



Forest Carbon and Climate Program
Department of Forestry
MICHIGAN STATE UNIVERSITY



State and Tribal Capacity Building on Forest Carbon

Forest Carbon and Climate Change in Delaware

This technical briefing summarizes topics such as forest densities and cover types, carbon storage, and climate considerations for the state of Delaware.

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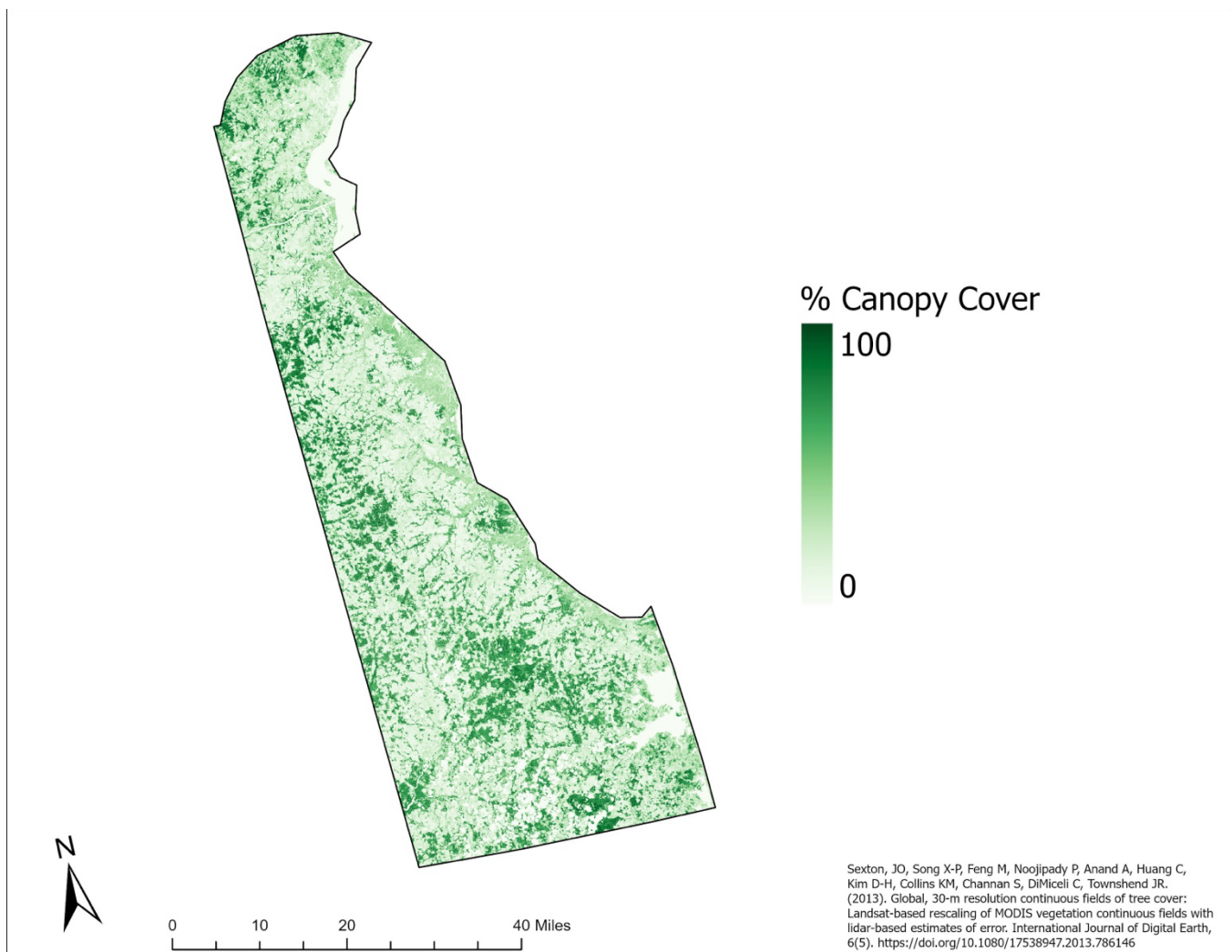
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Delaware Forest Overview

Delaware is situated along the east coast of the United States and lies within the US Forest Service's Eastern Region (USFS Region 9). Bordering states include Maryland to the west and south, Pennsylvania to the north, and New Jersey to the northeast, with the Atlantic coastline marking the majority of Delaware's eastern boundary.

A map of percent tree canopy cover in Delaware is shown in **Figure 1**. Forest coverage is highly variable across much of this state's extent, with relatively low overall forest densities interspersed by pockets of denser forest cover. Notably, the eastern side of the state which borders the Delaware Bay and Atlantic Ocean has reduced forest cover primarily driven by saturated conditions and seasonal flooding that can occur throughout this coastal and estuary zones. Sea level rise is one of the large climate change threats to both forests and other ecosystems as well as urban and agricultural zones.

Figure 1. Percent tree canopy cover in Delaware.



Temperature and Precipitation

Two major factors affecting forest carbon and productivity are temperature and precipitation. **Figure 2** shows normal mean temperatures throughout Delaware between 1991 and 2020. Over this 30-year period, mean annual temperatures varied by about 5 °F across this state. Temperature trends largely follow latitudinal gradients, with warmer mean temperatures occurring in the southernmost portions of the state and giving way to cooler temperatures to the north. The warmest mean annual temperature is around 58 °F and occurs across the southern portion of Delaware, while the coolest mean annual temperature is around 53 °F in the northernmost reaches of the state.

Figure 2. Normal mean temperature (°F) from 1991–2020 in Delaware.

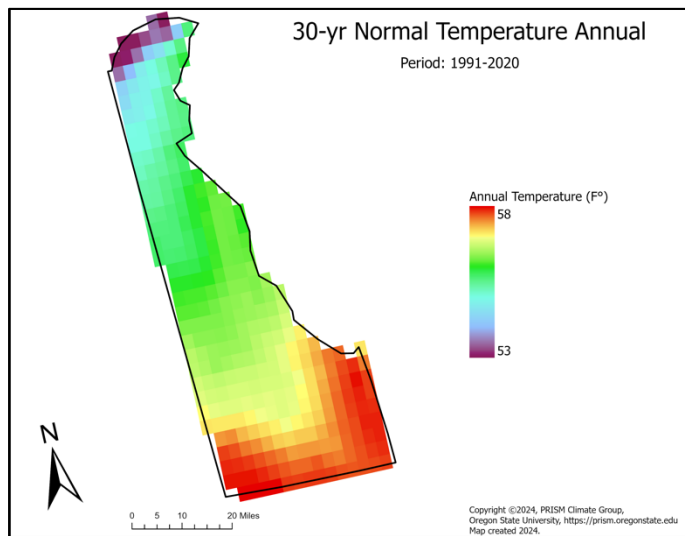


Figure 3. Normal mean precipitation (in.) from 1991–2020 in Delaware.

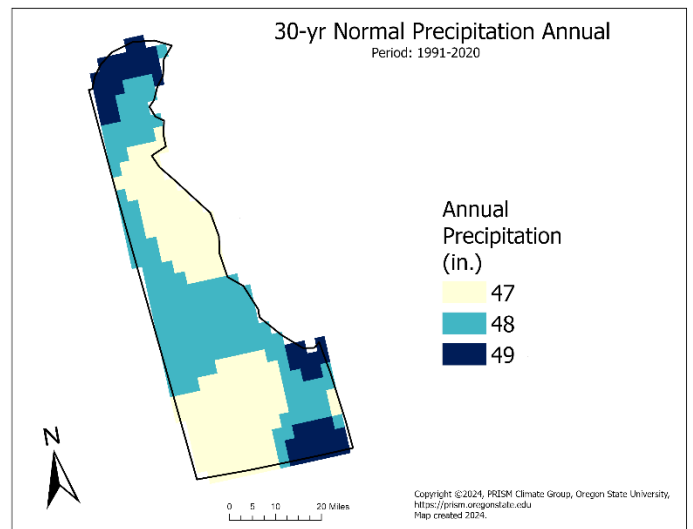


Figure 3 shows normal mean precipitation throughout Delaware between 1991 and 2020 and demonstrates the geographic variation in these trends. Over this 30-year period, mean annual precipitation levels varied by about 2 in. Areas that receive the lowest levels of precipitation (47 in.) occur in the southwest and east-central portions of the state. Areas receiving the highest amounts of precipitation (49 in.) occur in the southeastern corner of Delaware, as well as along its northern border.

Projected Future Trends in Temperature / Precipitation

Figure 4. Model results for potential changes in temperature and precipitation trends in Delaware through 2099 under a high emission scenario (RCP 8.5).

Potential Changes in Climate Variables

Temperature (°F)

2009 2039 2069 2099

Annual Average 56.0 58.4 61.5 65.0

Growing Season May—Sep 71.4 73.9 77.2 81.0

Coldest Month Average 33.0 35.1 36.4 36.9

Warmest Month Average 77.4 80.1 82.0 84.1

Precipitation (in)

2009 2039 2069 2099

Annual Total 44.8 50.2 50.6 53.8

Growing Season May—Sep 19.9 22.7 22.4 23.4

NOTE: For the six climate variables, four 30-year periods are used to indicate six potential future trajectories. The period ending in 2009 is based on modeled observations from the PRISM Climate Group and the three future periods were obtained from the NASA NEX-DCP30 dataset. Future climate projections show estimates of each climate variable within the region for the average of the CCSM4, GFDL CM3, and HADGEM2-ES models under RCP 8.5 emission scenario. The average value for the region is reported, even though locations within the region may vary substantially based on latitude, elevation, land-use, or other factors.

Citation: Iverson, L.R.; Prasad, A.M.; Peters, M.P.; Matthews, S.N. 2019. Facilitating Adaptive Forest Management under Climate Change: A Spatially Specific Synthesis of 125 Species for Habitat Changes and Assisted Migration over the Eastern United States. *Forests*. 10(11): 989. <https://doi.org/10.3390/f10110989>

Projected future trends in temperature and precipitation for Delaware between 2009 and 2099 are shown in **Figure 4**. Model results suggest average temperatures will continue to increase through the end of the century, a trend which is also projected for the coldest and warmest month averages, as well as throughout the growing season (May – Sep.). Over this 90-year period, average annual temperatures are expected to increase by an estimated 9 °F, with the most drastic increases expected to occur during the growing season (+9.6 °F).

Model results of future precipitation in Delaware follow similar trends, with totals projected to increase through 2099 (**Figure 4**). Over a 90-year period, annual precipitation is expected to increase by an estimated 9 in., which is a higher rate of change than projections for the growing season (+3.5 in.). This suggests that the most significant changes to precipitation in Delaware may occur during the winter months (Oct. – Apr.).

Forest Density

Figure 5. Forest density as live tree density (No. ha⁻¹) in Delaware.

Forest Density: Live tree number

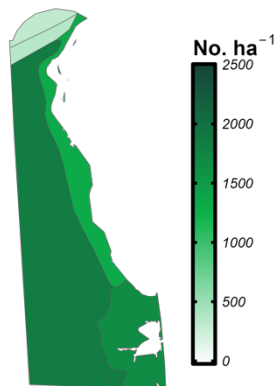
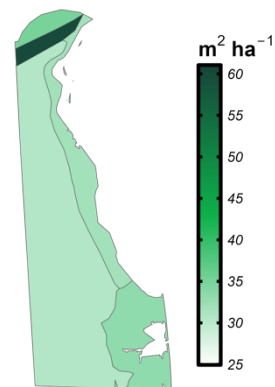


Figure 6. Forest density as live tree basal area (m² ha⁻¹) in Delaware.

Forest Density: Live tree basal area



Forest density¹ is both a structural characteristic of forests and a reflection of forest dynamics. It can be measured as the number of trees per unit area, or it can be measured in terms of live tree area per unit area, known as “basal area”. Live tree basal area represents the amount of ground covered by living trees in two-dimensional space. **Figure 5** shows average forest density in terms of live trees per hectare by ecosection² across the state of Delaware, while **Figure 6** represents forest density by ecosection in terms of basal area (m² ha⁻¹).

By comparing these figures we can see that the large, western ecosection in this state has a higher forest density than other ecosections in terms of number of trees per hectare (**Figure 5**), but its density in terms of basal area (**Figure 6**) is lower than other ecosections. This suggests that in this western portion of the state, there may be more total trees per unit area, but on average, these trees tend to be smaller than they are in other ecosections. Meanwhile, the ecosection directly south of the northernmost ecosection of Delaware, has lower forest density than other areas in terms of number of trees, but a very high forest density in terms of basal area, suggesting the presence of fewer, larger, trees in this zone.

¹All forest inventory and carbon data were estimated using data from the Forest Inventory and Analysis (FIA) Program which can be accessed through the FIA DataMart (USDA Forest Service, 2024. *Forest inventory and analysis program*. Available at: <https://www.fia.fs.usda.gov/>) using the rFIA package (Stanke et al, 2020. rFIA: an R package for estimation of forest attributes with the US Forest Inventory and analysis database. *Environ Model Softw.* **127**:104664. <https://doi.org/10.1016/j.envsoft.2020.104664>) in the R programming environment (R Core Team, 2020. *R: A language and environment for statistical computing*, Vienna, Austria: R Foundation for Statistical Computing.

²Ecosection definition can be found at Cleland et al, 2007. Ecological Subregions: Sections and Subsections for the conterminous United States. *General Technical Report WO-76D*, Washington Office, USDA Forest Service. <https://doi.org/10.2737/WO-GTR-76D>

Forest Cover Types and Carbon

Figure 7. Total forest area (thousand ha) by forest type³ in Delaware.

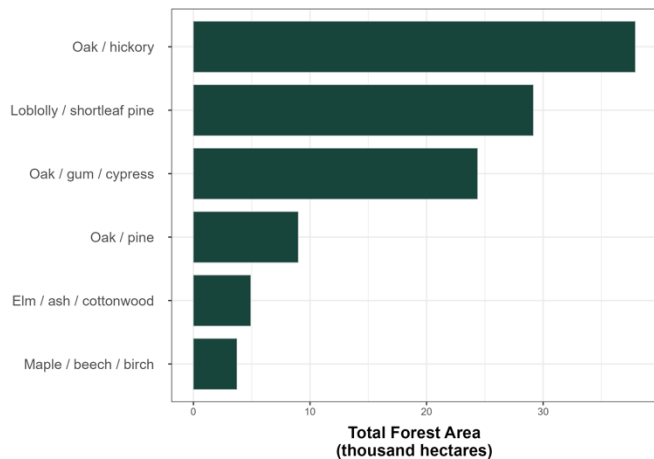
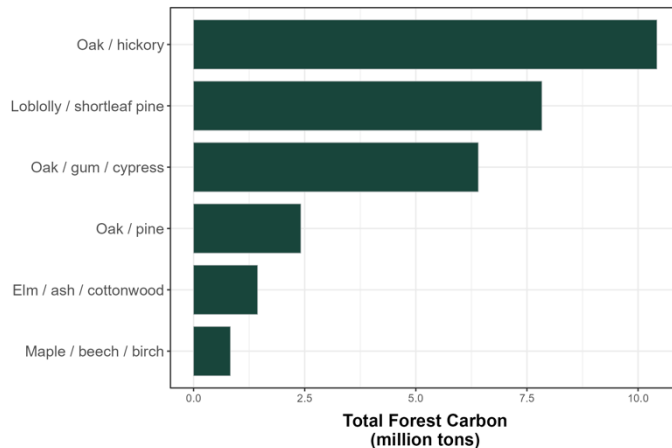


Figure 8. Total forest carbon (million tons) by forest type in Delaware. Total forest carbon is the sum of carbon stored across all aboveground and belowground pools (includes Soil Organic carbon + Live Belowground carbon + Live Aboveground carbon + Litter carbon + Dead wood carbon).

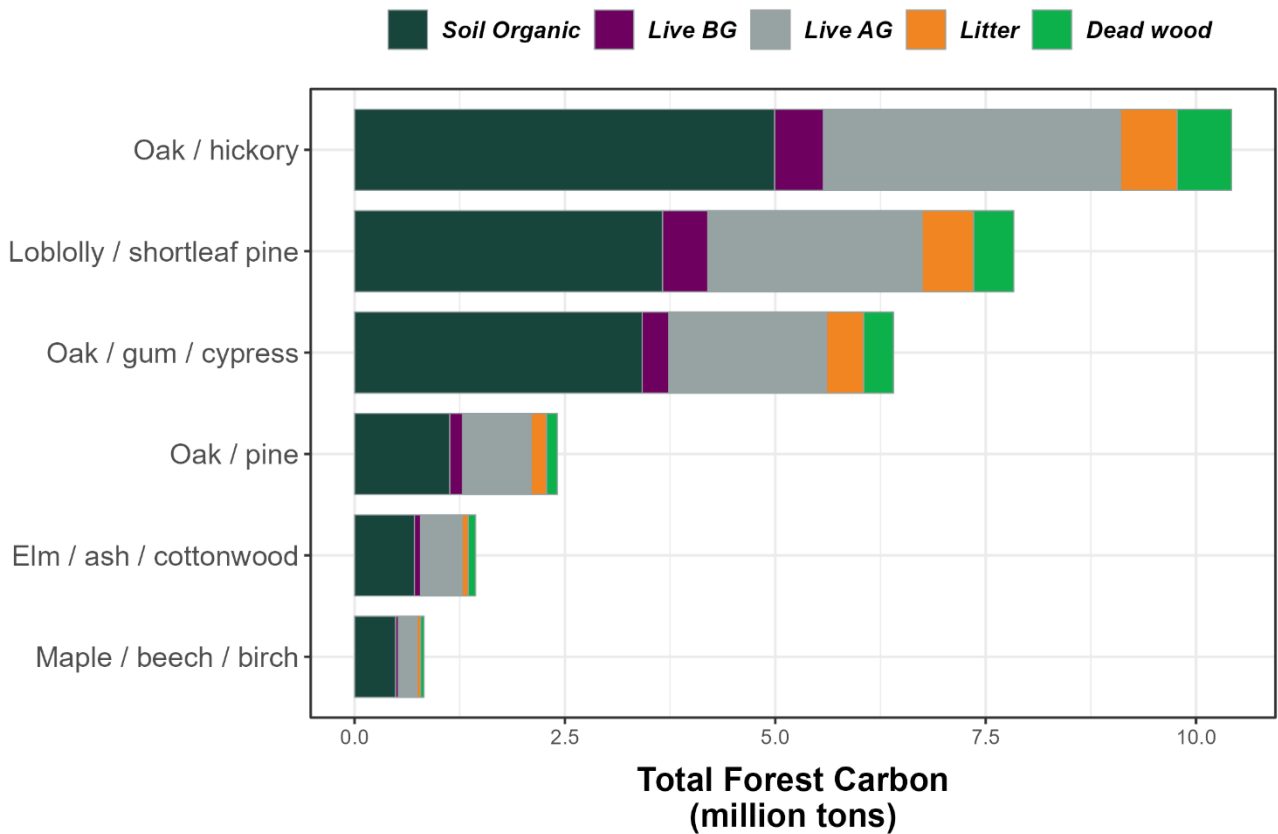


Delaware is dominated by 6 key forest cover types: Oak / hickory, Loblolly / shortleaf pine, Oak / gum / cypress, Oak / pine, Elm / ash / cottonwood, and Maple / beech / birch. **Figure 7** and **Figure 8** show state-level data of total forested area and total forest carbon, respectively, for each of these cover type groups. As these figures show, Oak / hickory is the dominant forest type of Delaware, spanning an area upwards of 35,000 hectares and storing over 10 million tons of carbon statewide. With coverage levels ranging from ~4,000-29,000 hectares, other forest types in this state are less abundant, yet play an important role contributing to enhanced biodiversity and landscape heterogeneity. Comparing trends from **Figure 7** with those in **Figure 8** demonstrates how carbon storage levels vary by forest cover type. For example, Elm / ash / cottonwood forests cover only slightly more land area than Maple / beech / birch stands in Delaware (**Figure 7**), yet when it comes to carbon, Elm / ash / cottonwood stands hold roughly double the amount of carbon of their Maple / beech / birch counterparts (**Figure 8**).

³Forest Types are a classification of forest land based upon and named for the tree species that forms the plurality of live-tree stocking. These forest types used in the briefing align with FIA's definition of Forest type group which are a combination of forest types that share closely associated species and site requirements. Longer definitions of both forest types and forest type groups are found in Appendix D of the Forest Inventory and Analysis Database: Database Description and User Guide for Phase 2 (version 9.1) which can be accessed here: https://research.fs.usda.gov/sites/default/files/2023-11/wo-fiadb_user_guide_p2_9-1_final.pdf

Forest Carbon Pools

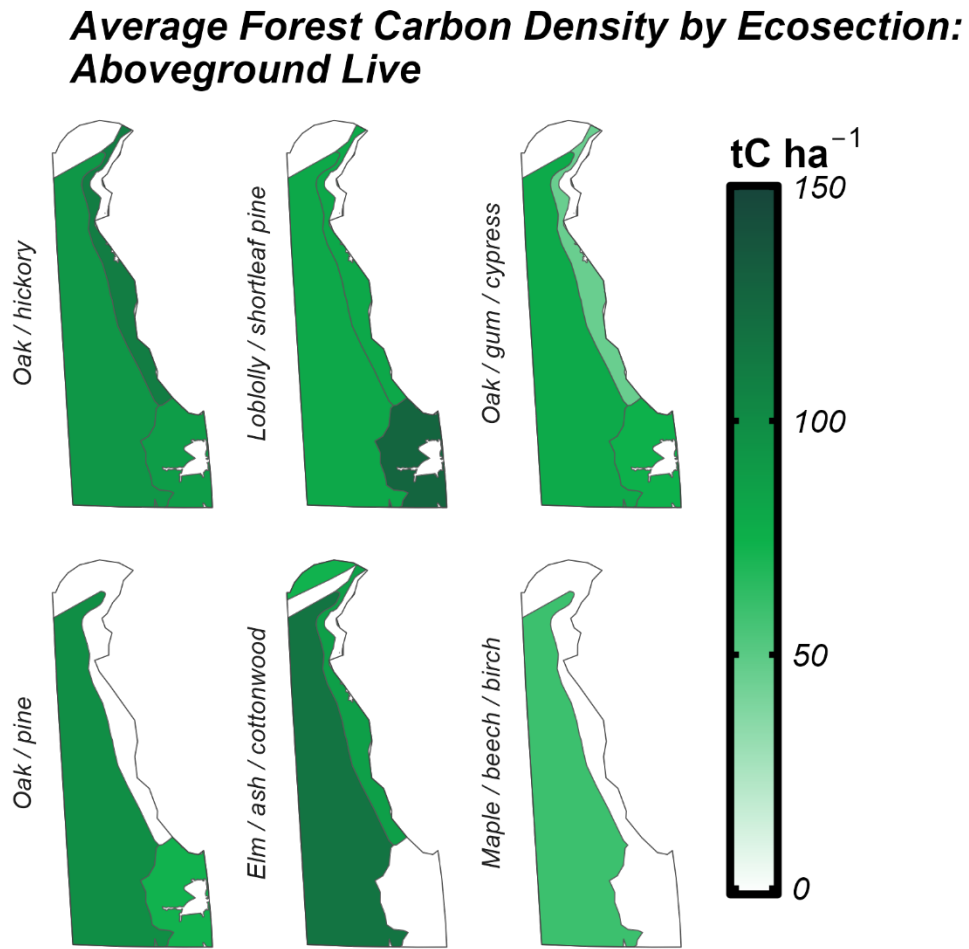
Figure 9. Total forest carbon (million tons) by pool and forest type in Delaware.



Forest carbon storage can be further assessed by examining how it's distributed across different ecosystem carbon pools. **Figure 9** shows the amount of carbon stored in different carbon pools of key forest cover types in Delaware. These values show how different forest types allocate distinct proportions of forest carbon into soil organic matter, live belowground (BG) biomass, live aboveground (AG) biomass, litter, and dead wood pools. For instance, forests composed of Oak / gum / cypress, and Maple / beech / birch allocate more ecosystem carbon to belowground pools (soil organic matter + live BG biomass), whereas forest types like Oak / pine, and Elm / ash / cottonwood tend to distribute stored carbon more evenly between aboveground and belowground pools. Another noteworthy trait shown in **Figure 9** is the magnitude of carbon storage levels across different pools and cover types. Oak / hickory's dominating presence on this landscape means its statewide carbon pools are outsized compared to other groups. For example, leaf litter and dead wood pools of Delaware's Oak / hickory forests on their own contain more stored carbon than the total ecosystem carbon (sum of carbon stored across all pools) contained by the Maple / beech / birch group.

Forest Carbon Density

Figure 10. Aboveground live forest carbon density (tC ha^{-1}) by forest type in Delaware.



Forest carbon density can be influenced by many ecosystem traits, such as tree density, stand age, species mix/ cover type, soil fertility, elevation, and a site's management and disturbance history. In **Figure 10**, the carbon density of aboveground living forest biomass is shown for 6 key cover types in Delaware. Of these, Loblolly / shortleaf pine and Elm / ash / cottonwood stands hold the highest levels of aboveground live carbon per unit area, represented by the deep shade of green in the southeastern region of the state (Loblolly / shortleaf pine) and in Delaware's large western ecoregion (Elm / ash / cottonwood). Across much of their extent Oak / hickory stands exhibit relatively even carbon densities, while cover types like Loblolly / shortleaf pine and Elm / ash / cottonwood show higher levels of variability across ecoregions. In these instances, variable carbon densities can be driven by the relative prevalence or absence of each forest type from a given ecoregion.

Species-Specific Considerations for Climate Adaptation

Climate change is expected impact the distribution of species into the future. Predictive modeling of potential future changes that incorporate species interactions, dispersal mechanisms, demography, physiology, and evolution is needed to assist in adaptive forest planning. The USDA Forest Service **Climate Change Tree Atlas, Version 4**, provides modeled potential suitable habitat for 125 species in the eastern US, with an additional 23 species. <https://www.fs.usda.gov/nrs/atlas/tree/>

Core Climate Change Atlas components:

- DISTRIB-II: Species habitat suitability model
- SHIFT: Migration model (when combined with DISTRIB-II, estimates colonization potential (HQCL) of future suitable habitats)
- Adaptability Ratings: Species adaptability ratings (species traits not included in DISTRIB-II and SHIFT models)

In addition to the modeled potential suitable habitat for individual tree species, the Climate Change Atlas includes Current and potential future habitat, capability and migration for individual tree species and potential changes in climate variables summarized by the following spatial extents:

Geographic Area	Description
National Forest Summaries	Results summarized for 55 national forests
National Park Summaries	Results summarized for 78 national parks
HUC6 Watershed	Results summarized by hydrologic unit codes level 3 (HUC 6) which are hierarchical classifications based on surface hydrologic features in which level 3 maps watershed basins (Seaber et al, 1987) https://pubs.usgs.gov/wsp/wsp2294/
Ecoregional Vulnerability Assessments (EVAS)	Results summarized by ecoregions used in the USDA Climate Hub Regional Vulnerability Assessments https://www.climatehubs.usda.gov/assessments
USDA Forest Service EcoMap 2007 Sections	Results summarized by ecological sections that delineate ecosystems with distinctive vegetation and other unique ecological characteristics (Cleland et al, 2007, McNab et al, 2007)
National Climate Assessment (NCA) 2015 Regional Summaries	Results summarized by National Climate Assessment Region which include the Midwest, Northeast, Northern Plains, Southeast, and Southern Plains
1 x 1° Grid Summaries	Results summarized by 1x1° latitude and longitude
State Summaries	Results summarized for 38 states
Urban areas	Results summarized for 185 urban areas across the eastern US

Additional background on this tool can be found at: <https://research.fs.usda.gov/centers/ccrc> along with short video tutorials on the Climate Change Atlas website.

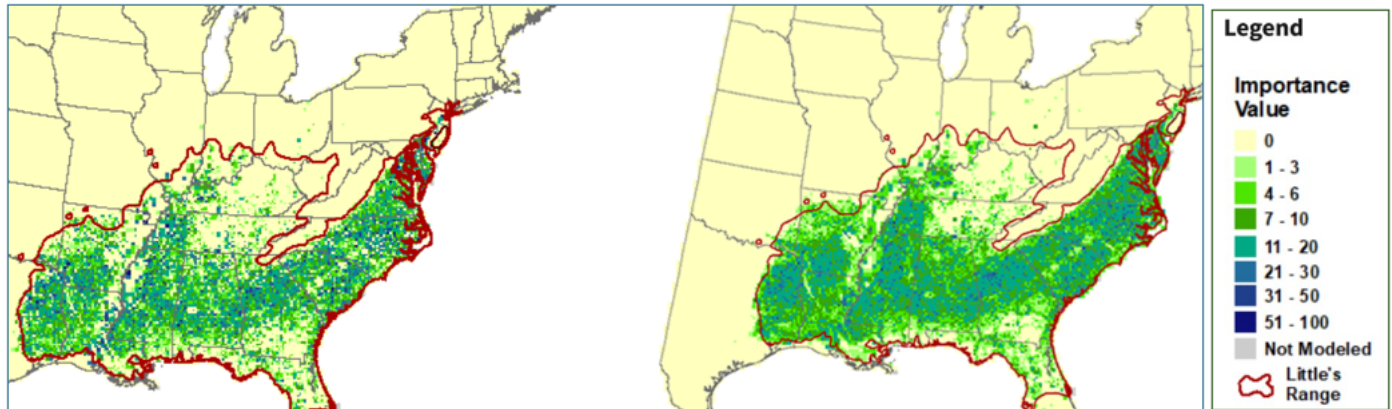
Habitat Suitability and Migration Models

Model Reliability: **High**

Key Species Example: Modeled potential suitable habitat for Sweetgum (*Liquidambar styraciflua*) through 2100

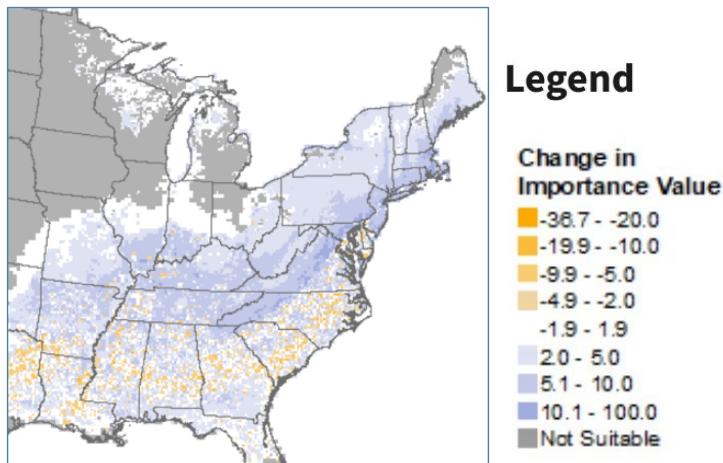
Current habitat quality and distribution (DISTRIB)

Potential migration (SHIFT) and colonization likelihood (CL)



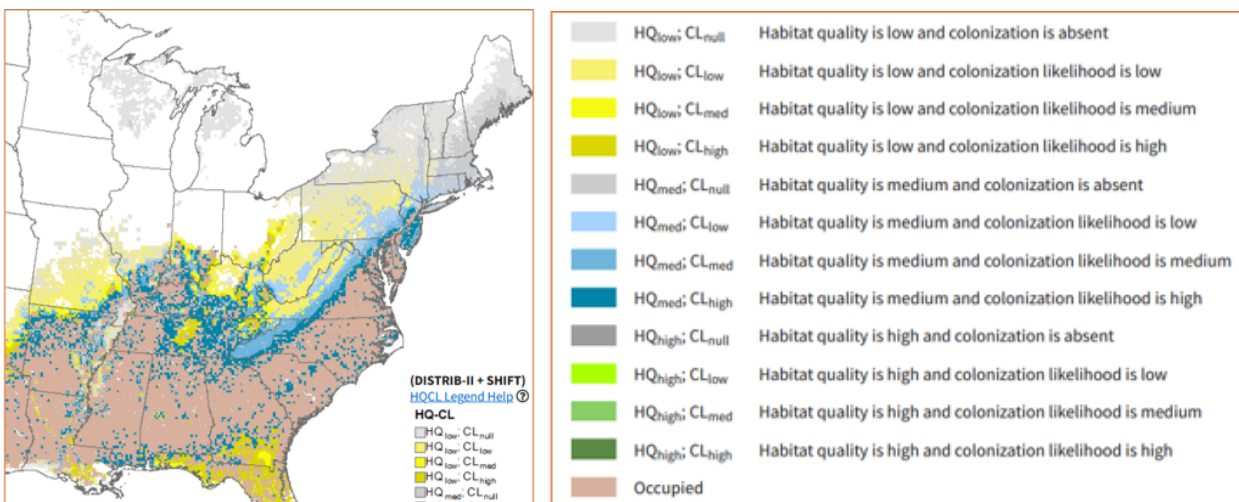
Importance value is a measure of abundance that accounts for both tree basal area and number of stems, ranging from 0-100

Colonization potential of future habitats under a high emission scenario (RCP 8.5)



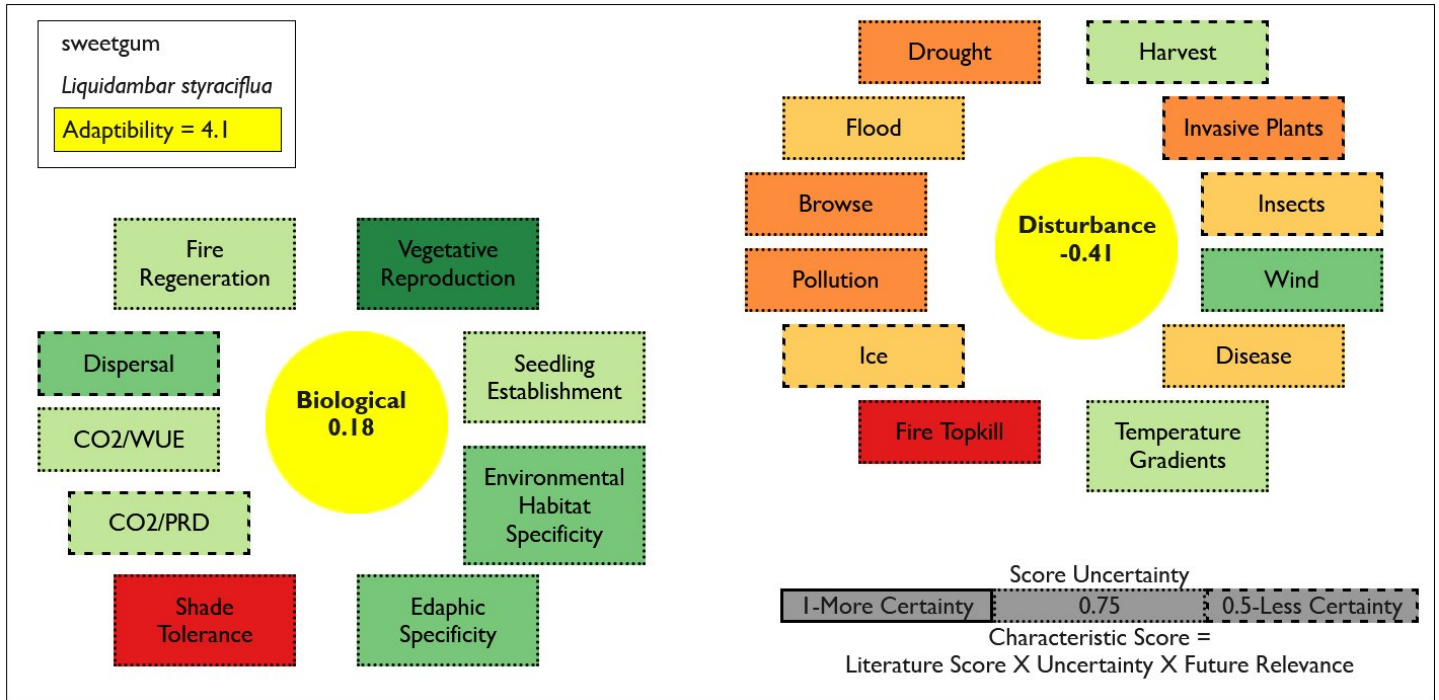
Colonization is limited to range margins and infill (Blue) which is derived from habitat quality (DISTRIB) and migration model (SHIFT) utilizing the colonization likelihood model (CL). Orange shading represents current species' distributions where abundance is predicted to decrease due to loss of habitat suitability.

DISTRIB-II + SHIFT: Habitat quality and colonization likelihood (RCP 8.5)



Adaptability Ratings

Key Species Example: Sweetgum (*Liquidambar styraciflua*)



V Hi Pos +3	High Pos +2	Low Pos +1	Minimal 0	Low Neg -1	High Neg -2	V Hi Neg -3
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The Adaptability score, which assesses 21 variables to assign adaptability ratings to tree species in the eastern US, reflects a species' potential adaptability to climate change-driven stressors and disturbances at range wide scale. Adaptability ratings provide broad insights into factors that cannot be directly included in the Climate Change Tree Atlas species migration models. Two types of species traits are evaluated: 1) biological and 2) disturbance, each with their own set of factors to help characterize species' traits and responses to disturbance. Uncertainty is also included for each trait or factor assessed. When coupled with other modeled projections, adaptability ratings can support future planning under a changing climate.

The Adaptability variable is single score derived from the Modification Factors which encompass scores for the 12 disturbance and 9 biological factors. The Adaptability results can be considered relative to other tree species. For example, a species with a low Adaptability variable likely does not have life history characteristics to allow it to thrive under most conditions whereas a high Adaptability variable will likely do better under the climate change outputs from the DISTRIB-II and SHIFT Models.

Climate Change Atlas Summary for Sweetgum

Sweetgum is distributed widely (22.5% of area), very abundant (third only to loblolly pine and red maple), densely occurring, and with high IV across the southern half of the eastern US. It occupies 23% of the eastern US territory and ranks highest in importance for some of the region (though loblolly pine beats it out much of the time). Its highly reliable model suggests an increase of habitat, including to the north all the way into Maine (under RCP 8.5), by 2100. However, the SHIFT model largely limits those northern locations from being naturally colonized within 100 years, though a fairly large northward expansion has some possibility. The species is also moderate in its adaptability, yielding a very good capacity to cope with a changing climate. The SHIFT model also indicates it a very good species for infilling.

Citations

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