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ABSTRACT In the southern Appalachians, *Rhododendron maximum* L. (Ericaceae) is a key evergreen understory species, often forming a subcanopy in forest stands. Little is known about the significance of *R. maximum* cover in relation to other forest structural variables. Only recently have studies used Global Positioning System (GPS) technology as a field-based method to map the perimeter of shrub patches as a means of estimating canopy cover. We assessed the viability of using GPS technology to accurately measure *R. maximum* canopy cover in mountainous terrain; and we compared canopy cover to other *R. maximum* abundance variables, forest structural attributes, and environmental factors. We selected forty 20 × 40 m permanent plots at Coweeta Hydrologic Laboratory in western North Carolina to employ a variety of methods (visual estimates, GPS, and x-y coordinate measurements) to estimate canopy cover of *R. maximum* within each plot. We found a positive relationship between the GPS method and the more accurate x-y coordinate measurements ($r = 0.967$, $p < 0.001$). We compared the GPS-derived estimates to other measures of *R. maximum* abundance and found positive relationships between cover and density ($r^2 = 0.800$, $p < 0.001$), basal area ($r^2 = 0.747$, $p < 0.001$), total biomass ($r^2 = 0.761$, $p < 0.001$), and leaf area index ($r^2 = 0.761$, $p < 0.001$). The GPS method is a reliable field-based technology to estimate evergreen canopy cover and it could be used to estimate more difficult to measure parameters of *R. maximum*, given the significant relationships found in this study.
Key words: Evergreen understory, global positioning system, hardwoods, shrub, southern Appalachians.

INTRODUCTION *Rhododendron maximum* L. (Ericaceae), an evergreen shrub, is a prominent species in the southern Appalachian forests. It is one of the most abundant understory plant taxa in forest stands of the region (Elliott et al. 1999), forming a dense subcanopy in many areas. *Rhododendron maximum* favors mesic, cove environments, often in riparian zones, with high soil organic matter (Graves and Monk 1985, Newell and Peet 1996, Newell et al. 1997, Elliott et al. 1999). *Rhododendron maximum* alters ecosystem processes through its contributions to photosynthetic activity and net primary productivity (NPP), hydrologic processes, and nutrient exchange (McGinty 1972, Monk et al. 1985, Wurzburger and Hendrick 2007). *Rhododendron maximum* and canopy tree saplings compete for light availability, water, and nutrients such as nitrate, ammonium, and phosphate (Clinton and Vose 1996, Nilsen et al. 2001). Because *R. maximum* is an abundant and key species in southern Appalachian forests, it is imperative to accurately assess its canopy cover and extent with the most practical methodology.

Forest structural variables such as stand density, basal area, tree height, canopy extent, and canopy cover are often used to

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characterize forests in support of inventory and mapping programs, management strategies, and conservation activities (Fiala et al. 2006). Measures of crown or canopy cover are used commonly to assist quantification of carbon fluxes and understanding of ecosystem function (Siedel et al. 2011). However, measuring and assessing forest structural variables can be a labor-intensive and comparatively costly field-based process (Siedel et al. 2011, Wilson 2011). Forest managers and inventory specialists have long sought alternative and more economical approaches to obtain forest structural variables, including canopy cover.

Canopy cover is an important and widely used measurement for characterizing forest structure; and it is related to ecological processes such as forest floor microclimate and light conditions, energy flux, temperature, leaf area index (a measure for leaf area per unit ground area that can photosynthesize) (Brantley et al. 2011), wildlife habitat (Vospernik and Reimoser 2008), and overstory-understory interactions (competition and gap dynamics) (Jørgensen and Kollman 2009, Rayburn et al. 2010). A variety of field-based (e.g., spherical densiometer, direct measurement of crown dimensions, hemispherical photography, line intercept, and ocular estimates), and airborne-based (e.g., remote sensing, LiDAR) canopy cover methods exist (for reviews: Paletto and Tosi 2009, Seidel et al. 2011, Wilson 2011). However, only recently have studies used Global Positioning System (GPS) technology as a field-based method to map the perimeter of shrub patches as a means of estimating canopy cover (e.g., Menges et al. 2008, Jørgensen and Kollmann 2009, Christensen et al. 2011).

Although a few studies have examined canopy cover of *R. maximum* (e.g., Elliott and Vose 2012), we are not aware of any studies that have used GPS and Geographic Information System (GIS) as a field-based method to estimate canopy cover, particularly in mountainous terrain. Our primary objective of this study was to assess the viability of using GPS technology to accurately measure *R. maximum* canopy cover. In addition, there is a need for developing relationships between variables used in physiological and ecological research and variables that are easier and more practical to measure in various forest types. Our secondary objective was to relate canopy cover to other *R. maximum* abundance variables, forest structural attributes, and environmental factors. Although *R. maximum* has been described as occurring predominantly along streams (Schafale and Weakley 1990, Clinton 2002, Dobbs and Parker 2004), we questioned whether more specific environmental variables would likely explain the variation in *R. maximum* coverage.

METHODS AND MATERIALS

Study Area

Coweeta Hydrologic Laboratory is an experimental forest of the Southern Research Station, USDA Forest Service. Coweeta is located (latitude 35°03′N, longitude 83°25′W) within the Nantahala National Forest, western North Carolina. The basin was commercially logged between 1919 and 1923, before Forest Service administration began (Douglass and Hoover 1988). Since then, numerous studies have been conducted at Coweeta, creating a collection of comprehensive ecological data (http://www.coweeta.uga.edu). The Coweeta Basin is 1626 ha within the total 2185 ha outdoor laboratory, with elevations ranging from 675 to 1592 m and steep slopes ranging from 30% to over 100%. Soils are deep sandy loams underlain by folded schist and gneiss (Thomas 1996). Mean annual temperature is 12.6°C and mean annual precipitation is 1800 mm (Swift et al. 1988). Vegetation was first surveyed in permanent plots in 1934 and resurveyed in 1969–1972, 1988–1993, and 2009–2011. Although some of the plots have not been resurveyed since their establishment in 1934, their permanent markers have mostly remained intact. Primary overstory taxa in the basin include *Quercus* (Fagaceae), *Carya* (Juglandaceae), and *Liriodendron tulipifera* L. (Magnoliaceae), with *Tsuga canadensis* (L.) Carrière (Pinaceae) and *Pinus rigida* Miller (Pinaceae) being less abundant (Elliott and Swank 2008). In many of the permanent plots, evergreen understory species *Rhododendron maximum* and *Kalmia latifolia* L. (Ericaceae) are present and sometimes abundant (Elliott et al. 1999, Elliott and Vose 2012).

Evergreen Cover Surveys

We measured *Rhododendron maximum* cover in 40 of the 20 × 40 m permanent plots at Coweeta Hydrologic Laboratory (Figure 1).

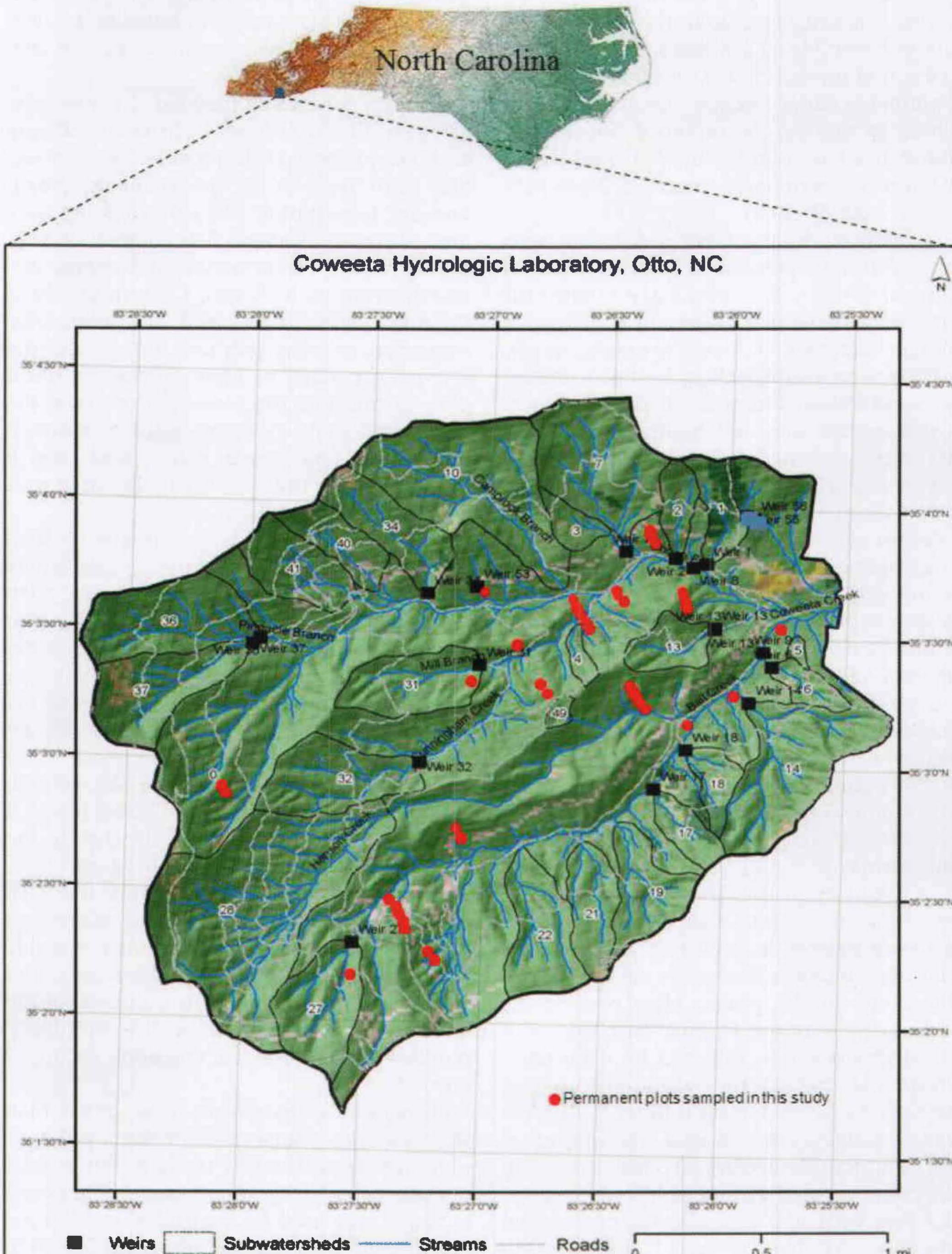

Figure 1. Location of the 40 permanent plots within the Coweeta Basin, western North Carolina.

We used three surveying techniques to examine the efficiency and accuracy of estimating canopy cover: visual estimates, mapping with a GPS, and measuring x-y coordinates around *R. maximum* canopy edges. The 40 plots were chosen to represent a range of *R. maximum* abundance based on the most current survey of Coweeta permanent plots in 2009–2011 (Elliott, unpubl. data).

To perform visual estimates of *R. maximum* cover within the permanent plots, an observer scanned the 20×40 m plot and estimated the percentage of the plot covered by *R. maximum*. Though this method is very simplistic, it was performed as a self-checking method to ensure that data collected from GPS or x-y coordinate measurements were not highly skewed, and also because archived data from the earliest survey in 1934 only recorded visual estimates of *R. maximum* percent cover.

Percentage cover was also calculated using a mapping-grade GPS (henceforth, referred to as the GPS method). Bolstad et al. (2005) recommended using a mapping-grade receiver and a telescoping pole with an external antenna to accurately and consistently collect GPS positions in the subcanopy, particularly where area features are small, $\leq$3.0 m. Thus, we used a Trimble® GeoExplorer® XH™ (Trimble Navigation Limited, Westminster, Colorado) handheld unit because of its capabilities for submeter accuracy. The GPS unit was used with TerraSync™ 5.21 software (Trimble). To collect data using the GPS method, pin flags were placed around the perimeter of *R. maximum* patches in each plot, with enough flags at all major inflections to convey the size and shape of the patch. After placing the flags, a GPS point was taken at each flag, with 30 satellite positions collected for each point recorded so that the unit would yield higher accuracy by averaging all positions. To maximize satellite reception and improve speed and accuracy of collecting 30 positions at each GPS point, we used a range pole that extended to 3.7 m with a Trimble Hurricane external antenna (Trimble) to avoid the blocking effects of the evergreen cover and mountain ridges on the GPS satellite reception. We set a maximum position dilution of precision (PDOP) of 6.0 with a minimum signal to noise ratio (SNR) of 30 dB Hz to ensure quality resolution. In each permanent plot, all GPS points were labeled to clearly indicate which set of points belonged to an individual patch. GPS points were also recorded at the plot corners.

The GPS data were uploaded to a computer using Pathfinder Office 5.1 (Trimble) software and post-processed using a differential correction with data from the Franklin, North Carolina base station. The corrected files were then exported as shape files compatible with ArcGIS 10.0® (Environmental Systems Research Institute, Redlands, California). Using the ArcGIS suite, the labeled GPS points were connected, creating polygons to represent the evergreen patches or open patches within a plot. To calculate the percentage cover in the permanent plots, polygons were also drawn around the plot corner points, and then a ratio of patch area to total plot area was calculated in ArcGIS.

For the x-y coordinate measurement system (henceforth, referred to as the x-y coordinate method), we established a grid in each permanent plot, with the x-axis (north-south direction) representing the 40 m side of the rectangular plot and the y-axis (east-west direction) representing the 20 m side of the plot. We measured x-y coordinates to the nearest 0.1 m at each inflection point, using the same pin flags placed for the GPS method, of each individual *R. maximum* patch within a plot. On graph paper, rough sketches of the patches were drawn to be used for later reference. In both the x-y and the GPS methods, the patch plotting was sometimes inverted. In cases where there was noticeably more evergreen cover than open area, pin flags were placed around the perimeter of the open patches rather than the evergreen patches and these points were recorded instead.

Rhododendron maximum cover percentage was calculated similarly with the x-y coordinate method as the GPS method, but instead of connecting GPS points, a coordinate graph template was used for each plot and the x-y coordinates were plotted using ArcGIS 10.0. Polygons were then drawn around the points in the same way as with the GPS method to calculate a ratio of evergreen cover area to total plot area.

In the 2009–2011 survey, diameter of all woody stems (shrubs and trees) $\geq$2.5 cm dbh

Table 1. Average density, basal area (BA), total aboveground biomass (leaf + wood), and leaf area index (LAI) of tree and shrub species (≥2.5 cm dbh) and proportional (*pi*) density, *pi* BA, *pi* biomass, and *pi* LAI

Species	Density (stems ha^{-1})	*pi* density (%)	BA (m^2 ha^{-1})	*pi* BA (%)	Biomass (Mg ha^{-1})	*pi* biomass (%)	LAI (m^2 m^{-2})	*pi* LAI (%)
Acer pensylvanicum	48.44	1.92	0.125	0.30	0.478	0.15	0.037	0.56
Acer rubrum	158.44	6.29	5.500	13.13	45.704	14.20	1.194	18.22
Betula lenta	53.44	2.12	1.904	4.54	15.492	4.81	0.205	3.13
Carya spp.	63.44	2.52	2.630	6.28	22.993	7.14	0.509	7.77
Cornus florida	26.56	1.06	0.150	0.36	0.507	0.16	0.035	0.53
Fagus grandifolia	22.50	0.89	0.125	0.30	0.537	0.17	0.019	0.29
Kalmia latifolia	48.75	1.94	0.127	0.30	0.226	0.07	0.003	0.04
Liriodendron tulipifera	48.13	1.91	4.115	9.82	33.709	10.47	0.539	8.22
Magnolia fraseri	26.56	1.06	0.333	0.79	2.026	0.63	0.052	0.79
Nyssa sylvatica	45.00	1.79	0.993	2.37	5.075	1.58	0.133	2.02
Oxydendrum arboretum	71.88	2.85	1.596	3.81	7.795	2.42	0.217	3.31
Quercus alba	13.75	0.55	2.194	5.24	17.858	5.55	0.349	5.32
Quercus coccinea	6.56	0.26	0.894	2.13	9.787	3.04	0.084	1.28
Quercus montana	57.50	2.28	6.570	15.68	75.754	23.54	1.271	19.38
Quercus rubra	18.75	0.74	3.246	7.75	29.859	9.28	0.658	10.04
Quercus velutina	7.81	0.31	1.271	3.03	11.315	3.52	0.254	3.87
Rhododendron maximum	1449.06	57.56	5.077	12.12	17.542	5.45	0.791	12.06
Tsuga canadensis	281.56	11.18	4.19	10.01	20.973	6.52	0.004	0.07

Note: Species nomenclature follows Kirkman et al. (2007). The majority of *Tsuga canadensis* were standing dead trees; little live foliage. Minor species with <0.5 % density, basal area, and total aboveground biomass were *Acer saccharum, Aesculus flava, Amelanchier arborea, Betula alleghaniensis, Carpinus caroliniana, Castanea dentata, Cornus alternifolia, Fraxinus americana, Hamamelis virginiana, Ilex opaca, Magnolia acuminata, Pinus rigida, Prunus serotina, Pyrularia pubera, Rhododendron calendulaceum, Robinia pseudoacacia, Sambucus canadensis, Sassafra albidium, Symplocos tinctoria*, and *Tilia americana*.

(diameter at 1.37 m above ground level) were measured to the nearest 0.1 cm and recorded by species in these 40 permanent plots. We calculated density, basal area, aboveground biomass, and leaf area index (LAI, m^2 m^{-2}) by species for each plot. We used species-specific allometric equations from Martin et al. (1998) to calculate aboveground biomass (foliage and total) of deciduous trees; equations from Santee and Monk (1981) for *Tsuga canadensis*; and equations from McGinty (1972) for *R. maximum* and *K. latifolia*. Leaf area index was estimated by multiplying the specific leaf area (SLA, cm^2 g^{-1}) of individual species by their foliage mass (g m^{-2}) (Martin et al. 1998). Measurements included *K. latifolia* and *R. maximum*, but *K. latifolia* was a minor component of the evergreen understory in these 40 plots; it contributed less than 1% to the total biomass and LAI (Table 1).

Statistical Methods

Simple linear regression (Zar 1999) was used to compare cover estimate methods (GPS, x-y coordinates, and visual), and to compare *R. maximum* canopy cover to its density, basal area, total biomass (leaf + stems), and LAI using the general linear model procedure (PROC GLM; SAS 2002–2003). We compared *R. maximum* canopy cover to deciduous tree density, basal area, total biomass, and LAI using simple linear regression. We also used natural logarithmic transformations of the dependent variables (i.e., density, basal area, total biomass, and LAI) because the spread of the points around the linear regression line appeared to be greater for large values than small values and the logarithmic transformation tends to equalize the variance (Meyers 1990).

We used Pearson product moment correlation analysis (Zar 1999) to relate *R. maximum* canopy cover measured by the GPS-method and 11 environmental variables. This analysis was followed by stepwise regression analysis (Zar 1999) to predict *R. maximum* canopy cover by the environmental variables using a regression procedure (PROC REG; SAS 2002–2003). The environmental variables included percent slope, elevation, modified azimuth, terrain shape, soil depth, depth of A-horizon, soil clay content, soil organic matter content, mean temperature during the growing season, growing season precipitation, and potential solar radiation (Swift 1976). Values of environmental variables were determined by direct measurements or calculated by digital GIS mapping methods (Elliott et al. 1999). In an earlier survey, percent slope, aspect, elevation, and slope position (ridge, upper slope, middle slope, lower slope, or cove) were recorded for each plot. Modified azimuth was calculated from aspect (360 degree circular scale) to a linear 0–180 scale (Dargie 1984), where NNE 40 was given the value 0, SSW 220 was given the value 180. Digital terrain shape yielded a unitless value for each ground position, from 0 (highest concavity, deep coves) to 10,000 (highest convexity, narrow, well-defined ridges) (Elliott et al. 1999). Terrain shape, mean temperature, and potential solar radiation were derived using ARC/INFO™ (Environmental Systems Research Institute, Release 10, Redlands, California). Soils data for the 40 individual plots used in this study were obtained from a first-order soil survey completed in 1985 by the Natural Resources Conservation Service (Thomas 1996). The soil survey map was overlain onto the permanent plots map using ARC/INFO. Only three of the 11 environmental variables were significant ($p \leq 0.10$) and entered into the step-wise regression model.

RESULTS AND DISCUSSION A few studies have used GPS technology as a field-based method to map the perimeter of shrub patches as a means of estimating canopy cover (e.g., Menges et al. 2008, Jørgensen and Kollmann 2009, Christensen et al. 2011). Not all of these have verified the accuracy of the GPS method by comparing it to other more time consuming and labor intensive, field-based methods. A commonly used field-based method to estimate canopy cover is the "crown radius" method, which assumes that the horizontal cover of canopies forms an elliptical shape (Ko et al. 2009, Wilson 2011). Because *R. maximum* patches rarely occur in symmetrical patterns, such as circles or ellipses, measuring two dimensions of the "crown" or patch would not have yielded reasonable estimates. Line-intercept and hemispherical photography are also common methods for estimating canopy cover, but these methods do not lend themselves well to mapping shrub patches (Seidel et al. 2011, Wilson 2011). Thus, we chose to map x-y coordinates around each *R. maximum* patch perimeter as our "true" estimate of canopy cover and then compared the x-y coordinate method to the GPS and visual methods to evaluate their viability.

Bolstad et al. (2005) found the greatest accuracy with a Geo XT receiver (GIS- or mapping-grade unit) under closed canopy forests compared to consumer-grade units. We followed protocols outlined by Bolstad et al. (2005) to obtain the highest accuracy possible with our GPS method. We used a telescoping pole and an external antenna (Trimble Hurricane), collected a high number of satellite position fixes, and post-processed differential correction by combining our handheld receiver (Trimble GeoExplorer XH) with data from a fixed base station (Franklin, North Carolina). By carefully following these protocols, our position accuracy was less than 1.0 m. Less expensive consumer grade GPS instruments would not likely achieve the same results as we found in our study. For example, consumer-grade receiver accuracies are much less consistent than GIS receivers, with higher frequencies of large errors (Bolstad et al. 2005).

Comparisons of X-Y Coordinates, GPS and Visual Estimates

An ideal mapping methodology should be both rapid and precise in order to minimize spatial error and enable collection of sample sizes that are large enough for significance tests and interpretation of results for meaningful comparisons. All three methods for estimating *R. maximum* canopy cover were used to evaluate their advantages and disadvantages. Visual estimates of *R. maximum* cover required the least amount of time and labor. The visual and x-y coordinate methods were significantly related (Figure 2), however, the results could differ depending on who performs the visual estimate. Field crews employed in large surveys would need to be trained properly to avoid high bias due to subjectivity. Another limit of this technique is tied to the necessity to use cover classes rather than finer scale, continuous data (Gauch 1982); in our study we used 5% intervals up to 20%, and 10% intervals above 20%. Greater precision using an ocular estimate for a 0.08 ha plot would not have been reliable or consistent. In addition, visual estimates would

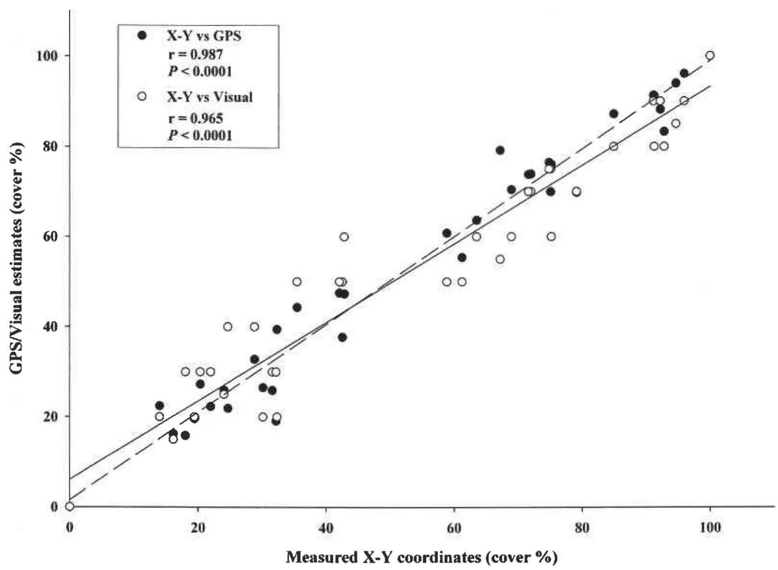

Figure 2. *Rhododendron maximum* canopy cover measured by the x-y coordinate method compared to estimates made with a Global Positioning System (GPS, dashed line) and a visual method (solid line).

not allow mapping of *R. maximum* distribution across a plot or larger areas.

The GPS method was less time-consuming and labor intensive than measuring x-y coordinates across each plot, and the GPS method provided a good estimate of cover. *R. maximum* cover estimates calculated by x-y coordinate measurements were significantly related to both GPS ($r = 0.987$, $p < 0.0001$) and visual ($r = 0.965$, $p < 0.0001$) methods (Figure 2). Though the x-y coordinate method was the most accurate, it would not be feasible to use this method on a large scale. Field time required to measure a single plot with the x-y coordinate method averaged two hours, whereas the GPS method required less than 30 minutes. For example, if all permanent plots at Coweeta were to be measured for evergreen cover using the x-y coordinate method it would take approximately one year to complete the survey (987 plots $\times$ 2 hours/ plot $=$ 1974 hours $\approx$ 50 [40 hour] weeks), at least four times longer than the GPS method; therefore, the most efficient method with reasonable accuracy would be GPS with GIS plotting. In addition, post-processing x-y coordinate measurements is necessary as each coordinate point must be entered into GIS so that *R. maximum* canopy cover can be mapped and percent cover estimated. Post-processing data for the x-y coordinate method required more time than the GPS method. Disadvantages of the GPS method include the difficulties encountered under closed canopy forests and mountainous terrain (potential blocking effect), the need to post-process the data (though a relatively simple process requiring 1 to 2 hours, depending on the number of sample points collected), the requirement of a nearby fixed base station for post-processing, and the initial expense of purchasing the GPS system and an external antennae.

Data from this study could be used to validate data collected using light detection and ranging (LiDAR). Terrestrial LiDAR scanners have recently emerged as promising tools for measuring 3D vegetation structure (Béland et al. 2011). LiDAR is a relatively advanced technological method using remote sensing through lasers on low altitude aircrafts to create landscape models to calculate cover, biomass, tree height, and other variables in forest stands (Fu et al. 2011). LiDAR is particularly relevant to this study, since it could be used to detect the presence and cover of understory shrub vegetation (Martinuzzi et al. 2009, Estornell et al. 2011). For example, Hill and Broughton (2009) showed that it is possible to characterize understory vegetation in closed forests, by integrating leaf-on and

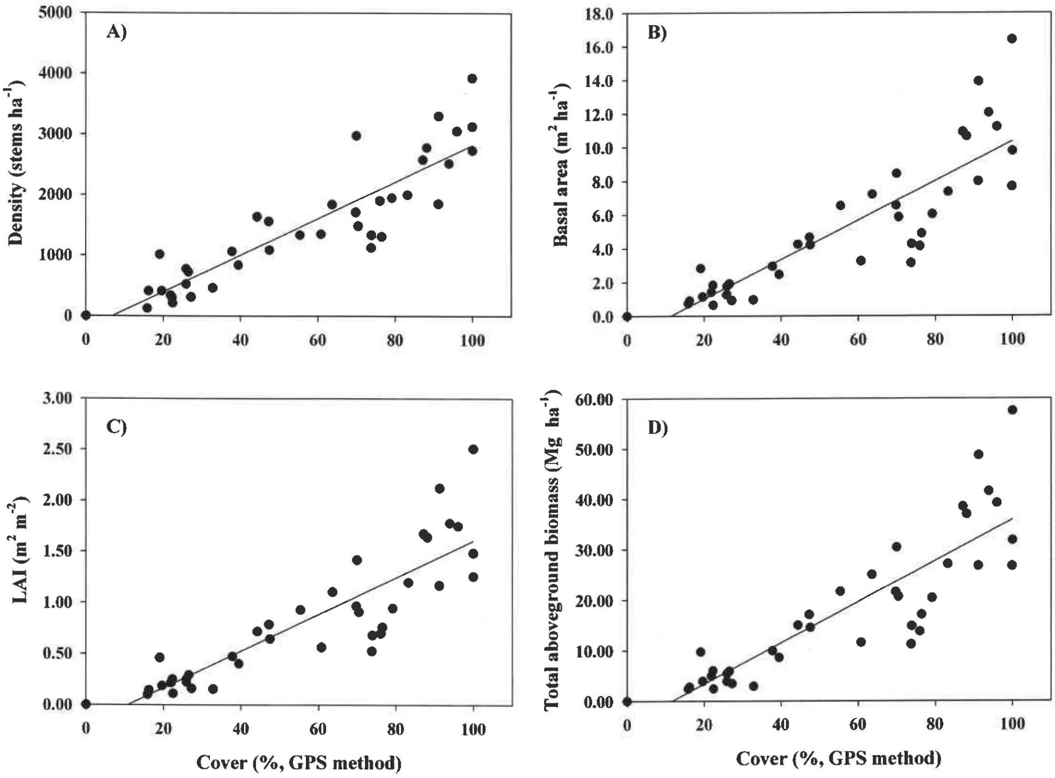

Figure 3. Relationships between *Rhododendron maximum* canopy cover using a Global Positioning System (GPS) and *R. maximum*: (a) stem density, (b) basal area, (c) leaf area index (LAI), and (d) total aboveground biomass.

leaf-off LiDAR data. The field-based methods (GPS or x-y coordinates) in this study could be used to validate airborne-based methods (i.e., LiDAR) that could be used for larger landscape scales, in this case for the entire Coweeta Basin (26 km^2) or even larger scales of the southern Appalachians (>100,000 km^2).

Comparisons with Other Rhododendron maximum Variables

Rhododendron maximum cover using the GPS method was significantly related to its density ($r^2 = 0.800$, $p < 0.0001$), basal area ($r^2 = 0.747$, $p < 0.0001$), total biomass ($r^2 = 0.761$, $p < 0.0001$), and LAI ($r^2 = 0.761$, $p < 0.0001$) in the permanent plots (Figure 3, Table 2). Coefficients of variation were slightly improved by using a natural logarithm transformation of the abundance variables (Table 2). Both the GPS and x-y coordinate cover values were statistically significant with the above variables, showing a strong relationship with either of the two methods. Though these relationships may seem intuitive, they do not necessarily hold true for all species (Bechtold 2003). For example, canopy cover of *Pinus ponderosa* L., a coniferous overstory species in the western United States, did not have a significant correlation with its density and only had a correlation with basal area up to 60% canopy cover; beyond 60% cover the relationship was no longer statistically significant (Mitchell and Popovich 1997). Whereas, another study showed significant relationships between canopy cover and other variables such as LAI and basal area of pine and oak stands (Buckley et al. 1999).

In our study, canopy cover of *R. maximum* was highly related to its stem density (Figure 3a), a factor which makes understory species such as *R. maximum* and *K. latifolia* unique with their high number of small stems per ha when compared to other understory and overstory species. According to Elliott et al. (1999), both of these understory evergreen species had the highest importance values of

Table 2. ***Rhododendron maximum*** **equations for predicting density (stems ha^{-1}), basal area (BA, m^2 ha^{-1}), leaf area index (LAI, m^2 m^{-2}), and total biomass (kg ha^{-1}) using a Global Positioning System (GPS) method for estimating canopy cover (%)**

Y variable	Equation	r^2	Root MSE	F-value	p-value
Density	Y = −272.16 + 31.0808 (GPS)	0.800	460.36	139.01	<0.0001
Ln(Density)	Y = 5.5151 + 0.02635 (GPS)	0.787	0.4042	129.59	<0.0001
BA	Y = −1.6825 + 0.12177 (GPS)	0.747	2.0915	103.38	<0.0001
Ln(BA)	Y = −0.3268 + 0.02863 (GPS)	0.820	0.3953	160.01	<0.0001
LAI	Y = −0.2475 + 0.01871 (GPS)	0.761	0.3097	111.32	<0.0001
Ln(LAI)	Y = −2.1681 + 0.02848 (GPS)	0.828	0.3825	169.07	<0.0001
Total	Y = −6.0053 + 0.42415 (GPS)	0.741	7.4031	100.10	<0.0001
Ln(Total)	Y = 0.8696 + 0.02919 (GPS)	0.821	0.4018	160.15	<0.0001

all 42 woody species surveyed in permanent plots across the entire Coweeta Basin largely because of their high stem densities. Both stem density and basal area have been used as a means to quantify abundance and compare abundance to biodiversity indices in forest stands (Powers et al. 1997, Naumberg and DeWald 1999, Pausas 2009).

Canopy cover of the evergreen understory explained 74.7% of the variation in *R. maximum* basal area (Figure 3b). Basal area for *R. maximum* has been related to species richness in the forest regeneration layer (woody stems <1 cm diameter at base) and shown to have a negative exponential relationship (Baker and Van Lear 1998). In other words, species richness in the regeneration layer decreases exponentially as *R. maximum* basal area increases. This relationship is instructive because species richness in the forest regeneration layer is often a good predictor of future biodiversity in the mature forest, especially in the absence of highly altering disturbance events. Therefore, a high-percentage canopy cover of *R. maximum* and its corresponding high density and basal area could result in low species richness in a forest stand. Additionally, studies have found relationships between canopy cover and habitat availability in forest ecosystems, where canopy cover and basal area were analyzed concurrently in habitat modeling for wildlife (Cade 1997, Vospernik and Reimoser 2008, McWethy et al. 2010).

Rhododendron maximum canopy cover explained 76.1% of the variation in LAI (Figure 3c). LAI is one of the most important predictive variables in estimating photosynthesis and CO_2 exchange within a forest stand. In addition, it can be used to determine the amount of light intercepted by the canopy (Bonan 1993). Canopy cover and LAI of *R. maximum* were positively related; therefore, *R. maximum* canopy cover could potentially be used to assess photosynthetic potential of the understory and to estimate *R. maximum's* contribution to primary productivity in southern Appalachian forests.

Rhododendron maximum canopy cover also had a significant relationship with its total aboveground biomass (leaves + stems), where canopy cover explained 74.1% of the variation in total biomass (Figure 3d). Biomass is often used to quantify the dominance of certain species within a forest ecosystem. For example, *R. maximum* ranked sixth out of 40 woody species (>2.5 cm dbh) in total standing crop biomass in a small watershed in the Coweeta Basin (Day and Monk 1977). This illustrates that relative abundance (in terms of biomass) of *R. maximum* in southern Appalachian forests can be quite high, and biomass can often indicate net primary productivity (NPP) in an ecosystem. According to Day and Monk (1977), *R. maximum* contributed 8.1% of the NPP in their studied forest watershed. The relationship between *R. maximum* canopy cover and its LAI and biomass could be useful in estimating primary productivity in forest stands where *R. maximum* is a key species.

Rhododendron and Overstory Species

Of the 38 species found in these plots, *R. maximum* averaged the highest density and ranked third in basal area and LAI (Table 1); even though we selected plots with a range in *R. maximum* abundance, i.e., cover ranged from 0% to 100% (Figure 2). *Quercus* spp. (*Q. alba* L., *Q. coccinea* Münch., *Q. montana* Willd., *Q. rubra* L., and *Q. velutina* Lam.), *Acer rubrum* L., *Carya* spp., *Liriodendron tulipifera*, and *Tsuga*

Table 3. Pearson correlation coefficients for *Rhododendron maximum* canopy cover measured by a Global Positioning System (GPS) method and the eleven environmental variables: elevation, percent slope, terrain shape index, modified azimuth, soil organic matter content, soil clay content, soil depth, A-horizon depth, mean annual temperature, solar radiation, and annual precipitation[a]

	Cover	Elevation	Slope	Terrain Shape	Modified Azimuth
Elevation	0.0622 (0.7030)	-	-	-	-
Slope	−0.1191 (0.4642)	−0.1420 (0.3822)	-	-	-
Terrain shape index	0.0531 (0.7448)	−0.2668 (0.0961)	0.0531 (0.7449)	-	-
Modified azimuth	−0.2403 (0.1352)	−0.0774 (0.6349)	−0.0003 (0.9984)	0.0121 (0.9408)	-
Soil OM	0.2420 (0.1324)	0.1073 (0.5097)	0.0397 (0.8080)	−0.2425 (0.1317)	0.2676 (0.0950)
Soil clay content	−0.0667 (0.6824)	0.3437 (0.0299)	−0.2701 (0.0919)	−0.2800 (0.0802)	−0.0596 (0.7149)
Soil depth	0.2900 (0.0695)	0.0826 (0.6124)	−0.0656 (0.6874)	−0.3981 (0.0110)	0.0979 (0.5478)
A-horizon depth	0.1867 (0.2486)	−0.0020 (0.9903)	−0.2101 (0.1932)	−0.4835 (0.0016)	0.1568 (0.3340)
Temperature	0.2482 (0.1025)	−0.6596 (0.0001)	0.0477 (0.7701)	0.5672 (0.0001)	0.0026 (0.9875)
Solar radiation	−0.2920 (0.0675)	−0.0913 (0.5754)	−0.1915 (0.2366)	−0.1953 (0.2273)	0.4152 (0.0077)
Precipitation	−0.0094 (0.9542)	0.8163 (0.0001)	−0.2046 (0.2054)	−0.3623 (0.0216)	−0.1153 (0.4786)

[a] Values are Pearson correlation coefficient (r) followed by their p-value in parenthesis (Zar 1999).

canadensis were the most abundant overstory species (Table 1), however, the majority of *T. canadensis* had succumbed to the hemlock woolly adelgid (*Adelges tsugae* Annand) infestation and were standing dead trees.

We found no significant relationships between *R. maximum* cover using the GPS method and basal area ($r^2 = 0.008$, $p = 0.590$), total biomass ($r^2 = 0.027$, $p = 0.310$), and LAI ($r^2 = 0.002$, $p = 0.789$) of deciduous trees of all sizes. There was a significant relationship between *R. maximum* cover and deciduous tree density ($r^2 = 0.173$, $p = 0.008$), and this relationship was slightly improved when compared to density of small trees <10 cm dbh ($r^2 = 0.215$, $p = 0.003$). Though this relationship is statistically significant, *R. maximum* cover explained only 21.5% of the variation in density of smaller deciduous trees. The poor relationship between *R. maximum* cover and overstory trees may have been an artifact of the sampling design. The sample size ($n = 40$) may have been insufficient to find a more explanatory relationship between *R. maximum* cover and overstory trees. In addition, relationships may have been stronger if we had separated trees within patches of *R. maximum* and trees in the open spaces between *R. maximum* patches. For example, Elliott and Vose (2012) showed that overstory tree density averaged 148 stems ha^{-1} within a *R. maximum* subcanopy and averaged 737 stems ha^{-1} in the absence of a *R. maximum* subcanopy. The differences in procedures between this study and those of Elliott and Vose (2012) likely explain why relationships were less explanatory in our study, as we did not differentiate between patch areas and non-patch areas within a plot.

Environmental Factors

We used the same eleven environmental variables as Elliott et al. (1999), who found that these environmental variables explained 50% of the variation in the overall vegetation pattern in the Coweeta Basin. In our analysis, several of the environmental variables were correlated with each other (Table 3). Canopy cover of *R. maximum* was significantly related to potential solar radiation, soil depth, and mean annual temperature, with these three environmental variables explaining 32.2% of the variation in *R. maximum* cover (Table 4). Of all eleven environmental variables tested, these three variables explained more varia-

Table 4. Stepwise regression analysis of *Rhododendron maximum* canopy cover using a Global Position System (GPS) method with associated environmental variables

Variables	Partial-r^2	Model r^2	F-value	p-value
Potential solar radiation	0.0853	0.0853	3.54	0.0675
Soil depth	0.1215	0.2068	5.67	0.0225
Mean annual temperature	0.1152	0.3220	6.11	0.0183

Table 3. Extended.

Soil OM	Soil Clay Content	Soil Depth	A-Depth	Temperature	Solar radiation
–	–	–	–	–	–
–	–	–	–	–	–
–	–	–	–	–	–
–	–	–	–	–	–
–	–	–	–	–	–
0.3049 (0.0558)	–	–	–	–	–
0.6585 (0.0001)	0.3089 (0.0524)	–	–	–	–
−0.6038 (0.0001)	0.2103 (0.1927)	0.7733 (0.0001)	–	–	–
−0.1305 (0.4221)	−0.3216 (0.0430)	−0.2493 (0.1208)	−0.2308 (0.1518)	–	–
0.2651 (0.0983)	0.1794 (0.2629)	0.1810 (0.2638)	0.3713 (0.0183)	−0.0226 (0.8898)	–
0.2792 (0.0810)	0.4479 (0.0038)	0.3675 (0.0196)	0.2751 (0.0857)	−0.6474 (0.0001)	−0.0052 (0.9746)

tion in *R. maximum* canopy cover than the other eight variables tested. The negative relationship with solar radiation was likely due to *R. maximum* being a shade-adapted species, which favors north- to northeast-facing slopes with relatively low solar radiation. *Rhododendron maximum* also occurs primarily in coves and near streams—areas that have deeper soils with greater organic matter content than upper slopes and ridges (Thomas 1996). Organic matter accumulates under *R. maximum* due to greater leaf and root litter inputs and slower decomposition relative to other species (Wurzburger and Hendrick 2007). Surprisingly, slope and modified azimuth (i.e., aspect) were not important explanatory variables; however, modified azimuth was correlated with solar radiation (Table 3) and did not explain additional variation. In addition, these variables are incorporated into the estimate of potential solar radiation. Potential solar radiation is based on an algorithm that incorporates solar declination (latitude), slope inclination and aspect, shading by adjacent hills, and cloud cover (Swift and Knoerr 1973, Swift 1976). Elevation and mean annual precipitation also were not explanatory variables, likely because *R. maximum* is abundant across the elevation gradient and subsequent precipitation gradient (mean annual precipitation ranges from 180 cm yr^{-1} at low elevation to 240 cm yr^{-1} at high elevation) (http://www.coweeta.uga.edu; Laseter et al. 2012).

SUMMARY In this study, the GPS method of evaluating *R. maximum* canopy cover was comparable to the x-y coordinate measurement of calculating canopy cover. Using GPS to calculate canopy cover of rhododendron was less labor intensive and less time consuming compared to measuring and mapping x-y coordinates. If protocols outlined in this study and others (Bolstad et al. 2005) are followed, then the GPS method for estimating canopy cover would yield reliable results. In addition, *R. maximum* canopy cover was significantly related to other abundance measures of *R. maximum*, such as density, basal area, biomass, and LAI. Methods for estimating LAI, biomass, density, or basal area are more laborious and time consuming to measure and calculate than using GPS technology to measure canopy cover. Further research could be conducted using the methods employed in this study to efficiently estimate these more difficult to measure attributes of *R. maximum*. Mapping plant canopies using GPS technology would allow for a better understanding of the distributional patterns of individual plants, provide easier estimations of LAI and other parameters, and provide validation of LiDAR or other airborne-based methods that are used at landscape levels.

We did not find significant relationships between *R. maximum* canopy cover and overstory tree parameters. This is likely a result of the specific surveying method that did not separate trees with a *R. maximum* subcanopy and those without a subcanopy. *Rhododendron maximum* canopy cover was related to various environmental variables, including solar radiation, soil organic matter content, and mean

annual temperature. However, a larger proportion of the variation in *R. maximum* cover was unexplained by environmental variables compared to the variation explained.

Rhododendron maximum plays an important role in southern Appalachian ecosystems. Competition between *R. maximum* and canopy tree seedlings for resources often leads to the detriment of the tree seedlings (Clinton and Vose 1996, Nilsen et al. 1999, Nilsen et al. 2001, Beckage et al. 2005, Lei et al. 2006). According to Nilsen et al. (2001), for example, *Quercus rubra* seedling survival was reduced by about 40% in the presence of *R. maximum* when compared to a forested stand without rhododendron in the understory. Light and water availability were the most limiting factors concerning *R. maximum* and tree seedling competition (Nilsen et al. 2001, Lei et al. 2006). *Rhododendron maximum* also influences ecosystems by altering hydrologic processes, nutrient cycling, and primary productivity, all of which could be affected by high coverage of the shrub. The negative associations with tree regeneration and the ecosystem as a whole illustrate the consequence of *R. maximum* in the understory layer of a forest stand, underscoring the need to quantify *R. maximum* canopy coverage across the landscape.

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