), there is no evidence that a rapid decline is currently occurring (Morin et al., 2007). Although beech bark disease is not expected to cause a loss of a large portion of the American beech cover, this example highlights the potential utility of this method for assessing impacts of a forest health threat on forest cover. There are historical examples where exotic pests have caused virtual extirpations of tree species from forests (e.g., chestnut blight). Ongoing monitoring is essential to further assess impacts of beech bark disease, as changes in canopy cover and the resultant gaps can substantially influence the growth and structure of the remaining stand (DiGregorio et al., 1999).

Given the current state of Pennsylvania forests and the recognition as a geographic area of breeding activity for Cerulean warbler (Hamel, 2000), it is useful to quantify the amount of desirable habitat based on Jones' (2001) criteria as 28% of existing forestland area. Many areas in the state appear to have suitable warbler habitat, although the sparsely forested/high population density areas in the southeast are somewhat sporadic (Fig. 4). Of importance to forest managers and bird conservationists is the direction and magnitude of change in this habitat. Considering the high-cover component of warbler habitat, it was not surprising to see an approximate 1.2% increase in canopy area from T1 to T2. However, this statistic was not different from zero at the 95% confidence level ($p = 0.10$). As noted above, there was an increase in forestland area of nearly 0.3% over this same time period; however, given the criteria used for Cerulean warbler habitat, it seems unlikely that newly forested areas would contribute to the habitat change estimate.

The results show that only about 1.1% of forestland in Pennsylvania currently has canopy cover from trees having dbh of 56 cm and larger in stands at least 100 years old. The occurrence of such canopy cover is more prominent on publically-owned lands. Geographically, the largest concentrations appear to be in the northcentral and northwestern part of the state, where most of the state and federal forest ownership occurs along with numerous private inholdings (Fig. 5). However, there were

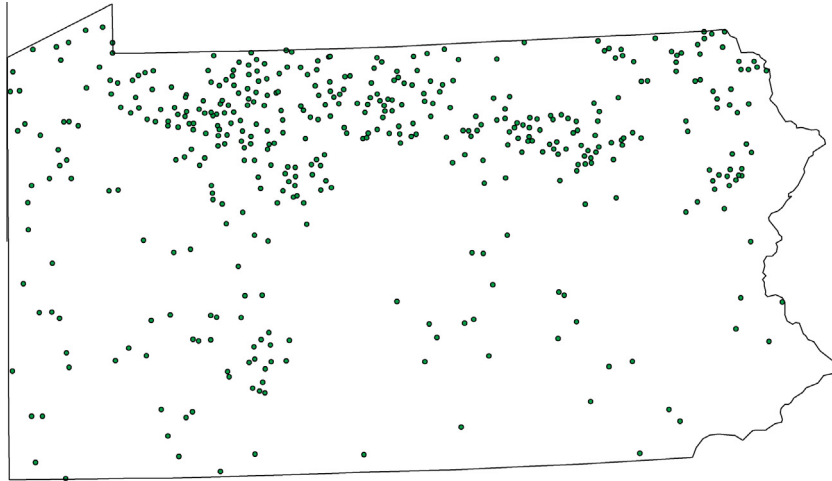


Fig. 3. Spatial depiction of plots having canopy cover of American beech with dbh ≥ 20.3 cm.

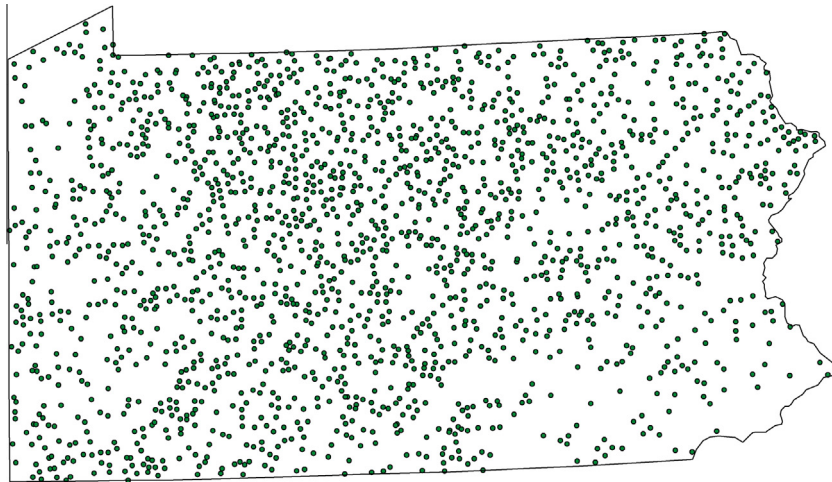


Fig. 4. Spatial depiction of plots having canopy cover suitable for Cerulean warbler habitat.

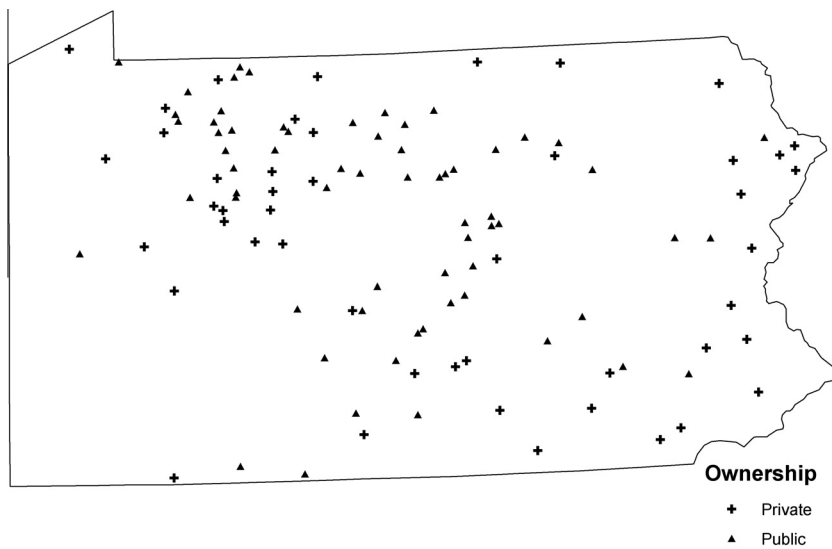


Fig. 5. Spatial depiction of plots having canopy cover of trees with dbh ≥ 56 cm in stands aged ≥ 100 years by ownership.

notable and statistically-significant ($\alpha = 0.05$) increases on both public and private lands over the 5-year interval. The increase in large tree canopy cover in stands aged 100+ years was nearly three times larger on public lands than on private lands, likely due to the trend of decreased harvesting on public land. Given that Pennsylvania was heavily logged in the early 20th century, a number of stands are crossing the 100-year age threshold. As such, it is expected that canopy cover of large trees in stands with ages of 100+ will continue to increase in the short term. Assessing cover of these large trees is important for management of wildlife habitat (Thomas et al., 1988) and stand regeneration dynamics (Runkle, 1981). Furthermore, such assessments may also be useful for scenic value evaluations for recreation purposes (Ribe, 1990).

One potential source of error in this study is the application of crown-width models to sapling-sized trees (dbh 2.54–12.69 cm). Bechtold (2003) used only trees having dbh of 12.7 cm and larger, thus the predicted values for saplings are an extrapolation of the model outside the range of intended application. It is likely that any bias in the predictions for saplings increases as tree size decreases. However, crown size becomes increasingly smaller as tree size decreases, which may limit the effect of issues related to model extrapolation. For best results, crown-width models applicable to the entire range of trees sizes should be employed.

Due to the method of assigning crown sizes to trees, the results are likely to be highly correlated with basal area or volume. However, interpretation of area metrics can be more intuitive in some cases. For instance, it would be difficult to meaningfully describe the amount of total canopy cover or Cerulean warbler habitat using basal area as the unit basis. Additionally, the cover estimate provides a different view of forest resources. For example, the old growth attributes analysis suggests about 1.1% of canopy cover on forestland; whereas these same trees comprise only 0.08% of all live trees and contain roughly 1.8% of tree biomass. This outcome suggests the usual descriptors of forest attributes do not provide information that is a direct surrogate for canopy cover.

5. Conclusion

Application of these canopy cover methods to national-scale forest inventory data such as FIA affords a wide range of analytical opportunities. Any individual-tree characteristic in the database can be used to define the canopy cover domain of interest. However, some analyses may be difficult to conduct if certain criteria are not easily quantifiable, particularly at the microsite scale. Canopy cover can be estimated not only for specific tree-level attributes but by a combination of tree and site variables (e.g., stand age) collected on each plot. Due to the spatially-distributed layout of inventory plots across the landscape, geographic scales of analysis can range from a single county to an entire region. As with any statistical estimate, minimum sample sizes may need to be considered in order to attain acceptable levels of error. In some cases (e.g., FIA), analysts can also take advantage of stratified estimation methods to help improve the precision of estimates.

Forest managers should consider adding canopy cover area to their portfolio of analytical metrics. Canopy estimates provide new information that has largely been unavailable in the past and may suggest alternative management strategies. The methods described can be adapted to any forest inventory data when applicable crown models are available and the locations of sample trees within the plot are known. In addition to assigning crown sizes to individual trees, accounting for overlapping canopy of neighboring trees must be accomplished using GIS or some alternative procedure. The dissolution of overlapping crowns is relatively easy and takes approximately 5–15 min (depending on the number of trees).

However, this process must be performed for each specified domain of interest, which precludes straightforward implementation in most forest inventory analytical tools. The additional effort may be worthwhile in cases where canopy cover is of particular importance.

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