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INTERCONNECTED BIODIVERSITY: MAPPING THE RELATIONSHIP BETWEEN TREE AND BREEDING BIRD SPECIES DIVERSITY IN GEORGIA'S FORESTS, USA

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Abstract. This study analyzes the distribution of tree species and breeding bird species across the diverse forest habitats of Georgia, utilizing data from the U.S. Forest Inventory and Analysis (FIA) program. We investigate the quantitative relationships between tree species diversity and bird species richness at a county scale, integrating FIA data with multi-source geographic information system (GIS) data to produce detailed spatial maps. Our findings reveal significant associations between the diversity of tree species and the richness of bird species, underscoring the ecological interconnectedness of Georgia's forest habitats. These results provide valuable insights for conservation planning and biodiversity monitoring, emphasizing the importance of maintaining diverse forest ecosystems to support varied wildlife populations.

Keywords: Forest Biodiversity; Species Distribution Modeling; Breeding Bird Richness; Wildlife-Habitat Relationships; GIS RS and FIA in Ecology; Georgia Ecosystems.

1 Introduction

Forests play a critical role in sustaining biodiversity, offering habitat, food, and protection for a broad variety of plant and animal species. The complex relationships between tree species diversity and wildlife populations is particularly important, as trees not only provide essential forest product resources but also influence microclimatic conditions which are crucial for bird survival and reproduction. There is a recognized need for an understanding of how tree species diversity directly impacts breeding bird species richness, especially at a localized scale within the varied forest ecosystems of Georgia.

Previous studies have shown that different forest types support distinct communities of flora and fauna, with tree diversity acting as a key determinant of faunal diversity (James and Wamer, 1982; Lee and Rotenberry, 2005). However, these studies often use broad spatial scales that may overlook the nuances of local ecological dynamics. The state of Georgia, with its diverse range of forest types from coastal plains to mountainous regions, presents a unique opportunity to study these ecological interactions in detail. Understanding these dynamics is crucial for effective conservation planning and management, particularly in light of ongoing environmental changes, and forest fragmentation associated with the expansion of urban developments.

A bird's habitat is the place where birds nest, roost, and forage. The central role of vegetation in the life of a bird is self-evident because birds can live in a given area only if the basic resources such as food, water, and cover are in sufficient supply and if the birds have adapted in the ways that allow them to cope with the climate, competitors, and predators (Morrison et al., 2012). The most significant influences on certain bird populations may be due to changes in ecosystems and communities and anthropogenic threats (Mace et al., 2010); habitat factors have been shown to account for a large portion of the variation in bird species density and richness (Acharya et al., 2011). The distribution of bird species can be significantly associated with tree species within a general biome type, after statistically controlling for physiognomic or structural variation and geographical location (Lee and Rotenberry, 2005). While beneficial to landscape-scale conservation planning objectives, these general statements concerning tree species richness and bird species richness are not universally valid; an increase in tree species richness is not always beneficial at a local scale. For example, in one case the presence of water oak (*Quercus nigra*) and sweetgum (*Liquidambar styraciflua*) in pine (*Pinus* spp.) forests has been shown to result in lower bird richness, particularly shrubland and grassland/pine savannah bird species (Klaus and Keyes, 2007). Nonetheless, habitat conditions are useful tools for environmental monitoring processes and can be used to predict bird community status (Canterbury et al., 2000).

Tree species richness is a measure of biodiversity that relates to the number of taxa that are present within a geographic area; often an estimation of this is performed at the community level using remotely sensed data (Cord et al., 2014). Environmental variables have been used to help explain the structure and composition of woody vegetation patterns across broad landscapes (Crespi et al., 2013). Tree species richness across a landscape can be related to mean annual air temperature, solar radiation, and evapotranspiration (Currie 1991). An understanding of the relationship vegetation has with climate variables can be paramount for estimating the distribution of vegetation across broad landscapes (Holmes et al., 2015). Modern statistical modeling and geographical techniques, such as remote sensing and geographical information systems (GIS), have enhanced the possibilities for the delineation and analysis of vegetation distribution patterns (Frescino et al., 2001, Zellweger et al., 2015). Applications of these can often yield accurate and timely area estimates for different forest cover types such as coniferous, deciduous, and mixed species.

The ability to precisely estimate tree species diversity across broad landscapes may be difficult with national forest inventories (Winter et al., 2012), yet national forest inventories are increasingly being used to assist in the spatial estimation of species diversity (e.g., Cord et al., 2014, Corona et al., 2011, Zellweger et al., 2015). Similarly, invasion intensity and patterns of non-native plant species have been modeled with national forest inventories (Oswalt et al., 2015). Invasive plant patterns have been assessed in conjunction with tree species richness through the use of national forest inventories (Hernández et al., 2014). Attempts have also been made using national forest inventories to associate tree species richness with carbon accumulation in forests (Ruiz-Benito et al., 2013), and to relate plant species distributions with land use history and ownership (Bèrges et al., 2013). The objective of this study was to estimate the spatial distribution of both tree species in forests and bird species richness associated with those forests, across a broad landscape (State of Georgia, USA), to illustrate in one respect the ecological importance of forests throughout the state. The study integrated national forest inventory data with remotely sensed imagery to enable us to describe in spatial terms the biodiversity potential of the landscape. Tree species assemblages have been estimated for large land areas using national forest inventories and environmental predictor variables (Finley et al., 2009), however, the link to bird species richness is a novel aspect of our work. Our work differs from Gil-Tena et al., (2007) in that we used a finer spatial resolution in the spatial data (30 m vs. 1 km), and we used functional relationships described in primary research (Lee and Rotenberry, 2005) rather than regression methods to associate tree species richness with bird species richness.

1.1 Objectives

This study aims to advance the understanding of some of the aforementioned issues by mapping the spatial distribution of tree and breeding bird species across Georgia's forests and analyzing the correlation between tree species richness and bird species richness at a county scale. Specifically, the research seeks to answer the following questions:

1. How does tree species diversity vary across different forest types in Georgia?

2. What is the relationship between tree species richness and breeding bird species richness within these forests?

3. How can this information be used to enhance conservation strategies in Georgia?

Utilizing data from the U.S. Forest Service's Forest Inventory and Analysis (FIA) program and advanced geographic information system (GIS) techniques, this study provides detailed mappings of biodiversity metrics across the state of Georgia. By integrating multi-source data, we aim to offer insights that are both scientifically robust and applicable to real-world conservation efforts.

We expect the outcomes of this research to contribute to the fields of conservation biology and landscape ecology by providing a detailed ecological assessment of Georgia's forests. Additionally, the findings will support policymakers and conservationists in making informed decisions to preserve and enhance the state's natural heritage, ensuring the sustainability of both tree and bird populations against the backdrop of global environmental change.

2 Methods

Georgia is located in the southeastern United States, is approximately 154,000 km^2 in size, and is about two-thirds forested. Ninety-one percent of the forests are privately owned and forestry-related industries are the second-largest manufacturing employer in the state (Georgia Forestry Commission, 2012), therefore social and economic considerations related to forest management are also important.

Our overall approach to the study consisted of the following steps:

1. At a plot scale, using data from the U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) database for Georgia, assess the number of unique tree species occurring on each forested plot.

2. At a plot scale, convert the number of unique tree species to estimates of the number of unique bird species that might be found there using an equation approach developed by Lee and Rotenberry (2005).

3. At a county scale, calculate an area-weighted value using the number of unique tree species and number of unique bird species for three broad forest cover types.

4. At a county scale, map the number of unique tree species and unique bird species by forest cover types using a geographic information system (GIS).

5. Perform multiple comparisons to investigate the pairwise differences of the number of unique tree species and number of unique bird species for different forest cover types at different geographical locations.

2.1 Forest inventory data

The U.S. Forest Service (2016) provides plot level FIA data for all states through the FIA DataMart website. The FIA DataMart contains a set of data files in the comma-separated values (CSV) format. The major files for each inventory are plot, condition, and tree tables. This allows analysis of tree species distribution on various levels of resolution such as plot, county, unit, state, region, and nation. Even though more recent data is now available, for this study the selected year of the sample inventory of the State of Georgia was 2004. About 300 variables are recorded for the considered three data tables: plot, condition, and tree. The tree table contains information about the tree species and the species group, which are collected directly in the field. The plot and condition tables contain information about the current FIA forest type and plot area expansion factors (the area that a given plot represents in the inventory when calculating area). It needs to be noted that the FIA inventories are designed to meet specified sampling errors at the state level at the 67 percent confidence interval., The maximum allowable sampling error for an area of one million acres (404,694 hectares) of timberland is 3 percent. Using the database for the estimation of values on a smaller scale (e.g., the county level) increases the level of error due to a decrease in the sample size.

2.2 The $\mathbf{S_T}$ and $\mathbf{S_B}$ at different scales

2.2.1 Estimates per plot

After downloading the plot level data from the FIA DataMart website, we extracted information regarding the number of live and dead trees on forested plots, tree conditions, and other information. Using this data, we assessed the unique number of tree species (S_T) residing within each plot. To estimate the unique number of bird species (S_B), we use a function that relates the S_B to the S_T as described in Lee and Rotenberry (2005). The model applied is a simple linear regression equation:

$$S_B = 14.6 + 0.72 S_T \qquad (1)$$

The relationship was developed using 47 breeding bird census plots (Johnston, 1990), and although the coefficient of determination was relatively low ($r^2 = 0.33$), the relationship was deemed significant by Lee and Rotenberry (2005).

2.2.2 Estimates per county/unit/state

Here, we estimate the S_T and S_B for different broad forest cover types at different scales, such as county, FIA unit, and state, based on the estimates from FIS plot data. We first classify the FIA forest types (discard non-stock forest type) into three broad forest types: evergreen, mixed, and deciduous. FIA plots consist of four subplots that may be used to split a plot to separate conditions if the subplots show inconsistent cover types. For plots having two or more conditions, we use the forest type corresponding to the condition with the largest proportion as its forest type. Table 1 shows the classification and plot distribution of three broad forest cover types. We then calculate S_T and S_B for three broad forest cover types at different scales (e.g., county) via an area-weighting procedure involving the corresponding plot scale values, that is:

$$S_j = \frac{\sum_{i=1}^{n_j} S_i \cdot A_i}{\sum_{i=1}^{n_j} A_i}, \qquad (2)$$

where:

- S_j is an estimate of the S_T or S_B for the j^{th} county, unit, or state;

Table 1: The classification and plot and area distribution of three broad forest cover types

FIA Forest Type	FIA Code	Plot No.	Plot %	Area (10^3ac)	Area %
Evergreen					
White / red / jack pine group[a]	100	7	0.1	37	0.1
Longleaf / slash pine group	140	707	13.7	3,685	13.6
Loblolly / shortleaf pine group	160	1,544	30.0	7,981	29.4
Pinyon / juniper group[b]	180	2	0.0	11	0.0
All evergreen	-	2,260	43.9	11,714	43.1
Mixed					
Oak / pine group	400	648	12.6	3,434	12.6
Oak / gum / cypress group	600	682	13.3	3,682	13.6
Tropical hardwoods group	980	2	0.0	11	0.0
All mixed	-	1,332	25.9	7,127	26.2
Deciduous					
Oak / hickory group	500	1,438	27.9	7,564	27.8
Elm / ash / cottonwood group	700	105	2.0	550	2.0
Maple / beech / birch group	800	1	0.0	5	0.0
Exotic hardwoods group	990	9	0.2	48	0.2
All deciduous	-	1,553	30.2	8,168	30.1
Total for All Forest Types		5,145	100.0	27,166	100.0

[a] Likely eastern white pine (*Pinus strobus*).
[b] Likely eastern red cedar (*Juniperus virginiana*).

- S_i is an estimate of the S_T or S_B for the i^{th} plot;
- A_i is the forest area that the i^{th} plot represents; and
- n_j is the number of plots in the j^{th} county, unit, or state.

This process yields an area-weighted mean S_T and S_B for a county/unit/state using the plot level estimates of S_T and S_B.

2.3 Mapping $\mathbf{S_T}$ and $\mathbf{S_B}$

S_T and S_B estimates are mapped in GIS by forest cover types at a county resolution. We reclassify GAP data into three forest cover types: evergreen, mixed, and deciduous (see Appendix Table A, for reclassification data). Then, we use the majority filter to eliminate small clumps and convert counties to grid on the county's FIPS code. Next, we merge the cover-type layer with the county-level FIPS code layer and convert it to a shapefile. Finally, we link the information of the S_T and S_B with the forest cover types in the shapefile and create maps of the distribution of S_T and S_B.

2.4 Multiple comparisons

Based on the S_T or S_B plot level estimates, we perform multiple comparisons to investigate the pairwise differences of the S_T and S_B for different forest cover types at different geographical locations. We consider three broad forest cover types (evergreen, mixed, and deciduous) and three physiographic regions (Coastal Plain, Gulf Coastal Plain, and Piedmont). Table 2 shows the detailed county list located in each physiographic regioext, we perform a general unbalanced fixed effects ANOVA. In SAS, the Dunnett-Hsu, Tukey-Kramer, GT2, and SIMULATE options are available in the LSMEANS statement. Since it is not known if the Tukey-Kramer test controls the FWE for pairwise comparisons for general unbalanced designs, we used a more conservative GT2 test.

3 Results

Since all the FIA plots have the same size, the estimates of S_T at the plot level are compatible and comparable. We note that the size of each FIA sample plot is much smaller than the average plot size (8 ha) considered by Lee and Rotenberry (2005), who proposed the bird species - tree species relationship. Since the FIA plots are discretely distributed, and the tree compositions vary according to the location and region, S_T increases when we combine several non-adjacent plots. This way of combining plots is not a proper one to meet the area requirement and hence properly deal with the

Table 2: The county list in each physiographic region

Region	Counties
Coastal Plain	Appling, Atkinson, Bacon, Baldwin, Bleckley, Brantley, Bryan, Bulloch, Burke, Camden, Candler, Charlton, Chatham, Coffee, Dodge, Effingham, Emanuel, Evans, Glascock, Glynn, Jeff Davis, Jefferson, Jenkins, Johnson, Laurens, Liberty, Long, Montgomery, Pierce, Richmond, Screven, Tattnall, Telfair, Toombs, Treutlen, Twiggs, Ware, Washington, Wayne, Wheeler, Wilkinson
Gulf Coastal Plain	Baker, Ben Hill, Berrien, Bibb, Brooks, Calhoun, Chattahoochee, Clay, Clinch, Colquitt, Cook, Crawford, Crisp, Decatur, Dooly, Dougherty, Early, Echols, Grady, Houston, Irwin, Lanier, Lee, Lowndes, McIntosh, Macon, Marion, Miller, Mitchell, Muscogee, Peach, Pulaski, Quitman, Randolph, Schley, Seminole, Stewart, Sumter, Taylor, Terrell, Thomas, Tift, Turner, Webster, Wilcox, Worth
Piedmont	Banks, Barrow, Bartow, Butts, Carroll, Catoosa, Chattooga, Cherokee, Clarke, Clayton, Cobb, Columbia, Coweta, Dade, Dawson, DeKalb, Douglas, Elbert, Fannin, Fayette, Floyd, Forsyth, Franklin, Fulton, Gilmer, Gordon, Greene, Gwinnett, Habersham, Hall, Hancock, Haralson, Harris, Hart, Heard, Henry, Jackson, Jasper, Jones, Lamar, Lincoln, Lumpkin, McDuffie, Madison, Meriwether, Monroe, Morgan, Murray, Newton, Oconee, Oglethorpe, Paulding, Pickens, Pike, Polk, Putnam, Rabun, Rockdale, Spalding, Stephens, Talbot, Taliaferro, Towns, Troup, Union, Upson, Walker, Walton, Warren, White, Whitfield, Wilkes

effect of species-area. Yet, the estimated S_T per plot has similar ranges of numbers of tree species (1–19) as that in Lee and Rotenberry's (2005) article (1–18). Therefore, we use the estimates at the plot level even though, admittedly, the plot size is smaller than the average size used in the source article. However, it may be noted that in the FIA design, each FIA plot theoretically represents approximately 6,000 acres in Georgia, which is much larger than 8 ha. Also, in the considered article (Lee and Rotenberry, 2005), the authors state that the species-area relationship was non-existent for trees.

3.1 $\mathbf{S_T}$ and $\mathbf{S_B}$ estimates

In total, 153 tree species were found on the FIA plots in Georgia. The estimated S_B on each forested plot ranges from 15.3 to 28.3, with an area-weighted average of 18.8, whereas the S_T ranges from 1 to 19, with an area-weighted average of 5.8. No plot contains more than 13% of the total number of tree species. As expected, the average S_T and S_B on the deciduous and mixed cover types are generally larger than the corresponding values on the evergreen cover type. The Piedmont region distributes more tree or bird species than the Coastal Plain and Gulf Coastal Plain regions. Table 3 shows the detailed average S_T and S_B by different forest cover types and physiographic regions. Figure 1 depicts summary statistics of the S_T and S_B by different forest cover types and physiographic regions. Large variations are observed for S_T and S_B on all combinations of the three cover types and the three regions. The multiple comparisons of the pairwise differences of the S_T and S_B for three forest cover types (evergreen, mixed, and deciduous) in three physiographic regions (Coastal Plain, Gulf Coastal Plain, and Piedmont) are listed in Table 4.

Different letters in Table 4 indicate significant differences at a level of 5%. The order of letters (A to C) indicates the magnitude (descending order) of the mean of S_T or SB. The interaction of the cover types and re-

Table 3: Average ST and SB plot and area by different forest cover types and physiographic regions

Cover Type	Physiogr. Region	S_T Mean	S_T Range	S_B Mean	S_B Range	Plot No.	Area %
Evergreen	Coastal Plain	3.6	1–15	17.2	15.3–25.4	897	17.4
	Gulf Coastal Plain	3.7	1–13	17.3	15.3–24.0	607	11.8
	Piedmont	5.9	1–15	18.9	15.3–25.4	756	14.7
Mixed	Coastal Plain	5.9	1–19	18.9	15.3–28.3	547	10.6
	Gulf Coastal Plain	5.8	1–19	18.8	15.3–28.3	443	8.6
	Piedmont	8.3	1–17	20.5	15.3–26.8	342	6.6
Deciduous	Coastal Plain	5.8	1–15	18.8	15.3–25.4	287	5.6
	Gulf Coastal Plain	5.7	1–15	18.7	15.3–25.4	311	6.0
	Piedmont	8.4	1–19	20.6	15.3–28.3	955	18.6

Table 4: Multiple comparisons of the pairwise differences of the S_T and S_B for different forest cover types in different physiographic regions*

Region	ECP	EGCP	EP	MCP	MGCP	MP	DCP	DGCP	DP
ECP	-	C	C	B	B	A	B	B	A
EGCP	C	-	B	A	B	B	B	A	B
EP	C	B	-	B	B	A	B	B	A
MCP	B	A	B	-	A	B	A	A	A
MGCP	B	B	B	A	-	A	A	A	A
MP	A	B	A	B	A	-	A	A	A
DCP	B	B	B	A	A	A	-	A	A
DGCP	B	A	B	A	A	A	A	-	A
DP	A	B	A	A	A	A	A	A	-

*ECP – Evergreen Coastal Plain; EGCP – Evergreen Gulf Coastal Plain; EP – Evergreen Piedmont; MCP – Mixed Coastal Plain; MGCP – Mixed Gulf Coastal Plain; MP – Mixed Piedmont; DCP – Deciduous Coastal Plain; DGCP – Deciduous Gulf Coastal Plain; DP – Deciduous Piedmont.

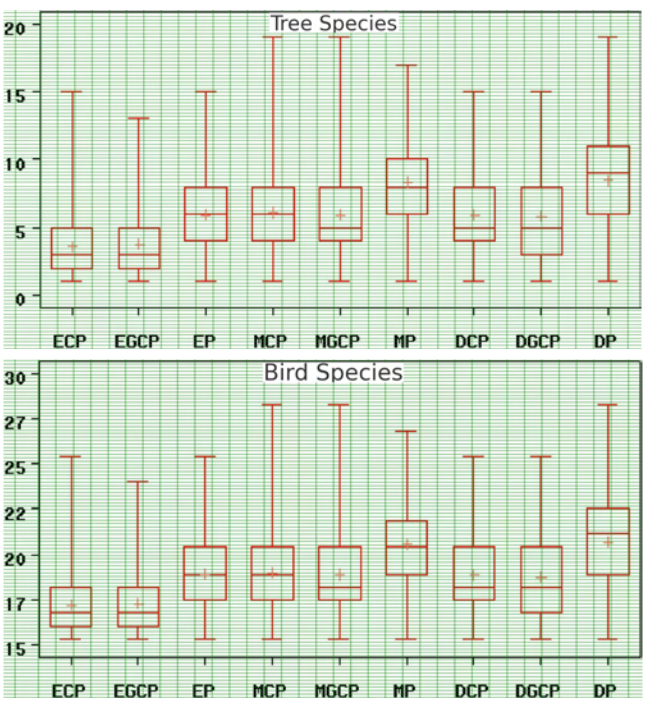

Figure 1: Summary statistics of the number of tree species (top) and the number of breeding bird species (bottom) by different forest cover types and physiographic regions. ECP — Evergreen, Coastal Plain; EGCP — Evergreen, Gulf Coastal Plain; EP — Evergreen, Piedmont; MCP — Mixed, Coastal Plain; MGCP — Mixed, Gulf Coastal Plain; MP — Mixed, Piedmont; DCP — Deciduous, Coastal Plain; DGCP — Deciduous, Gulf Coastal Plain; DP — Deciduous, Piedmont. Maximum — Endpoint of upper whisker; Third quartile (75^{th} percentile) — Upper edge of box; Median (50^{th} percentile) — Line inside box; Mean — Symbol marker; First quartile (25^{th} percentile) — Lower edge of box; Minimum — Endpoint of lower whisker.

gions significantly affects the S_T and SB. We found that S_T and S_B in the deciduous and mixed cover types in the Piedmont region are the most abundant (more than 8 tree species and 20 bird species), and are significantly larger than those in evergreen in the same region and in all cover types in other regions (Coastal Plain and Gulf Coastal Plain). The S_T and S_B in the evergreen cover types in two southern regions (Coastal Plain and Gulf Coastal Plain) are rare (fewer than 4 tree species and 18 bird species), and are significantly smaller than those in deciduous in the same region and in deciduous and mixed cover types in all regions. In a given cover type, S_T and S_B in the Piedmont region are generally larger than those in the Coastal Plain and the Gulf Coastal Plain. In a given region, S_T and S_B in the deciduous and mixed cover types are generally larger than those in evergreen cover types.

3.2 Mapping $\mathbf{S_T}$ and $\mathbf{S_B}$

We produced the maps of the distribution of S_T (Fig. 2) and S_B (Fig. 3) for different cover types at the county resolution. The S_T and S_B are area-weighted averages of S_T and S_B in a county, which do not show all individual S_T and S_B values occurring in each county. Since S_T and S_B estimates from FIA plot-scale datasets contain large variations of values when using the expanded plot values to adjacent regions, we use the area-weighted means of the tree and bird species on the county scale to produce the maps of S_T and S_B distributions with the generalized mean values.

It may be noted that the method for mapping S_T and S_B ignores the area differences between FIA plot-based and GAP-based estimates as well as the differences between the used data and the source publication mentioned earlier. As an alternative approach, one can may

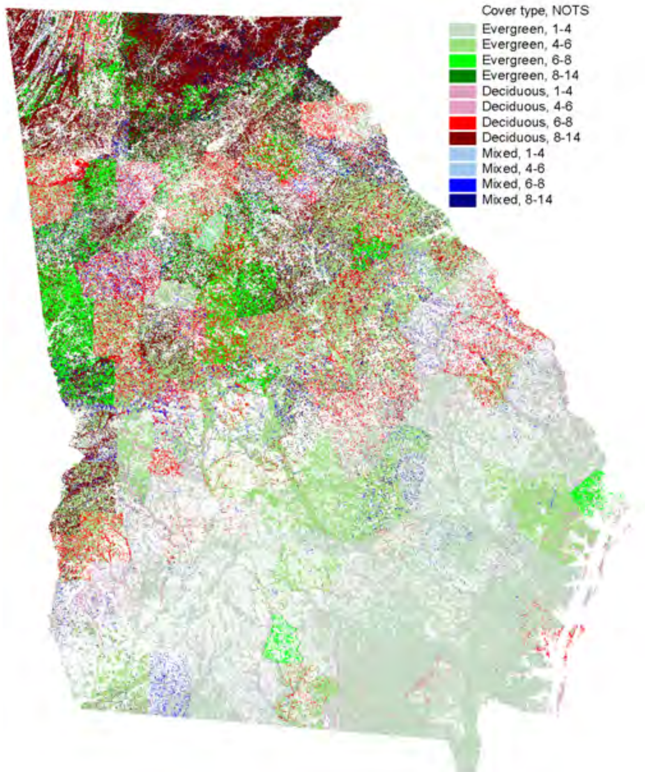

Figure 2: The distribution of the number of tree species (S_T) for different forest cover types at the county resolution.

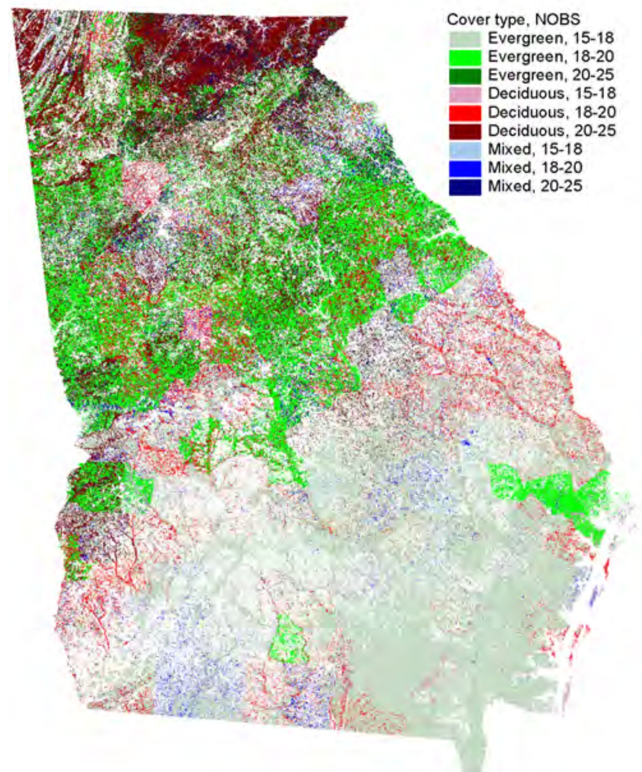

Figure 3: The distribution of the number of bird species (S_B) for different forest cover types at the county resolution.

make changes in the image delineations based on the FIA plot measurements or updated satellite imagery.

The maps of the distribution of S_T (Fig. 2) and S_B (Fig. 3) for different cover types at the county resolution are consistent with the multiple comparison results above (see section 3.1 for details). They provide powerful and explicit representations of the forestland cover. Deciduous forest cover types with the highest S_T (>8) and S_B (>20) are mostly located in the Blue Ridge, Appalachian Plateaus and Valley and Ridge, located in northern Georgia. Counties in northern and north central Georgia have evergreen forests with some of the highest S_T (>6) and S_B (>20), while the southern counties have evergreen forests with low S_T (<4) and S_B (<18). The mixed forests are lightly scattered in various areas of the state.

S_T and S_B are generally in the order of deciduous >mixed >evergreen. S_T (area-weighted plot scale estimates) for the deciduous cover type, at the county scale of resolution, ranges from 1.5 to 12.0, with an area-weighted mean of 7.4. For the evergreen cover type, S_T ranges from 1.6 to 9.7 (one exception, Catoosa county in the northwest part of the state, shows a S_T of 14.0), with an area-weighted mean of 4.4. For the mixed cover type, S_T ranges from 3.2 to 13.1, with a weighted mean of 6.5. About 50 percent of all counties have deciduous forests with S_T between 6.0 and 8.8, evergreen forests with S_T between 3.4 and 5.4, and mixed forests with S_T between 5.4 and 7.2 (Fig. 4).

S_B for deciduous cover types at the county scale, ranges from 15.7 to 23.2, with the area-weighted mean of 19.9. For evergreen cover type, S_B ranges from 15.7 to 21.6 (one exception, Catoosa county, shows a S_T of 24.7), with the area-weighted mean of 17.8. For the mixed cover type, S_B ranges from 16.9 to 24.0, with the area-weighted mean of 19.3. About 50 percent of all counties have deciduous forests with S_B between 18.9 and 20.9, evergreen forests with S_B between 17.0 and 18.5, and mixed forests with S_B between 18.5 and 19.8 (Fig. 4).

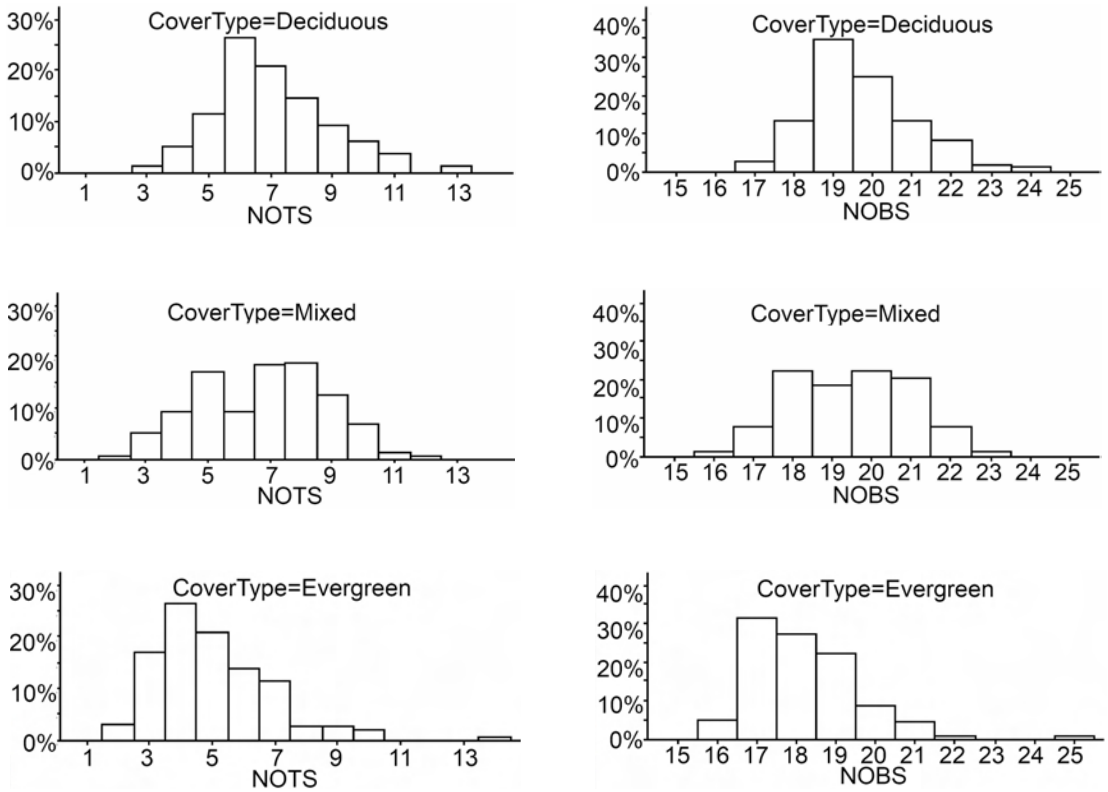

Figure 4: Frequency distribution of S_T and S_B for Deciduous, Mixed, and Evergreen in Georgia.

4 Discussion

Our study provides robust empirical evidence on the association between tree species diversity and breeding bird species richness in Georgia's forests. These findings build upon the work of Lee and Rotenberry (2005), which emphasized the significance of tree diversity for bird species richness across North American forests. However, our research advances this understanding by employing finer spatial resolution and a comprehensive set of biodiversity and environmental variables. We present a framework for large-scale estimates of the relative richness of vertebrate species in a very active human development setting. The State of Georgia, along with most other states and Canadian provinces along the Atlantic seaboard, has undergone significant ecosystem changes since European settlement began over four hundred years ago. Perhaps the most important issue confronting the current landscape is the spread of urbanization and associated with it forest fragmentation, sources of food, water, recreation, and forest products that society desires.

Researchers have long noted that there is a general relationship between tree species assemblages and bird species assemblages among the forests of eastern North America (Lee and Rotenberry, 2005), that landscape patterns and heterogeneity may have a great influence on the distribution and occurrence of bird species (Saab 1999, Atauri and de Lucio, 2001), and that anthropogenic changes to the landscape can affect bird species richness (Findlay and Houlahan 1997). At a local scale, bird species richness may be associated with variation in local habitat conditions. However, at larger scales, bird species richness may not be functionally related to tree species richness except in low-richness environments, and the two may co-vary across a broad landscape based on climate variables that represent energy availability (Currie 1991). In sum, estimates of large-scale species richness of different taxa may be important for landscape planning and biodiversity monitoring efforts.

Differences in bird species composition over broad landscapes are essentially related to differences in tree species composition and the type of nesting and foraging opportunities (niches) that different tree species facilitate. Although the relative number of bird species in a certain type of habitat may change annually, the floristics of trees and the types of tree species present can help describe the relative number of bird species for certain types of habitat (Arnold 1988). Unfortunately, the broad-scale analysis we presented ignores fine-scale differences in forest structure that may exist among forest measurement plots, as structural heterogeneity might be biologically meaningful to measures of bird species diversity (Roth 1976). The density of trees, their structure, and the corresponding crown closure and seral stages were not used in the analysis of plot-level data, and bird species diversity may be associated with these factors (James and Wamer 1982). In this respect, the structure of vegetation can affect site selection by birds, yet the functional relationships we employed connecting tree species diversity to bird species diversity lacked this fine-scale structure resolution. However, Lee and Rotenberry (2005) note that when the potential effects of geographic patterns and forest structure are removed, there remain direct associations of bird species to tree species.

On a technical level, our mapping process which restricted geographical descriptions of the relationship between bird species and tree species was restricted to county-level political boundaries. An improvement to the mapping process would be to develop a process that uses a moving window type analysis for each local area (pixel, collection of pixels). Perhaps this could employ the analysis of the FIA plots within some distance of each local area to arrive at the broader scale mapped representations of bird species richness. This would prevent the significant differences observed in Figures 2 and 3 along county boundaries, and smooth out the changes in bird and tree species richness estimates. With such large areas, and when using essentially point estimates (plot locations) of diversity, a kriging or spatial interpolation process may also be employed to provide smoother transitions in the estimates of richness.

Our framework for large-scale estimates of the relative richness of a vertebrate species can nonetheless inform the broad-scale conservation picture of a large geographic area, such as the whole state (e.g., Georgia), and provide policymakers and stakeholders insight into the potential of a large, variable landscape to accommodate vegetative and vertebrate biodiversity. The use of national forest inventory data, which is periodically re-measured, can help elucidate trends in tree species composition. The use of satellite imagery, which is periodically re-captured, can help elucidate trends in land use. Functional relationships that utilize these sources of data and help effectively estimate ecosystem conditions and important areas of diversity are important to society today, since resources for ground-based extensive surveys are limited (Prendergast et al., 1993, Lawton et al., 1998), and as greater emphasis is being applied to our understanding of global changes.

Future research in the discussed area should aim to incorporate high-resolution multi-source data, as suggested in other studies (e.g., Iles, 2009 and 2018; Liu and Cieszewski, 2009; Lowe and Cieszewski, 2014). We recommend using longitudinal data to assess trends over time, especially in the context of climate change and its impact on species distributions, and cross-sectional data, to address the site-dependent variability across the landscape. Additionally, studies could explore the functional aspects of biodiversity, such as the role of specific tree species in providing resources specific for diverse bird species, such as different nesting sites and food supplies. Expanding the scope to include phenological data could also provide insights into how seasonal dynamics affect the interplay between tree and bird species diversity.

5 Summary and Conclusion

This study explores the relationship between tree species diversity and breeding bird species richness in various forest habitats of Georgia. Utilizing data from the U.S. Forest Service's Forest Inventory and Analysis (FIA) program, the study provides county-scale resolution maps depicting tree and bird species richness across the state. The research highlights the significant association between the diversity of tree species and bird species, using both FIA data and various geographic information systems (GIS) sources.

Key methods involved assessing the number of trees and bird species at the plot and the county levels, converting tree species data to estimates of bird species, and mapping the distributions using GIS. The results showed varying species richness across different forest types and geographic regions within Georgia. For example, deciduous and mixed forest types generally harbored more tree and bird species compared to evergreen forests, with particularly high diversity noted in the Piedmont region.

The study underscores the ecological importance of forests in Georgia, illustrating how tree species diversity correlates with bird species richness, which can help in conservation planning and biodiversity monitoring. The findings also contribute to understanding how national forest inventories and remote sensing can be integrated to assess biodiversity at large scales effectively.

The presented analysis suggests that deciduous and mixed forests generally support higher biodiversity in terms of tree and bird species, compared to evergreen forests. This pattern is especially demonstrable in the Piedmont region, which shows the highest species richness. The results from the county-level mapping of species richness provide a clear visualization of these patterns and are useful for identifying areas of higher conservation value. The methodologies used, such as integrating national forest inventory data with GIS and remote sensing technologies, can be applied to other geographic areas to assess biodiversity and guide environmental policy and land management decisions.

Overall, the paper calls for continued and enhanced monitoring of forest and bird species to better under-stand their interactions and to support biodiversity conservation efforts effectively. The authors advocate for the use of detailed, large-scale data to inform regional and national conservation policies that can accommodate both current and future environmental challenges. The study contributes to the understanding of the ecological dynamics within Georgia's forests and offers a methodological framework that can be adapted for similar ecological assessments in other states. By exploring the links between tree diversity and bird richness, we address the concerns of the need for integrated environmental management practices that support and enhance biodiversity.

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References

Acharya, B. K., Sanders, N. J., Vijayan, L., & Chettri, B. (2011). Elevational gradients in bird diversity in the eastern Himalaya: An evaluation of distribution patterns and their underlying mechanisms. *PLoS ONE, 6*(12), e29097. https://doi.org/10.1371/journal.pone.0029097

Arnold, G. W. (1988). The effects of habitat structure and floristics on the densities of bird species in Wandoo Woodland. *Australian Wildlife Research, 15*(5), 499–510.

Atauri, J. A., & de Lucio, J. V. (2001). The role of landscape structure in species richness distribution of birds, amphibians, reptiles, and lepidopterans in Mediterranean landscapes. *Landscape Ecology, 16*, 147–159.

Bèrges, L., Avon, C., Verheyen, K., & Dupouey, J.-L. (2013). Landownership is an unexplored determinant of forest understory plant composition in Northern France. *Forest Ecology and Management, 306*, 281–291. https://doi.org/10.1016/j.foreco.2013.06.053

Canterbury, G. E., Martin, T. E., Petit, D. R., Petit, L. J., & Bradford, D. F. (2000). Bird communities and habitat as ecological indicators of forest condition in regional monitoring. *Conservation Biology, 14*, 544–558.

Cord, A. F., Klein, D., Gernandt, D. S., Pérez de la Rosa, J. A., & Dech, S. (2014). Remote sensing data can improve predictions of species richness by stacked species distribution models: a case study for Mexican pines. *Journal of Biogeography, 41*, 736–748. https://doi.org/10.1111/jbi.12242

Corona, P., Chirici, G., McRoberts, R. E., Winter, S., & Barbati, A. (2011). Contribution of large-scale forest inventories to biodiversity assessment and monitoring. *Forest Ecology and Management, 262*(11), 2061–2069. https://doi.org/10.1016/j.foreco.2011.08.044

Crespi, A. L., Ferreira, M., Fonseca, T. F., & Marques, C. P. (2013). Structural and floristic behaviors in East Timor forest vegetation. *Ecological Research, 28*(6), 1081–1090. https://doi.org/10.1007/s11284-013-1070-4

Currie, D. J. (1991). Energy and large-scale patterns of animal- and plant-species richness. *The American Naturalist, 137*, 27–49.

Findlay, C. S., & Houlahan, J. (1997). Anthropogenic correlates of species richness in southeastern Ontario wetlands. *Conservation Biology, 11*(4), 1000–1009.

Finley, A. O., Banerjee, S., & McRoberts, R. E. (2009). Hierarchical spatial models for predicting tree species assemblages across large domains. *The Annals of Applied Statistics, 3*(3), 1052–1079. https://doi.org/10.1214/09-AOAS239

Frescino, T. S., Edwards, T. C., & Moisen, G. G. (2001). Modeling spatially explicit forest structural attributes using generalized additive models. *Journal of Vegetation Science, 12*(1), 15–26.

Georgia Forestry Commission. (2012). Georgia forest facts. Georgia Forestry Commission, Macon, GA.

Gil-Tena, A., Saura, S., & Brotons, L. (2011). Effects of forest composition and structure on bird species richness in a Mediterranean context: Implications for forest ecosystem management. *Forest Ecology and Management, 242*(2–3), 470-476. https://doi.org/10.1016/j.foreco.2007.01.080

Hernández, L., Martínez-Fernández, J., Cañellas, I., & Vázquez de la Cueva, A. (2014). Assessing spatio-temporal rates, patterns, and determinants of biological invasions in forest ecosystems: The case of Acacia species in NW Spain. *Forest Ecology and Management, 329*, 206–213. https://doi.org/10.1016/j.foreco.2014.06.035

Holmes, K. R., Coops, N. C., Nelson, T. A., Fontana, F. M. A., & Wulder, M. A. (2015). Indicators of vegetation productivity under a changing climate in British Columbia, Canada. *Applied Geography, 56*, 135–144. https://doi.org/10.1016/j.apgeog.2014.11.015

Iles, K. (2009). Total-Balancing an inventory: A method for unbiased inventories using highly biased non-sample data at variable scales. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS), 1*(1), Pages: 10–13 (4). Retrieved from https://mcfns.com/index.php/Journal/article/view/MCFNS.1-10

Iles, K. (2018). Are Models the Answer?. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS), 10*(1), 6–8(3). Retrieved from https://mcfns.com/index.php/Journal/article/view/10.2

James, F. C., & Wamer, N. O. (1982). Relationships between temperate forest bird communities and vegetation structure. Ecology, 63(1), 159–171.

Johnston, D. W. (1990). Descriptions of surveys: Breeding Bird Census. Pages 33-36 in J.R. Sauer and S. Droege (Eds.), *Survey designs and statistical methods for the estimation of avian population trends*. U.S. Fish and Wildlife Service, Washington, D.C., Biological Report 90(1).

Klaus, N., & Keyes, T. (2007). Effect of two native invasive tree species on upland pine breeding bird communities in Georgia. *The Wilson Journal of Ornithology, 119*, 737–741.

Lawton, J. H., Bignell, D. E., Bolton, B., Bloemers, G. F., Eggleton, P., Hammond, P. M., Hodda, M., Holt, R. D., Larsen, T. B., Mawdsley, N. A., Stork, N. E., Srivastava, D. S., & Watt, A. D. (1998). Biodiversity inventories, indicator taxa, and effects of habitat modification in tropical forest. *Nature, 391*, 72–76. https://doi.org/10.1038/34166

Lee, P.-Y., & Rotenberry, J. T. (2005). Relationships between bird species and tree species assemblages in forested habitats of eastern North America. *Journal of Biogeography, 32*(7), 1139–1150. https://doi.org/10.1111/j.1365-2699.2005.01285.x

Liu, S., & Cieszewski, C. (2009). Impacts of Management Intensity and Harvesting Practices on Long-term Forest Resource Sustainability in Georgia. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS), 1*(2), Pages: 52–66 (15). Retrieved from https://mcfns.com/index.php/Journal/article/view/MCFNS.1-52

Lowe, R., & Cieszewski, C. (2014). Multi-source K-nearest neighbor, Mean Balanced forest inventory of Georgia. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS), 6*(2), 65–79 (15). Retrieved from https://mcfns.com/index.php/Journal/article/view/6_65

Mace, G. M., Collen, B., Fuller, R. A., & Boakes, E. H. (2010). Population and geographic range dynamics: Implications for conservation planning. *Philosophical Transactions of the Royal Society B, 365*, 3743–3751. https://doi.org/10.1098/rstb.2010.0264

Morrison, M. L., Marcot, B., & Mannan, W. (2012). *Wildlife-habitat relationships: Concepts and applications*. Island Press.

Oswalt, C. M., Fei, S., Guo, Q., Iannone, B. V. III, Oswalt, S. N., Pijanowski, B. C., & Potter, K. M. (2015). A subcontinental view of forest plant invasions. *NeoBiota, 24*, 49–54. https://doi.org/10.3897/neobiota.24.7720

Prendergast, J. R., Quinn, R. M., Lawton, J. H., Eversham, B. C., & Gibbons, D. W. (1993). Rare species, the coincidence of diversity hotspots and conservation strategies. *Nature, 365*, 335–337. https://doi.org/10.1038/365335a0

Roth, R. R. (1976). Spatial heterogeneity and bird species diversity. *Ecology, 57*(4), 773–782.

Ruiz-Benito, P., Gómez-Aparicio, L., Paquette, A., Messier, C., Kattge, J., & Zavala, M. A. (2013). Diversity increases carbon storage and tree productivity in Spanish forests. *Global Ecology and Biogeography, 23*(3), 311–322. https://doi.org/10.1111/geb.12026

Saab, V. (1999). Importance of spatial scale to habitat use by breeding birds in riparian forests: A hierarchical analysis. *Ecological Applications, 9*(1), 135–151.

U.S. Forest Service. (2016). FIA DataMart. U.S. Department of Agriculture Forest Service, Washington, D.C. Retrieved January 12, 2016, from http://apps.fs.fed.us/fiadb-downloads/datamart.html

Winter, S., Böck, A., & McRoberts, R. E. (2012). Estimating tree species diversity across geographic scales. *European Journal of Forest Research, 131*(2), 441–51. https://doi.org/10.1007/s10342-011-0521-4

Zellweger, F., Braunisch, V., Morsdorf, F., Baltensweiler, A., Abegg, M., Roth, T., Bugmann, H., & Bollmann, K. (2015). Disentangling the effects of climate, topography, soil, and vegetation on stand-scale species richness in temperate forests. *Forest Ecology and Management, 349*, 36–44. https://doi.org/10.1016/j.foreco.2015.04.008

A Appendix: Georgia Land Cover Manual

Table A: Reclassed To: 1=pine; 2=hwd; 3=mix; NoData=Other

GAP Landcover	GAP Class	GAP Description	Reclassed To
Beach	7	Open sand, sandbars, mud, and some sand dunes - natural environments as well as exposed sand from dredging and other activities. Mainly in coastal areas, but also inland, especially along the banks of reservoirs.	NoData
Coastal Dune	9	Sand dunes and associated vegetation.	NoData
Open Water	11	Lakes, rivers, ponds, ocean, industrial water, aquaculture.	NoData
Transportation	18	Roads, railroads, airports, and runways.	NoData
Utility swaths	20	Open swaths maintained for transmission lines.	NoData
Low Intensity Urban - Non-forested	22	Low intensity urban areas with little or no tree canopy.	NoData
High Intensity Urban	24	Commercial/industrial and multi-family residential areas.	NoData
Clearcut - Sparse Vegetation	31	Recent clearcuts, sparse vegetation, and other early successional areas.	1
Quarries, Strip Mines	33	Exposed rock and soil from industrial uses, gravel pits, landfills.	NoData
Rock Outcrop	34	Rock outcrops and mountain tops.	NoData
Parks, Recreation	72	Cemeteries, playing fields, campus-like institutions, parks, schools.	NoData
Golf Course	73	Golf courses.	NoData
Pasture, Hay	80	Pasture, non-tilled grasses.	NoData
Row Crop	83	Row crops, orchards, vineyards, groves, horticultural businesses.	NoData
Forested Urban - Deciduous	201	Low intensity urban areas containing mainly deciduous trees.	2
Forested Urban - Evergreen	202	Low intensity urban areas containing mainly evergreen trees.	1
Forested Urban - Mixed	203	Low intensity urban areas containing mixed deciduous and evergreen trees.	3
Mesic Hardwood	410	Mesic forests of lower elevations in the mountain regions (Blue Ridge, Cumerland Plateau, and Ridge and Valley) and upper Piedmont. Includes species such as yellow-poplar, sweetgum, white oak, northern red oak, and American beech.	2
Sub-mesic Hardwood	411	Moderately mesic forests of the mountain regions and upper Piedmont. Includes typical oak-hickory forests. The dominant natural cover class in most mountain areas.	2
Hardwood Forest	412	Mesic to moderately mesic forests of the lower Piedmont and Coastal Plain. Includes non-wetland floodplain forests of yellow-poplar and sweetgum, ravines of oaks and American beech, and many upland oak-hickory stands.	2
Xeric Hardwood	413	Dry hardwood forests found throughout the state, although most common in the mountain regions, and progressively more rare southward. Includes areas dominated by southern red oak, scarlet oak, post oak, and blackjack oak.	2
Deciduous Cove Hardwood	414	Mesic forests of sheltered valleys in the Blue Ridge and Cumberland Plateau at moderate to high elevations. Typically includes northern red oak, basswood, buckeye, and yellow-poplar.	2
Northern Hardwood	415	Restricted to the highest elevations of the Blue Ridge. Dominant tree species may include yellow birch, black cherry, and American beech.	2
Live Oak	420	Forests dominated by live oak. Most common in maritime strands along the Atlantic Coast. Also may occur in strip along southern border into southwest Georgia.	2
Open Loblolly-Shortleaf Pine	422	Only mapped in the Piedmont. Includes older, fairly open stands that may be almost savanna-like in appearance.	1
Xeric Pine	423	Very dry evergreen forests restricted to the mountain regions and upper Piedmont. Includes Virginia, shortleaf, pitch, and table mountain pines.	1

Continued on next page

Table 5 – continued from previous page

GAP Landcover	GAP Class	GAP Description	Reclassed To
Hemlock-White Pine	424	Mesic evergreen forests frequently associated with riparian areas. Restricted to Blue Ridge and Cumberland Plateau.	1
White Pine	425	Moderately mesic evergreen forests of the Blue Ridge, usually dominated by white pine.	1
Montane Mixed Pine-Hardwood	431	Moderately mesic mixed forests of the Blue Ridge. Typical species include white pine, white oak, hickories, and yellow-poplar.	3
Xeric Mixed Pine-Hardwood	432	Dry mixed forests found throughout the state, although most common in the mountain regions, and progressively more rare southward. Includes areas dominated by a mix of pines (most frequently shortleaf or Virginia in the mountains, and shortleaf or longleaf elsewhere) and hardwood species such as southern red oak, scarlet oak, post oak, and blackjack oak.	3
Mixed Cove Forest	433	Mesic mixed forests of sheltered valleys and riparian areas in the Blue Ridge and Cumberland Plateau at moderate to high elevations. Typically includes eastern hemlock, yellow-poplar, and black birch.	3
Mixed Pine-Hardwood	434	Mesic to moderately dry forests of mixed deciduous and evergreen species found throughout the state at lower elevations. May include areas dominated by sweetgum, yellow-poplar, various oak species, and loblolly or shortleaf pine.	3
Loblolly-Shortleaf Pine	440	Found from the upper Coastal Plain northward (rare in the Blue Ridge except at the lowest elevations). Includes many stands heavily managed for silviculture as well as areas regenerating from old field conditions.	1
Loblolly-Slash Pine	441	Found on the lower Coastal Plain. Includes many heavily managed stands as well as a few natural areas.	1
Shrub Bald	511	Restricted to mountain tops at high elevations of the Blue Ridge. May be dominated by mountain laurel, rhododendron, or blueberry.	NoData
Sandhill	512	Areas of scrub vegetation on deep, sandy soils on the Coastal Plain, especially near the Fall Line and along larger streams. May be dominated by turkey oak, blackjack oak, live oak, holly, and longleaf pine.	NoData
Coastal Scrub	513	Thickets between coastal dunes, typically dominated by wax myrtle. Sometimes found adjacent to saltmarsh areas.	NoData
Longleaf Pine	620	Open, savanna-type stands. Heavily managed plantations would likely be classed with 440 or 441. Most common on the lower Coastal Plain, although found up to the lower Piedmont and historically in the Ridge and Valley.	1
Cypress-Gum Swamp	890	Regularly flooded swamp forests mainly found on the Coastal Plain. May include either riparian or depressional wetlands. Usually dominated by pond or baldcypress and/or tupelo gum.	1
Bottomland Hardwood	900	Less frequently flooded wetland forests found throughout the state, but most common on the Coastal Plain. To the north, may be dominated by sweetgum, elms, and red maple. To the south, wetland oaks (water oak, willow oak, overcup oak, swamp chestnut oak), black gum, and even spruce pine become more common.	2
Saltmarsh	920	Emergent brackish or saltwater wetlands dominated by Spartina or Juncus.	NoData
Freshwater Marsh	930	Emergent freshwater wetlands found throughout the state. May be dominated by grasses or sedges.	NoData
Shrub Wetland	980	Closed canopy, low stature woody wetland. Found throughout the state, although most common on the Coastal Plain. May be result of clearcutting of wetland forests. Frequently includes willows, alders, and red maple.	NoData
Evergreen Forested Wetland	990	Restricted to the Coastal Plain. Includes forests dominated by bay species, wet pine forests (typically slash or pond pine), or Atlantic white cedar.	1