Environ Monit Assess (2016) 188:297
DOI 10.1007/s10661-016-5281-8

Comparative assessment of methods for estimating tree canopy cover across a rural-to-urban gradient in the mid-Atlantic region of the USA

Rachel Riemann · Greg Liknes · Jarlath O'Neil-Dunne · Chris Toney · Tonya Lister

Received: 30 September 2015 / Accepted: 31 March 2016

Abstract Tree canopy cover significantly affects human and wildlife habitats, local hydrology, carbon cycles, fire behavior, and ecosystem services of all types. In addition, changes in tree canopy cover are both indicators and consequences of a wide variety of disturbances from urban development to climate change. There is growing demand for this information nationwide and across all land uses. The extensive inventory plot system managed by the USDA Forest Service Forest Inventory and Analysis (FIA) offers a unique opportunity for acquiring unbiased tree canopy cover information across broad areas. However, the estimates it produces had not yet been examined for comparative accuracy with other sources. In this study, we compared four different methods readily available and with significant potential for application over broad areas. The first two, field-collected and photointerpreted, are currently acquired by FIA on approximately 44,000 plots annually nationwide. The third method is a stem-mapping approach that models tree canopy cover from variables regularly measured on forested plots and is efficient enough to calculate nationwide. The fourth is a Geographic-Object-Based Image Analysis (GEOBIA) approach that uses both high-resolution imagery and leaf-off LiDAR data and has reported very high accuracies and spatial detail at state-wide levels of application. Differences in the spatial and temporal resolution and coverage of these four datasets suggest that they could provide complementary information if their relationships could be better understood. Plot- and county-level estimates of tree canopy cover derived from each of the four data sources were compared for 11 counties in Maryland, Pennsylvania, and West Virginia across a range of urbanization levels. We found high levels of systematic agreement between field and photointerpreted, stem-mapped and field, photointerpreted and GEOBIA estimates. In several cases, the relationship changed with the level of tree canopy cover. GEOBIA produced the highest tree cover estimates of all the methods compared. Results are discussed with respect to known differences between the methods and ground conditions found in both forest and nonforest areas.

Keywords Tree canopy cover · Object-based image analysis · Accuracy · Comparative assessment · Forest inventory

R. Riemann (✉)
Forest Inventory and Analysis, USDA Forest Service, Northern Research Station, 425 Jordan Road, Troy, NY 12180, USA
e-mail: rriemann@fs.fed.us

G. Liknes
Forest Inventory and Analysis, USDA Forest Service, Northern Research Station, 1992 Folwell Ave, St. Paul, MN 55108, USA

J. O'Neil-Dunne
Spatial Analysis Laboratory, University of Vermont, 205 George D. Aiken Center, Burlington, VT 05405, USA

C. Toney
USDA Forest Service, Rocky Mountain Research Station, 5775 US West Highway 10, Missoula, MT 59808, USA

T. Lister
Forest Inventory and Analysis, USDA Forest Service, Northern Research Station, 11 Campus Blvd, Suite 200, Newtown Square, PA 19073, USA

Published online: 18 April 2016

Introduction

Tree canopy cover provides ecosystem services across all lands, from natural forests to urban trees. Across all lands, tree canopy cover information is used for characterizing disturbance (e.g., Roberts 2007; Hansen et al. 2013) and potential wildlife habitat (Martinuzzi et al. 2009; Nelson et al. 2012), for supporting biomass and carbon stock estimates (O'Neil-Dunne et al. 2014; Johnson et al. 2014), and for fire fuels modeling (Mutlu et al. 2008). In more developed areas, in addition to the above uses, tree canopy cover is an important factor for mitigating the effects of urbanization on water quality and quantity (Riva-Murray et al. 2010) and has been observed to have a negative relationship to crime (Troy et al. 2012). Tree canopy cover is used in the calculation of urban tree effects on air quality, home energy use, and carbon sequestration, and tracking how these are changing over time (Nowak et al. 2013). Accurate canopy cover information is also used to improve the efficiency of ground-based inventories in urban and other nonforest areas by targeting field resources more effectively and by improving statistical precision using techniques such as post-stratification (Bechtold and Patterson 2005).

Some tree canopy cover monitoring efforts have focused on forested areas because of the importance of canopy cover to fire fuels modeling, habitat characterization and assessment, and the contribution of canopy cover to the definition of forest land in national and international monitoring efforts (e.g., Toney et al. 2009; FAO 2010). However, there can also be a sizeable proportion of tree biomass and tree canopy cover in nonforest areas, particularly in residential land uses (e.g., Riemann 2003; MacFaden et al. 2012). For example, nonforest areas in the 5-county area around Baltimore contained an average of 18 % of the basal area that occurred on forest land in the same area (Riemann 2003). In addition, tree cover is both highly variable in urbanized and agricultural areas and there is often less ground inventory data available for comparison. Thus, investigating the accuracy of available tree canopy cover data and potentially augmenting FIA's inventory of canopy cover with other sources may be greatest in these areas. There have been a number of efforts to map tree canopy cover using high-resolution data for use in urban settings. Myeong et al. (2001) used 0.61 m imagery to map urban tree cover in Syracuse, New York. Ground-based remote sensing approaches, such as hemispherical photography, have also been evaluated for assessing canopy cover (King and Locke 2013), and Fiala et al. (2006) compared four different ground-based methods to estimates based on measured crown radii parameters in the western Oregon Cascades. Developing a more automated approach suitable for broad areas across a variety of land cover types, the Urban Tree Canopy Assessment Program, a collaboration between the US Forest Service and the University of Vermont, has produced high resolution maps of tree canopy in 70 urbanized areas across the USA (http://go.uvm.edu/dd3g6).

State and local monitoring of tree canopy cover has become increasingly important as cities and states recognize its importance to air and water quality, moderation of the urban heat island effect, mitigation of stormwater runoff, and community livability (property values, recreational opportunities, crime rates). Additional benefits include wood products, renewable energy, carbon sequestration, and wildlife habitat. In Maryland, via Maryland House Bill HB 706 "Forest Preservation Act of 2013", the state formally set their goal to maintain 40 % tree cover both statewide and in individual urban areas.[1,2] The bill in Maryland is the first of its kind in the USA to codify tree cover goals into law, but both states and cities nationwide are increasingly interested in filling their gaps in information on tree cover. One such example is the increasing commitment of resources to urban forest inventories. In 2016, only 2 years after national implementation, seventeen cities and two states have invested in a cooperative effort with FIA's urban inventory program to acquire detailed tree cover information in their urban areas (Mark Majewsky, personal communication). In addition, these efforts have been combined with an increasing commitment to putting that information, including tree canopy cover data, into immediate application for calculations of ecosystem services, biodiversity, carbon storage and sequestration, and watershed health. This information is then used for increasingly effective planning and management of a city's urban forest, and for increasing community education and engagement in the care of urban trees. These efforts have been visible in popular articles (e.g., Esposito 2015), reports (e.g. Nowak et al. 2016), and the development of more effective data delivery tools on webpages (http://tfsgis.tamu.edu/UTC/) and apps (will be available in 2016 at: http://texasforestinfo.tamu.edu/). Because canopy cover is defined on a local scale (i.e., the proportion of ground area covered by canopy above), goals set for percent canopy cover, such as those set in Maryland, can only be supported and enforced by accurate and relatively fine-resolution monitoring of tree canopy cover.

For much larger spatial extents across both urban and rural landscapes, there have been several efforts to model tree canopy cover from coarser resolution satellite data in order to generate wall-to-wall tree canopy cover across the coterminous USA, an area over 7.7 million km^2 in size. Two examples are the tree canopy cover layer associated with the 2011 National Land Cover Database (NLCD2011) (Coulston et al. 2012; Homer et al. 2015), and the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) (Toney et al. 2012b). Both of these efforts relied on plot-level field- or airphoto-acquired canopy cover information for model development and for accuracy assessment of the resulting modeled estimates.

This study compares four different methods for estimating tree canopy cover. The first two methods, field and photointerpreted, are currently used by the national forest inventory of the USA to acquire tree canopy cover information for each plot in its extensive network—approximately 340,000 plots nationwide in the base grid (USDA Forest Service 2014). FIA's data collection methods for canopy cover were designed in 2010 in response to a recognized need for reliable statistics on tree cover across all lands. Both field and photointerpretation canopy cover methods were implemented on forest and nonforest plots, respectively, beginning with the 2012 field inventory. The photointerpreted canopy cover method is a dot-grid photointerpretation of tree canopy cover using aerial imagery acquired by the National Agriculture Imagery Program (NAIP) (Goeking et al. 2012). Similar dot-grid photointerpretation methods have been known for some time to be robust (e.g., Slama 1980), and Jackson et al. (2012) observed a high level of repeatability between photointerpreters using dot-grid interpretation with digital NAIP imagery. The photointerpreted tree canopy cover data used in this study was also used in the nationwide NLCD2011 canopy cover mapping effort.

The third method, stem-map modeling, was developed by Toney et al. (2009) for the national LANDFIRE project. Canopy cover is modeled from species-specific relationships between tree diameter at breast height (dbh) and crown diameter. This method can be used for any location where tree diameter and tree locations are observed, including FIA plots visited in previous years, as well as plots where field-based canopy cover protocols have not yet been implemented. This method is perfectly repeatable because it is derived by algorithm from the tree characteristics and tree location data collected during one of the field inventories.

The fourth method, Geographic-Object-Based Image Analysis (GEOBIA), has been applied over smaller geographic extents and provides tree canopy cover information at a finer spatial resolution than any of the previous three. This particular implementation of GEOBIA integrated both LiDAR and high resolution spectral imagery such as NAIP (National Agricultural Imagery Program) into a single classification workflow to exploit the height, spectral, and spatial information contained in both datasets (O'Neil-Dunne et al. 2012). The accuracies reported for these data are very high. In Maryland, for example, tree canopies at point locations were identified correctly 98 % (producer's accuracy) and 99 % (user's accuracy) of the time. An independent assessment of GEOBIA-derived tree canopy for New York City found strong agreement with field-based estimates (King and Locke 2013). In addition, the approach that has been developed can utilize leaf-off LiDAR imagery, making it possible to generate this highly accurate canopy cover information in more areas since the majority of statewide LiDAR collections are collected under leaf-off conditions. Since 2010, LiDAR data has become increasingly available over wider areas, making possible broader application of these GEOBIA methods (O'Neil-Dunne et al. 2014).

Tree canopy cover data collected during the regular forest inventory, whether from photointerpreted aerial imagery at FIA plot locations, from ocular estimates when plots are visited, or derived from field plot data (e.g., in situ tree measurements), has the advantage of being collected every year on some portion of the plots in any given area. It has the disadvantage, however, of being available for those sample plot locations only, with full sampling intensity coverage (one plot per 6000 acres) constrained by FIA's remeasurement period which ranges from 5 to 10 years nationwide. In addition, different methods are used depending on whether a plot is defined as forest land or nonforest land—with field-collected tree measurements and ocular estimates of tree cover being collected on visited forest plots, and dot-grid photointerpretation of tree canopy cover for plots that are not visited (primarily nonforest plots). Importantly, the relationship between tree canopy cover information acquired using these different methods for forest vs. nonforest lands is unknown. In contrast, the GEOBIA method has the advantage of providing canopy cover information across the entire area of interest (i.e., wall-to-wall coverage) with high spatial detail (Fig. 1). The primary disadvantage of the GEOBIA method at present is that it is limited to areas where LiDAR has been acquired, and updates are constrained by both the

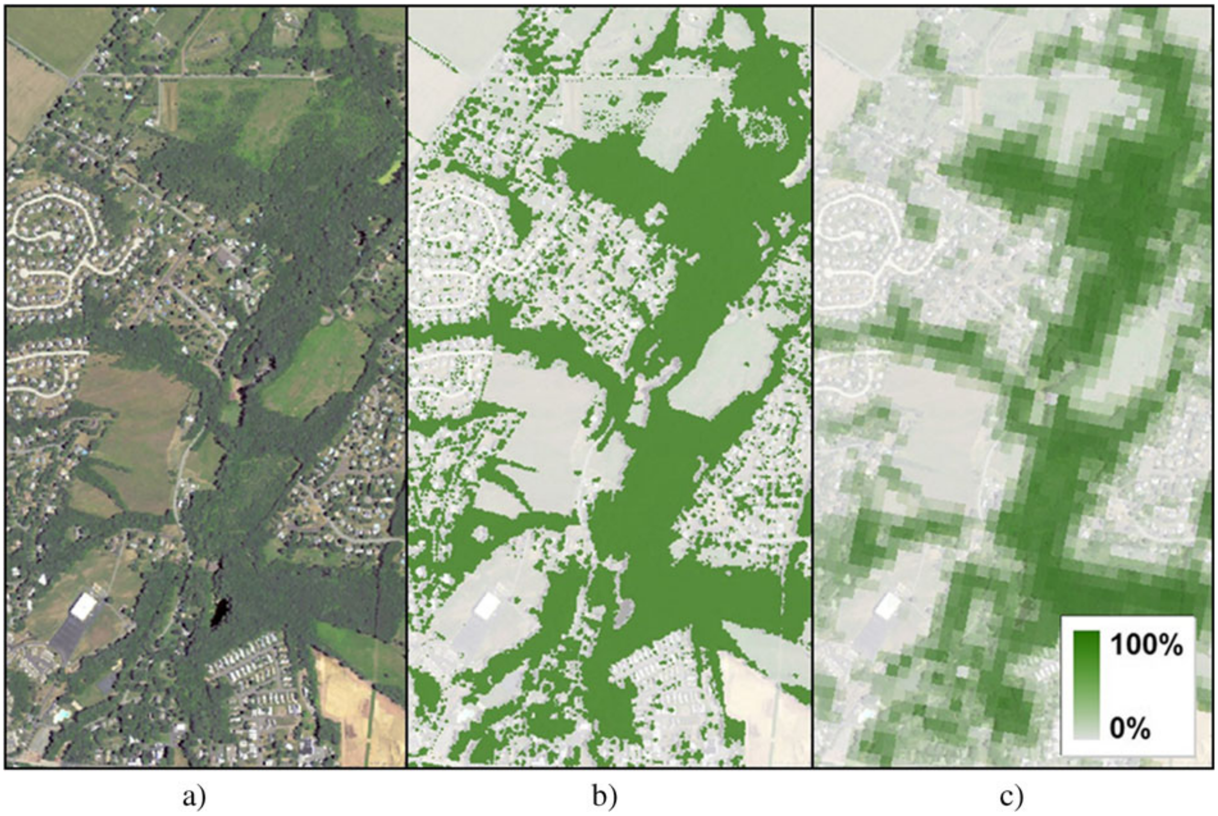


Fig. 1 Illustration of the additional level of spatial detail/precision present in a GEOBIA tree canopy dataset (2010) for an example area including both continuous forest patches and development: (**a**) the area as visible in aerial photography from the National Agriculture Imagery Program (NAIP), (**b**) presence/absence of tree canopy cover as modeled by GEOBIA, and (**c**) percent tree canopy cover from the 2011 National Land Cover Dataset (NLCD). While the methods appear similar in the forested areas, the GEOBIA approach captures and spatially resolves small patches of tree canopy and individual tree canopies that are missing or only weakly visible in the NLCD dataset

NAIP and LiDAR data collection cycles. The applicability of LiDAR across a range of disciplines including hydrology and transportation has resulted in an increasing number of states acquiring state-wide coverage; however, a re-acquisition interval of 10 years is typical.

Effectively incorporating tree canopy cover into management and policy activities requires sufficient spatial and temporal resolution, sufficient accuracy, and repeated measurements over time for monitoring change. In this study, we investigate the relationship between GEOBIA-derived canopy cover, photointerpreted canopy cover, field-collected canopy cover, and canopy cover calculated and modeled from field-collected tree data using a stem-mapping approach. All four methods are compared at both the plot- and county-levels. Improving our understanding of the relationships between available tree canopy cover data sources and their individual accuracies allow us to better integrate and utilize this information. In this 11-county study area where all data sources were simultaneously available, we examined/asked the following questions:

- Can stem-mapped canopy cover be used to support canopy cover estimates on forested plots? How closely do stem-mapped estimates relate to the field-collected ocular estimates of tree canopy cover?
- Do field and photointerpreted estimates of tree canopy cover report similar enough results that they can be used together to estimate tree cover across all lands?
- How do field, photointerpreted, and stem-mapped county-level estimates (all sample-based) compare to GEOBIA sample and GEOBIA wall-to-wall estimates?

After examining the magnitude and characteristics of any disagreement between methods, we also examine three factors that could potentially contribute to disagreement observed in this study. All three factors are independent of the methods themselves and/or could be addressed in the application of the methods.

- How internally consistent are field and photointerpreted estimates of tree canopy cover?
- How much does potential geolocation error associated with GPS coordinates contribute to observed disagreements?
- Does sampling intensity contribute to differences in observed county-level disagreements?

Methods

Data

The FIA program is responsible for monitoring forests throughout the nation every year using an extensive grid of sample plots. For example, in 2014 approximately 44,000 plots were sampled (USDA Forest Service 2015), representing about 13 % of the total base grid of plots, although this number will vary somewhat from year to year and by region depending on funding and other factors. FIA's sample plots occur on all land use and land cover types, ranging from agricultural lands to urban forests to forested wilderness and include both public and private lands. Locations are screened using high-resolution aerial imagery for the potential presence of forest cover. Those plots potentially having forest cover are visited in situ with a design consisting of a central subplot (7.3-m radius) surrounded by three peripheral subplots of equal radius in a triangular arrangement (Fig. 2a). In general, FIA plots are collected at a spatial sampling intensity of approximately 1:6000 acres. When the inventory is on a 5-year cycle, as was true during the inventory years used by this study, 20 % of plots in the study area are inventoried each year.

Four types of tree canopy cover data were available for FIA plots in the study area, each acquired via a different method and with some variation in the data footprint at each plot location. Not all canopy cover data sources were available for all plots, and there was some variation in collection date depending upon the imagery used. These details and other differences are described below and summarized in Table 1. The terms for "forest", "nonforest" and "mixed forest/nonforest" plots follow FIA definitions for forest land and generally dictate the types of FIA data that are available for that plot. By FIA definition, a forested plot has at least 10 % tree canopy cover (or had, if a recent clearcut or other canopy-removing disturbance) occupying a minimum of one acre, ≥120 ft in width, and is not subject to nonforest use(s) that prevent normal tree regeneration (USDA Forest Service 2014). A nonforest plot fails to meet one or more of the above criteria for a forest plot, and a mixed plot contains both "forest" and "nonforest" conditions in two or more spatially distinct areas within the plot.

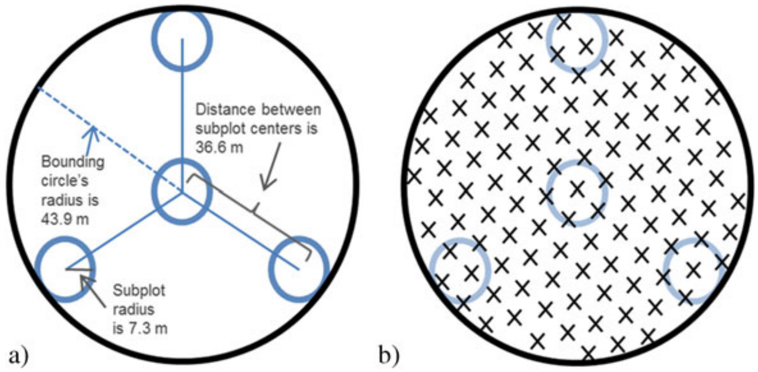


Fig. 2 FIA plot footprint and the areas over which canopy cover data was collected. Field canopy cover (FCC) and stem-mapped canopy cover (SMCC) correspond to the footprint of the four subplots (*blue circles*) (**a**). Photointerpreted canopy cover (PCC) and GEOBIA canopy cover (GCC) correspond to the footprint of the 0.607 ha (1.5 acre) bounding circle (*black circle*) (**b**). The dot-grid used in the photointerpreted plot design consists of a 109 dot-grid over the 0.607 ha area (*black X's*). The GCC estimate is derived from all 1 m grid cells within the bounding circle

Table 1 Characteristics of the four sources of tree canopy cover data compared in this study: field canopy cover (FCC), stem-mapped canopy cover (SMCC), photointerpreted canopy cover (PCC), and GEOBIA canopy cover (GCC)

	Plot footprint	Dates	Data source	Data acquisition method	Proportion of full inventory available for this study	Reference	# plots
FCC	1/6th acre cluster	2011–2012	Ground and NAIP	Occular estimate	40 % of forested plots	O'Connell et al. 2014	72
SMCC	1/6th acre cluster	2008–2012	Measured plot data	Calculated from FIA tree data plus statistical modeling of sapling cover	100 % of forested plots	Toney et al. 2009	70
PCC	1.5 acre circle	2007–2010	NAIP	Photointerpretation of a 109-point dot grid	60 % of all plots	Goeking et al. 2012	304
GCC	1.5 acre circle	2010–2011	NAIP and LiDAR	Object-based image analysis using LiDAR and NAIP	100 % of all plots	O'Neil-Dunne et al. 2012	533

Plot-level data

1) Field-collected percent canopy cover (FCC) is the percentage of the sample area covered by a vertical projection of live tree canopy cover, including trees, saplings, and seedlings. In this study, all FCC estimates were acquired using an ocular method of estimation derived from ground-based observation and supported by 1:8000 NAIP image sources. Ocular estimates are regularly used when tree canopy cover is clearly less than or greater than 10 % live tree canopy cover. For conditions where this is uncertain, every crown width within the canopy cover sample area is measured and if the 10 % threshold is reached the ocular method is used to determine the total tree canopy cover. Field-collected canopy cover estimates correspond to all live tree canopies within the 4-subplot footprint; however, it is noted in the field guide that when the ocular estimate is used, it is likely to be easier for the observer to ignore subplot boundaries and assess the percentage of canopy cover over the stand in question (USDA Forest Service 2014). These data were collected during the 2011 and 2012 field seasons for all visited plots (both forested and mixed forest/nonforest).
2) Stem-mapped canopy cover (SMCC) is derived directly from ground inventory data using modeled relationships between tree diameter at breast height (dbh) and crown diameter for each tree species or species group. SMCC is an estimate of the vertically projected canopy cover of FIA tally trees and saplings one inch and greater in diameter. Crowns are modeled for each tree, and the position of each tree is known, allowing for the calculation of the area covered by tree canopy with overlap between crowns subtracted. The full method is described in Toney et al. (2009). SMCC was calculated for all plots in study area between 2008 and 2012 that had tree data (the forested portion of forest and mixed forest/nonforest plots).
3) Photointerpreted percent canopy cover data (PCC) is collected from leaf-on, 1 m resolution, digital color-infrared National Agriculture Imagery Program (NAIP) imagery using a fixed 109-dot-grid overlaid on the 1.5 acre circular area encompassing all 4 FIA subplots and the area in between them (Fig. 2b). The photointerpreted canopy cover (PCC) estimate is the proportion of dots that fall on a tree canopy (Goeking et al. 2012). The dates of the imagery used, and thus the dates of the PCC data were 2007–2010. PCC estimates were available for all plot types in the study area, which included forest, nonforest, and mixed forest/nonforest plots.
4) GEOBIA canopy cover (GCC) was mapped at 1 m (3.28 ft) resolution for each county in the study area using the method described in O'Neil-Dunne et al. (2012). GCC is dated 2010–2011 for the three states in the study area, corresponding to the dates of the LiDAR data used in the analysis. Plot-level GCC estimates were acquired from the wall-to-wall modeled dataset by summarizing the canopy cover information for the 0.607 ha (1.5 acre) circular area around plot center ("cut-outs"), replicating the area used in the PCC data collection.

County-level data

County-level summaries of mean percent canopy cover were calculated from each canopy cover data source using the available data, and thus there were some differences in the number of plots used to calculate county-level estimates. For example, FCC and SMCC canopy cover estimates were available for forested lands only. Since GCC estimates were available as a wall-to-wall 1 m grid resolution dataset for each county, several different county-level estimates were used for comparison:

(a) The proportion of the county's area in the mapped tree class. This was considered to be a census of canopy cover in each county rather than a sample.
(b) The sample mean of percent canopy cover using GCC "cut-outs" at all plot locations in the study area, to replicate the intensity of the full FIA plot sample.
(c) The sample mean of percent canopy cover using GCC "cut-outs" at 60 % of plot locations in the study area, to replicate the available sampling intensity of the PCC information and investigate how well 60 % of the standard FIA plot intensity was able to summarize county-level tree canopy cover in these counties.
(d) The sample mean of percent canopy cover using GCC "cut-outs" at forested plot locations only in the same 60 % sample.

Given the small number of forest plots with available FCC data ($n = 22$), estimates of tree canopy cover on forest land were calculated and compared for the entire study area instead of individual counties.

Additional data

We acquired additional information for each plot location that might explain some of the differences observed.

- Both field data and photointerpreted data collected by FIA are subject to blind checks/remeasurements so they can be assessed for the measurement consistency of the data. This quality assurance (QA) data is collected on 4 % of the plots nationwide. Data from 2012 for the entire states of MD, PA, and WV were used to check the consistency of photointerpreted (PCC) canopy cover estimates. Data from 2011 to 2013 for the entire states of MD, PA, and WV was used to check the consistency of field-collected (FCC) canopy cover estimates.
- Plot coordinates are re-acquired using current GPS technology each time they are visited. Two sets of GPS coordinates were available for 60 plots that had been visited twice since GPS coordinate collection began.

Study area

The study area consisted of 11 counties in PA, MD, and WV where all four canopy cover data sources were available (Fig. 3). This included counties with a range of percent tree cover from 19 % (Philadelphia, PA) to 58 % (Anne Arundel County, MD), a range of urbanization from 5 % impervious cover (Jefferson, WV) to 52 % (Philadelphia, PA), and a range of agriculture from 19 % grass cover (Baltimore City) to 65 % (Lancaster, PA) as derived from the land cover mapping provided by the wall-to-wall GEOBIA dataset (Fig. 4). This range covers a broad spectrum of conditions widely encountered in the northeastern USA, excluding the most heavily forested and least developed counties. The study represents a case study, in an area where all four datasets of interest were readily available for a sufficient proportion of FIA plots.

Analysis

We performed pairwise comparisons for each of the four canopy variables described in Table 1 at the plot- and county-level, with the exception of the FCC variable. Given the small number of forest plots with available FCC data ($n = 22$), an estimate of tree canopy cover on forest land was calculated for the entire study area instead of individual counties. Agreement was assessed using root mean square error (RMSE), and the symmetric, bounded, non-parametric agreement coefficient (AC) developed by Ji and Gallo (2006) which calculates independently the level of systematic (AC_{sys}) and unsystematic (AC_{uns}) agreement present, allowing examination of these two types of error separately. In addition, unlike Willmott's index of agreement, AC uses the reduced major axis (RMA) regression line (also known as the geometric mean functional relationship or GMFR regression line; e.g., Draper and Smith 1998) because it is a symmetric regression model that assumes both X and Y are subject to error (Ji and Gallo 2006). In this study, AC was used

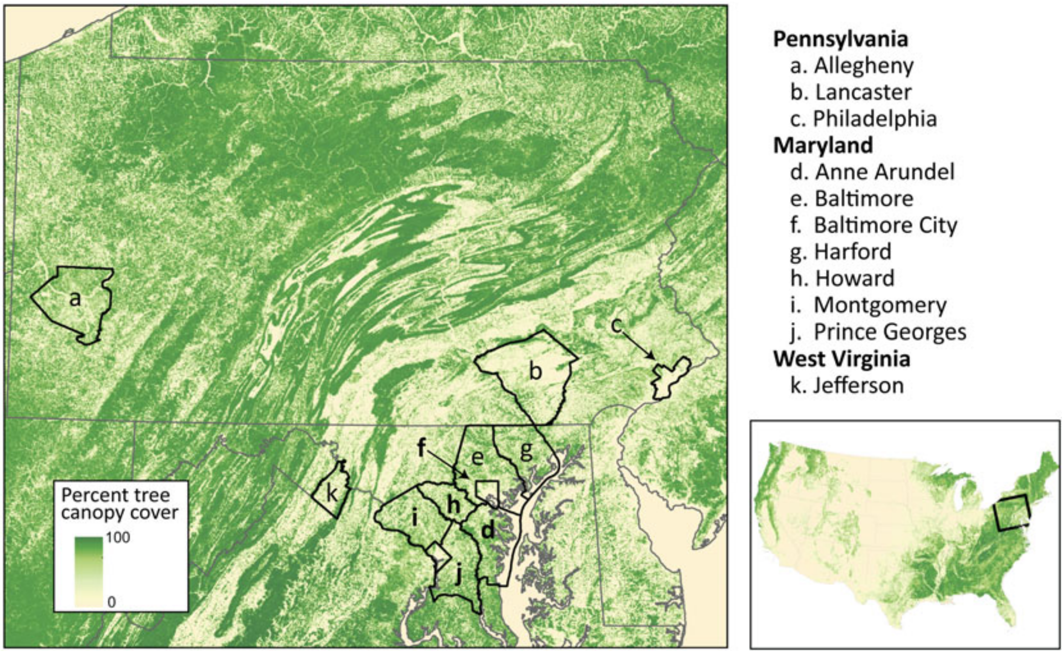
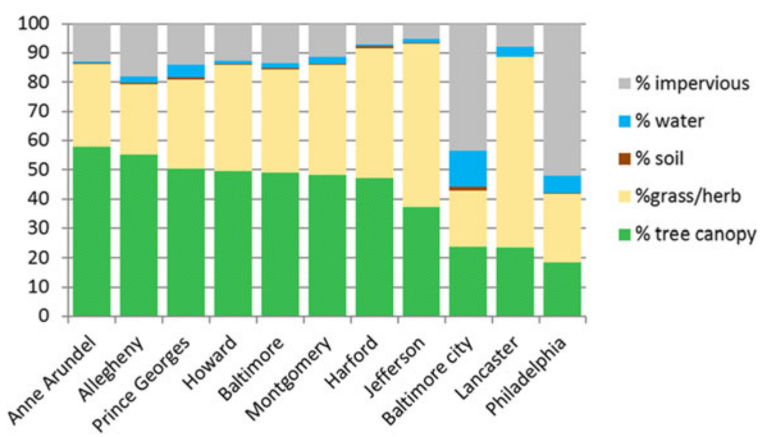


Fig. 3 Counties included in the study area

because all datasets used are assumed to contain some measurement errors. Systematic agreement (AC_{sys}) describes the proximity of the RMA regression line to the y = x line, and thus that difference which could be predicted by a simple linear model. Unsystematic agreement (AC_{uns}) describes the level of scatter about the RMA regression line, and thus those differences which appear to be random and unrelated to the reference dataset. Overall agreement includes both systematic and unsystematic differences. All AC metrics are standardized (value range does not change with size of data values) with a maximum possible AC values of 1. $AC_{sys} = 1$ if the RMA line is in line with the y = x line, and $AC_{uns} = 1$ if all points fall directly on the RMA line. Desired levels of agreement will depend on the magnitude of error that translates into a significant impact on the results for a particular application (Riemann et al. 2010). In this study, we used target values similar to target values used in Riemann et al. (2012): AC values above 0.95 were considered to indicate a high level of agreement, and AC values below 0.70 were considered to indicate very little agreement. Root mean square deviation (RMSD) was calculated to provide information on the magnitude of difference in data units (percentage points).

We examined internal consistency of field (FCC) and photointerpreted (PCC) estimates of tree canopy cover on FIA plots using data from quality assurance (QA)

Fig. 4 Land cover composition in each of the 11 counties in the study area as identified in the wall-to-wall GEOBIA data, arranged in order of decreasing proportion of forest cover



check plots. Stem-mapped canopy cover estimates were considered to be highly internally consistent as they were calculated (for tree canopy cover) and modeled (for sapling canopy cover) directly from FIA tree-level inventory data. Wall-to-wall estimates of GEOBIA canopy cover (GCC) have a high level of reported consistency and accuracy in previous studies (King and Locke 2013; O'Neil-Dunne et al. 2014). Extraction of GCC estimates for FIA plot locations was dependent upon the accuracy of the plot coordinates available, and more specifically, whether the location monumented and inventoried on the ground (FCC) was the same location that was photointerpreted (PCC) and the same location for which GCC was extracted. Plot coordinate consistency was examined using a second set of coordinates collected on those plots that were repeat plots from a previous inventory, and used as an indication of location accuracy—the likelihood that FCC, PCC, and GCC were all acquired for the same location. In addition, to assess the actual impact of these plot coordinate differences on plot-level GCC estimates used in this study, we compared GCC estimates acquired via the two different sets of GPS coordinates for the 60 plots where repeat coordinates were available.

Results

Pairwise comparison of plot-level canopy cover estimates

Comparison of plot-level field (FCC) and photointerpreted (PCC) canopy cover estimates (Fig. 5 and Table 2) reported relatively strong AC_{sys} agreement overall, but exhibited a bias of approximately 10 % at low levels of canopy cover, with PCC estimating higher tree canopy cover than FCC at those low levels.

Plot-level agreement between stem-mapped canopy cover (SMCC) vs. FCC and PCC estimates was examined to characterize how closely stem-mapped estimates relate to field-collected estimates on forested plots (Fig. 6 and Table 2). SMCC and FCC protocols cover an identical footprint and exhibited generally high systematic agreement (0.96), with more bias on plots with high levels of canopy cover, although also not without considerable scatter ($AC_{uns}=0.81$). Some of the difference could be due to the possibility for FCC data collected via the ocular estimate method to "find it easier to ignore subplot boundaries and assess the percentage of tree canopy cover over the [stand] in question without

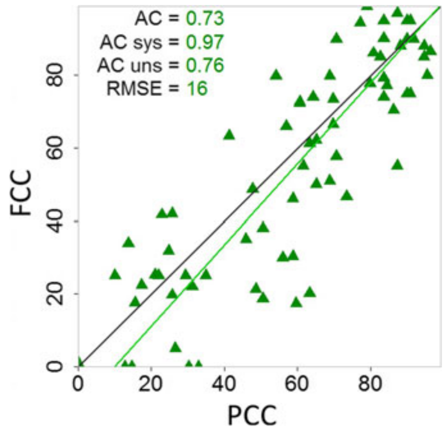


Fig. 5 Scatterplot comparison of field canopy cover (FCC) and photointerpreted canopy cover (PCC) estimates for forest and mixed plots, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)

regard to the location of the stems supporting the canopy cover on the plot" (USDA Forest Service 2014). In the SMCC vs. PCC comparison, an AC_{sys} value of 0.87 indicated that there was some bias present in the relationship, with photointerpreted estimates generally higher than the stem-mapped estimates across the full range of values, consistent with similar observations by Toney et al. (2012a). The SMCC estimates for mixed plots assume no tree cover on the nonforest portions of the plots, whereas PCC estimates include all tree canopy cover across the entire plot regardless of forest/nonforest status, which could be a source of some of the difference observed on mixed plots.

Comparison of plot-level agreement between GEOBIA canopy cover estimates (GCC) and PCC, FCC, and SMCC estimates (Fig. 7 and Table 2) indicated that GCC canopy cover estimates were generally larger than all other estimates of canopy cover. Photointerpreted canopy cover (PCC) estimates exhibited the highest agreement with GCC, although GCC appears to generally overestimate cover relative to PCC estimates by approximately 15 percentage points at the largest levels of percent canopy cover, down to quite close to zero for canopy cover less than 20 %. Dividing the dataset into two separate populations for comparison (above and below 20 % canopy cover), clearly shows this result (Fig. 8). Both PCC and GCC canopy protocols use the same 1.5 acre data footprint. SMCC and FCC both exhibited substantially lower agreements when compared with GCC. Both SMCC and FCC data protocols use the 1/6th acre plot cluster footprint and the SMCC protocol applies only to forest portions

Table 2 Plot-level agreement estimates for either forest and mixed plots (F/M), or forest, mixed and nonforest plots together (F/M/NF), corresponding to the data available from each of the four data sources—photointerpreted canopy cover (PCC), field canopy cover (FCC), stem-mapped canopy cover (SMCC), and GEOBIA canopy cover (GCC)

	Population	AC	AC_{sys}	AC_{uns}	RMSE	# plots
PCC vs. FCC	F/M	0.73	0.97	0.76	16	72
PCC vs. SMCC	F/M	0.59	0.87	0.72	21	163[a]
FCC vs. SMCC	F/M	0.78	0.96	0.81	14	52[a]
GCC vs. PCC	F/M/NF	0.9	0.96	0.94	13	303
GCC vs. FCC	F/M	0.7	0.88	0.81	23	72
GCC vs. SMCC	F/M	0.5	0.63	0.87	39	163[a]

[a] SMCC estimates for mixed plots assume no trees on the nonforest portion of the plot

while assuming no trees on nonforest portions of plots; both PCC and GCC protocols estimate canopy cover across their 1.5 acre sample areas regardless of forest/nonforest status.

County-level agreement

We compared county-level estimates of average percent canopy cover to examine the cumulative impact of differences between the canopy cover data sources for areas the size of counties.

County-level estimates of tree canopy cover across all lands could be calculated from the PCC and GCC data sources that were available for both forest and nonforest plots. Photointerpreted (PCC) mean percent canopy cover estimates were consistently lower than the GEOBIA (GCC) estimates, with the exception of Baltimore City and Lancaster County where the PCC estimate and the GCC estimates were the same (Fig. 9). This was also true when looking at canopy cover on nonforest areas only (Fig. 10). Baltimore City and Lancaster both had lower levels of canopy cover overall, and thus may be dominated by plots with low percent canopy cover (e.g., <20 %). The similarity of PCC and GCC estimates in these counties may therefore be a reflection of greater agreement between plot-level PCC and GCC estimates at these lower levels of canopy cover (Figs. 7 and/or 8).

Estimates of tree canopy cover on forest land were calculated for the entire study area. GCC reported the highest average canopy cover for forest land in the study area, at 92 %, FCC reported 83 %, and PCC reported 79 % for forest land.

Clearly evident in Fig. 10 is the amount of tree canopy cover present on the nonforest land in each of these counties—averaging between 12 and 45 percent tree canopy cover depending on the county and method used. These 11 counties are reported by FIA to range from 58 to 82 % nonforest land. Historical FIA inventories do not collect data on this “nonforest” tree canopy cover, which is nonetheless important for estimates of carbon/biomass (Jenkins and Riemann 2002; Johnson et al. 2014) and for calculating some of the ecosystem services provided by trees (Nowak et al. 2013). Areas of urban development can sometimes contain the highest levels of tree canopy cover in nonforest areas (Riemann 2003), and current efforts by FIA to facilitate the implementation of

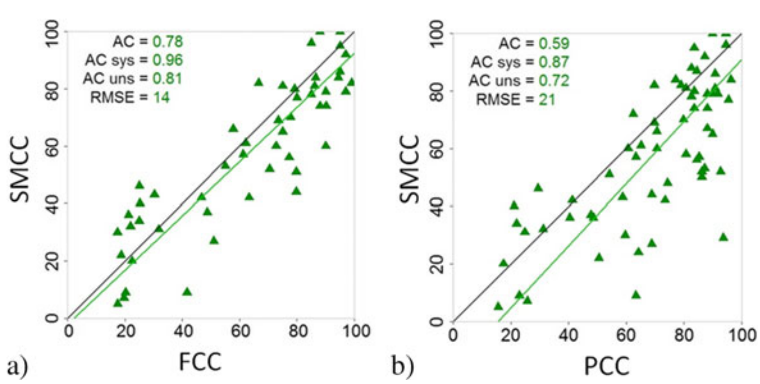


Fig. 6 Scatterplot comparison of stem-mapped canopy cover (SMCC) vs. **a** field canopy cover (FCC) and **b** photointerpreted canopy cover (PCC) estimates for both forested and mixed plots, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)

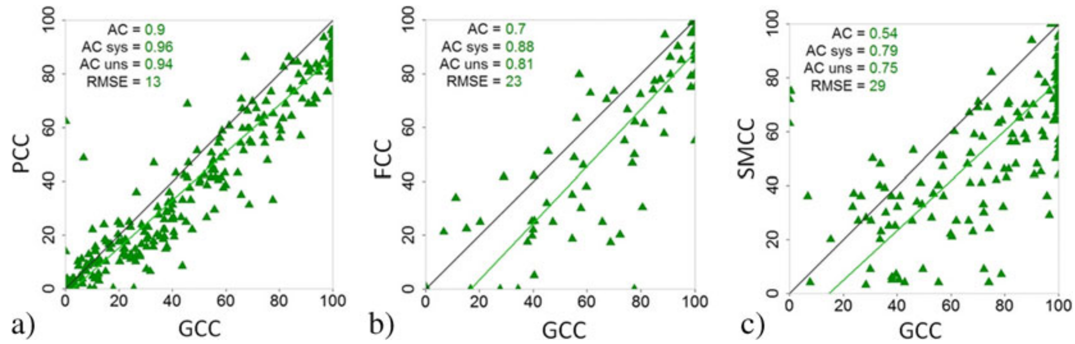


Fig. 7 Scatterplot comparison of GEOBIA canopy cover (GCC) vs. **a** photointerpreted canopy cover (PCC), **b** field canopy cover (FCC), and **c** stem-mapped canopy cover (SMCC) estimates, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)

inventories into these nonforest areas will increase the amount of additional information we have about this tree cover and its characteristics.

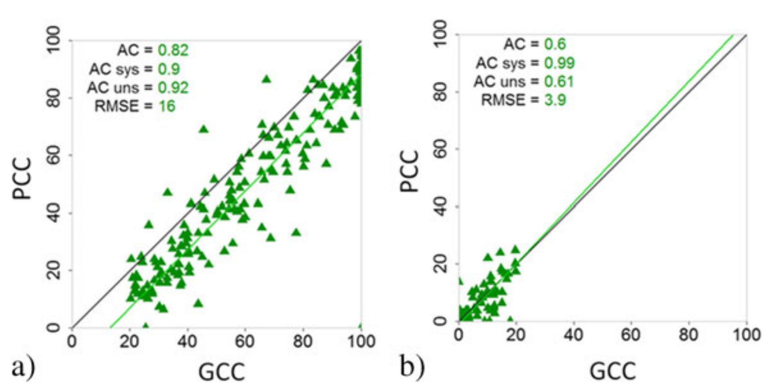
Potential sources of disagreement

Quality assurance (QA) of field canopy cover (FCC) Four percent of FIA plots are subjected to revisit and re-inventory by a separate crew and all variables are remeasured. We compared original and QA measurements for FCC collected between 2011 and 2013 in the three states in the study area (PA, MD, WV) to examine level of consistency in FCC estimates (Fig. 11). Of the 183 plots using field protocols for both the original and QA inventories, all but 6 used the ocular estimation method. Results using all 183 plots reported a high level of agreement, with ACsys = 1, ACuns = 0.92, and an RMSD of 7.4 % canopy cover.

Quality assurance (QA) of photointerpreted canopy cover (PCC) Four percent of photointerpreted data points collected by FIA were subjected to remeasurement by a second interpreter using the same imagery for quality assurance purposes. PCC estimates exhibited high levels of consistency for low canopy cover plots, with increasing variation at higher canopy cover levels (Fig. 12). Overall agreement was high, with $AC_{sys} = 0.98$, $AC_{uns} = 0.97$, and an RMSD of 9 % canopy cover, however there appeared to be some tendency for QA PCC estimates to be lower than the original PCC estimates, particularly at higher canopy cover levels. This was perhaps due to additional time spent by QA interpreters, particularly to determine which dots fell between tree crowns in relatively closed canopy. However, insufficient data was available to examine this more closely.

Sensitivity of GEOBIA canopy cover (GCC) to location errors Extraction of GEOBIA canopy cover (GCC) for FIA plot locations relied on the accuracy of the GPS coordinates collected by FIA at each location. Sixty of the plots within the study area had been visited in more than one inventory cycle and GPS coordinates were collected at each visit. We compared these coordinate pairs to get an estimate of the impact of potential plot coordinate error at these locations. Geolocation differences between current and previous GPS coordinates for

Fig. 8 Scatterplot comparison of photointerpreted canopy cover (PCC) vs. GEOBIA canopy cover (GCC) for **a** plots with a GCC value ≥20 % canopy cover and **b** plots with a GCC value of <20 % canopy cover, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)



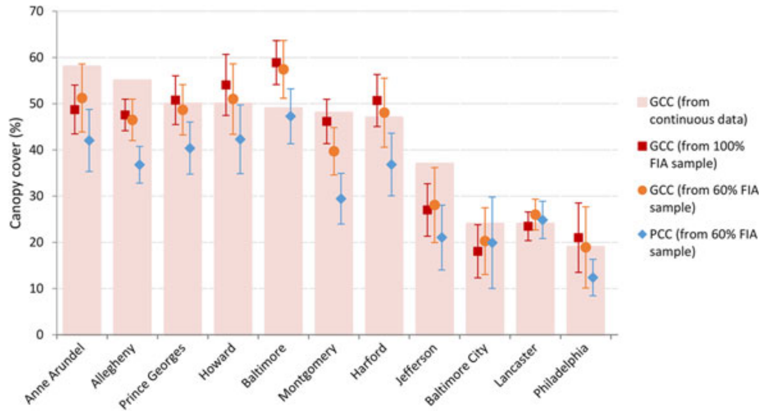


Fig. 9 Comparison of county-level estimates from each of the canopy cover data sources available for all plot types: Photointerpreted canopy cover (PCC 60 % sample), GEOBIA canopy cover calculated from 60 % of the plots (GCC 60 % sample), and GEOBIA canopy cover calculated from 100 % of the plots (GCC 100 % sample). *Histogram bars* represent the percent tree canopy cover present in the wall-to-wall GEOBIA dataset for each county

FIA plots in this study averaged 8 m, and the sensitivity of GCC canopy cover estimates to this difference was less than 1 %.

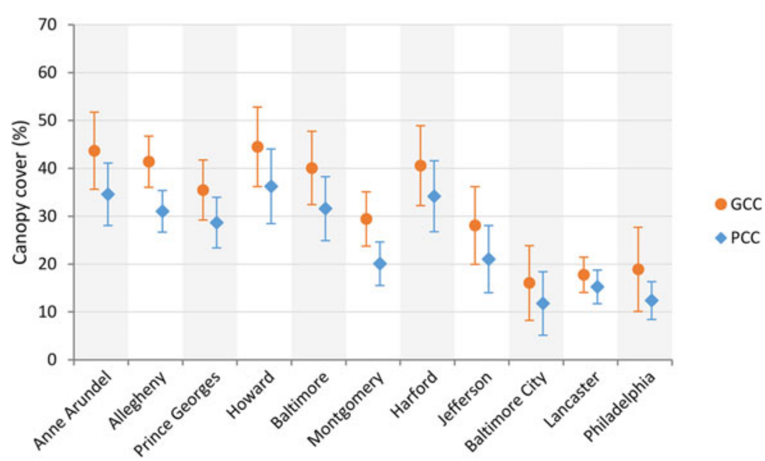
Possible effect of sample size The availability of wall-to-wall canopy cover estimates for each county from the high resolution modeled GEOBIA dataset allowed examination of possible differences in county-level tree canopy cover estimates that might simply be the result of the sampling intensity in the available plot sample. GEOBIA estimates of percent canopy cover calculated from a sample consisting of 100 % of the FIA plots and a sample of 60 % of the plots both tracked GEOBIA percent canopy cover calculated from the full set of wall-to-wall data fairly closely, with AC_{sys} values of 0.98 in both cases, and AC_{uns} values of 0.84 and 0.88, respectively (Fig. 13).

When compared with the wall-to-wall GEOBIA data, both GCC sample estimates (from 60 and 100 % of FIA plot locations) underestimated percent canopy cover by about 10 % in Anne Arundel, Allegheny and Jefferson counties, overestimated percent canopy cover in Baltimore County by about 10 %, and fell within 6 % of the actual percent canopy cover in the remaining counties (Fig. 9). It was also evident in Fig. 9 that the 60 % sample was not substantially different from the 100 % sample in canopy cover estimate reported.

Discussion

Differences in method and plot-footprint between field-collected (FCC) and photointerpreted (PCC) canopy

Fig. 10 Comparison of county-level estimates of mean tree canopy cover on FIA-designated "nonforest" land from each of the data sources



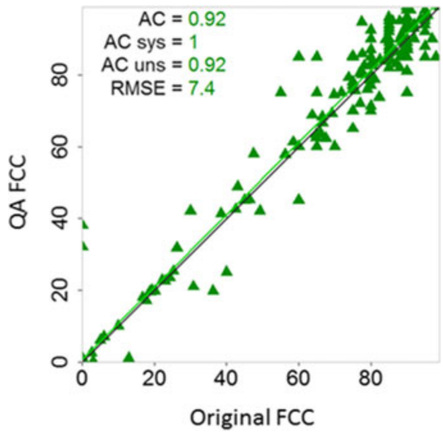


Fig. 11 Scatterplot of original field-collected canopy cover estimates (FCC) against the QA field-collected estimate, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)

cover estimates is a concern because one is used on field-visited (primarily forest and mixed) plots, and the other is used on non-visited (primarily nonforest and inaccessible) plots and the two must therefore be used together in order to get an estimate of canopy cover across all lands. In this study, FCC and PCC estimates of tree canopy cover reported high systematic agreement overall, but this was split between almost no bias at high levels of canopy cover, and nearly a 10 % bias at low levels of canopy cover. Field canopy cover data was only available for 40 % of FIA plots, making it a smaller sample. There was some evidence that when summarized to the study area-level, these differences in agreement

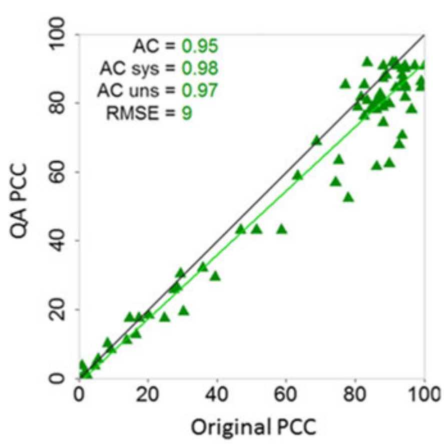


Fig. 12 Scatterplot of original photointerpreted canopy cover estimates (PCC) vs. QA photointerpreted estimate for the states of MD, PA, and WV, 2012 data, including the 1:1 line (*black*) and geometric mean functional relationship (GMFR) regression line (*green*)

between FCC and PCC may improve if enough plots are available, however this improvement in agreement may be dependent upon the proportion of low canopy cover plots within the county or study area. When more data becomes available, an expanded study of county-level FCC and PCC estimates for forest land may include a sufficient number of counties to investigate whether this is generally true, or if the differences can be predicted from any county-level characteristics. The high level of scatter ($AC_{uns} = 0.76$) present in plot-level comparisons between field and photointerpreted estimates could be the result of several factors. At higher levels of canopy cover (e.g., ≥25 %), QA results for both FCC and PCC indicated that some variability existed between observers. At canopy cover levels less than approximately 25 %, where QA results demonstrated high levels of internal consistency in both FCC and PCC estimates, differences between the methods may be the primary contributing factor. For example, in areas with low levels of tree canopy cover, it is likely that that tree cover is also more patchy, more spatially variable. In such situations, the relatively large difference between FCC and PCC methods in sample area size (1/6th acre and 1.5 acres, respectively) could explain the higher variability observed in the relationship between FCC and PCC estimates in these areas—i.e., the 1/6th acre FCC footprint could coincide with a higher or lower patch of tree canopy cover than a PCC estimate averaging canopy cover over a larger 1.5 acre. This type of difference should decrease when canopy cover estimates are aggregated. Several other differences in FCC and PCC methods may have contributed to PCC estimates being higher. View angle of NAIP photography is rarely from directly above, and any other view angle will introduce some "lean" to trees in the imagery, causing tree canopies to visually cover more ground than they actually do (Toney et al. 2012a). In this region, PCC estimates could also be higher because they can include recently dead trees while FCC estimates do not, or because they include tree species that are not in FIA's list of species that are included in the inventory. This species-related discrepancy should be small, particularly in this area, but could be more of a factor in urban areas where more exotic or ornamental species occur. As FIA data collection and analysis begins to include lands in traditionally 'nonforest' areas, such as the Urban FIA initiatives, it begins to include areas with a higher variability of tree cover, species, and landscape characteristics that could affect tree canopy cover estimates (canopy height, stand structure, canopy closure, shrub cover, building shadows, etc.). Further examination of tree canopy cover

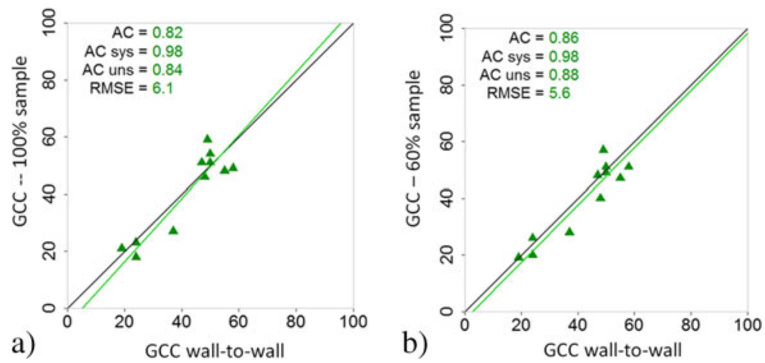


Fig. 13 Scatterplot comparison of county-level mean canopy cover estimates from GEOBIA canopy cover (GCC), as calculated from **a** 100 % of the FIA plot sample and **b** 60 % of the FIA plot sample vs. average tree canopy cover for each county summarized from the wall-to-wall GEOBIA canopy cover dataset

estimates using additional data is suggested to better understand the nature and desirability of the slightly higher tree canopy cover estimates provided by PCC in areas of lower tree canopy cover.

Stem-mapped estimates of canopy cover (SMCC) are modeled directly from the inventoried plot data itself. SMCC generally agrees well with FCC, suggesting that it can be used successfully to provide canopy cover estimates for plots that pre-date implementation of FCC, assuming that accurate location coordinates are available for those plots. This has the potential to expand application of FIA plot data for remote sensing, wildlife habitat, and vegetation analyses requiring canopy cover data. When compared with the other sources of tree canopy cover data—PCC and GCC—the stem-mapped estimates exhibited less agreement than field canopy cover estimates. One possible explanation for both this and the observed differences between SMCC and FCC is that while SMCC estimates are calculated directly from FIA plot inventory data which is only collected from the 1/6th acre plot area (Table 1), the ocular protocol used by the FCC estimate may allow for some influence of the surrounding/intervening area into the estimate since the goal of the FCC estimate is to provide percent canopy cover associated with the stand. Thus, even though the FCC estimate is nominally specific to the 1/6th acre area of the four subplots, implementation of the ocular estimate could make it potentially more similar to the larger footprints of the PCC and GCC estimates.

GCC estimates of canopy cover are of considerable interest because they represent a potential source for consistent, wall-to-wall canopy cover of very high spatial resolution comparable in scale to canopy cover derived from FIA plots. If sufficiently accurate, wall-to-wall data provides off-plot information as well as an opportunity to analyze spatial pattern of tree canopy cover. The high reported accuracies of GCC estimates in previous studies provided an opportunity to assess the comparative accuracy of FIA field, photointerpreted, and stem-mapped estimates of canopy cover. At the plot level, GCC estimates reported higher percent tree canopy cover than any of the other three sources, with the largest discrepancies typically at the higher percent canopy cover values. Of all four data sources, GCC estimates exhibited the highest agreement with PCC estimates, although with some bias at higher levels of canopy cover. When examined above and below the 20 % canopy cover threshold, the relationship between PCC and GCC plot-level estimates reported different levels of agreement. Below 20 %, agreement between the two estimates exhibited almost no bias and an RMSE less than 4 percentage points, while above the 20 % threshold PCC canopy cover estimates were consistently lower on average than GCC estimates by 10 percentage points. Plot-level differences between PCC and GCC persist at the county-level, with PCC estimates consistently lower than GCC estimates by approximately the same amount. A likely explanation is that the GCC modeling approach differs from FIA photointerpretation in its treatment of tree crowns that are relatively close together. For example, in the PCC method, photointerpreters of tree canopy cover took particular care to note when a dot falls in a tree gap. In contrast, the GCC approach is designed to fill in small gaps between tree canopy in forested deciduous areas as way to deal with the leaf off nature of the LiDAR data and to improve the cartographic representation (see Fig. 1a). This routine to fill in canopy gaps typically results in changes in mean tree canopy in the tenths of a percent at the county level, but the effects of this routine at the plot level are unknown and could explain differences observed in this study. At the same time, because LiDAR is not sensitive to shadowing, PCC estimates could underestimate canopy in shadowed areas of the imagery if no tree canopy is assumed in shadowing such as that caused by buildings or terrain. The advantage of the GEOBIA data is its wall-to-wall coverage. The advantage of the FIA collected PCC estimate is the potential for it to contribute to data currency because of the persistent acquisition of data on a fixed percentage of FIA plots each year, which in our study area was 20 %. Further analysis of the two data sources using more data over a broader area may reveal a consistent relationship that could be used, or a pattern of differences that could be predicted, so that the two data sources can be used to support each other either temporally or spatially.

Any spatial overlay analysis depends on the accuracy of plot coordinate locations. The high spatial resolution of the GEOBIA data represented a unique opportunity to examine the potential effect of current levels of error in FIA's most accurate set of plot locations. Although GPS locations collected during two separate visits to each plot differed on average by 8 m, percent canopy cover was typically within 1 % when comparing GCC extracted at each pair of coordinates. We concluded that, in this study, geospatial accuracy of the coordinates was not a substantial contributing factor to differences between any of the canopy cover datasets, even in this area of many mixed forest and nonforest plots and thus presumably high spatial variability of tree canopy cover. In areas where coordinate location errors are higher, and in areas of high local variability at scales finer than the GPS location accuracy available, more substantial effects would be expected (Coulston et al. 2006; Prisley et al. 2008; McRoberts 2010).

In this study, only small differences were observed between county-level estimates of tree canopy cover derived from 60 vs. 100 % of the plot data at FIA's standard sampling intensity. More substantial differences were observed between the estimates derived from either of the plot samples (60 or 100 %) and the wall-to-wall modeled data, however insufficient data were available in this study to investigate possible reasons for these differences. Additional data, such as that resulting from the Urban FIA inventories for an increasing number of urban areas, may be able to address this question.

Conclusions

In this study, we examined four different sources of tree canopy cover that have been or have the potential to be applied nationwide—field (FCC) and photointerpreted (PCC) canopy cover methods currently used by FIA, stem-mapped (SMCC) calculation of canopy cover from tree characteristics collected on the ground by forest inventory, and canopy cover modeled using a combination of high-resolution imagery, leaf-off LiDAR data, and GEOBIA methods (GCC).

Field and photointerpreted data sources (FCC and PCC) produced plot-level canopy cover estimates with a high level of systematic agreement, although they exhibited increased differences and more scatter (lower AC_{uns}) at low levels of canopy cover. At these low canopy cover levels, PCC estimates were on average higher than FCC estimates and reported tree cover on plots where FCC reported none. PCC estimates should provide more accurate plot-level tree canopy cover in areas of sparse tree canopy cover because of the larger sample area size, and the inclusion of ornamental species in PCC tree canopy estimates is desirable for many applications. However, PCC estimates can also include dead tree canopies in some regions, and perhaps more broadly, may be affected by tree "lean" in the imagery used, resulting in undesirably higher estimates.

Consistent with other studies, SMCC produced plot-level results similar to FCC, exhibiting a high level of systematic agreement at all levels of tree canopy cover. This result suggests that SMCC can be used to generate similar tree canopy cover estimates back in time and for plots where FCC has not yet been acquired.

Plot-level estimates of GCC were very similar to PCC estimates at percent tree canopy cover levels below 20 %, but GCC was consistently higher when canopy cover was greater than 20 %. This pattern persists in comparisons of county-level estimates of tree canopy cover. Specific differences in the methods were identified that could be contributing to this difference. Which method is preferable will depend upon how the data is used. Further investigation of these datasets over a larger area may allow for consistent modeling of this relationship.

Acquiring tree canopy cover data across all lands requires equally accurate and consistent information to be collected on both forest and nonforest lands. Although the relationship was noisy at times, we observed similarities between FCC and PCC estimates across most levels of canopy cover that suggest potential for FCC and PCC data to be used together to estimate percent canopy cover estimates across all lands.

We are interested in finding a method, or combination of methods, for acquiring estimates of tree canopy cover that provide both accurate fine-scale information over this wide variety of conditions, and can be applied efficiently and consistently over broad areas. Plot-level methods currently used by FIA fit the criteria of efficient and consistent application, but were of unknown accuracy relative to other fine-resolution data sources such as GCC which are increasingly being used across cities and even states. In this study, we found a seemingly predictable consistency between estimates produced by the PCC method currently used by FIA and those produced by GCC at both plot and county levels. Although definitive conclusions cannot be drawn due to the small study area size, the results suggest that PCC estimates have a high level of internal consistency, and a predictable relationship to GCC estimates that may be largely due to differences in how spaces between closely spaced tree canopies are classified.

References

Bechtold, W. A., & Patterson, P. L. (2005). *The enhanced forest inventory and analysis program—national sampling design and estimation procedures*. Asheville: USDA Forest Service, Southern Research Station. 85 p.

Coulston, J. W., Riitters, K. H., McRoberts, R. E., Reams, G. A., & Smith, W. D. (2006). True versus perturbed forest inventory plot locations for modeling: a simulation study. *Canadian Journal of Forest Research, 36*(3), 801–807.

Coulston, J. W., Moisen, G. G., Wilson, B. T., Finco, M. V., Cohen, W. B., & Brewer, C. K. (2012). Modeling percent tree canopy cover: a pilot study. *Photogrammetric Engineering and Remote Sensing, 78*(7), 715–727.

Draper, N. R., & Smith, H. (1998). *Applied regression analysis*. New York: Wiley.

Esposito, K. (2015). Taking good ideas from rural Wisconsin: a statewide urban forest inventory is underway for communities big and small. *Wisconsin Natural Resources, 39*(5), 21–23.

FAO. (2010). *Global forest resources assessment 2010*. Rome: Food and Agriculture Organisation.

Fiala, A. C. S., Garman, S. L., & Gray, A. N. (2006). Comparison of five canopy cover estimation techniques in the western Oregon Cascades. *Forest Ecology and Management, 232*, 188-197.

Goeking, S. A., Liknes, G. C., Lindblom, E., Chase, J., Jacobs, D. M., & Benton, R. (2012). A GIS-based tool for estimating tree canopy cover on fixed-radius plots using high-resolution aerial imagery. In R. S. Morin & G. C. Liknes (Eds.), *Moving from status to trends: Forest Inventory and Analysis (FIA) symposium 2012* (pp. 237–241). Newtown Square: USDA Forest Service, Northern Research Station.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., & Tyukavina. (2013). High-resolution global maps of 21st-century forest cover change. *Science, 342*(6160), 850–853.

Homer, C. G., Dewitz, J. A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N. D., Wickham, J. D., & Megown, K. (2015). Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing, 81*(5), 345–354.

Jackson, T. A., Moisen, G. G., Patterson, P. L., & Tipton, J. (2012). Repeatability in photo-interpretation of tree canopy cover and its effect on predictive mapping. In W. McWilliams & F. A. Roesch (Eds.), *Monitoring across borders: 2010 joint meeting of the Forest Inventory and Analysis (FIA) Symposium and the Southern Mensurationists* (pp. 189–192). Asheville: USDA Forest Service, Southern Research Station.

Jenkins, J. C., & Riemann, R. (2002). What does nonforest land contribute to the global carbon balance? In R. E. McRoberts, G. A. Reams, P. C. Van Deusen, & J. W. Moser (Eds.), *Proceedings of the third annual forest inventory and analysis symposium* (pp. 173–179). St. Paul: USDA Forest Service, North Central Research Station.

Ji, L., & Gallo, K. (2006). An agreement coefficient for image comparison. *Photogrammetric Engineering and Remote Sensing, 72*(7), 823–833.

Johnson, K. D., Birdsey, R., Finley, A. O., Swantaran, A., Dubayah, R., Wayson, C., & Riemann, R. (2014). Integrating forest inventory and analysis data into a LIDAR-based carbon monitoring system. *Carbon Balance and Management, 9*, 3.

King, K. L., & Locke, D. H. (2013). A comparison of three methods for measuring local urban tree canopy. *Arboriculture & Urban Forestry, 39*(2), 62–67.

MacFaden, S. W., O'Neil-Dunne, J. P. M., Royar, A. R., Lu, J. W. T., & Rundle, A. G. (2012). High-resolution tree canopy mapping for New York City using LIDAR and object-based image analysis. *Journal of Applied Remote Sensing, 6*(1), 063567–1–063567–23. doi:10.1117/1.JRS.6.063567.

Martinuzzi, S., Vierling, L. A., Gould, W. A., Vierling, K. T., & Hudak, A. T. (2009). Incorporating remotely sensed tree canopy cover data into broad scale assessments of wildlife habitat distribution and conservation. *Journal of Applied Remote Sensing, 3*, 1–17.

McRoberts, R. E. (2010). The effects of rectification and global positioning system errors on satellite image-based estimates of forest area. *Remote Sensing of Environment, 114*(8), 1710–1717.

Mutlu, M., Popescu, S. C., Stripling, C., & Spencer, T. (2008). Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. *Remote Sensing of Environment, 112*(1), 274–285.

Myeong, S., Nowak, D. J., Hopkins, P. F., & Brock, R. H. (2001). Urban cover mapping using digital, high-spatial resolution aerial imagery. *Urban Ecosystems, 5*, 243–256.

Nelson, M. D., Tavernia, B. G., Toney, C., & Walters, B. F. (2012). Relating FIA data to habitat classifications via tree-based models of canopy cover. In R. S. Morin & G. C. Liknes (Eds.), *Moving from status to trends: Forest Inventory and Analysis (FIA) symposium 2012* (pp. 254–259). Newtown Square: USDA Forest Service, Northern Research Station.

Nowak, D. J., Hoehn, R. E., Bodine, A. R., Greenfield, E. J., & O'Neil-Dunne, J. (2013). Urban forest structure, ecosystem services and change in Syracuse. *NY. Urban Ecosystems*. doi:10.1007/s11252-013-0326-z.

Nowak, D. J., Bodine, A. R., Hoehn, R. E., III, Edgar, C. B., Hartel, D. R., Lister, T. W., & Brandeis, T. J. (2016). *Austin's Urban Forest, 2014. Resource Bulletin NRS-100*. Newtown Square: USDA, Forest Service, Northern Research Station. 55 p.

O'Connell, B. M., LaPoint, E. B., Turner, J. A., Ridley, T., Pugh, S. A., Wilson, A. M., Waddell, K. L., & Conkling, B. L.

(2014). *The Forest Inventory and Analysis Database: Database description and user guide version 6.0.1 for Phase 2*. USDA, Forest Service. 748 p.

O'Neil-Dunne, J. P. M., MacFaden, S.W., Royar, A. R., & Pelletier, K. C. (2012). An object-based system for LiDAR data fusion and feature extraction. *Geocarto International*, (May 29),1–16.

O'Neil-Dunne, J., MacFaden, S., Royar, A., Reis, M., Dubayah, R., & Swatantran, A. (2014). An object-based approach to statewide land cover mapping. *Proceedings of the ASPRS 2014 Annual Conference*. March 23–28, 2014. Louisville, KY. 6 pp.

Prisley, S. P., Wang, H.-J., Radtke, P. J., & Coulston, J. (2008). Combining FIA plot data with topographic variables: are precise locations needed? In W. McWilliams, G. Moisen, & R. Czaplewski (Eds.), *2008 Forest Inventory and Analysis (FIA) symposium* (pp. 1–10). Fort Collins: USDA Forest Service, Rocky Mountain Research Station.

Riemann, R. (2003). *Pilot inventory of FIA plots traditionally called "nonforest"*. Newtown Square: USDA, Forest Service, Northeastern Research Station. 44 pp.

Riemann, R., Wilson, B. T., Lister, A. J., & Parks, S. (2010). An effective assessment protocol for continuous geospatial datasets of forest characteristics using USFS Forest Inventory and Analysis (FIA) data. *Remote Sensing of Environment, 114*, 2337–2352.

Riva-Murray, K., Riemann, R., Murdoch, P., Fischer, J. M., & Brightbill, R. (2010). Landscape characteristics affecting streams in urbanizing regions of the Delaware River Basin (New Jersey, New York, and Pennsylvania, U.S.). *Landscape Ecology, 25*, 1489–1503.

Roberts, M. R. (2007). A conceptual model to characterize disturbance severity in forest harvests. *Forest Ecology and Management, 242*(1), 58–64.

Slama, C. C. (1980). *Manual of photogrammetry* (4th ed.). Falls Church: American Society of Photogrammetry.

Toney, C., Shaw, J. D., & Nelson, M. D. (2009). A stem-map model for predicting tree canopy cover of Forest Inventory and Analysis (FIA) plots. In W. McWilliams, G. Moisen, & R. Czaplewski (Eds.), *2008 Forest Inventory and Analysis (FIA) symposium* (pp. 53-1–53-19). Fort Collins: USDA Forest Service, Rocky Mountain Research Station.

Toney, C., Liknes, G., Lister, A., & Meneguzzo, D. (2012a). Assessing alternative measures of tree canopy cover: photo-interpreted NAIP and ground-based estimates. In W. McWilliams & F. A. Roesch (Eds.), *Monitoring across borders: 2010 Joint meeting of the Forest Inventory and Analysis (FIA) symposium and the Southern Mensurationists* (pp. 209–215). Asheville: USDA Forest Service, Southern Research Station.

Toney, C., Peterson, B., Long, D., Parsons, R., & Cohn, G. (2012b). Development and applications of the LANDFIRE forest structure layers. In R. S. Morin & G. C. Liknes (Eds.), *Moving from status to trends: Forest Inventory and Analysis (FIA) symposium 2012* (pp. 305–309). Newtown Square: USDA Forest Service, Northern Research Station.

Troy, A., Grove, J. M., & O'Neil-Dunne, J. (2012). The relationship between tree canopy and crime rates across an urban-rural gradient in the greater Baltimore region. *Landscape and Urban Planning, 106*, 262–270.

USDA Forest Service. (2014). *Forest Inventory and Analysis national core field guide, volume 1: Field data collection procedures for phase 2 plots, version 6.1*. Washington, DC: USDA Forest Service.

USDA Forest Service. (2015). *Forest inventory and analysis: fiscal year 2014 business report*. Washington, DC: USDA Forest Service. 68 pp.