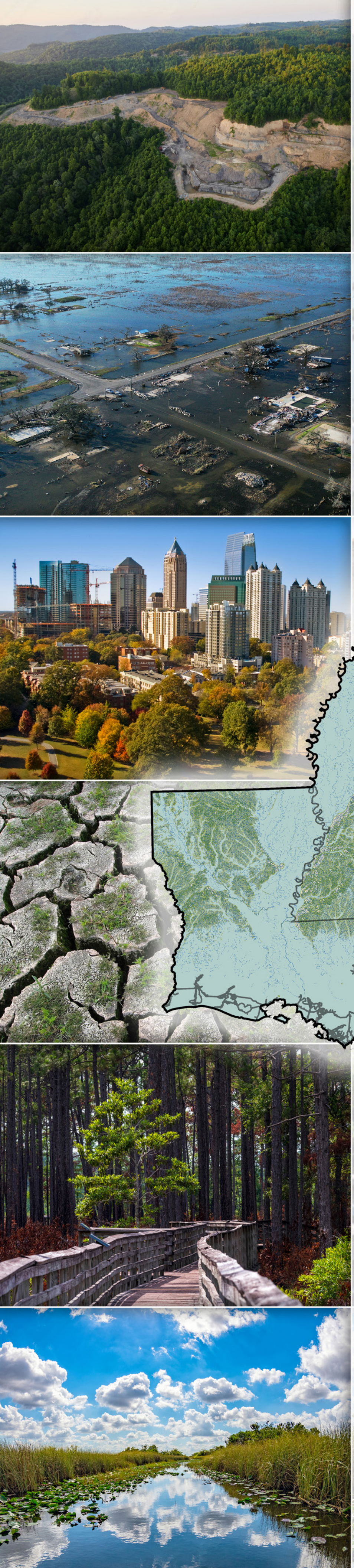
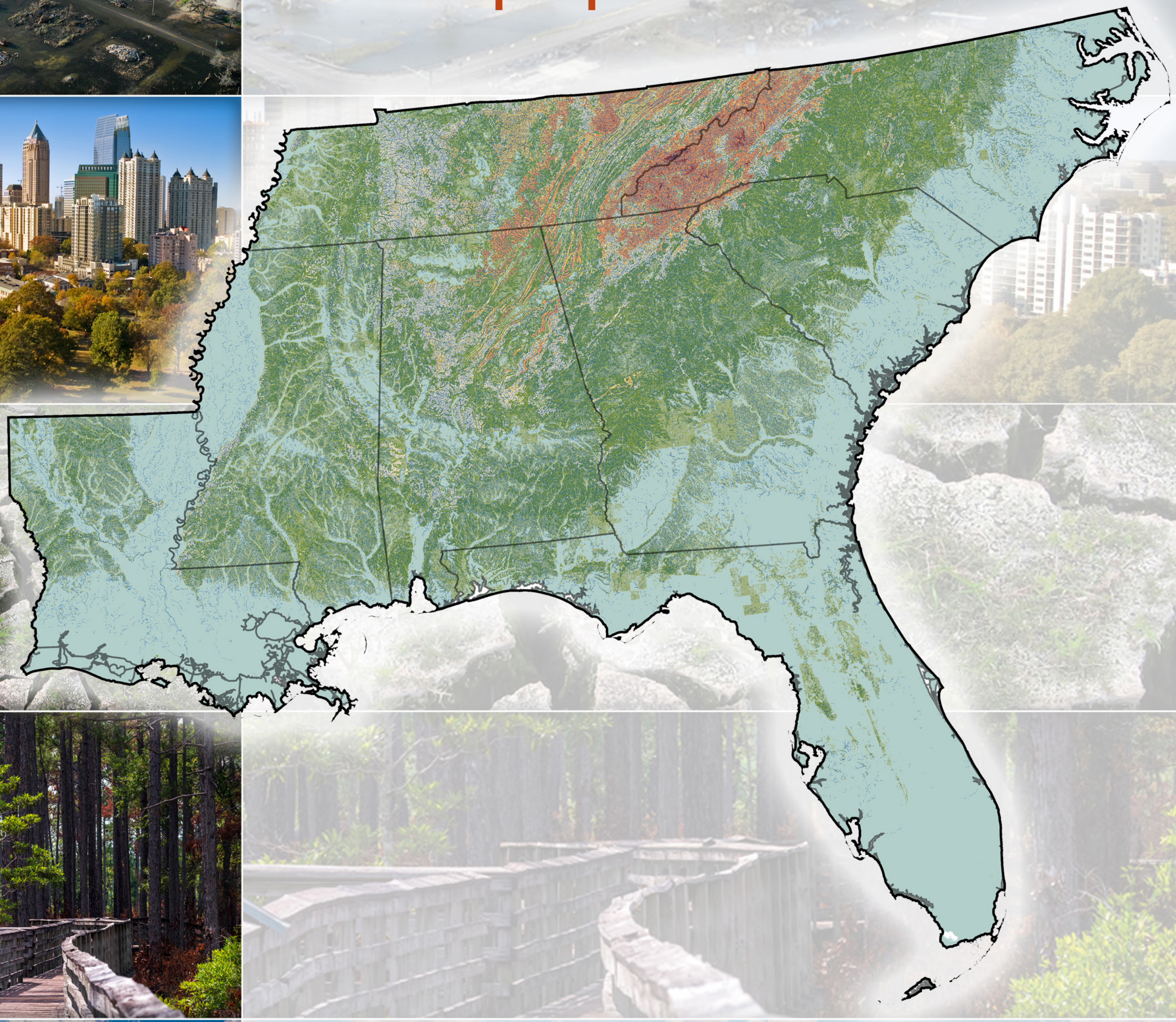
DOE/SC-0220

Optimizing DOE Opportunities to Research Land–Atmosphere Interactions in the U.S. Southeast

Workshop Report





U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program

Southeast Land–Atmosphere Research Opportunities

Virtual Workshop

August 23–24, 2023

Convened by

U.S. Department of Energy

Office of Science, Biological and Environmental Research Program

Meeting Co-Chairs

C. Ross Hinkle
University of Central Florida

Andrew Christopher Oishi
U.S. Forest Service

Nina Wurzburger
University of Georgia

Organizer

Beth Drewniak
U.S. Department of Energy
Intergovernmental Personnel Act Assignment

Additional Contributors

Jeff Atkins, U.S. Department of Agriculture; **Doug Aubrey**, University of Georgia; **Vanessa Bailey**, Pacific Northwest National Laboratory; **Rosvel Bracho**, University of Florida; **Chongai Kuang**, Brookhaven National Laboratory; **Nicki Hickmon**, Argonne National Laboratory; **April Hiscox**, University of South Carolina; **Ashley Matheny**, University of Texas–Austin; **Melanie Mayes**, Oak Ridge National Laboratory; **Georgianne Moore**, Georgia Southern University; **Asko Noormets**, Texas A&M University; **Tom O'Halloran**, Clemson University; **Eric Pierce**, Oak Ridge National Laboratory; **Tom Powell**, Lawrence Berkeley National Laboratory; **Dan Ricciuto**, Oak Ridge National Laboratory; **Fernanda Santos**, Oak Ridge National Laboratory; **Shawn Serbin**, Brookhaven National Laboratory; **Gregory Starr**, University of Alabama; **Ben Sulman**, Oak Ridge National Laboratory; **Margaret Torn**, Lawrence Berkeley National Laboratory; **Carl Trettin**, U.S. Forest Service; **Yun Yang**, Mississippi State University

About BER

The Biological and Environmental Research (BER) program advances fundamental research and scientific user facilities to support U.S. Department of Energy missions in scientific discovery and innovation, energy security, and environmental responsibility. BER seeks to understand U.S. biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecular and genomics-controlled mechanisms to environmental and Earth system change. BER advances understanding of how Earth's dynamic, physical, and biogeochemical systems (atmosphere, land, oceans, sea ice, and subsurface) interact and affect future Earth system and environmental change. This research improves Earth system model predictions and provides valuable information for energy and resource planning.

Cover Images

Top to bottom: (1) Aerial view of quarry in the southern Appalachian Mountains. Courtesy Adobe Stock. **(2)** Flooding from Hurricane Delta in Creole, La. Courtesy Getty Images. **(3)** Atlanta, Ga., skyline. Courtesy Getty Images. **(4)** Drought at Lake Jordan, N.C. Reprinted under a Creative Commons license (CC BY-SA 2.0 DEED) from Keith, Flickr. **(5)** Weeks Bay Pitcher Plant Bog, Baldwin County, Ala. Courtesy Adobe Stock. **(6)** Florida Everglades. Courtesy Adobe Stock. **Cover Map:** Landforms map of the Southeast land–atmosphere study area. Courtesy Chris DeRolph, Oak Ridge National Laboratory.

Suggested Citation

U.S. DOE. 2024. *Optimizing DOE Opportunities to Research Land–Atmosphere Interactions in the U.S. Southeast: Workshop Report*, DOE/SC-0220. U.S. Department of Energy Office of Science. https://doi.org/10.2172/2440215.

DOE/SC-0220

Optimizing DOE Opportunities to Research Land–Atmosphere Interactions in the U.S. Southeast

Workshop Report

October 2024

U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program

Contents

Executive Summary

The southeastern United States (Southeast), with its complex and varied environments, is an area of tremendous economic, ecological, and societal importance to the country. The region is characterized by heterogeneous landscapes (i.e., geology and soil type) and a long history of human land use coupled with a warm temperature regime and high precipitation. As a result, soil erosion and deposition are pronounced, vegetation recovery is rapid, and human modification is extensive across the region.

To better understand land–atmosphere interactions in this important and complex region, research communities supported by the U.S. Department of Energy's Biological and Environmental Research (BER) program identified the Southeast as a priority region of interest. In fall 2024, the third Atmospheric Radiation Measurement Mobile Facility (AMF3), one of three mobile monitoring facilities designed to collect atmospheric and climate data from undersampled regions around the world, will begin operations in northwestern Alabama's Bankhead National Forest (BNF). The AMF3-BNF 5-year deployment, from 2024–2029, will monitor the effects of feedbacks among aerosols, clouds, and precipitation on plant physiology and canopy-scale fluxes. It will also focus on scale aggregation to resolve the role of local forcing on larger-scale processes.

To enable broader AMF3 involvement by the science community, the BER Environmental System Science (ESS) program organized the Southeast Land–Atmosphere Research Opportunities (SELARO) workshop in August 2023. The purpose was to identify gaps in scientific understanding of terrestrial processes in the Southeast (defined as states bounded by the Gulf of Mexico to the south, the Atlantic Ocean to east, the Mississippi River to the west, and extending through Tennessee and North Carolina to the north) and explore opportunities to use the AMF3-BNF deployment to coordinate and leverage research efforts across the region.

Many parts of the Southeast have experienced repeated anthropogenic forcings. Farming, hunting, burning, and settlement of the region by Indigenous Peoples first shaped the distribution of plant communities, which in turn influenced European colonization patterns. Timber harvesting was common during the expansion of European settlements, and production forestry continues today. Agricultural production was extensive and then waned through the 20th century, creating a period of afforestation following agricultural abandonment. Today, many formerly agricultural landscapes are undergoing rapid urbanization and suburbanization. Overlying these patterns of anthropogenic land use are frequent disturbances from hurricanes, tornadoes, wildfires, drought, flooding, ice storms, and the occasional blizzard.

An additional characteristic of the Southeast is its overall landscape complexity. Unlike the western United States, where broad expanses may share similar characteristics, Southeast topography, drainage patterns, vegetation, and development patterns vary widely across relatively small spatial scales (<1 km). This is due to the region's underlying geology and soil development, species biodiversity patterns, and land ownership and use coupled with strong forces of erosion, weathering, and rapid plant growth in the warm, wet climate.

Emerging Themes and Challenges

The SELARO workshop sought to identify research opportunities across the Southeast region that can leverage and expand upon the AMF3-BNF deployment. The workshop was organized around the following research topics: two-way carbon, energy, and water fluxes and land–atmosphere interactions; ecology, biogeochemistry, and disturbance; and hydrology, ecohydrology, and the terrestrial–aquatic interface. Despite the diverse range of perspectives and expertise among workshop participants, discussion coalesced around the following similar themes and challenges.

- **Wide-ranging spatial heterogeneity scales across the landscape complicate generalization of ecosystem processes and lead to differential land–atmosphere coupling.** The Southeast is characterized by strong heterogeneity driven by topography, climate, physiography, and human land use that results in a land cover mosaic. Knowledge gaps exist in understanding how to upscale parameters, represent processes across diverse landscapes, capture uncertainties across scales from soil microtopography to entire landscapes, and characterize interactions between land cover and biological processes.
- **Climate change predictions suggest future changes in vegetation growing season and productivity.** The Southeast is expected to experience changes in temperature, growing season length, drought, and flooding, which can interact with other disturbances endemic to the region. Key challenges include improving understanding of how climate change will impact land–atmosphere interactions. Precipitation changes alter soil moisture, flooding, and drought, and rising temperatures extend growing seasons, but their combined effects on primary productivity and carbon-nutrient cycles remain unknown. Soil and plant processes must be linked to the atmosphere to understand climatic drivers on ecosystems. Improvements to models to capture high-resolution spatiotemporal data for temperature and precipitation are needed to address these challenges.
- **Disturbance regimes are expected to shift.** The Southeast is subject to a wide range of disturbance events that shape the landscape and drive ecosystem responses. A need exists to understand the trajectories and transitions of ecosystems, compound disturbances, resistant or resilient responses, and impacts on turbulent and radiative fluxes, boundary layer characteristics, and carbon and nutrient cycling. Research requires long-term field experiments, comparing sites with different levels of disturbance severity, and studying sites with different disturbance histories and legacies. Understanding individual ecosystem stress responses, which are highly unique, can help determine ecological resilience and capture transitions in models.
- **Land management and land use change in the Southeast is highly dynamic.** Changes in Southeast land characteristics are influenced by the large fraction of land under private ownership, high levels of land management, and rapid urbanization. A need exists to understand historical trends and extent and to predict the direction of change in land development and use. Furthermore, establishing a baseline is imperative before predicting future effects. A research challenge is to improve understanding of how changes in ecosystem structure and composition impact evapotranspiration, soil water, biogeochemical cycles, and carbon dynamics.
- **Hydroclimatic feedbacks require a good understanding of the water budget.** Intense water cycling in the Southeast is driven by warm temperatures, long growing seasons, dense vegetation, abundant atmospheric moisture, abundant precipitation, and high rates of evapotranspiration. Understanding impacts on the water cycle from changes in atmospheric forcing, land use, and land management requires knowledge of the missing components of the water budget. These components include evapotranspiration, soil water storage, and plant response to the atmospheric environment. Evapotranspiration is difficult to capture in complex environments containing mixed-species and/or mixed-age ecosystems. The few measurements that exist for soil water storage are shallow and fail to capture the full depth of plant-accessible water as well as small-scale microtopographic effects. Shifting vegetation patterns in the Southeast, combined with increasing human demand for water resources, necessitate improved understanding of plant response to increased carbon dioxide, changes in vapor pressure deficit, and increased temperature.
- **Land–atmosphere coupling, boundary layer dynamics, and surface-aerosol interactions are highly uncertain**. Southeast boundary layer dynamics are influenced by heterogeneous canopy cover, high rates of biogenic volatile organic carbon

(BVOC) emissions, aerosol interactions, and radiation. Coupling between the land and atmosphere drives turbulence, fluxes of mass and momentum, and boundary layer characteristics. However, a major knowledge gap exists in understanding how spatial heterogeneity, canopy structure, surface layer roughness, and boundary layer height contribute to cloud and convective processes. Radiative and cloud processes are also influenced by BVOC emissions that contribute to the formation of secondary organic aerosols. Research aimed at resolving seasonal, species, and environmental influences on BVOCs is needed. Furthermore, studies should focus on BVOC contribution to aerosols and the resulting scattered and diffuse light, which will impact canopy photosynthesis, ecosystem evapotranspiration, carbon sequestration, surface heating, and precipitation patterns.

Opportunities for Scientific Advancement

Workshop participants identified several opportunities for scientists to leverage and coordinate with the AMF3-BNF deployment to further scientific advances. These include:

- **Adding supplemental observational sites and instrumentation.** Future effects should capture a variety of different land covers, topography and underlying geologic formations, and short- and long-term meteorology that can be used to (1) enhance understanding of land–atmosphere coupling and (2) provide supplemental data for validation. Needs exist for additional monitoring sites outside BNF to capture diverse elements of the Southeast and additional instrumentation within and outside BNF to complement and extend observational activities. For example, additional *in situ* ecosystem and ecohydrology measurements could be linked with atmospheric measurements, and remote sensing data could be used to address scaling issues. Additional light, radiation, and aerosol measurements within existing and deployable tower sites (e.g., AmeriFlux) could enhance understanding of land–atmosphere coupling.
- **Including hierarchical observations**. Integrated measurements of eddy covariance, radiation, and remote sensing across the soil–plant–atmosphere continuum can improve translation from individual scales to larger spatial and temporal scales. Furthermore, a variety of gauged watersheds lie within the AMF3-BNF coverage area, and opportunities to gauge smaller watersheds can help explore interactions between hydrology and ecosystem processes. Finally, observations across a gradient will help inform how processes and parameters aggregate across land cover transitions over spatial scales.
- **Co-locating existing data.** A wealth of existing data (e.g., long-term ecohydrology monitoring, AmeriFlux, Long-Term Agroecosystem Research, Long-Term Ecological Research, National Ecological Observatory Network and remote sensing) can be leveraged to enhance AMF3 data and achieve a more holistic understanding of the system and various interactions between the land and atmosphere. Several sites support long-term ecological studies that have produced data that may support the AMF3-BNF effort beyond its current footprint (e.g., Jones Ecological Center, Tall Timbers, military bases, and national laboratory facilities). Not all data are readily available, so establishing a data integrator to access existing data and potentially develop and test models will be critical.
- **Improving models and modeling frameworks.** Some of the biggest challenges in ecosystem modeling are capturing processes across multiple scales and understanding nuanced processes that drive component fluxes. The variability and stress responses that occur in complex environments with heterogeneous terrain, mixed-species and/or mixed-age vegetation, and transitional ecosystems are poorly represented by the plant functional types used in existing models. Some approaches that can strengthen understanding and predictability of ecosystem behavior and response to forcing include (1) utilizing functional traits to represent vegetation and improve species-specific responses, (2) leveraging artificial intelligence tools to simplify parameters, (3) using linked modeling frameworks to explore uncertainties that guide measurements, and (4) capturing heterogeneity and climate resilience in coupled land surface models.

1 Introduction

1.1 Overview of the Southeastern United States

In the coming decades, a combination of climate change and regional land use changes is expected to force natural and human processes to trigger dynamic land–atmosphere interactions in the southeastern United States (Southeast). This region supports a wide variety of ecosystems including natural forests, scrub, grasslands, and wetlands, as well as managed forests, farmland, and developed areas, all influenced by a generally warm and humid climate. Precipitation decreases from west to east and with distance from the coast. Winters are generally mild in all but the northeastern portion of the region.

In addition, the Southeast is subject to extreme events such as hurricanes, heat waves, drought, flooding, and fire, which result in large-scale disturbance of vegetative processes and changes in hydro-biogeochemical cycling and land cover. Furthermore, rapid growth of urban centers and changing land management practices result in increased stress and vulnerability of natural Southeast ecosystems. Scientists currently lack data to appropriately represent interactions among these processes and their feedbacks to the Earth system in predictive models.

To help address this data deficit, the Southeast Land–Atmosphere Research Opportunities (SELARO) community workshop was held in August 2023 to identify critical knowledge gaps in a variety of ecosystems and land surface processes unique to the Southeast (see Appendix B: Workshop Agenda, p. 62, and Appendix C: Breakout Questions, p. 65). Workshop participants summarized research needs and priorities as well as how the Southeast can serve as a study region (see Ch. 3–8, p. 11–43; see Appendix D: Workshop Participants, p. 66). Participants also provided guidelines for potential opportunities to coordinate ongoing and new research with the deployment of the third Atmospheric Radiation Measurement Mobile Facility (AMF3) to the Southeast (see Ch. 9, p. 45). Specific topics discussed included:

- Defining the state of the science of land–atmosphere processes in the Southeast.
- Identifying gaps in key processes of hydro-biogeochemistry, disturbance, climate resilience, land–atmosphere interactions across the water–soil–plant–atmosphere continuum, and land use and land cover changes in the Southeast.
- Identifying relevant and important research and modeling gaps and questions to advance understanding and predictability of terrestrial processes.
- Identifying potential research driven by a model-experiment (ModEx) approach that would benefit from data provided by the AMF3 user facility.
- Developing strategies in experimental design, data needs, and model development to advance workshop goals in understanding atmospheric–terrestrial interactions and leveraging AMF3 activities.

Workshop participants considered the Southeast domain to include states bounded by the Gulf of Mexico to the south, the Atlantic Ocean to east, the Mississippi River to the west, and extending through Tennessee and North Carolina to the north. This area incorporates numerous ecoregions, such as the Southern Coastal Plain, Mid-Atlantic Coastal Plain, Southeastern Plain, Piedmont, Mississippi Valley Loess Plain, Mississippi Alluvial Plain, Blue Ridge and the southern portion of the Ridge and Valley, Southwestern Appalachians, and Interior Plateau, and includes several major rivers and their watersheds.

1.2 Major Workshop Themes

A set of major themes emerged during the workshop that help frame the primary factors influencing land–atmosphere processes in the Southeast. These themes provide a useful organizational tool for understanding the underlying drivers, agents, and subsequent biophysical responses to change in the region. These themes are described briefly in the sections that follow and are explored in greater detail in subsequent chapters. The boundaries among the categories can be blurry, and interactions among them are important.

Spatial Heterogeneity

Interactions among geophysical, climatic, ecological, and anthropogenic processes have resulted in a high degree of spatial heterogeneity in the Southeast (see Ch. 3, p. 11). The varied topography of the region ranges in elevation from below sea level along the Gulf Coast to the highest peak east of the Mississippi River in the highly weathered, unglaciated southern Appalachian Mountains. This topography affects the diversity of weather and climate patterns, biogeochemistry, and biota. The Southeast is analogous to a large regional biodiversity hotspot, with high species turnover and dramatic shifts in ecosystem types. This ecological heterogeneity is amplified by diverse land use types (e.g., urban, exurban, managed forests, and agriculture) governed across private, Tribal, local, and federal entities.

Climate Change

Climate change in the Southeast is expected to manifest with subtle but important differences from much of the rest of the globe (see Ch. 4, p. 15). Expected warming can drive lengthening of the growing season, shifts in species ranges, and increased potential evapotranspiration (ET). Precipitation predictions do not show a consistent trend in annual totals, but frequent and more intense precipitation events are expected to trigger more severe drought events.

Disturbance

For the purposes of this report, disturbance primarily includes natural disturbance events such as extreme weather, native or invasive pest outbreaks, and wildfire. However, climate change and other anthropogenic activities can clearly facilitate or exacerbate these processes, making compounding disturbances an important theme in the Southeast (see Ch. 5, p. 21). Combinations of extreme events (including weather) have long played an important role in shaping southeastern ecosystems, and their role is likely to increase in the future.

Land Management and Land Use Change

The Southeast is characterized by shifting economic and demographic drivers that continue to affect land use patterns. Legacy effects of historical agricultural and forest management practices, such as soil erosion, continue to shape the current distribution of vegetation, primary productivity, and carbon storage. Much of the Southeast is a center of intensive land management, including animal production (e.g., poultry and swine), row crop agriculture, and plantation forestry. Rapid urbanization has fragmented forests, expanded the wildland–urban interface, and exacerbated urban heat islands that can potentially alter local weather patterns. Together, these land use and land management changes affect ecosystem biogeochemistry and land–atmosphere exchange of carbon, water, and energy (see Ch. 6, p. 27).

Hydroclimate Feedbacks

The humid-subtropical climate of much of the southeastern United States can produce large amounts of precipitation, as well as drive high potential ET. Serving as a critical flux in land–atmosphere interactions, ET is tightly coupled to the water, energy, and carbon budgets of terrestrial ecosystems (see Ch. 7, p. 33). ET effectively competes with streamflow and groundwater recharge for water supplied to the landscape as precipitation. ET, as latent heat flux, can account for a large component of the terrestrial energy budget, with the potential to offset sensible heat flux. Plant transpiration is tightly coupled with carbon uptake through stomatal conductance. Spatial variability in climate and vegetation, along with temporal variability in weather and disturbance, can cause high ET variability.

Land–Atmosphere Coupling and Boundary Layer Dynamics

Interactions between the land and atmosphere strongly impact convective, cloud, and radiative processes. Turbulence and convection mix heat, energy, and moisture in the lower troposphere, creating the planetary boundary layer. The thickness of this layer changes with diurnal and seasonal evolution of temperature and humidity, creating feedbacks to the land surface. Land cover and spatial heterogeneity (e.g., surface roughness gradients and gradients across urban–rural or geomorphic areas) can affect coupling mechanisms by influencing turbulent flow and boundary layer height (see Ch. 8, p. 39). The Southeast also exhibits high biological volatile organic compound (BVOC) emissions, which contribute to high secondary organic aerosol concentrations. As future climate change triggers changes in temperature, vegetation distribution, and growing seasons, BVOC production and light scattering effects will alter vegetation productivity, carbon, and hydrology cycles.

1.3 AMF3 Deployment

The AMF3 deployment to the Southeast, with full operations planned to begin fall 2024, will provide opportunities to improve understanding and model representation of coupled land–aerosol–cloud processes through long-term observations in an environment strongly driven by local forcing (see Ch. 9, p. 45). Located in Alabama's Bankhead National Forest (BNF) (see Fig. 1.1, this page), AMF3-BNF research will focus on three main thrusts: aerosol processes, convective cloud processes, and regional two-way interactions between the land and atmosphere that play a strong role in mass and energy exchange (see Fig. 1.2, p. 4). The deployment seeks to understand how processes such as radiative transfer, canopy-driven turbulence, and land surface heterogeneity influence fluxes of carbon, water vapor, energy, atmospheric boundary layer dynamics, BVOC emissions, and energy and water cycles using model–data integration methods (i.e., ModEx). The AMF3-BNF will produce multiscale observational datasets, value-added products, and synthesis activities that the broad Earth system science community can access through the ARM user facility.

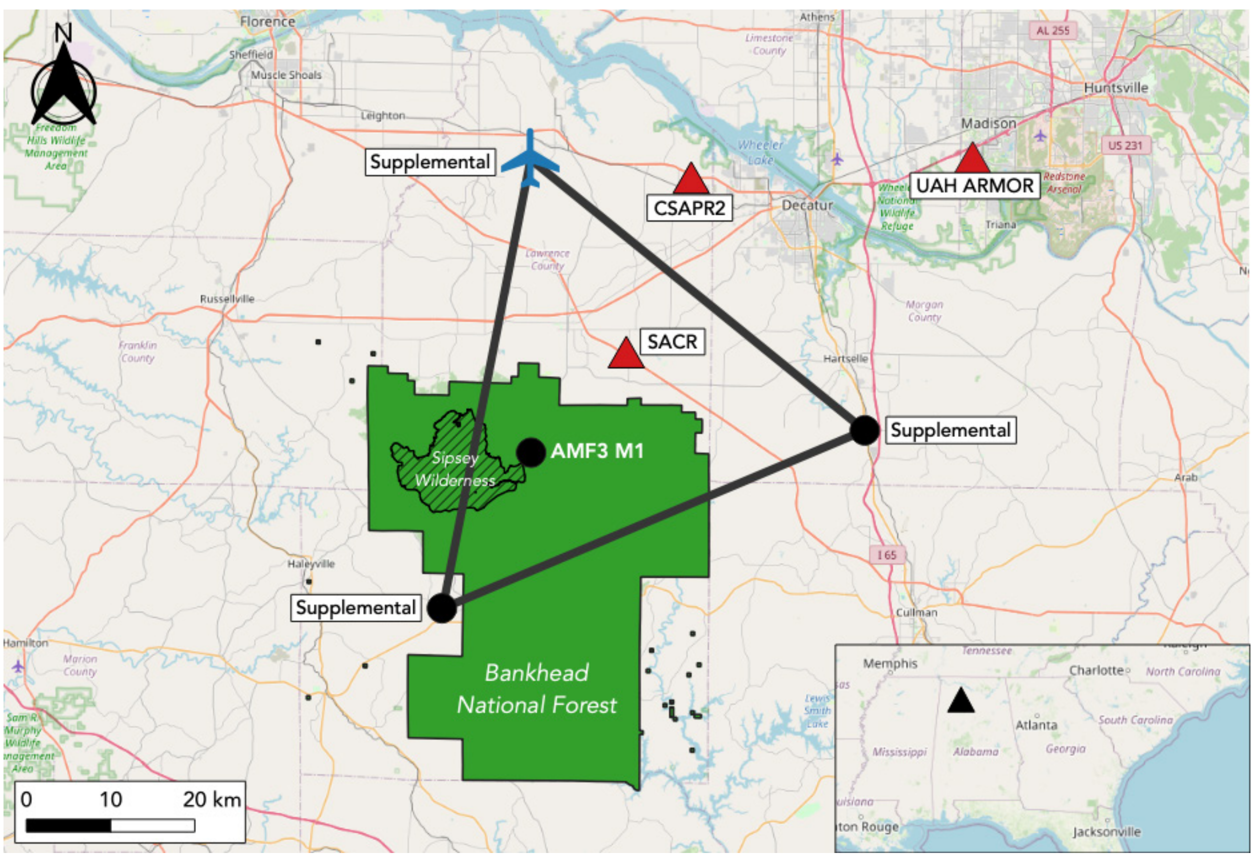


Fig. 1.1 Location of the Third Atmospheric Radiation Measurement Mobile Facility (AMF3). AMF3 is one of three ARM mobile monitoring facilities designed to collect atmospheric and climate data from undersampled and climatically impactful regions around the world. It will begin operations in northwestern Alabama's Bankhead National Forest in fall 2024. The AMF3 5-year deployment, from 2024 to 2029, will monitor the effects of two-way feedbacks among aerosols, clouds, and precipitation on plant physiology and canopy-scale fluxes. [Courtesy Brookhaven National Laboratory]

The deployment will also benefit from leveraging nearby surface networks and partnering with multiple agencies to understand the role of spatiotemporal variability on larger-scale surface and subsurface processes across a diverse landscape. An opportunity exists to coordinate additional research efforts to complement ongoing activities across the region to achieve significant scientific advances. Some opportunities for measurements identified by AMF3-BNF community feedback include fluxes of carbonyl sulfide, carbon, and water; tree physiology and sap flux; heterogeneity in managed forests; soil flux measurements across land transects; soil moisture and groundwater; and remote sensing. More broadly, the AMF3-BNF can provide a testbed for emerging measurement technologies and artificial intelligence/machine learning applications, multiscale products for Earth system model evaluation, accessible analysis and modeling workflows for engaging empiricists with modelers, and multiscale and multidomain remote sensing data products.

These collaborations can help advance crosscutting topics in land–atmosphere interactions. Examples include (1) coupling of the land surface (i.e., vegetation and topography) with aerosol formation, evolution, and transport as well as other atmospheric processes; (2) surface–atmosphere feedbacks; (3) the influence of landscape and vegetation heterogeneity on land-surface modeling; (4) precipitation and ET cycles; (5) the water–energy balance; and (6) the influence of surface dynamics on regional biogeochemistry. The Southeast's diversity of large urban regions also provides an opportunity to advance research into the role of urban systems in local and regional climates and climate changes.

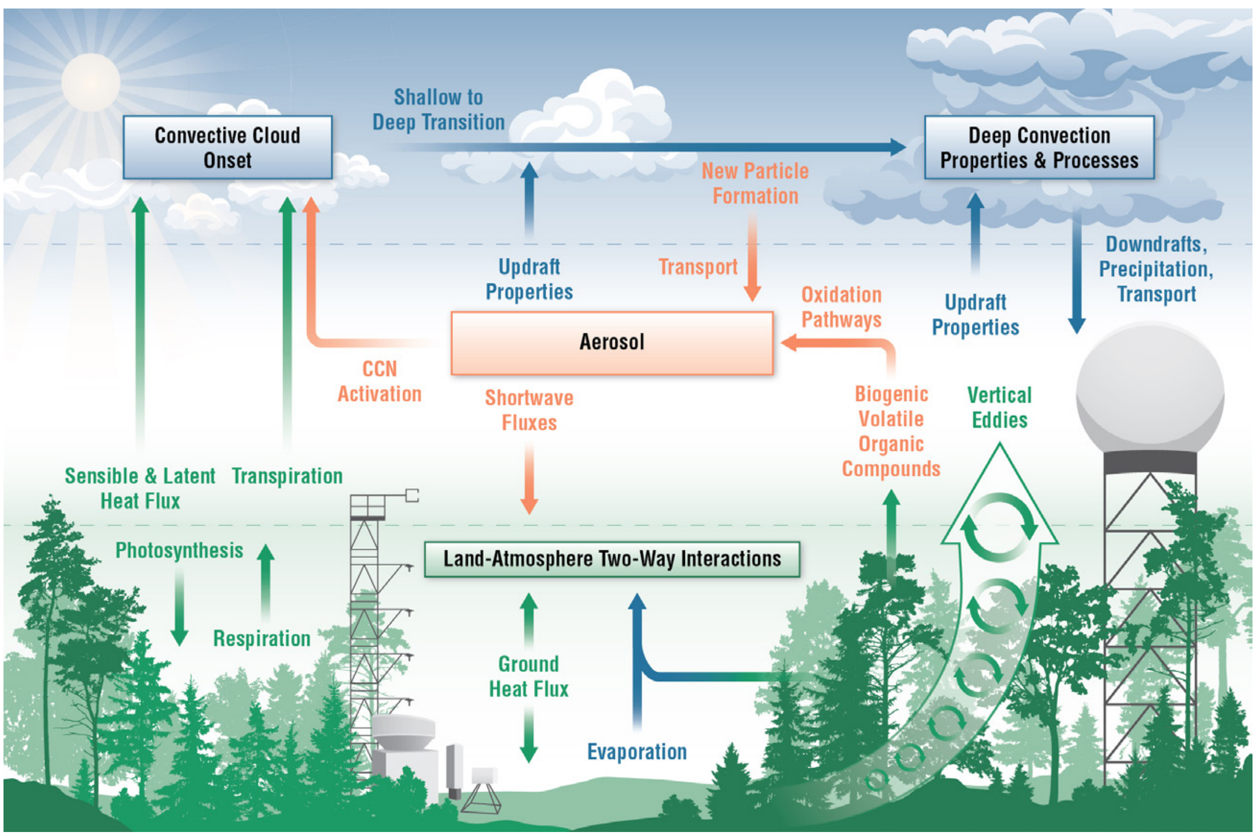


Fig. 1.2. Mass and Energy Exchange from the Land Surface to the Atmosphere. The Atmospheric Radiation Measurement Mobile Facility deployment in Alabama's Bankhead National Forest (AMF3-BNF) presents a unique opportunity to improve understanding and process-level model representation of coupled aerosol, cloud, and land surface processes (e.g., the crosscutting science drivers shown above) in an environment where such processes are strongly driven by local forcing. [Courtesy Brookhaven National Laboratory]

2 Southeast Characteristics, Forces, and Stressors

This chapter describes the geological, pedological, biological, climatological, and anthropogenic forces and stressors occurring in the southeastern United States that influence investigations of the region's current and future land–atmosphere interactions. The Southeast exhibits considerable heterogeneity due to its diverse geologic and weathering history and possesses a broad range of topographies, soil types, ecosystems, hydroclimatic settings, socioeconomic diversity, and land management and history. Landscape characteristics and history, in turn, exert feedbacks on water, energy, and carbon cycles that can drive regional land–atmosphere interactions.

2.1 Geology and Geomorphology

Distinct physiographic regions in the Southeast reflect its underlying geology and subsequent weathering and climate (Vigil et al. 2000; see Fig. 2.1, this page). The region's geomorphic setting is broadly characterized by coastal plain, piedmont, and mountains (see Fig. 2.2, p. 6). All three of these geomorphic provinces occur in Alabama, grading from the state's southern coast to the

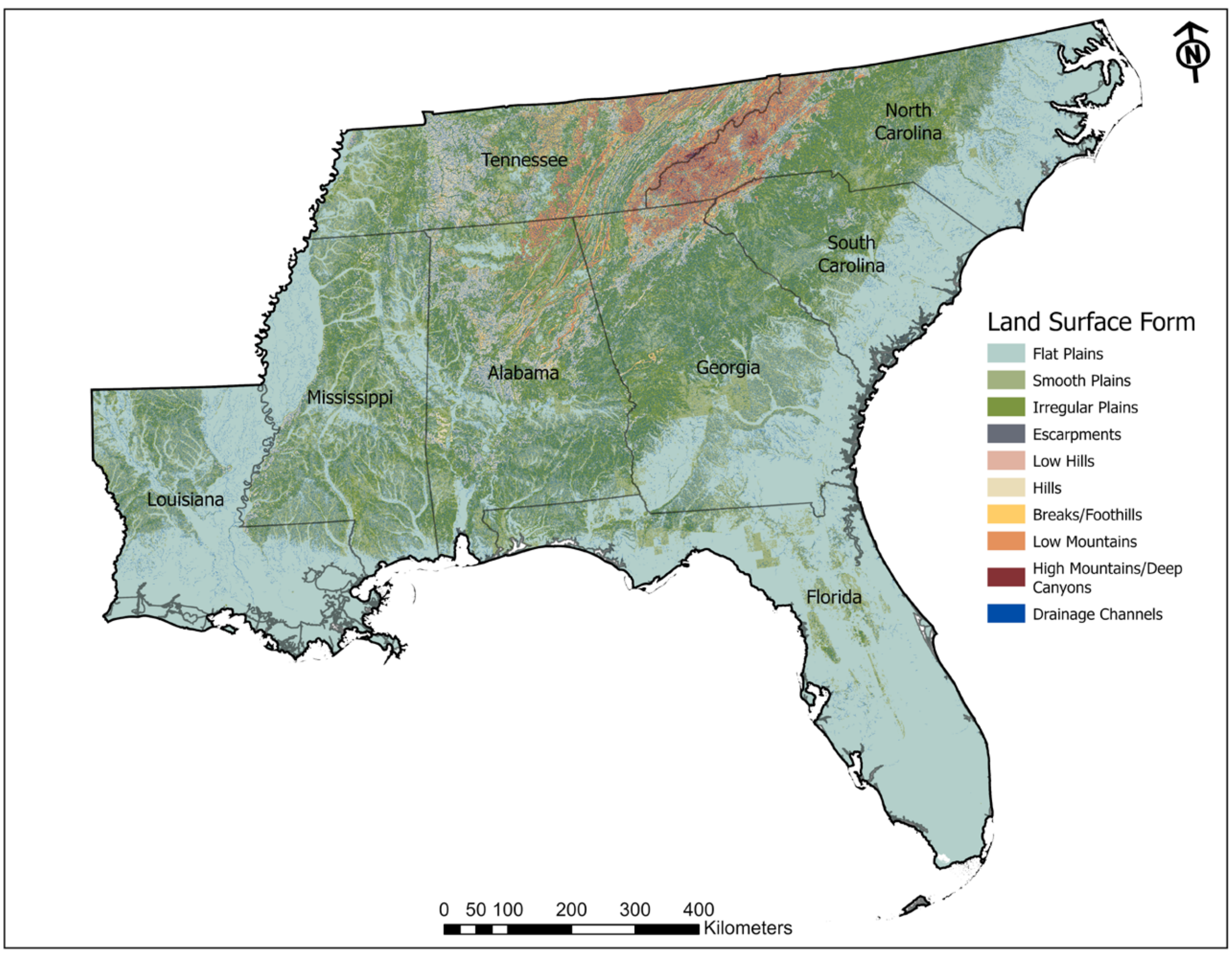


Fig. 2.1. Land Surface Forms of the Southeastern United States. [Courtesy Oak Ridge National Laboratory]

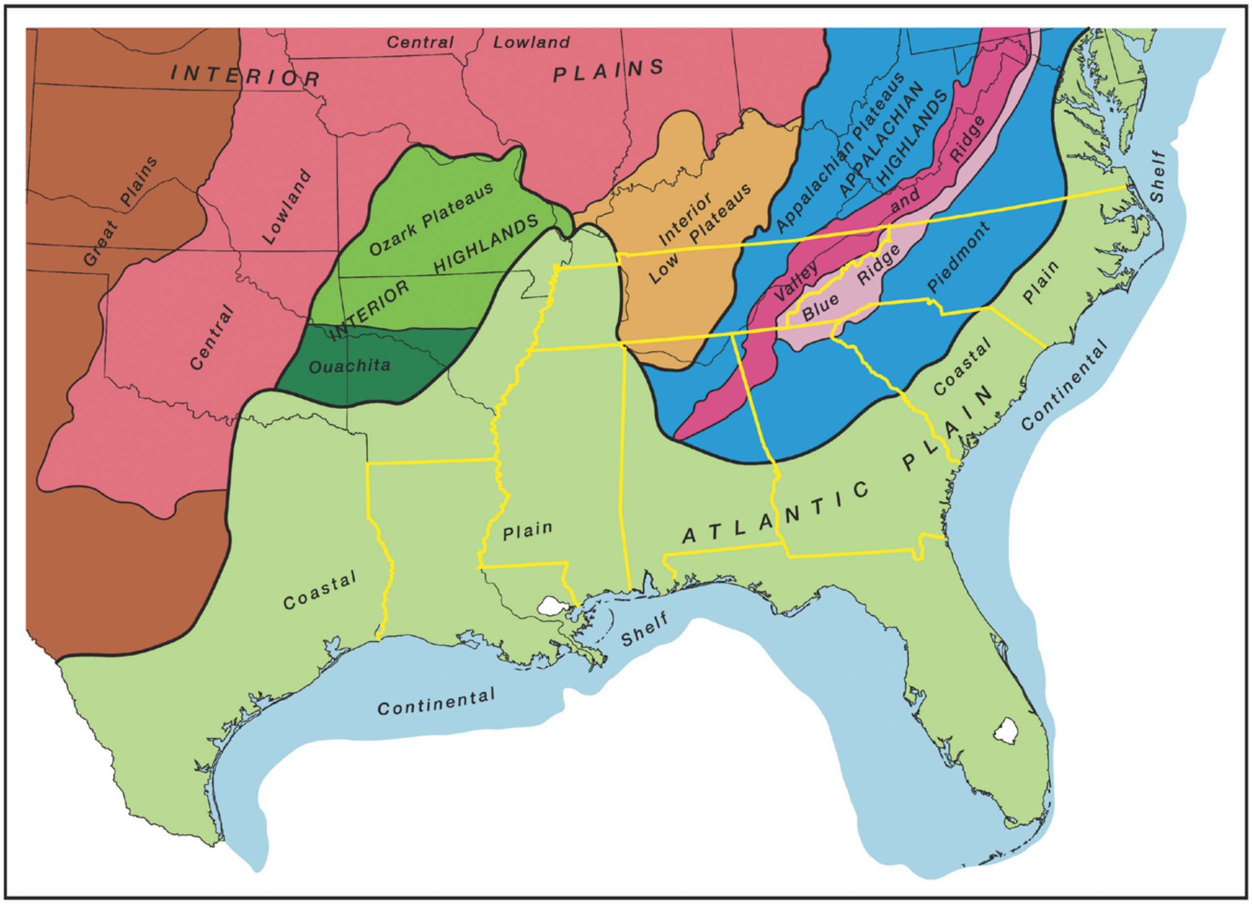


Fig. 2.2. Geologic and Geomorphic Provinces of the Southeastern United States. The study region's eight states (outlined in yellow) contain primarily coastal plain, piedmont, and mountain geomorphologies. Landscape characteristics such as these exert feedbacks on water, energy, and carbon cycles that can drive regional land–atmosphere interactions. [Reprinted with permission from Reynolds, J.W. 2011. "The Earthworms (Oligochaeta: Acanthodrilidae, Eudrilidae, Glossoscolecidae, Komarekionidae, Lumbricidae, Lutodrilidae, Ocnerodrilidae, Octochaetidae, Megascolecidae and Sparganophilidae) of Southeastern United States," *Megadrilogica* **14**(9–12): 175–318.]

Cumberland Plateau and Highland Rim in the north. Mississippi and southern Alabama, Georgia, North Carolina, and South Carolina comprise coastal plain sediments, including both the Mid-Atlantic Coastal Plain and the Southeastern Plain. The Mississippi Valley Loess Plain and Mississippi Alluvial Plain are associated with the Mississippi and Ohio River valleys.

Farther inland, Alabama, Georgia, North Carolina, and South Carolina are underlain by the Piedmont geological province, composed of highly weathered crystalline rocks in the former core of the ancient Appalachian Mountains. The Blue Ridge province, primarily in western North Carolina, consists of metamorphosed sedimentary and crystalline rocks of the ancestral Appalachian Mountains, with current elevations as high as 2,000 m. The Valley and Ridge geomorphic province, extending through eastern Tennessee and northern Georgia and Alabama, consists of folded and faulted sedimentary rocks, resulting in a dissected hilly landscape with abundant river corridors. The Piedmont, Blue Ridge, and Valley and Ridge provinces have each experienced some degree of uplift and mountain-building, followed by intense weathering and erosion fueled by the region's humid subtropical climate.

The Appalachian Plateau, primarily in central Tennessee and northern Alabama, consists of younger sedimentary rocks that have become deeply incised due to regional uplift. The Interior Low Plateaus of central Tennessee and northern Alabama consist primarily of flat-lying limestone rocks.

2.2 Soils

The predominance of folded and faulted geologic materials, coupled with intense precipitation and long exposure of the land surface, has created deeply weathered profiles in the northern parts of the Southeast. This area was not glaciated during past ice ages and, consequently, has been exposed to weathering for hundreds of millions of years. Soils are therefore often rich in clays, iron, and aluminum hydroxides and have low pH and low cation exchange capacity. Several Southeast states are dominated by Ultisols exemplifying these characteristics: Georgia, Alabama, Tennessee, North Carolina, and South Carolina (see Fig. 2.3, this page).

Alfisols are more common near the western borders of Mississippi and Tennessee and are associated with

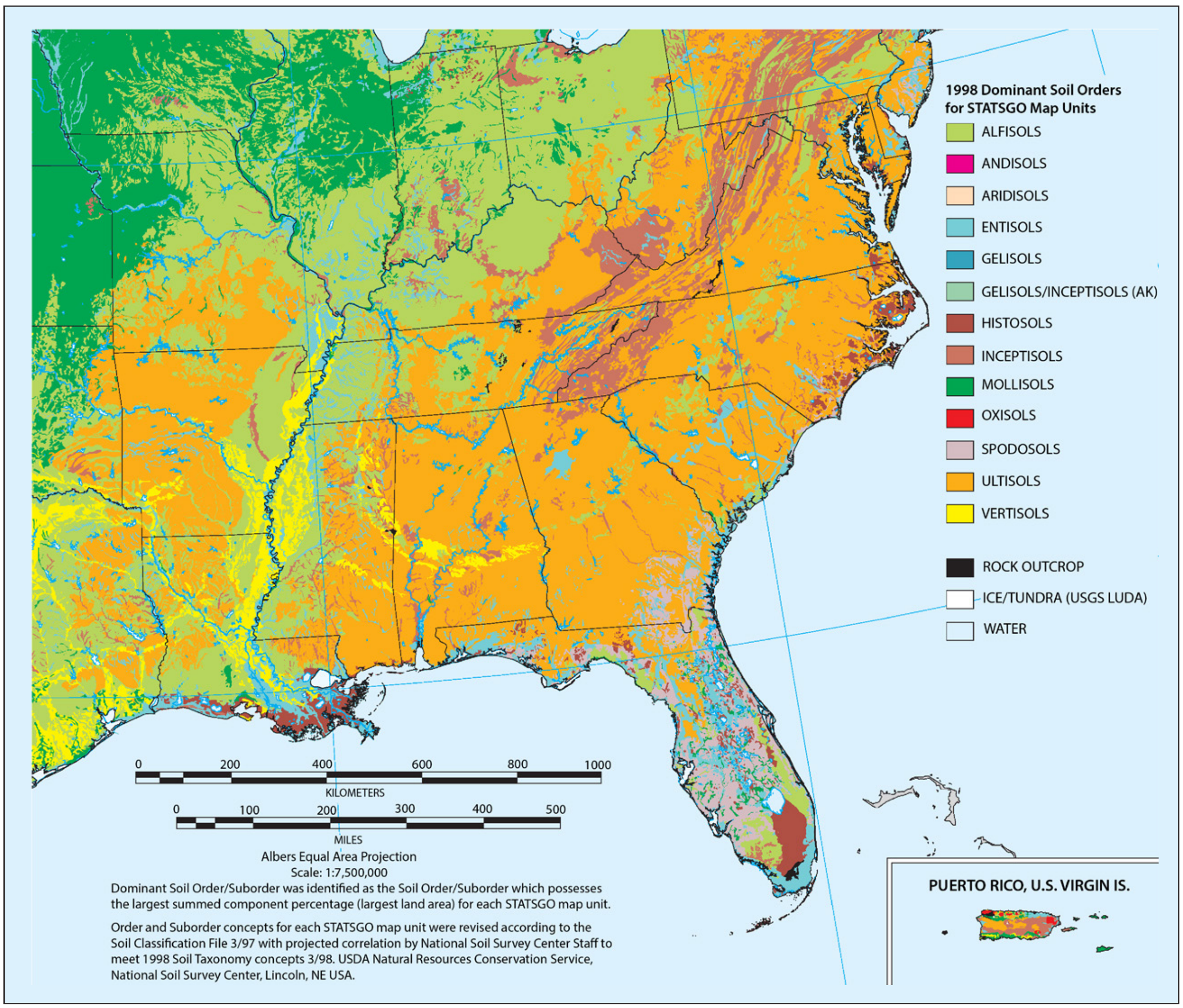


Fig. 2.3. Distribution of Soil Orders Across the Southeastern United States. [Courtesy U.S. Department of Agriculture]

weathering of glacial loess from the Mississippi River floodplain and environs. Inceptisols are especially common in the Blue Ridge province due to a combination of steep topography and high precipitation. Inceptisols are also found at more dynamic topographic positions throughout the Valley and Ridge and Appalachian Plateau provinces and in stream valleys in the Coastal Plain province. Spodosols are common in pine forests across Florida and southeastern Georgia. Central Florida also contains Mollisols. Histosols are common in parts of Florida and the North Carolina coastal wetlands. Entisols are common in coastal and inland wetlands and near coastal environments such as the sand hills of longleaf pine forests.

The Southeast has served as a major carbon sink over the past century, averaging 13.5 kg C per m^2; climate simulations suggest that these trends will persist into the future (Song et al. 2013). Erosion due to historical land use (e.g., agriculture and logging) has compromised many Southeast soils, resulting in deep erosional profiles and topsoil removal. Land use history (e.g., intensive agriculture, forest management, urbanization, and dam or reservoir management) is a major factor governing soil and soil carbon storage characteristics.

2.3 Climate

The Köppen climate classification system characterizes the Southeast as warm temperate, with mountain temperate or humid continental climate in the high Blue Ridge Mountains and equatorial at the southern tip of Florida. The Florida peninsula has a distinct summer rainy season while the rest of the Southeast receives more uniform yearly precipitation. Precipitation varies considerably, ranging from 100 to 125 cm per year, with areas of the Gulf Coast exceeding 150 cm per year and southern Appalachian Mountains exceeding 200 cm per year (PRISM Climate Group). Increased precipitation from larger and more frequent storm events significantly increases flooding risks (U.S. Climate Resilience Toolkit).

The entire Southeast region is susceptible to hurricanes and tropical storms from June through November from both the Gulf of Mexico and the Atlantic Ocean. In addition to thunderstorms and tornadoes resulting from other sources, such as severe convection associated with southerly flow and tropical storms, the convergence of weather systems from the inland United States with warm and humid air from the Gulf of Mexico results in predominant strong thunderstorms and tornadic activity. Tornadoes tend to be spatially sporadic but devastating in their target areas. In the winter, snow, ice storms, and blizzards may occur. However, the region is also susceptible to droughts, especially in La Niña years. Drought and extreme precipitation events may occur simultaneously, imposing uncertain interactions among hydrologic and biogeochemical processes.

2.4 Vegetation

Southeast vegetation is highly diverse due to the region's widely diverse geologic, climatic, and topographic environments (see Fig. 2.4, p. 9). The shallow continental slope of the coastal region creates vast expanses of wetlands and tidal and near-tidal environments. Coniferous forest and forested wetlands tend to dominate the Coastal Plain province, which contains many areas of managed forest for pulp, paper, and pellets; yet biodiversity remains high across the region (Noss et al. 2015). In the Piedmont province, former cotton farms have given way to timbering operations (Nagy and Lockaby 2010). Southeastern forests, which cover 62% of the region, comprise 27% of total U.S. forests, most of which are owned by private corporations (Oswalt et al. 2014). In the northern portions of Mississippi, Alabama, and Georgia and in western North Carolina and most of Tennessee, broadleaf deciduous forest dominates. The highest mountain peaks may support northern conifers such as spruce and fir. Florida has a higher proportion of grasslands and grass wetlands than other regions of the Southeast.

Managed vegetation is common throughout the Southeast. For example, fire and fire management are common land treatments, particularly in the Coastal Plain and Piedmont provinces where many forest ecosystems depend on fire to control understory growth and promote seed germination. Traditional row crop agriculture tends to dominate river bottoms and floodplains throughout the Southeast and in central Florida.

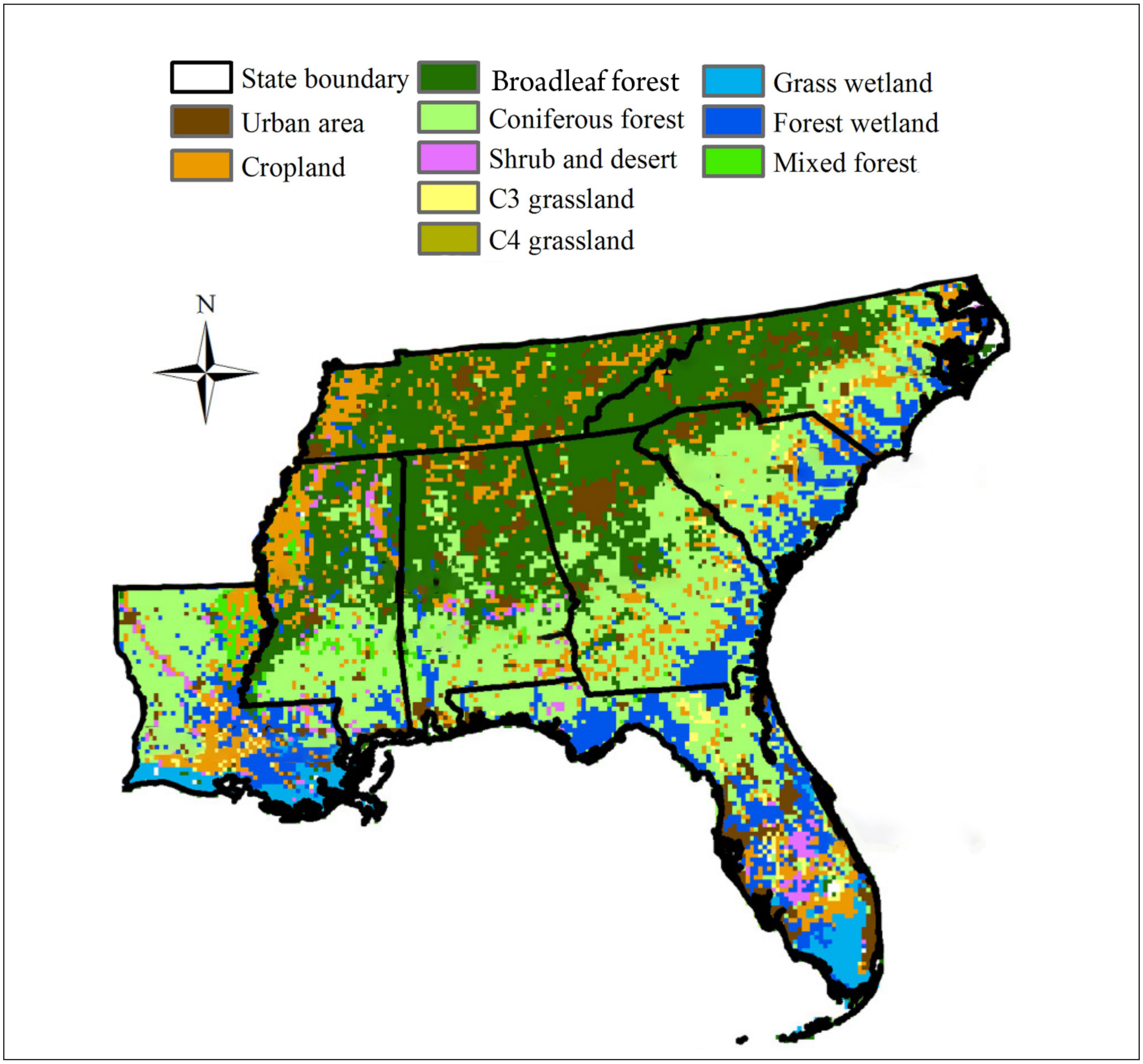


Fig. 2.4. Distribution of Major Vegetation Classes Across the Southeastern United States. [Reprinted under a Creative Commons License (CC-By-3.0) from Song, X., et al. 2013. "Projecting Terrestrial Carbon Sequestration of the Southeastern United States in the 21st Century," *Ecosphere* **4**(7), 1–18.]

Animal production is also common throughout the Southeast. Farms may be small-scale and nestled within the Valley and Ridge province or more expansive as in the traditional Black Belt of the Deep South.

The Southeast is particularly well-known for its high diversity of plants, animals, insects, and aquatic life. In the early 20th century, forest composition changed significantly with the loss of the American Chestnut, widespread timber extraction, and wildfires resulting from accumulated slash. However, vegetation has rapidly recovered, and carbon sequestration is responding positively to nitrogen and carbon dioxide (CO_2) fertilization with soils responsible for uptake in coniferous forests and biomass in deciduous forests (Song et al. 2013).

The introduction of non-native insects and fungal pathogens continues to impact southeastern forests (e.g., Emerald Ash Borer, Hemlock Wooly Adelgid, Thousand Cankers Disease affecting black walnuts, and Beech scale). Additionally, invasive plants (e.g., Princess tree, Tree of Heaven, Mimosa tree, kudzu vine, honeysuckle vine, bush honeysuckle, Japanese barberry, English ivy, and Bradford pear trees) are changing forest and, particularly, understory compositions.

The Southeast landscape is a mosaic of uplands (i.e., forest and agriculture), wetlands, open water, and urban areas. The region contains approximately 47% of all wetlands in the conterminous United States and nearly 91% of coastal wetlands. These wetlands serve as critical hotspots within the landscape for water quality and runoff amelioration but also produce greenhouse gases. The soil water regime regulates biogeochemical processes through a complex microtopography setting. These zones of land–water interactions are sensitive to conditions and activities in the surrounding landscape; however, relatively few measurements capturing these interactions exist. Correspondingly, considerable uncertainties exist regarding the functionality of restored wetlands.

3 Spatial Heterogeneity

High spatial heterogeneity in the Southeast has influenced weather and climate patterns, biogeochemistry, and biota, creating regional biodiversity hotspots. The SELARO workshop discussion identified two overarching knowledge gaps within the topic of spatial heterogeneity that will be important for improving understanding of land–atmosphere interactions and prediction of these interactions under future anthropogenic and biophysical conditions. These gaps are summarized as topical grand challenges at the end of this chapter: (1) how to identify parameters that capture and represent processes across scales in a diverse and spatially heterogeneous landscape and (2) how landscape heterogeneity influences surface–atmosphere coupling that in turn affects regional climate (see Spatial Heterogeneity Grand Challenges, p. 14).

3.1 Forces Contributing to a Heterogeneous Southeast Landscape

Complex multifactor interactions generate a land cover and land use mosaic across the Southeast and within each of its physiographic areas. Landscape heterogeneity gives rise to potential variability in land surface–atmosphere interactions, which, in turn, affects local and regional climate by influencing surface–aerosol interactions, changing water and energy cycles, and driving shifts in boundary layer dynamics.

Covering nearly 1.4 million km^2, the Southeast is characterized by heterogeneous topography, soils, ecosystems, and human land use over long and short spatial scales (see Fig. 3.1, p. 12). The region's physical geography arises from interactions among several important gradients. For example, strong gradients in mean annual temperature and precipitation in its various physiographic areas (i.e., Appalachian Mountains, piedmonts, and coastal plains) are driven by latitude, distance from the sea, and elevation. At coarse scales, soils, ecoregions, and land use follow these gradients.

However, pre- and post-colonial land use has created legacies of burning, farming, and settlements that have contributed to a mosaic landscape that continues to define the region. Forests cover 62% of land area in the Southeast (Bigelow and Borchers 2017), but they are significantly temporally and spatially variable (Nedd and Anandhi 2022) due to a high proportion of intensively managed plantation forests on short rotation cycles (Hansen et al. 2013). The region's high fraction of privately owned land, expanding suburban development, and small management units further contribute to a patchwork of land covers that vary significantly in physical structure.

The Southeast once hosted vast stands of fire-adapted pine and oak forests, savannas, and grasslands interspersed with lowland and riparian forests and wetlands. Today, the region's highly fragmented landscape is defined by agricultural production, commercial plantations, and abandoned lands in various stages of regrowth. Private land ownership prevails over public ownership. The rapid expansion of transportation networks and urban, suburban, and exurban areas has further reduced the patch size of natural vegetation (Griffith et al. 2003). In addition, the Southeast has experienced strong economic and population growth, eliciting shifting demands for natural resources.

3.2 Feedbacks in a Heterogeneous Landscape

The Southeast's spatial heterogeneity affects the balance of carbon, water, and energy fluxes as well as local and regional patterns in ecosystem biogeochemistry. Because this heterogeneity also complicates efforts to generalize, model, and predict processes (Song et al. 2013), the Southeast is an ideal location to study how to upscale model parameters and represent processes across diverse landscapes.

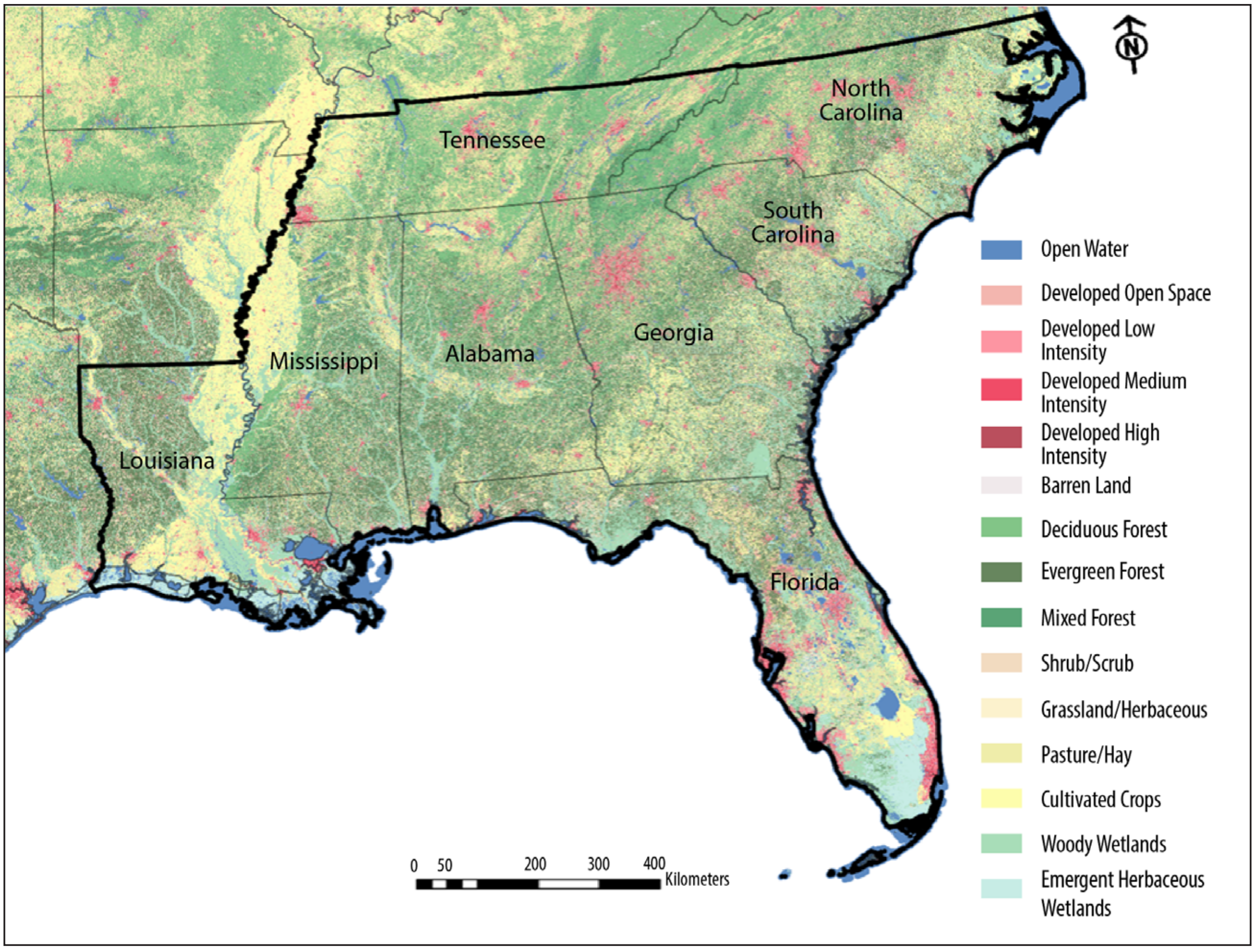


Fig. 3.1. Land Cover Types in the Southeastern United States. The targeted study area for land–atmosphere research opportunities (outlined in bold black) covers nearly 1.4 million km^2 and is characterized by heterogeneous topography, soils, ecosystems, and human land use, shown here from the National Land Cover Database. [Courtesy U.S. Geological Survey]

Hydrological Feedbacks

The effects of contemporary landscape spatial heterogeneity on hydrological flow regimes and associated biogeochemical processes are uncertain. Expanding residential, commercial, and industrial developments across contemporary landscapes in the Southeast are increasing landscape coverage by impervious surfaces, including water-resistant paved areas like roads and parking lots, business and industrial complexes such as airports and distribution centers, and soils compacted by urban development (see Fig. 3.2, p. 13). This expansion is shifting peak hydrologic flows, increasing chemical runoff, and altering hydrologic pathways.

Uncertainties associated with spatial heterogeneity manifest at scales ranging from less than 10 m^2 to greater than 100 km^2. At the large scale, these uncertainties relate to how the spatial arrangement of land-use types affects watershed-scale processes. Due to the rapid expansion of urban and suburban areas, these impacts are particularly important yet often excluded from many watershed-scale simulations.

At the small scale, microtopographic differences at the soil surface may exhibit distinct biogeochemical patterns, particularly at sites that experience seasonal or periodic fluctuations at the water table. The fine spatial

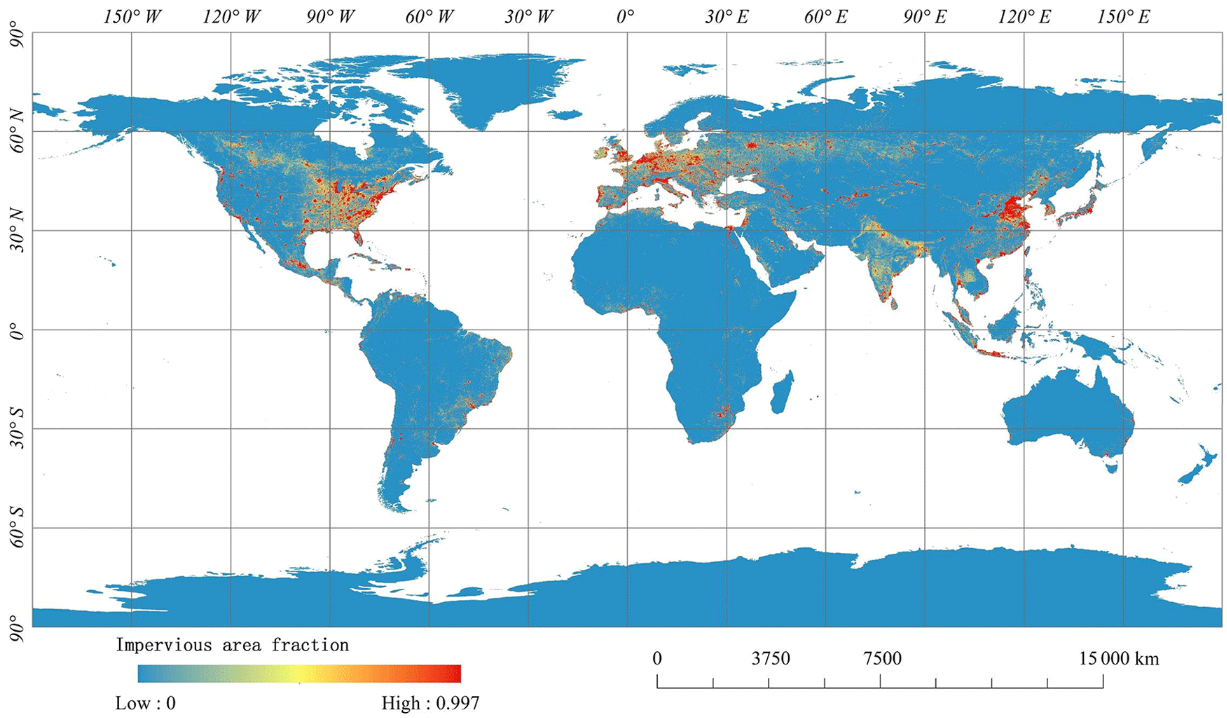


Fig. 3.2. Map of Soils Compacted by Urban Development. Impervious surfaces are particularly prevalent in the southeastern United States compared to the rest of the country. This global 30-m impervious surface map was created using multisource and multitemporal remote sensing datasets with the Google Earth Engine platform (copernicus.org). [Republished under a Creative Commons License (CC BY 4.0) from Zhang, X., et al. 2020. "Development of a Global 30 m Impervious Surface Map Using Multisource and Multitemporal Remote Sensing Datasets with the Google Earth Engine Platform," *Earth System Science Data* **12**(3), 1625–48. DOI:10.5194/essd-12-1625-2020.]

and temporal scales characteristic of key biogeochemical or hydrological processes in the Southeast pose challenges to their representation in models. For example, subsurface soil heterogeneity can drive biogeochemical processes but is not typically considered in modeling applications. Improving models requires understanding how patch-scale processes aggregate upwards across a diverse landscape mosaic and how changes in landscape heterogeneity affect aggregate outcomes in biogeochemical cycling.

Land–Atmosphere Feedbacks

Interactions among land use intensification, increased landscape fragmentation, and climatic variability create outcomes in land–atmosphere interactions that are increasingly challenging to predict from past observations. SELARO workshop participants identified several research gaps that would help improve future predictions.

Increased spatial heterogeneity in the landscape affects processes that control the exchange of mass and energy between the land and atmosphere, with ramifications for local to regional climate. The research community is greatly interested in understanding how this heterogeneity affects land surface–atmosphere coupling, surface fluxes, surface temperature, and humidity as well as how boundary layer formation impacts climate in different physiographic zones across the Southeast.

Research challenges include understanding the effects of fine-scale landscape heterogeneity on cloud formation processes or, inversely, attributing large downstream phenomena, such as convective cloud characteristics, to specific land cover types. Particular challenges involve identifying vegetation metrics that affect land–atmosphere feedbacks (e.g., leaf area index) and collecting data at the scales and resolution needed for process-based modeling.

Albedo is sensitive to different vegetation types as well as management activities, such as prescribed fire and crop harvesting. These factors affect the land–atmosphere energy balance and the partitioning of net radiation into latent, sensible, and soil heat fluxes. Land cover types also differ in their (1) canopy physiology, (2) production of greenhouse gases (e.g., carbon dioxide, methane, and nitrous oxide), (3) emissions of biogenic volatile organic compounds, and (4) aerosol formation. Therefore, it is necessary to explore how spatiotemporal variation in land cover explains differences in bottom-up versus top-down (inversion) greenhouse gas budgets in the Southeast.

Topographic and edaphic variability add an additional source of heterogeneity, contributing to differences in soil moisture and water availability. Increasing climate variability and growing economic pressure have led to greater use of irrigation in both row crop agriculture and forestry, which stresses aquifers and influences the boundary layer and local climate.

The following list of grand challenges emerged from the workshop discussion on spatial heterogeneity described in this chapter.

Spatial Heterogeneity Grand Challenges

How can parameters be identified to capture and represent processes across scales in a diverse and spatially heterogeneous landscape?

- How does landscape heterogeneity influence aggregate outcomes in biogeochemical cycling?
- How do patch-scale processes aggregate upwards across a diverse landscape mosaic?
- At what scale must various properties and processes be represented to simulate the coupled ecosystem–land–atmosphere interactions that control local, regional, and global climate?

How does landscape heterogeneity influence surface-atmosphere coupling (i.e., surface fluxes, surface temperature, humidity, and boundary layer formation), which in turn affects climate in the Southeast's different physiographic zones?

- How does fine-scale land cover heterogeneity affect cloud formation processes?
- What are the critical scales at which vegetation structure affects land–atmosphere feedbacks?
- How does spatiotemporal variation in land cover explain differences in bottom-up versus top-down greenhouse gas budgets in the Southeast?

4 Climate Change

Climate change in the Southeast is expected to manifest with subtle but important differences from much of the rest of the globe. SELARO workshop participants discussed these differences, targeting specific ways that climate change will affect vegetation and ecosystem responses to temperature and precipitation changes in the Southeast. Participants' discussions of projected climate change effects in the Southeast revealed key knowledge gaps that can provide opportunities for further research (see Climate Change Grand Challenges, p. 19). These challenges are further discussed throughout this chapter and include (1) advancing understanding of how climate change will impact vegetation and ecosystem responses in the Southeast, (2) linking soil and plant processes to the atmosphere to understand climatic drivers on ecosystems, and (3) making improvements to models to capture high-resolution spatiotemporal data for temperature and precipitation needed to address these challenges.

4.1 Temperature Changes and Vegetation Responses

The Southeast's climate is changing, with current projections suggesting a lower rise in temperature in the Southeast compared to other areas of the country (U.S. NCA 2023; Carter et al. 2018; Kupfer et al. 2020). However, the associated increase in atmospheric moisture demand, combined with altered precipitation and storm regimes, will create novel conditions throughout the region. A U.S. Department of Agriculture (USDA) map of plant hardiness zones shows profound changes in the geographic ranges of different zones when the averages of two time periods were compared: 1976–2005 and 1991–2020 (see Fig. 4.1, p. 16). This zonal change map shows a northward progression of average annual extreme minimum temperatures across most of the Southeast, suggesting that areas warmed 0 to 3°C between the two time periods. Thus, despite the slow climate warming trend noted in the Fourth National Climate Assessment (NCA4; U.S. NCA 2023), the USDA map strongly indicates that climate warming is affecting Southeastern ecosystems.

Under the highest level of projected future warming, plant hardiness zones are expected to shift even farther (see Fig. 4.2, p. 17), and the Southeast's freeze-free season will increase by more than a month, with fewer below-freezing temperatures (Carter et al. 2018). During the 2010s in the Southeast, the minimum number of nights with temperatures over 24°C was almost double the average from 1901 to 1960, and the freeze-free season was nearly 1.5 weeks longer than any other period in the record (Carter et al. 2018). In the Representative Concentration Pathway 8.5 scenario, nighttime minimum temperatures over 24°C and daytime maximum temperatures above 35°C will become typical in the Southeast (Carter et al. 2018; U.S. NCA 2023). The number of cooling degree days will almost double, and heating degree days will decrease by one-third. Consequently, studies examining the role of increased temperatures on vegetation growth and productivity are important to illuminate current and future changes in the Southeast. Possible studies include investigations into the impacts of and responses to extreme seasonal events (e.g., late frosts, early freezes, and droughts) and urban heat waves and heat islands on vegetation and ecosystem processes.

Responses of Vegetation and Ecosystems to Changing Temperatures

Extreme Seasonal Events

Both longer growing seasons and increased average winter temperatures can affect the ability of plants to achieve dormancy needed for bud production. Early budbreak in the spring carries a risk of normal spring freezes destroying the current year's buds (Gu et al. 2008), which can impact agricultural production of economically important southeastern perennial crops, including oranges, peaches, and blueberries. Therefore, studies examining the occurrence and long-term outcomes of extreme seasonal events (e.g., late frost

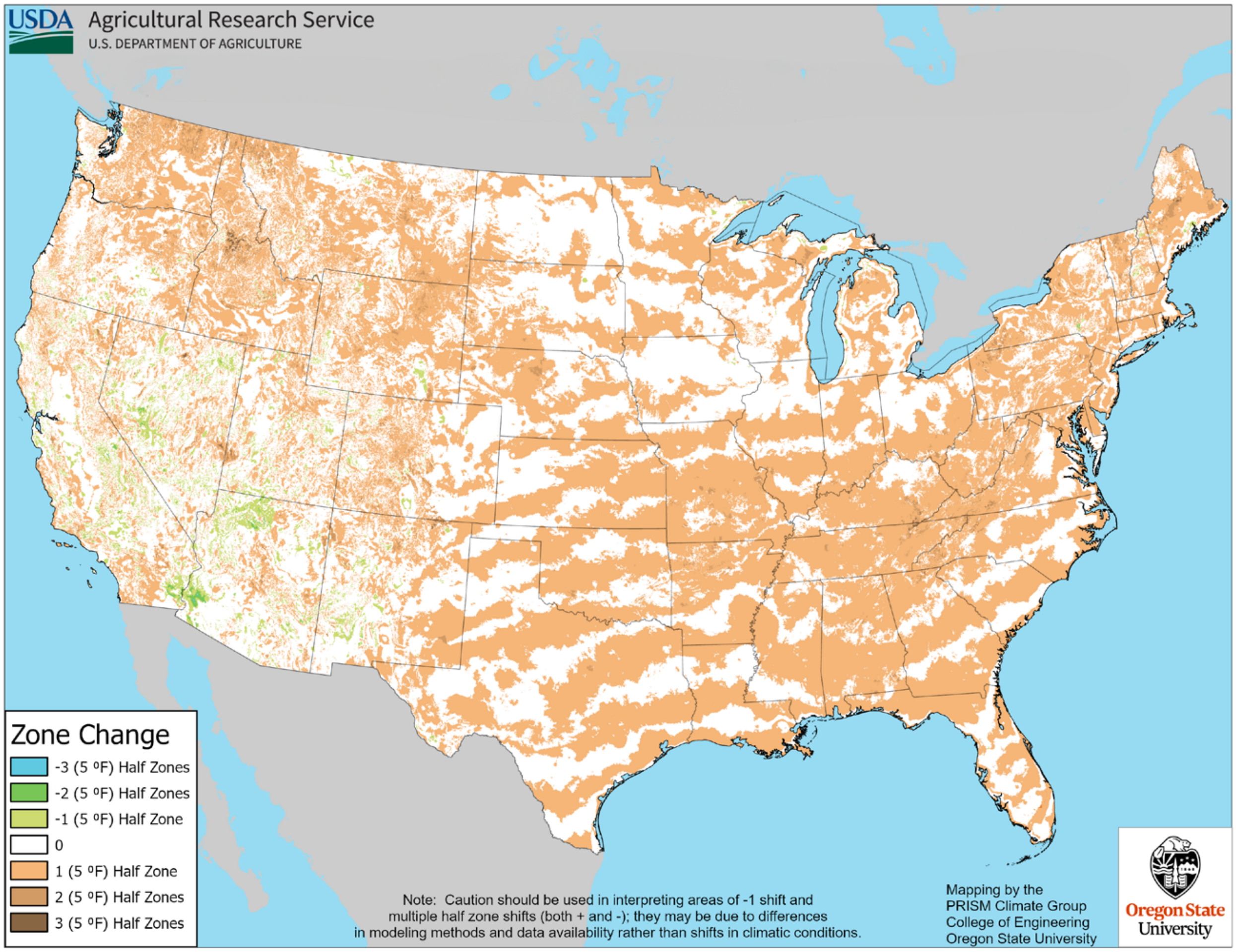


Fig. 4.1. Changes in Plant Hardiness Zones in the Southeastern United States. A comparison of hardiness zones during 1976–2005 with those during 1991–2020 suggests that climate change has driven a northward migration of plant hardiness zones by about half a zone in much of the Southeast. [Courtesy U.S. Department of Agriculture and Oregon State University]

and early freeze) would aid in understanding the risks imparted by these kinds of events on economic and agricultural productivity in the Southeast. Finally, a priority for coupled climate model studies should be evaluating the climate resilience of southeastern ecosystems by using the best possible representations of temperature and drought stress on plant physiology under elevated atmospheric carbon dioxide.

Urban Heat Waves and Heat Islands

More than 60% of major cities in the Southeast have experienced worsening heat waves since 1961—the highest percentage of any region in the United States (Hadeeb et al. 2015). Urban and suburban corridors are especially prone to periodic and severe heat waves (Nagy and Lockaby 2011). In particular, elevated nighttime temperature is a symptom of the urban heat island effect, in which urban areas experience warmer temperatures than surrounding rural areas due to less vegetation and higher concentrations of infrastructure that absorb and re-emit the sun's heat (U.S. EPA 2024).

Urban heat waves in the Southeast are further compounded by historic inequalities (Tuccillo and Spielman 2022), which have led to lower tree cover and higher urban heat islands in poorer, minority-occupied neighborhoods relative to more wealthy white neighborhoods (Muse et al. 2022; Elmore 2010; Spielman et al. 2020). Migration from rural to urban areas has intensified in recent years (Carter et al. 2018), potentially exacerbating these patterns. Poor communities, particularly those in the Southeast, are likely to suffer greater economic losses and health risks from climate change (Hsiang et al. 2017). Because the processes that generate and dissipate heat and moisture are expected to vary across rural–urban transition areas, understanding how ecosystem processes either moderate or exacerbate the urban heat island is important. In particular, studies are needed that implement stressors representative of extreme climate change projected for this region. Such research would help planners in the Southeast mitigate expected impacts due to climate change.

4.2 Precipitation Changes and Ecosystem Responses

Changes in moisture are the most important climatic perturbation affecting the Southeast (Pedersen et al. 2015). While overall precipitation levels are not expected to change, precipitation is expected to become more variable with an increase in frequency and severity of events (Carter et al. 2018; Perica et al. 2013). Specifically, more than 70% of precipitation-recording stations in the Southeast show an increase in extreme events, which are defined as the number of days with greater than 3 inches of precipitation.

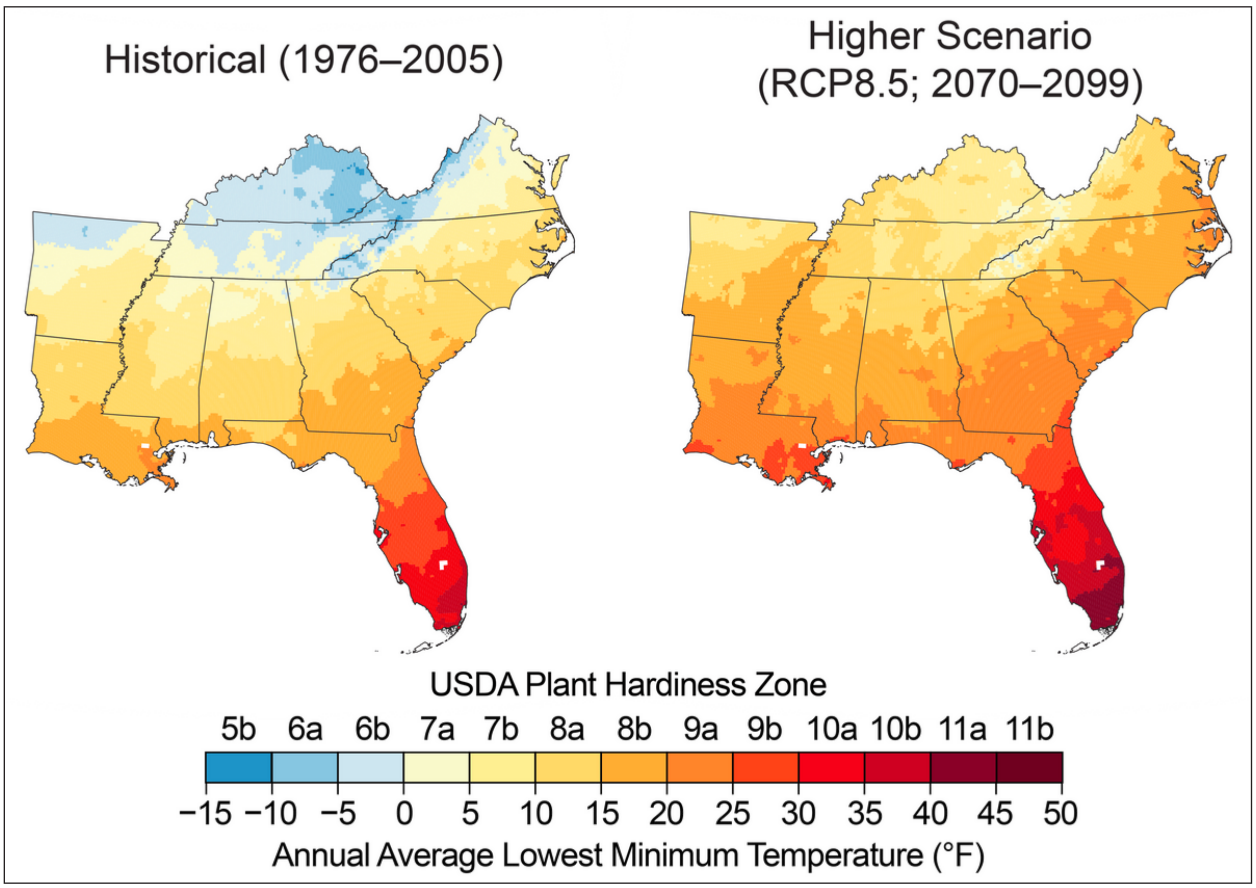


Fig. 4.2. Projected Plant Hardiness Zones for the Southeast. Drawing on U.S. Department of Agriculture plant hardiness zone data, the Fourth National Climate Assessment (NCA4) compares historical zones from 1976 to 2005 **(left)** with projected zones for 2070 to 2099 **(right)**. In this higher Representative Concentration Pathway (RCP) 8.5 scenario generated by NCA4, rising temperatures in the Southeast will cause plant hardiness zones to continue trending northward and upslope over the next 75 years. [Courtesy U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, National Centers for Environmental Information, and Cooperative Institute for Climate and Satellites–North Carolina]

Larger precipitation events are being observed in the fall and winter, and storm intensity coupled with elevated humidity can result in flooding in river corridors, mountains, and urban environments. From 2014 to 2016, four major inland flooding events occurred in the Southeast (NOAA NCEI 2018). Strong evidence also suggests that hurricanes are more intense and retain strength over greater distances inland, meaning they remain hurricanes for longer and reach farther into the Southeast (Li and Chakraborty 2020). Therefore, research is needed to evaluate whether trends of increasing flood frequency and hurricane extent will continue.

However, predictions from the Coupled Model Intercomparison Project Phase 5 (CMIP5) downscaled models suggest increasing cool-season drought throughout much of the region (Keellings and Engstrom 2019). In the future, more intense but less frequent storms could not only result in increased flooding but also promote more frequent drought conditions, particularly in the summer. These impacts will result in more extreme and fluctuating hydrology as well as longer droughts and could possibly accelerate land cover shifts toward more seasonal and drought-tolerant vegetation. The rest of this section explores precipitation changes and ecosystem responses in more detail and offers potential approaches for further investigation.

Responses of Biogeochemical Functions, Water Supply, and Plant Productivity to Extreme Events

The changes to dominant forest species composition, tree encroachment into grasslands, and land aridification already occurring in the Southeast are expected to intensify under different future climate scenarios (Bachelet et al. 2001). Extended droughts have been observed in recent history (e.g., 1897, 1899, 1904, 1931, 1951 to 1954, 1997 to 1999, 2007 to 2008, and 2016) with increasing frequency (Williams et al. 2017). Additionally, water cycle changes are already affecting irrigation patterns and can further impact land–atmosphere interactions, particularly during droughts. As a result, the timing and amount of available water to support ecosystem processes could change. For example, increasing evapotranspiration due to higher temperatures could reduce available soil water, and the high proportion of runoff resulting from intense storms may fail to adequately recharge soil moisture.

Changes in precipitation and temperature regimes can also alter aerosol production, transport, and dissemination. Research investigating changes in precipitation and soil moisture (particularly the effects of extreme events such as drought or flooding) is needed to better constrain the risk to biogeochemical functions, water supply, and plant productivity. In particular, studies that link soil and plant processes to atmospheric outcomes, such as aerosol production and transport, would improve understanding of the mechanisms underpinning control over these key processes.

Consequences of Wetlands Undergoing Hydrological Transformations

Southeastern wetlands are particularly sensitive to changes in the local water balance. For example, relatively small alterations in aerated soil volume may induce large changes to carbon dynamics. However, relatively few measurements of greenhouse gas emissions exist to support modeling and emissions reporting. Despite the widespread distribution of highly hydrologically altered alluvial wetlands in the Southeast, little is known about the consequences and feedbacks on regional atmospheric fluxes.

Improvements to Hydrological Predictions Using High-Frequency, High-Resolution Climate Data

A critical gap in predicting hydrological responses and the associated changes in biogeochemical processes due to climate change is the availability of high-resolution (e.g., hourly) future climate data at the 1-km grid scale. This information could advance understanding of local to regional convective processes that increase the probability of severe storms and tornadoes. Furthermore, models of rainwater recycling and near-surface latent heat fluxes over the Southeast's heterogeneous terrain could improve predictions of storms that threaten human safety.

4.3 Climate Change Interactions with Other System Disturbances

Effects of climate change cannot be viewed independently from land use, land management, and other disturbances. The effects of recent anthropogenic disturbance and land management (e.g., logging and fire exclusion) dominate vegetation changes in the Southeast, resulting in ecosystems in climate disequilibrium (Nowacki et al. 2015). Because differentiating the effects of climate change from other factors is often difficult, considerable uncertainty remains about the composition and function of future ecosystems. Further investigation is also needed into how wildfires and prescribed fires that occur in southeastern agricultural areas, managed forests, and wetlands are impacted by climate.

Climate Impacts on Fire in the Southeast

Changing climate is also expected to affect wildfire and prescribed fire impacts on the landscape. As recently as 2016, a regional fall drought resulted in an unusually severe wildfire outbreak across the Southeast (Carter et al. 2018). The 2017 Okefenokee Swamp fires also highlight the risk that wildfires pose to the large carbon stocks in southeastern coastal swamps. Prescribed fire is one of the primary tools for managing fuel loads and vegetation. However, rising temperatures and increased frequency of drought events reduce opportunities to conduct prescribed fires safely in the Southeast (Kupfer et al. 2020), which could enhance wildfire risk and create barriers for maintaining certain land cover types. Therefore, critical gaps persist in understanding the climate impacts on regional fires, including both wildfires and prescribed fires in southeastern agricultural areas, managed forests, and wetlands.

More recently, efforts have expanded to restore ecosystems to their historic conditions or to create climate-resilient compositions. However, given the loss and gain of influential species, landscape fragmentation, and climate change, whether restored ecosystem composition and function can be achieved remains an open question. For example, further investigation is needed to determine whether fire-managed oak and pine forests are more resilient to extreme climate events compared to unrestored forests.

The following list of grand challenges emerged from the workshop discussion on climate change in the Southeast described in this chapter.

Climate Change Grand Challenges

How will vegetation growth and productivity respond to temperature changes in the Southeast?

- When and why do shifts in species occur, and how long do they last?
- How do ecosystem processes either moderate or exacerbate the urban heat island effect?
- How can the risk and resilience of the Southeast under future climate change be evaluated?

How can the effects of climate change be differentiated from other system disturbances?

- What are the climate impacts of fire in the Southeast, including wildfires and prescribed fires that occur in agricultural areas, managed forests, and wetlands?

How can the predictability of precipitation events and the resulting ecosystem response to increased variability be improved?

- What are the responses of biogeochemical functions, water supply, and plant productivity to increased drought and flooding events?
- What are the consequences of wetlands undergoing hydrologic transformations?
- How can high-frequency, high-resolution climate data be captured to improve hydrological predictions?

5 Disturbance

Disturbance events are important factors in shaping landscape and altering ecosystems of the Southeast. As anthropogenic activities intensify under a changing climate (Turner 2010; Goetz et al. 2012), disturbance regimes, including the size, frequency, intensity, and severity of disturbance events, will likely change at an increasing rate (Keane 2013). While several types of disturbance are inextricably linked to climate change and manifest gradually over time, other disturbances may be characterized by acute (i.e., pulse) impacts on ecosystems. Thus, workshop participants classified disturbance as a driver of change in the Southeast that should be addressed separately from climate change and identified key gaps in knowledge about disturbance impacts and disturbance response trajectories (see Disturbance Grand Challenges, p. 25). This chapter provides an overview of the current state and future outlook of landscape and ecosystem disturbance in the Southeast and discusses potential opportunities for further research to enhance current understanding of disturbance impacts and response trajectories.

5.1 Current State and Future Outlook of Southeast Landscape and Ecosystem Disturbance

The Southeast is susceptible to landfalling tropical storms and extreme weather events, including tornadoes, ice storms, extreme hot and cold events, as well as floods and droughts. Wildfires also occur in the Southeast and are exacerbated by historical fire exclusion and periods of drought (Brey et al. 2018). Furthermore, the region is subject to intensive land use–related disturbances, including prescribed burning and logging (Williams et al. 2016; Schleeweis et al. 2020). Pest and pathogen outbreaks can also cause landscape-scale forest mortality that affects surface fluxes (e.g., carbon and heat) and boundary layer properties (Wiedinmyer et al. 2012). Along the coast and into estuaries, sea level rise (see box Sea Level Rise, p. 22) and associated saltwater intrusion and periodic storm surge create disturbances through soil salinization (Jiao et al. 2018). At the coast, trees weakened or killed by salt stress and storm surge can also initiate outbreaks of invasive pests, such as beetles, which have the potential to spread (Gardner et al. 1992).

Disturbance regimes are also anticipated to shift in response to a warmer climate and human activities. For example, projections indicate that a warmer climate will likely generate more intense precipitation and extreme warm night events in the Southeast (Batibeniz et al. 2020; Swain et al. 2020). In addition, elevated temperatures, extreme drought, and land use change can amplify fire's impact on the spatial distribution of plants and dead fuel loads, resulting in a worldwide shift in the spatial and temporal variation of fire regimes (Archibald et al. 2013). Moreover, projections anticipate changes in common compound disturbances (i.e., combined events), such as intense forest management and fire, wind and fire, and wind and salvage logging (Kleinman et al. 2019).

The Southeast has the highest area burned by prescribed fire and the highest number of wildfires across the United States (see Fig. 5.1, p. 23; Balch et al. 2017; Carter et al. 2018). Wildfire risk may be exacerbated in a warmer and drier climate because these conditions not only facilitate wildfire but also limit land managers' ability to reduce fuel load with low-intensity prescribed fire. Climate change might also result in novel sequences of compound disturbances. Warm temperatures and abundant rainfall can accelerate ecological processes in disturbed areas, but uncertainty persists around whether these conditions will lead to faster recovery or facilitate colonization by exotic species.

As disturbance regimes shift in the Southeast, reshaping the landscape and driving ecosystem responses, a need exists to understand (1) the impacts on turbulent and radiative fluxes, boundary layer characteristics, and

Sea Level Rise

While very susceptible to sea level rise (SLR), the Southeast has many areas that will also experience land subsidence in conjunction with SLR. For example, the Gulf and Atlantic coasts experience some of the highest SLR in the world, recently as high as 10 mm per year (Dangendorf et al. 2023).

Not only will SLR result in land area lost to sea, but it will also alter the hydrology of much of the coastal plain (e.g., slower drainage of freshwater as well as saltwater intrusion). Human land management will further accelerate SLR effects, notably through land-draining activities that have increased hydrological connectivity. Predicted impacts of SLR in the Southeast include (1) changes in vegetation viability; (2) plant and microbial community composition; and (3) ecosystem hydrological, carbon, and nutrient cycles. Therefore, accurately representing these cycles in current modeling frameworks is vitally important.

carbon and nutrient cycling and (2) trajectories and transitions of ecosystems, compound disturbances, and resistant or resilient responses.

5.2 Disturbance Impacts

Ecosystem disturbances have significant potential to modify surface fluxes and land–atmosphere interactions in the Southeast. However, current understanding is limited about the impacts of extreme weather events and compound disturbances on southeastern ecosystem processes, such as carbon and nutrient cycling. This section outlines existing knowledge gaps surrounding disturbance impacts to surface fluxes, land–atmosphere interactions, hydrology and biogeochemistry, and plant stress response and resilience in the Southeast and offers potential research opportunities to address these gaps.

Impacts to Surface Fluxes, Land–Atmosphere Interactions, and Hydrological and Biogeochemical Cycles

Disturbances affect land–atmosphere fluxes by changing the structure and function of vegetation and soil. Effects are highly variable, depending on disturbance intensity and type. For example, severe wind disturbances from tropical storms or tornadoes can instantaneously transform vegetation canopies, moving a majority of aboveground biomass into dead pools. The biogeochemical responses to this shift include a large pulse of carbon to the atmosphere (Chambers et al. 2007) and changes in nutrient pools and fluxes. However, the details of these processes, along with how they affect different greenhouse gas fluxes, are relatively understudied. The potential for disturbances to create positive climate feedbacks through enhanced greenhouse gas fluxes remains an active area of inquiry (Loescher and Staudhammer 2011; Oishi et al. 2018).

Partial or total canopy disturbances also change physical land surface processes that affect turbulent and radiative fluxes, including albedo, roughness, and the Bowen ratio (O'Halloran et al. 2012). For larger disturbances, changes to these processes can affect boundary layer characteristics and cloudiness, although attributing and modeling such phenomena across multiple scales is a challenge. Furthermore, given the scale and duration of a disturbance along with differential stress tolerance, resistance, and acclimation abilities, each constituent species within an ecosystem may have unique disturbance responses. For example, plant species regulate transpiration in different ways depending on their hydraulic strategies, which are combinations of traits and responses accumulated along the root, stem, and leaf hydraulic transport system. Such contrasting behaviors are often further complicated through vegetation–landscape interactions with heterogeneous terrain (e.g., slope, aspect, and elevation) and subsurface conditions (e.g., shallow bedrock and heterogeneous soils).

These interactions frequently occur with strong feedbacks that select for specific vegetation traits in particular locations and lead to the development of a complex network of ecosystem patches, which are characterized by low-lying wetlands, riparian areas, bottomland forests, and upland forests. In the same

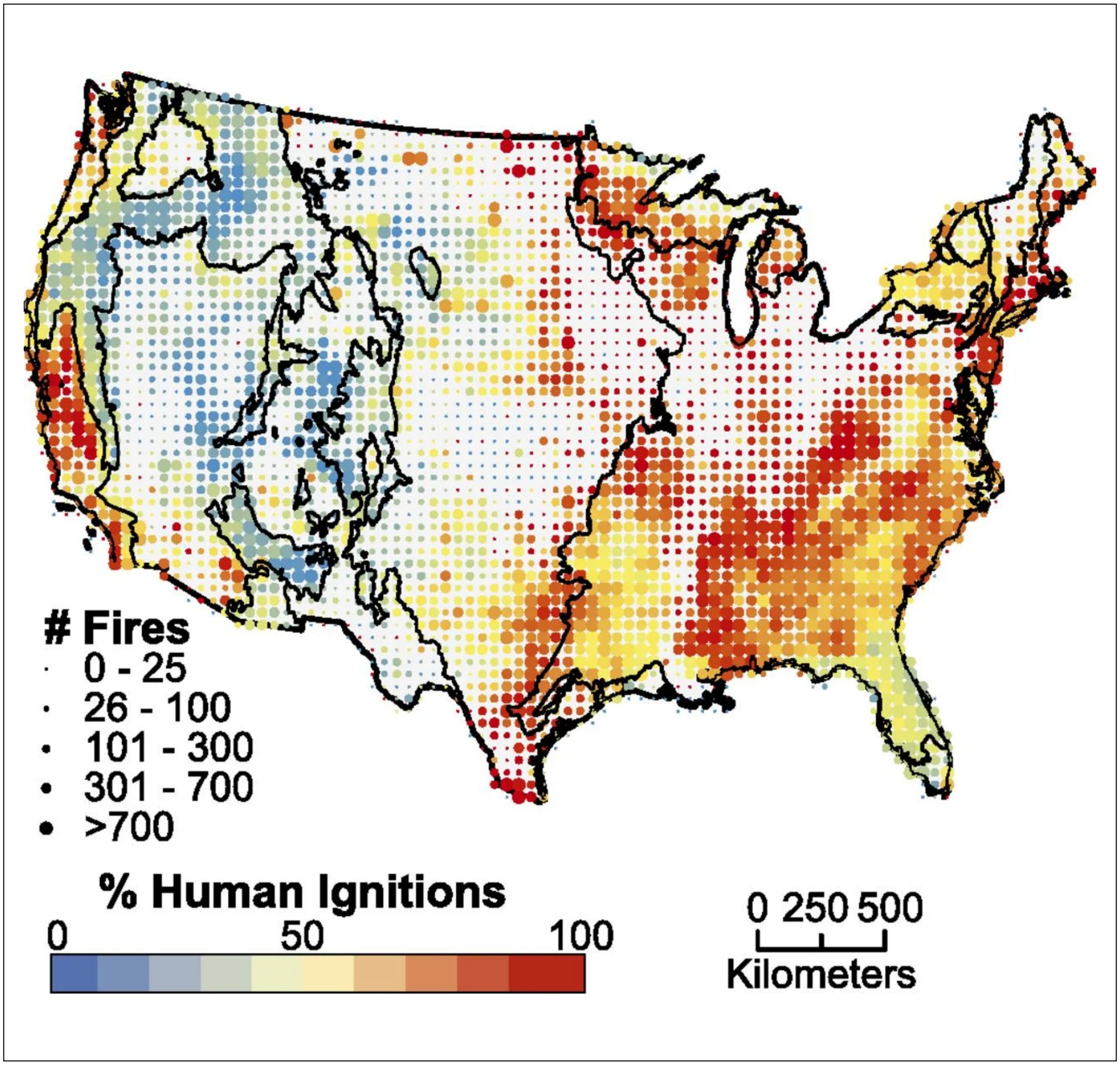


Fig. 5.1. Fires in the Southeast. The total number of wildfires (dot size) and the proportion started by humans (dot color: red indicating greater number of human-started fires) within each 50 km × 50 km grid cell across the conterminous United States from 1992 to 2012. Black lines are ecoregion boundaries. [Reprinted from Balch, J., et al., 2017. "Human-Started Wildfires Expand the Fire Niche Across the United States," *Proceedings of the National Academy of Sciences* **114**(11), 1946–51. DOI:10.1073/pnas.1617394114.]

way that each patch type contains specific vegetation species, the fluxes of ET, carbon dioxide, and methane are also unique to each and necessitate specific attention to the ecosystem mosaic to accurately represent fluxes.

Addressing Spatial Variability Across Multiple Scales

Land surface models that capture plant functional attributes, such as the Functionally Assembled Terrestrial Ecosystem Simulator (FATES; Fisher et al.

2015), have the potential to improve mechanistic understanding of species-specific contributions to atmospheric carbon and water fluxes and improve predictions of how changes in land use and land cover affect those fluxes. The combination of disturbance, stress response, and patch composition is ultimately a determining factor for multiple ecosystem- and regional-scale land–atmosphere fluxes. Therefore, understanding individual plant stress responses is critically important for determining and simulating whole ecosystem resilience.

Ultimately, addressing the knowledge gaps identified in this section and improving current understanding of disturbance impacts in the Southeast will require conducting long-term field experiments. Potential candidates for future field studies on disturbances and extreme weather events include several climate-vulnerable ecosystems in the Southeast that are considered susceptible to changing climate conditions and disturbance regimes (Costanza et al. 2016): (1) karst-depression wetlands (from Virginia to Florida); (2) Nashville Basin limestone glades and woodlands (including Tennessee, Kentucky, Virginia, Alabama, and Georgia); (3) Southern Appalachian balds (from West Virginia to Georgia); and (4) southern loess bluff forests (in Mississippi and Louisiana). Such field experiments should be closely aligned with modeling efforts such that model uncertainties can inform experimental design and experimental results can help test and refine models (i.e., ModEx).

5.3 Disturbance Response Trajectory

Valuable opportunities exist to investigate the impact of disturbance severity on ecosystem recovery in the Southeast through long-term studies and compare these results with those from other regions known to be impacted by moderate- to high-severity compound disturbances. Additional research opportunities to enhance current understanding of disturbance response trajectories include studying sites with different disturbance histories and legacies, tipping points, and ecosystem recovery processes.

Compound Disturbances

Long-term studies are needed to monitor and evaluate ecosystems that are both resistant to compound disturbance regimes (i.e., harmed but unchanged) and resilient to them (i.e., able to return to their previous states). For example, long-term field experiments can monitor the entire recovery span, from pre-disturbance or pre-extreme weather events to several decades after their occurrence. Such experiments will be needed to understand temporal response to disturbances.

Disturbance Legacies

Disturbance legacies can influence the recovery trajectory of an ecosystem. As such, site histories should be explicitly evaluated in future studies. Specifically, research is needed to monitor and evaluate forest ecosystems that regenerate from different land uses (e.g., forests, homesites, and pastures), which differ in their soil physical and chemical properties. This approach would enable researchers to better predict how current and future disturbances will alter ecosystem processes.

Tipping Points and State Changes

The research community also lacks understanding about when and where disturbances will trigger an ecosystem state change. Ecosystem states are reinforced by multiple interacting biotic and abiotic factors, which can be disrupted by disturbance. Addressing this knowledge gap requires identifying (1) the tipping points that lead to a regime or state change, (2) the disturbance types that trigger these changes, and (3) the internal processes that resist change back to the prior state. Meeting these challenges will require assessing resistance and resilience of an ecosystem's numerous biophysical processes.

Managing for Ecosystem Recovery

Management practices should also be considered in the context of ecosystem disturbance. The Southeast has experienced a decline in valuable hardwood tree species, such as white oak, largely due to the lack of regular fire. Forest management strategies, such as prescribed fire and thinning, have the potential to improve regeneration of these desirable trees (Schweitzer et al. 2019). Understanding the relationships between disturbance and ecosystem processes can inform management practices that can favor rapid reproduction and regeneration of valuable tree species. Research in this area can also focus on how disturbances amplified by climate change can alter ecosystem processes during recovery. Additionally, understanding individual ecosystem stress responses, which are highly unique, can help determine ecological resilience and capture transitions in models.

The following list of grand challenges emerged from the workshop discussion on disturbances in the Southeast described in this chapter.

Disturbance Grand Challenges

How do ecosystem disturbances modify surface fluxes, land-atmosphere interactions, and hydrological and biogeochemical cycles in the Southeast?

- What is the role of a single disturbance event versus multiple smaller disturbance events?
- How can individual plant stress responses be used to understand ecosystem resilience to disturbance events?

How does the trajectory of ecosystem response to varying disturbance severity in the Southeast compare to other regions?

- How does the history of an ecosystem influence the recovery trajectory of an ecosystem?
- What are the tipping points that lead to a long-term regime or state change for different intensities and different kinds of disturbance?
- How do compound disturbances affect biogeochemical cycling and the trajectories of vegetative succession?
- How can models capture transitional states of recovery?

6 Land Management and Land Use Change

Land management, land use change, and their growing intensification play pivotal roles in land–atmosphere interactions in the Southeast. In recent decades, this region has experienced many changes that have contributed to high rates of land use and land cover change (Nedd and Anandhi 2022; see Fig. 6.1, this page). These changes include rapid urbanization and suburbanization due to population growth, the prevalence of forestry and agriculture in private small-scale land ownership, climate variability and change, and significant disturbances from storms and fire (see Ch. 5, p. 21). These changes have also given rise to dynamic land cover in the Southeast that is distinct from the rest of the continental United States.

Furthermore, land cover changes have created ecosystems that lay at various points along successional or transitional trajectories. In most cases, processes operating at multiple temporal scales may be interacting, such as increasing disturbance frequencies embedded within climate change–related hydrologic regime shifts (e.g., hurricane disturbances manifesting in increasingly drought- or flood-prone regions). Specifically, forestry and agriculture create rapidly changing landscapes that affect greenhouse gas fluxes; nutrient cycling; evapotranspiration (ET); and carbon, water, and energy balances.

Accurately predicting the effects of ongoing land use conversions on future carbon fluxes requires understanding and appropriately modeling land cover change impacts. As such, the Southeast is a rich landscape for studies involving natural and anthropogenic disturbances, resilience, and recovery

Fig. 6.1. Southeastern United States is a Hot-Spot for Land Cover Change. The geospatial distribution and magnitude of land cover change across the conterminous United States between 2001 and 2016 shows a high concentration of change in the Southeast. Forest logging, agriculture land use changes, and urban development are key factors in southeastern land cover change. Change was calculated as the proportion of 30 m change pixels in a 1 km square grid. [Courtesy U.S. Geological Survey]

trajectories. This chapter addresses two of the largest contributors to land use and land cover change in the Southeast: urbanization and land management, which includes forest management, agriculture, and animal production (see Land Management and Land Use Change Grand Challenges, p. 31).

6.1 Urbanization Impacts on Land–Atmosphere Interactions and Ecosystem Processes

Due to rapid growth, the Southeast is particularly well-suited to studies examining the effects of urbanization on land–atmosphere interactions and ecosystem biogeochemical processes. With a population growth rate of 2.59% annually (Nedd and Anandhi 2022), the Southeast is expected to experience the largest population increase of any U.S. region in the next century (Carter et al. 2018). Growth is primarily anticipated in urban centers, and 12 of the top 20 fastest growing U.S. cities are located in the Southeast. Based on 2009 growth rates, a 2014 study predicted that rapid urbanization would create a connected "megalopolis" stretching from Atlanta, Ga., to Raleigh, N.C., by 2060 (see Fig. 6.2, this page; Terando et al. 2014). Possible studies include examinations into the impacts of urbanization on land–atmosphere interactions (e.g., urban heat islands) and ecosystem processes (e.g., water yield and quality, carbon sequestration, and other biogeochemical processes in watersheds).

Impacts to Land–Atmosphere Interactions

The environmental consequences of urbanization include urban heat islands (UHIs) and emissions of greenhouse gases, volatile organic compounds (VOC), and aerosols due to transportation, industry, and energy use (see Ch. 8, p. 39). Urban residents are affected by a city's microclimate, which can be exacerbated by the energy profiles of buildings (Javanroodi et al. 2022) but moderated by green spaces (Drewniak et al. 2014; Winbourne et al. 2020).

Differences in urban heat are associated with historic inequalities, such as redlining, slavery, and busing (Tuccillo and Spielman 2022). For example, compared

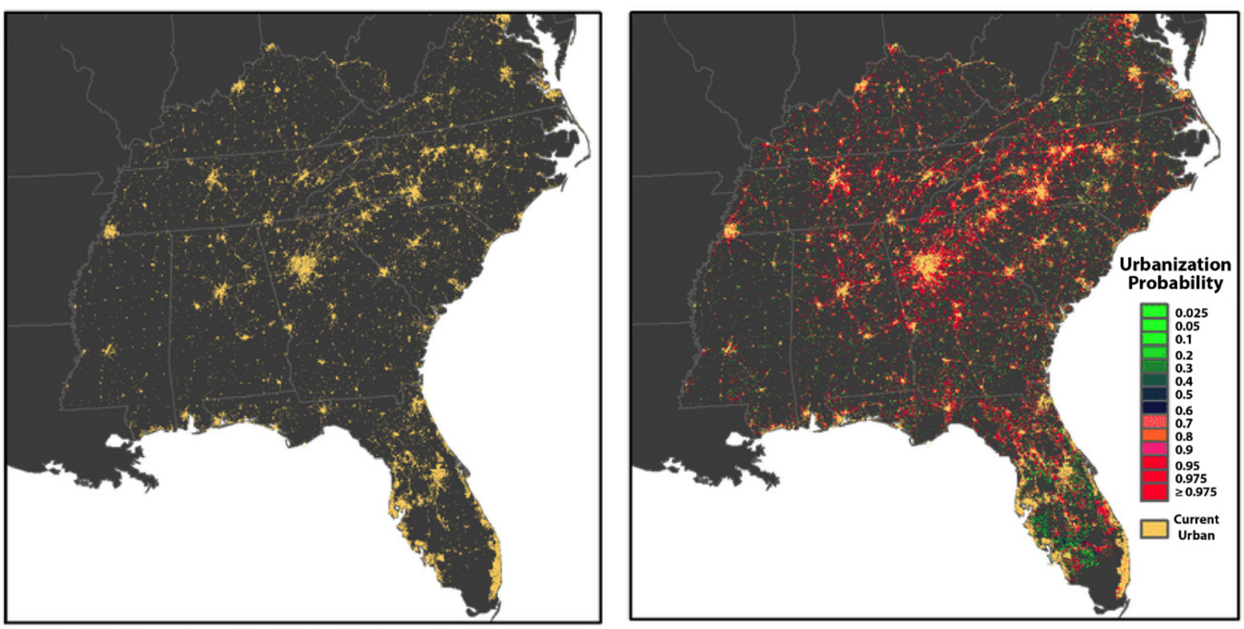


Fig. 6.2. Rapid Urbanization in the Southeast. Urbanization, visualized here, shows urban land cover in 2009 **(left)** and projected urban extent in 2060 **(right)**. Colors in the 2060 projection (right) represent the probability of urbanization, where red colors have a high probability and green colors have a lower probability. [Reprinted under a Creative Commons License (CC0 1.0 DEED) from Terando, A., et al. 2014. "The Southern Megalopolis: Using the Past to Predict the Future of Urban Sprawl in the Southeast U.S.," *PloS One* **9**, e102261.]

to minority-occupied neighborhoods, predominantly white portions of several Southeast cities have higher tree cover and experience lower effects from UHIs (Muse et al. 2022; Elmore 2010; Spielman et al. 2020), which affect local microclimate (i.e., peak temperatures and air quality) and human health. Because of the potential for urban systems to influence both local microclimates and broader regional climates, future studies that examine UHIs along urban-rural gradients would aid predictions of how urban development and heat extremes patterns will affect the Southeast. Such efforts could be coordinated by, or make use of, existing data generated by DOE's Urban Integrated Field Laboratories (ess.science.energy.gov/urban-ifls).

Impacts to Ecosystem Processes

Urbanization also impacts ecosystem carbon balance, freshwater resources, and water quality (Nagy and Lockaby 2010; Van Metre et al. 2019). Urban development patterns common to the Southeast tend to encourage sprawl and increase fragmentation of native ecosystems. For example, agricultural land is a common precursor to urbanization; however, grasslands and forests also undergo conversion (Terando et al. 2014), and wetlands are often first urbanized in mountainous areas. A major uncertainty is how different land uses within watersheds interact to affect water yield and quality, carbon sequestration, and other biogeochemical processes. As such, development of linked modeling frameworks would provide a basis to explore major uncertainties and guide needed measurements.

6.2 Land Management Influence on Energy, Hydrology, and Biogeochemistry

Rising population and simultaneous economic growth increase demand for natural resources, including fiber and timber. As such, managed forests comprise a significant proportion of the forested landscape within the Southeast. The region's forests are one of the most dynamic environments across the globe, primarily due to the degree of private ownership and intensive forestry practices (Hansen et al. 2013). Historic and contemporary trends in forest management practices can have significant effects across a landscape, influencing current and future trajectories of vegetation distribution and biogeochemical cycling. Trends in forest management practices can also impact regional climate through biophysical mechanisms or fluxes that affect cloud formation. In addition to forest management practices, agricultural and animal production practices also influence energy, hydrology, and biogeochemistry across a landscape. Improved understanding of these land management practices will enable better representations in land surface models and generate more accurate predictions of the effects of these practices on carbon, water, and energy fluxes.

Forest Management Practices

Plantation forestry often involves site preparation, species and genetic selection, fertilization, competition control, prescribed fire, and periodic harvesting, which is often performed by clearcutting on short rotations. These management practices have significant landscape effects. For example, over a 13-year period, southeastern forests experienced a 31% turnover, attributed to rapid tree growth in a favorable climate combined with investment in silvicultural techniques. Local markets drive much of the demand for forest products, and the closure of a single mill can have a regional effect on forest management practices. Global markets and policies can also drive management activities. For example, renewable energy policies in the United States and the European Union have contributed to the harvesting of marginal forests in the Southeast, potentially resulting in decades-long degradation of forest land cover (Clarke et al. 2021).

Generally, the effects of these diverse forest management practices on carbon, water, and energy fluxes are thought to manifest as changes in biomass and forest structure and composition. Given that ET is the dominant water flux from most forested landscapes, harvesting and the manipulation of stand density can increase soil water, thereby altering soil biogeochemistry and water yields. Furthermore, forests managed with or without fire can have differing effects on biogeochemistry, land–atmosphere interactions, and plant diversity.

Prescribed Fire in Forest Management

Prescribed fire is a common silvicultural tool used in many forest types and may enhance ecosystem services and decrease risks of catastrophic wildfire. Even naturally regenerated forests, particularly pine forests across the coastal plain and piedmont, are often managed with prescribed fire and are periodically harvested. Simultaneously, portions of the landscape have been prioritized for conservation efforts. For example, fire-dependent longleaf and shortleaf pine forests are being reintroduced on previously cultivated lands. However, expanded use of prescribed fire is expected to increase atmospheric emissions of gases and particulates. Moreover, drought threatens forests by increasing their susceptibility to pests and, in some cases, causing wide-spread mortality. These events, while unfortunate, may provide opportunities for synoptic studies to address ecosystem processes and provide measurements to support modeling.

Fire Exclusion in Forest Management

Another important, but less explored, aspect of forest management is the impact of fire exclusion, which leads to changes in vegetation composition and structure. Prior to European colonization of North America, most forests in the Southeast burned frequently, particularly in the piedmont and coastal plain (Guyette et al. 2012). A century or more of fire exclusion has increased understory density, shade, and moisture while decreasing fuel load and flammability (Alexander et al. 2021; Varner et al. 2021). The resulting closed-canopy forests create unfavorable conditions for fire-adapted species (e.g., pines and oaks), bringing about their displacement by fire-sensitive, shade-tolerant species (e.g., red maple) over time in a process termed "mesophication" (Nowacki and Abrams 2008). Mesophication can reduce forests' ability to sustain water resources and important ecosystem services (Caldwell et al. 2016).

Agricultural and Animal Production Practices

Agricultural practices within the Southeast are intensifying. At the same time, cropping systems are being modified to adapt to climate change and markets. Moreover, animal feeding operations can be expansive, resulting in the production and transport of dust and microbial particles, while traditional row crop agriculture can release fertilizers, herbicides, and pesticides into the atmosphere and into receiving water bodies. Ultimately, additional research is needed to understand how agricultural practices affect ecosystem processes at the watershed scale, particularly with respect to aerial emissions (e.g., dust and chemicals) and runoff (e.g., water and water quality).

Improved Understanding of Land Management Practices

Land management and land use change impacts on processes governing land–atmosphere interactions must be understood to accurately predict future fluxes of mass and energy. Land use patterns also drive tremendous variation in atmospheric aerosols across the Southeast over both temporal and spatial scales (Tegen and Schepanski 2018; Bai et al. 2022; see Ch. 8, p. 39). Furthermore, better understanding is needed of how novel (i.e., nonproduction) management activities, such as managing for carbon sequestration, Climate-Smart Forestry, or restoring the longleaf and shortleaf pine ecosystems, affect regional climate through biophysical mechanisms or by impacting cloud formation.

Capturing these land management practices in land surface models could help (1) resolve their effects on carbon, water, and energy fluxes and (2) identify the carbon cycle's sensitivity to land cover characteristics. Recent development of a module for the Functionally Assembled Terrestrial Ecosystem Simulator that represents intensive management as a plant functional type (i.e., loblolly pine) provides opportunities for more modeling studies in this area (Rady 2022). Key questions include assessing the impact of changing land use on climate resilience and whether the prevalence of agriculture and forestry increases the region's vulnerability to climate change. Also needed is an improved understanding of whether legacies of prior land use (e.g., agriculture or pasture) influence trajectories of vegetation growth, contemporary land–atmosphere interactions, and the short-term versus long-term effects of forest management.

The following list of grand challenges emerged from the workshop discussion on land management and land use change in the Southeast described in this chapter.

Land Management and Land Use Grand Challenges

How does urbanization impact land–atmosphere interactions and ecosystem processes?

- How do natural ecosystem processes either moderate or exacerbate the urban heat island?
- How do different land uses within watersheds interact to affect water yield and quality, carbon sequestration, and other biogeochemical processes?

How do diverse forest management practices influence energy, hydrology, and biogeochemistry across a landscape?

- How does past land use influence current and future trajectories of vegetation distribution and biogeochemical cycling?
- Do trends in forest management practices impact regional climate through biophysical mechanisms or fluxes that affect cloud formation?
- Can forest management practices be represented in land surface models well enough to resolve their effects on carbon, water, and energy fluxes?
- How sensitive are carbon allocation, soil carbon balance, and soil carbon processing to land cover characteristics?
- How do agricultural practices affect ecosystem processes at the watershed scale?

7 Hydroclimate Feedbacks

Understanding hydroclimatic feedbacks that occur due to changes in atmospheric forcing, land use, and land management requires improved understanding of an ecosystem's water budget components. These components include evapotranspiration (ET), plant response to the atmospheric environment, and soil water storage.

The Southeast is characterized by intense water cycling and has the highest ET rate across the United States (Reitz et al. 2023; see Fig. 7.1, this page). This distinctive hydroclimate is driven by high insolation rates, extensive vegetation, relatively long growing seasons, and abundant atmospheric moisture from the Gulf of Mexico and South Atlantic Ocean.

The Southeast water cycle (see Fig. 7.2, p. 34) is largely driven by rainfall with a relatively even temporal distribution throughout the year, except in parts of Texas and Florida that experience dry seasons. Climate models predict that rainfall patterns will become more variable over the next decades, with slightly more rainfall delivered by fewer, more intense rain events. Future increases in frequency and severity of extreme drought are also expected. In addition, air temperature is expected to continue rising, driving extreme heat events and higher nighttime temperatures that could significantly feed back to the hydroclimate cycle (see also Ch. 4, p. 15).

With these changing conditions and potential hydroclimate feedbacks in mind, workshop participants discussed key knowledge gaps in understanding water budget components in the Southeast. ET, which serves as a critical flux in land–atmosphere interactions, is difficult to capture in complex environments containing mixed-species or mixed-age ecosystems. Shifting vegetation patterns and increasing human demand for water resources necessitate improved understanding of plant response to increased CO_2, vapor pressure deficit changes, and increased temperature. Finally, regarding soil water storage, the few measurements that currently exist fail to capture the full depth of plant-accessible water as well as small-scale microtopographic effects.

This chapter discusses these knowledge gaps and focuses on two overarching grand challenges detailed at the end of the chapter: (1) determining the sensitivity

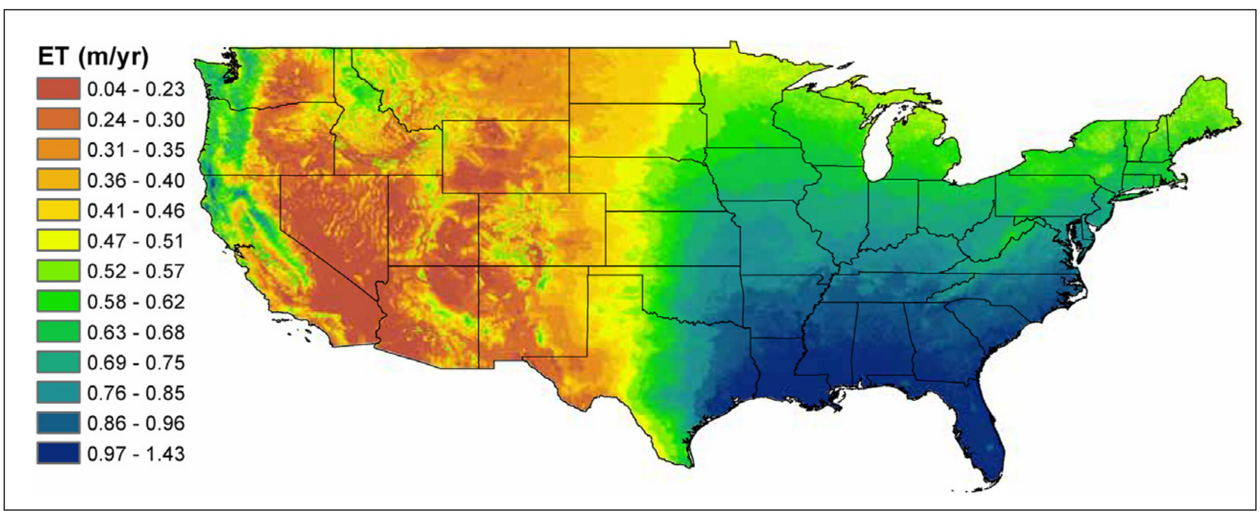


Fig. 7.1. Long-Term Annual Average Evapotranspiration in the United States, 1895–2018. The Southeast is characterized by the highest ET in the continental United States. [Courtesy U.S. Geological Survey]

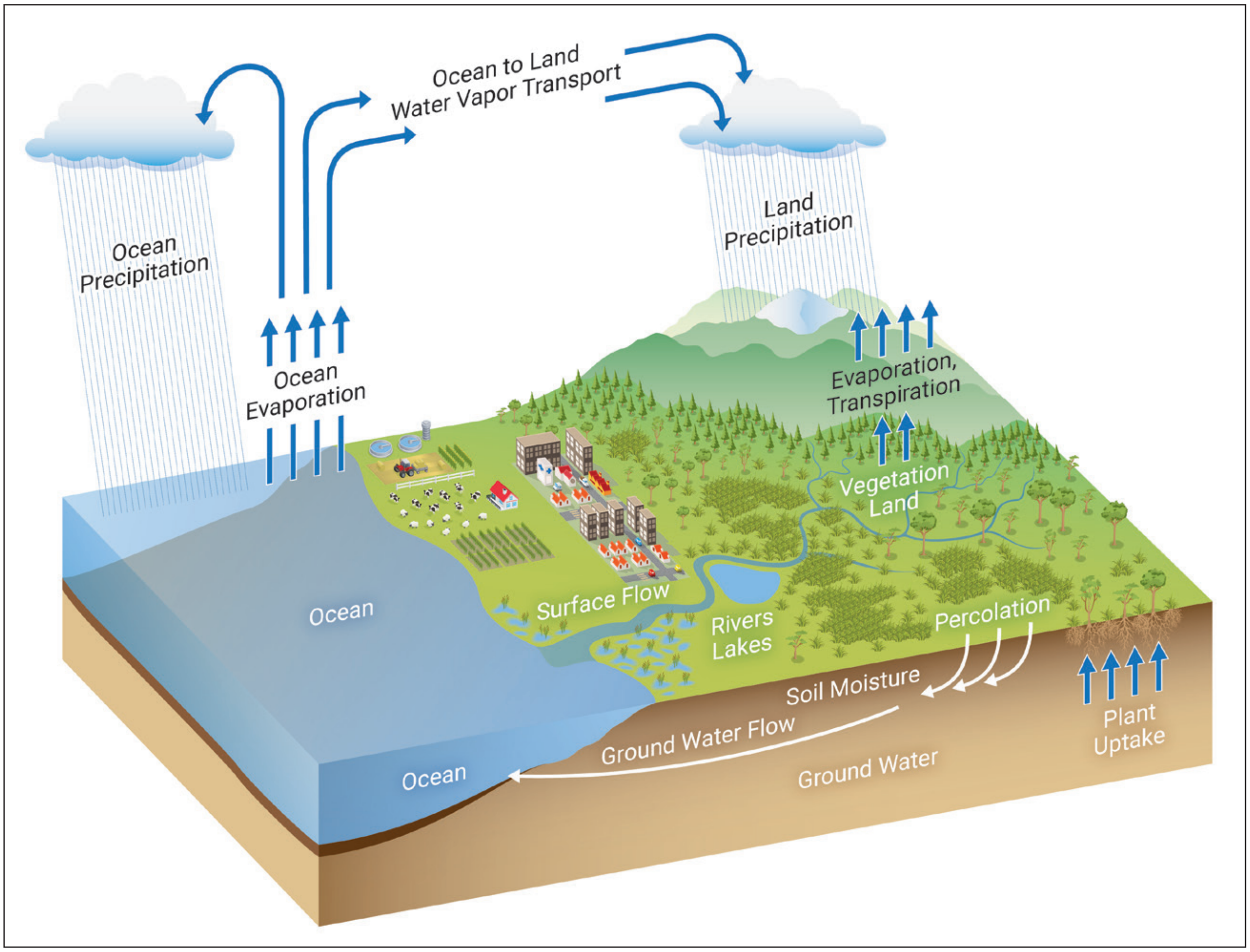


Fig. 7.2. Major Hydrologic Features of the Southeast Water Cycle. [Courtesy Oak Ridge National Laboratory]

of plant transpiration and ecosystem ET to climate change and how changing vegetation composition may alter these dynamics and (2) discovering how high-resolution data from the third Atmospheric Radiation Measurement mobile facility in Bankhead National Forest (AMF3-BNF) can help understand convective storm impact on hydrological cycles in a watershed (see Hydroclimate Feedbacks Grand Challenges, p. 37).

7.1. Evapotranspiration Controls

ET is a dominant hydrologic flux affecting an ecosystem's water budget and serves as an important feedback mechanism for water exchange between land and atmosphere. Potential ET is driven largely by atmospheric demand for water, expressed as vapor pressure deficit (VPD). Rising temperatures due to climate change are expected to increase VPD, potentially resulting in atmospheric drought. Similar to soil drought, atmospheric drought will exhibit increasingly strong effects on biosphere–atmosphere water exchange (Novick et al. 2016).

While atmospheric drought increases potential ET, actual ET can be limited by multiple atmospheric and biophysical factors, discussed below. In general, low moisture availability on surfaces can limit evaporation, and low soil moisture availability can limit transpiration.

Dynamic Plant Responses

As the dominant component of ET in many ecosystems, transpiration would in principle correlate positively with VPD. However, plants tend to close their stomata at high VPD when the gradient between soil and atmospheric water potential reaches a certain high threshold, thus creating a nonlinear relationship between VPD and transpiration. Rising temperatures drive increased VPD and can also increase the frequency of heat stress for individual plants, shift the ranges of plant species or communities, and alter leaf phenology. These effects may significantly alter the spatial and temporal variability of ET. A need exists to improve understanding of plant responses to VPD changes in different ecosystems, which can inform model development.

Agricultural Ecosystem Management

Further research is also needed on intensively managed production ecosystems in the context of climate change and scarce water resources. The absolute and relative contributions of evaporation and transpiration to ET change through time in agricultural production systems as a function of leaf area and soil exposure. In annual row crops, evaporation from soil surfaces is initially the dominant component of ET, but as the crop leaf area develops, transpiration becomes the dominant component. The same is true of forest plantations, although the shift between dominant ET components occurs over multiple years as opposed to a single year. Despite this conceptual understanding, empirical data capturing these dynamics are rare.

Climate projections also show that the Southeast will experience more frequent drought periods, which will increase irrigation demand on agricultural lands. Irrigation use is already increasing in parts of the region. Much of the irrigation water will be withdrawn from groundwater, which has already caused rapid groundwater depletion over the Mississippi Alluvial Plain.

Complex Land Usage

Much more challenging, from a modeling framework, is predicting ET and its components from more complex land uses, like mixed-species and mixed-age forests or old fields and pastures. A research gap exists in understanding the major land and atmospheric controls over plant ET, how the controls change seasonally and annually, and how they differ across the Southeast's complex mosaic.

In contrast to agricultural systems, forested ecosystems typically exhibit greater variability in vegetation species and structure. Even monoculture forest plantations often include an understory of emergent woody and herbaceous vegetation. Notable differences exist among tree species, which are typically not distinguished by model plant functional type. For example, different tree species within a broadly classified deciduous broadleaf forest can exhibit isohydric or anisohydric responses to water stress, resulting in variable feedbacks to the hydrologic cycle and primary productivity (Elliott et al. 2015). Another contrasting feature of Southeast forests compared to agricultural systems is the typical lack of irrigation, which increases the likelihood of soil moisture limitations.

Forest Disturbance and Restoration

Within the broader category of forested ecosystems, changes in stand composition due to management activities (e.g., harvesting and restoration; see Ch. 6), disturbance (e.g., invasive pests and pathogens, hurricanes, and drought; see Ch. 5), and natural factors (e.g., mesophication and maturation; see Ch. 4) are expected to alter ET dynamics. ET changes related to longleaf pine restoration require further study.

CO_2 and Other Fluxes

A more nuanced understanding of ET component fluxes and their drivers is necessary for modeling ET across the Southeast's range of land uses. Rising CO_2 levels can modify stomatal opening dynamics and thus can affect the amount of transpiration and latent heat fluxes to the atmosphere. Some studies have shown that increasing CO_2 will result in lower transpiration rates. However, other covariates may affect transpiration response to a changing climate.

Eddy covariance measurements of atmospheric gas exchange over various land types have become a widespread tool for estimating ET across heterogeneous ecosystems. However, recent reports suggest that eddy covariance assessments may underestimate evaporation, particularly following precipitation events (van Dijk et al. 2015). Given the sensitivity of the water budget in the Southeast to ET, resolving this uncertainty has potentially significant ramifications for understanding hydrologic and energy balances.

7.2 Water Movement Within the Soil–Plant–Atmosphere Continuum

In addition to influencing ET, biophysical factors also play a role in the land–atmosphere feedbacks that affect the hydrologic cycle. Several of these factors, including vegetation structure, evapotranspiration and soil moisture, storm effects, and watershed hydrology, deserve additional study.

Vegetation Structure

Southeast vegetation structure, which can range from cropland to grassland to dense forests with nearby urban and fluvial spaces over small spatial scales (i.e., one to tens of kilometers), affects albedo, energy exchange, and surface roughness. While leaf area is positively correlated with transpiration in both row crop production systems and forest plantations, important differences and sources of uncertainty exist among varying land cover types. Interactions between surface water and groundwater and the impact on leaf area require more research.

Evapotranspiration and Soil Moisture

Understanding connections between plant ET and soil moisture remains an area that requires further study, particularly the properties and functions of plant roots in supplying water and nutrients. Soil depth, order, and characteristics vary locally and regionally across the Southeast, which can affect water availability (i.e., soil water potential) and biogeochemical cycling differently.

Storm Effects

Convective storms may yield high intensity rainfall and strong winds in localized portions of a watershed, affecting biogeochemical processes. Understanding how soil biogeochemical processes are affected by specific types of storms and how those responses are mediated within the watershed would provide novel data for testing model performance with respect to physical and biogeochemical processes. High-resolution data from AMF3-BNF can facilitate better understanding of the effects of convective storms on water and cycling within a watershed.

Watershed Hydrology

Understanding fundamental processes affecting watershed-scale hydrology is critical for predicting watershed water yield and interactions between surface and groundwater. The proportion of precipitation resulting in runoff ranges from 24% along the coast to 64% in the mountains. Throughout the Southeast, millions of people depend on groundwater and surface water generated from sources crossing wide geographical and political boundaries for domestic, industrial, and agricultural uses (Caldwell et al. 2014). Novel combinations of climate, vegetation, and human impacts are likely to challenge the validity of existing hydrologic models.

7.3 Methodological Challenges and Opportunities

Workshop participants identified several methodological challenges and opportunities for improving understanding of hydroclimate feedbacks. One challenge is closing the water and energy balance and understanding biomass heat storage impacts on surface energy balance and cooling effects. Thermal remote sensing currently estimates differential heat fluxes over large spatial areas, but large gaps remain in understanding smaller-scale governing processes and how they differ across spatial and temporal scales.

Soil water storage is another important factor in the region's water budget. Few measurements have been collected regarding soil water content, especially in forests. Such measurements are typically collected near the surface, whereas forest root zones may be several meters deep. Spatial scale is an important consideration in soil water storage. Small-scale microtopographic relief, especially in forests, may exhibit large differences in soil water potential that in turn can regulate biogeochemical processes.

Understanding the sensitivity of carbon pools and fluxes to hydroclimatic forcings is another key uncertainty. Measurements of water and carbon exchange using eddy covariance systems provide needed information on net exchange. Expanded soil water monitoring in the vicinity surrounding eddy covariance towers will improve information regarding water usage by forested ecosystems. Expanded use of co-located measurements of soil water potential within the upper 2 m of soil in the vicinity of eddy covariance measurement sites or in small first-order watersheds would provide needed information to improve models.

Similarly, it is important to identify how subsurface hydrology interacts with plant physiology, plant water storage, sources of plant water (e.g., deep or shallow) and how processes like hydraulic redistribution provide drought resilience. This challenge will depend on improved knowledge about interactions among hydrology, soil physical characteristics, and root dynamics, with emphasis on variability across different plant communities and tree species.

ET partitioning between evaporation and transpiration is a major knowledge gap in ET research. One reason is that the accurate evaporation and transpiration measurements needed to test and improve ET partitioning in models are challenging to obtain and extrapolate to the field scale. Combining existing and emerging measurement methods, including sap flow, eddy covariance, stable isotopes, and remote sensing, can help to fill these knowledge gaps. In addition, improved energy flux measurements associated with forest structures (e.g., above- and in-canopy) would also benefit ET modeling.

The following list of grand challenges emerged from the workshop discussion on hydroclimate feedbacks described in this chapter.

Hydroclimate Feedback Grand Challenges

How sensitive are plant transpiration and ecosystem evapotranspiration (ET) to changing climatic conditions, and how will compositional changes to vegetation in future ecosystems alter these dynamics?

- How do controls on ET differ across the complex Southeast mosaic?
- How can uncertainty in ET data collected from flux towers be resolved, and what are the ramifications to understanding the Southeast's water and energy balance?

How can high-resolution data from AMF3-BNF contribute to understanding convective storm impacts on hydrological cycles in a watershed?

- How do different types of storms affect soil biogeochemical processes, and how are those responses mediated in the watershed?
- Which data can be used to test model performance?
- How sensitive are carbon allocation, soil carbon balance, and soil carbon processing to hydroclimatic forcing?
- How do surface water and groundwater interact with leaf area index?

8 Land–Atmosphere Coupling and Boundary Layer Dynamics

Atmospheric boundary layer dynamics over the Southeast are influenced by the region's heterogeneous land cover, soil moisture, aerosol interactions, and radiation. However, a major knowledge gap exists in understanding how these characteristics contribute to cloud and convective processes and their feedbacks on photosynthesis, evapotranspiration, carbon sequestration, surface heating, and biogenic volatile organic compound (BVOC) emissions. As future climate change triggers changes in temperature, growing seasons, and vegetation distribution, BVOC production and light scattering effects will alter vegetation productivity, carbon, and hydrologic cycles.

This chapter discusses knowledge gaps in atmospheric boundary layer dynamics and surface–atmosphere interactions. Two overarching grand challenges identified by workshop participants are detailed at the end: (1) what feedbacks occur between the atmospheric boundary layer and terrestrial ecosystems, and how will the interactions change in the future and (2) which factors control BVOC emissions and aerosol formation, and how will they differ among different land uses and landscapes (see Land–Atmosphere Coupling and Boundary Layer Dynamics Grand Challenges, p. 43).

8.1. Understanding Atmospheric Boundary Layer Dynamics

An idealized planetary atmospheric boundary layer grows when turbulent eddies generated at the Earth's surface, either convectively or mechanically, entrain air from the free atmosphere (see Fig. 8.1, p. 40). Models of boundary layer depth therefore depend on accurate measurements of changing vertical temperature and moisture gradients to represent convective processes.

Opportunities also exist to better understand how different land cover types, vegetation types, and forest structures influence thermal and mechanical turbulence generation. These and other active research areas provide avenues to improve understanding of how land surface properties and processes affect boundary layer dynamics, and ultimately, cloud processes and climate.

Atmosphere–Canopy Coupling

Coupling between atmospheric and vegetation canopy processes is a major driver of mass, heat, and momentum fluxes between Earth's surface and atmosphere. Many open research questions probe the role of canopy structure on vertical eddy development within and above canopies, which has downstream impacts on carbon and water cycles. Additionally, a need exists to identify specific drivers of turbulence intensity changes throughout the day and across seasons, as well as to investigate how canopy changes (e.g.., agricultural crops and managed forests) influence regional surface roughness characteristics.

Multiscale Influences on Carbon Flux Dynamics

Much of the current understanding about carbon cycling comes from long-term monitoring with eddy covariance systems. Fluxes derived from these systems exhibit signatures of mesoscale processes. Better representation is needed of processes on scales larger than the boundary layer that exhibit local flux signatures in highly heterogeneous regions (e.g., complex terrain or near coastal zones). Similarly, it is important to examine nonlocal land cover types in the context of local flux analyses. Observations are needed to find links between multiple spatiotemporal-scale processes to derive local fluxes as scale-aware phenomena.

Land Cover

The role of land cover in driving mechanical and thermal turbulence and their influence on cloud processes is not well understood. Convective turbulence generated at the Earth's surface is a main driver of boundary layer growth. However, convection high within the boundary layer may sometimes decouple from surface processes.

Fig. 8.1. Planetary Atmospheric Boundary Layer Schematic. Knowledge gaps exist in understanding boundary layer dynamics that in turn affect cloud processes and climate. [Reprinted with permission from Teixeira, J., et al. 2021. "Toward a Global Planetary Boundary Layer Observing System: The NASA PBL Incubation Study Team Report," NASA]

Attribution of specific boundary layer characteristics to a specific land cover type should start with a good understanding of the potential spatial heterogeneity of boundary layer height around an area of interest. This includes investigating how land–atmosphere interactions change across urban to rural gradients and geomorphic provinces.

Linkages between surface fluxes and boundary layer height can thus be matched through simple approaches, such as considering the effects of wind speed and direction. Alternatively, linkages can be studied by implementing a full numerical model that considers the advection of turbulent kinetic energy at multiple boundary layer levels.

8.2. Uncertainties in Surface–Aerosol Interactions

The Southeast is characterized by high emissions of BVOCs, which drive relatively high secondary organic aerosol (SOA) loading in the atmosphere (see Fig. 8.2, p. 41). The drivers of BVOC emissions and SOA formation and how both are influenced by land use and landscape remain uncertain. SOAs exert direct effects on radiative transfer and indirect effects on clouds and the hydrologic cycle. These processes can feed back to the vegetation responsible for BVOC emissions and therefore represent an important coupled mode of land–atmosphere interactions.

This section highlights several mechanisms and uncertainties that, if addressed, could help improve future representations of terrestrial ecosystem functioning.

Innate Biogenic Volatile Organic Carbon Variability

BVOC emissions vary by plant species, so land use patterns drive tremendous temporal and spatial variation in atmospheric aerosols across the Southeast (Tegen and Schepanski 2018; Bai et al. 2022). BVOCs are emitted by many southeastern forest species, including oaks (e.g., isoprenes) and conifers (e.g., terpenes and monoterpenes) [Dudareva et al. 2013]. Agriculture, including both row crops and animal facilities, can enhance aerosol formation and transport through BVOC production. Emissions are also driven by abiotic factors like leaf temperature and intercepted irradiance. As such, the Southeast exhibits high BVOC emissions owing largely to its mix of tree species and favorable abiotic conditions for emissions, including warm temperatures and long growing seasons.

Much progress has been made in cataloging species emission factors using leaf and branch level measurements as a function of temperature and sometimes photosynthetically active radiation or other abiotic variables. However, some of these factors were measured decades ago under different environmental conditions, such as lower ambient CO_2 concentrations or higher ambient ozone concentrations.

Biogenic Volatile Organic Carbon Responses to Stressors

Plant BVOC emissions are sensitive to biotic stress, such as from drought. Plant responses to stress are extremely diverse, with different species responding with either enhanced or reduced BVOC emissions. However, studies of BVOC emission responses to multiple interacting stressors and to simulated future conditions like elevated CO_2 are relatively rare.

Different plant species can respond to stress by producing different BVOC compounds. While some plant families produce similar BVOCs, stress responses are ultimately species-specific and do not map to biomes, plant functional types, or even plant functional traits. This creates an added challenge to representing these processes within existing frameworks in coupled land surface models. As such, this area requires continued research and may provide opportunities for emerging artificial intelligence tools to identify simplifying parameterizations.

Secondary Organic Aerosols

Anthropogenic emissions, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x), have historically played a significant role in aerosol formation through interactions with BVOCs. In the Southeast, high sulfur emissions from coal-fired power plants combined with BVOCs lead to the formation of sulfate aerosols and SOAs. These aerosols scatter sunlight, increasing the proportion of diffuse light reaching the Earth's surface and influencing regional air quality, visibility, ecosystem processes, and climate.

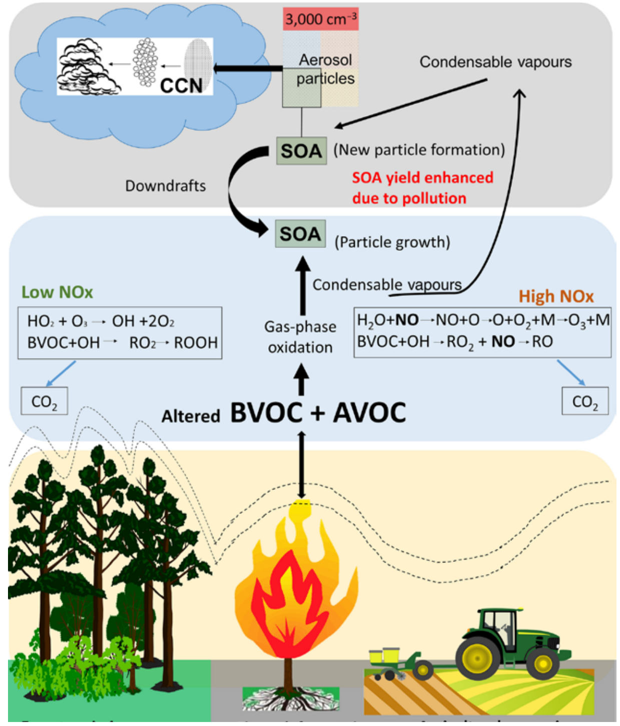


Fig. 8.2. Biogenic Volatile Organic Compound (BVOC) Dynamics in a Polluted Atmosphere. This schematic shows BVOC sources and interactions with and without anthropogenic volatile organic compounds (AVOCs), BVOC oxidation in the atmosphere, and subsequent aerosol and cloud dynamics. CCN, cloud condensation nuclei; SOA, secondary organic aerosol. [Republished with permission from Yáñez-Serrano, A. M., et al. 2020. "Amazonian Biogenic Volatile Organic Compounds Under Global Change," *Global Change Biology* **26**, 4722–51. DOI:10.1111/gcb.15185.]

Aerosol–Ecosystem Interactions

SOAs can indirectly affect light quality by scattering it and by acting as nuclei for cloud droplets and ice. This behavior potentially alters the reflecting and scattering properties of clouds, modifying the light environment at the land surface. Plant canopy light use efficiency (per unit total radiation) of scattered or diffuse light is higher than direct beam light, because scattered light reaches deeper into the canopy, enabling more of the leaf area vertical profile to photosynthesize. Other potentially important factors include leaf temperature, correlations with vapor pressure deficit, and shifts in spectral light distribution.

The impact of this light scattering effect on regional-scale carbon sequestration has been estimated (Keppel-Aleks and Washenfelder 2016), but future work should incorporate species-level responses to diffuse light, as well as confounding effects of declining ozone concentrations, elevated CO_2 concentrations, spectral dependance of light scattering and photosynthetic response, and realistic radiative transfer in plant canopies. In addition to the effects of diffuse light on carbon sequestration, its effects on ecosystem evapotranspiration deserve greater research focus as well.

Emissions Trends and Impacts

Looking to the future, several emerging factors complicate predictions of aerosol impacts. Rising temperatures, changing land use and precipitation patterns, and increasing vapor pressure deficits are expected to modify BVOC emissions. Additional uncertainty exists in understanding how declining anthropogenic emissions may alter the physical and chemical characteristics of SOAs resulting from emissions interacting with BVOCs.

Prior to the 1963 Clean Air Act, air quality in the Southeast was poor and resulted in strong light scattering due to high aerosol loading from the interaction of BVOCs and sulfur pollution producing SOAs and sulfate aerosols. A steady decline in sulfur emissions over the subsequent decades, primarily from coal-fired power plants, has directly improved air quality and reduced regional light scattering. Urban areas like Atlanta continue to experience aerosol formation from agricultural BVOCs, although these processes are now influenced by the reduced availability of SO_2 and NO_x (Xu et al. 2015 a and 2015b).

A combination of rising temperatures, vapor pressure deficit, and changing land use patterns may alter BVOC emissions. BVOC emissions in turn can react with NO_x from fossil fuel combustion to produce tropospheric ozone (Shen et al. 2016). The Southeast experiences smoke and pollutants from various local and endogenous sources, which may contribute to aerosol formation and human health hazards.

Aerosols can influence climate by scattering and absorbing solar radiation, concomitantly affecting surface heating (Charlson et al. 1992). Aerosols also serve as condensation nuclei, thereby altering cloud formation and downgradient precipitation patterns (Dixon and Mote 2003).

These factors will likely impact convective processes, cloud dynamics, and regional climate patterns in ways that are not yet fully understood.

Urban Heat Islands

Urban heat islands are landscapes that exhibit uneven surface heating and are typically urban centers with higher surface temperatures than surrounding areas (Allegrine 2018). Such conditions can enhance low-level convergence (Bornstein and Lin et al. 2000), which, along with increased aerosol emissions, can induce unusually large precipitation events within or downgradient of cities (Shepherd et al. 2002; Lacke et al. 2009; McLeod et al. 2017). Extreme weather events are becoming increasingly common in the Southeast, with dramatic implications for people, ecosystems, and agriculture. Therefore, research is needed to better understand how BVOCs and aerosols affect precipitation in urban ecosystems.

Land–Atmosphere Coupling and Boundary Layer Dynamics Grand Challenges

What feedbacks occur between the atmospheric boundary layer and terrestrial ecosystems, and how will those interactions change in the future?

- How does different land cover affect turbulent flow and influence coupling between air within and above canopies across space and time?
- How can differences between large synoptic and mesoscale processes and those happening within a flux tower footprint be resolved?
- How do land–atmosphere interactions change across gradients from urban to rural spaces, and how do they differ across the spectrum of southeastern geomorphic provinces?

Which factors control biogenic volatile organic compound (BVOC) emissions and secondary organic aerosol (SOA) formation, and how do they differ among different land uses and landscapes?

- What are the key drivers of spatiotemporal BVOC emission variability, and how will they be affected by changing climate, land use, and other compound stressors?
- How will declining anthropogenic emissions alter chemical reactions with BVOCs to change resulting SOA chemical and physical characteristics?
- How will SOAs interact with future atmospheric conditions (e.g., temperature and humidity) to affect convective processes?

9 Research Strategies to Support and Leverage AMF3-BNF

The AMF3-Bankhead National Forest (AMF3-BNF) domain (Kuang et al. 2023) includes a central site in Bankhead National Forest, located in northwestern Alabama. AMF3-BNF is surrounded by supplemental sites triangulating the main deployment and includes multiple land cover types. With its comprehensive suite of instrumentation across sites linked by observations and modeling activities, including airborne remote sensing (i.e., flights between sites), spaceborne remote sensing, and cloud radars, AMF3-BNF is poised to provide detailed, novel understanding of land–atmosphere interactions. AMF3-BNF's particular strengths would be linking gas to particle conversion, showing aerosol formation processes and their influences in clouds, revealing effects of aerosols and clouds on the light environment, and uncovering subsequent impacts on ecosystem functioning (i.e., fluxes). During the workshop, participants identified opportunities for researchers addressing ecological questions in the Southeast to leverage with AMF3. This chapter outlines these opportunities and offers strategies for AMF3-BNF to address the grand challenges in land–atmosphere and ecological research identified and discussed in Chapters 3–8 of this report (see Grand Challenges in Land–Atmosphere and Ecological Research, p. 53).

9.1 Supplemental Observation Sites and Instruments

Strategic implementation of supplementary observing stations could improve process understanding and extract the most value from these larger domain-scale observing systems. Supplemental observation sites would help quantify land–atmosphere fluxes, rainfall, soil moisture, phenology, and other data that would assist with data validation or with accessing data that cannot otherwise be retrieved from the existing design. Many land–atmosphere processes tend to be poorly understood and would potentially benefit from leveraging AMF3-BNF observations.

For example, the effects of diffuse and direct radiation on plant productivity and evapotranspiration can be examined in AMF3-BNF and other flux towers. The effects of vegetation phenology on atmospheric processes, such as the effects of senescence on albedo, turbulence, roughness, and evapotranspiration (ET), can be readily studied by teaming with AMF3-BNF. Phenological measurements using RGB cameras would enable better connection to the existing PhenoCam network. Measurements of sensible heat exchange, biogenic volatile organic compound (BVOC) production, boundary layer height controls, and decoupling instances between microclimate and synoptic weather patterns can facilitate investigations into how the land influences convection, atmospheric humidity, and cold pool duration. Additional measurements from remote sensing techniques and gauged watersheds would also provide beneficial information.

Remote Sensing Techniques

AMF3-BNF's large assessment area suggests considerable opportunity to not only link *in situ* ecosystem measurements with high-resolution atmospheric measurements (e.g., AMF3) to test and utilize remote sensing data but to also integrate remote sensing data into mechanistic models to consider scaling issues more efficiently. For example, high-resolution Lidar-derived surface digital elevation models could be combined with remote sensing data on soil moisture to better simulate biogeochemical processes. Remote sensing platforms, particularly spaceborne and airborne, are excellent complements to surface observations to help bridge scales (see Appendix A: Remote Sensing Sources, Products, and Platforms, p. 54).

Remote sensing has tremendous potential to inform processes across the region, particularly the functional attributes of the land unit (e.g., surface energy fluxes and canopy structure). Components of surface energy balance, such as reflected shortwave and outwelling longwave radiation (e.g., radiometric temperature), can be quantified and used to model sensible and latent heat fluxes. This approach, which serves as the basis of NASA's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) algorithm for ET, presents a significant opportunity given the importance of ET in the Southeast and the ability of flux observations to provide some validation of ET.

Additionally, sap flow measurements provide more detailed information on partitioning evaporation (E) and transpiration (T). Remotely sensed reflectances and fluorescence data can be combined with eddy covariance observations to upscale or model photosynthesis at continental scales using artificial intelligence algorithms for training or principles of light use efficiency.

Furthermore, thermal data can provide landscape-scale measurements of ET and information on forest health using ecological thermodynamics (e.g., NASA/USGS Landsat Program's Operational Land Imager and NASA's ECOSTRESS satellite). Measuring surface temperature change over time in relation to solar input will ascertain the surface partitioning of latent and sensible heat and storage. Hyperspectral data at 30-m resolution can determine species composition and canopy physiological processes (e.g., DLR Earth Sensing Imaging Spectrometer [DESIS]), and WorldView satellite imagery at 50 cm resolution can provide multispectral data with additional information that could compliment the 30 m data.

Gauged Watersheds

Furthermore, gauged watersheds provide a useful framework for considering interactions between hydrology and other ecosystem processes. The U.S. Geological Survey gauges 15 watersheds in the vicinity of AMF3-BNF (see Fig. 9.1, p. 47). These relatively large watersheds provide an opportunity for large- and smaller-scale investigations and a basis for scaling and simulation studies. The presence of these large watersheds suggests an opportunity to gauge smaller watersheds within the primary watershed, which, in turn, could facilitate consideration of different land uses, disturbance, or management regimes, effectively having a set of nested catchments.

Other university and agency first- and second-order watershed facilities in the region provide potential opportunities for collaboration to address studies linked to the AMF3 facility. Such a facility would provide a unique opportunity for testing ecohydrology models due to the presence of multiple internal validation points (e.g., gauging stations) for assessing hydrologic and water quality responses in conjunction with high-resolution data from AMF3-BNF.

9.2 Hierarchical Observations

The Southeast contains a large number of related environments conducive to the study of land–atmosphere interactions—such as topographic variations, land-water interfaces, forest edges, and complex vegetation community structures. All these interactions are overlaid by diverse land use histories consisting of agricultural, silvicultural, residential, suburban, and urban development. Many decisions on land use planning in the Southeast remain at the local level, so consideration of management is an important forcing factor.

The landscape's heterogeneity, topography, and vegetation suggest a strong potential for studying questions that involve upscaling parameters and complex processes from the patch to landscape scale. For example, carbon, water, and energy cycling can be studied throughout the soil–plant–atmosphere continuum by examining ecosystem compartments (e.g., soil, trees, and water) and using integrated measurements (e.g., eddy covariance, atmospheric radiation measurements, and remote sensing) to understand how individual influences are translated to broader spatial scales and longer temporal timeframes. Hierarchical observations are key to increase current understanding of plant- and soil-level controls and improve existing knowledge of physical and biogeochemical processes.

Increased Understanding of Plant and Soil-Level Controls

Understanding how soil characteristics, topography, and drainage influence plant ET should constitute a major endeavor. Gaining insight into plant-level controls requires hierarchical observations that start with organ-level plant measurements like leaf gas exchange and xylem hydraulic characteristics, proceed

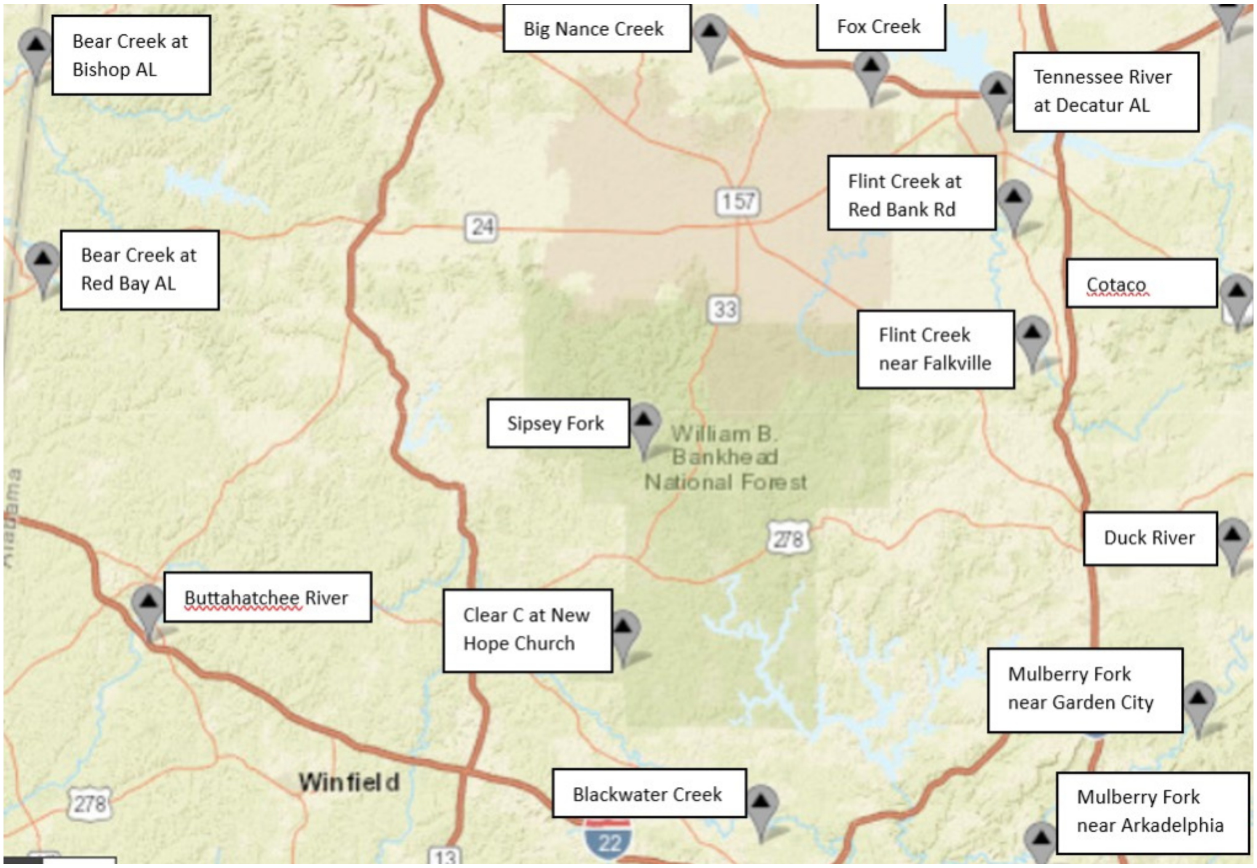


Fig. 9.1. Watersheds Gauged by the U.S. Geological Survey. The U.S. Geological Survey (USGS) gauges 15 relatively large watersheds in and around AMF3-BNF that not only provide an opportunity for large- and smaller-scale investigations but also serve as a basis for scaling and simulation studies. [Courtesy USGS]

to observations at the patch level, and end with atmospheric data to represent the aggregate effect on ecosystems, including eddy covariance, balloon measurements, radiative fluxes, and remote sensing. Using water isotopes from plant and soil water could help quantify deep and shallow sources tapped by plant roots. Connecting these measurements with root characteristics could enable development of new modules in models to predict root function and its impacts on land–atmosphere interactions.

Better knowledge of linkages with soil processes, including soil chemistry and physical characteristics and heterotrophic and autotrophic respiration, would enable improved understanding and prediction of soil carbon storage and greenhouse gas flux spatial variability in the context of disturbance response. Discerning the thermal response of plants can help inform the extent of plant stress. Increased awareness of plant stress as a function of atmospheric conditions, soil environment, land use history, and vegetation type will be a key outcome. For example, soil and leaf water potential measurements could be coupled with sap flow and atmospheric vapor pressure deficit (VPD) measurements to understand how water moves through the soil–plant–atmosphere system.

Improved Knowledge of Physical and Biogeochemical Processes

Additionally, the high-resolution data from AMF3-BNF could be used to enhance current knowledge of convective storm effects on water and biogeochemical cycling within a watershed. Convective storms may yield high-intensity rainfall and strong winds in localized portions of a watershed. Understanding how storms affect soil biogeochemical processes and how those responses are mediated within the watershed would provide novel data for testing model performance with respect to physical and biogeochemical processes.

Distinguishing gradients between urban and rural spaces and between agricultural and forested spaces will be important to determine how these processes aggregate across the complex southeastern landscape. Studies that pair hierarchical observations and measurements across important land use gradients provide key insights for aggregating processes and parameters with increasing observational scales.

The diversity of the Southeast's landscape mosaic could be used in studies exploiting topographic gradients; disturbance, land use, and fire disturbance and recoveries; managed versus unmanaged landscapes; urbanization; and successional stages. The ground-based and remote sensing datasets could help situate the landscape in a spatial and temporal context, and these observations could be used to study disturbance and recovery and how those processes change across the landscape.

9.3 Co-Locating Existing Data

Co-Location Through Data Synthesis

Observations and experiments in the southeastern U.S. provide a wealth of existing data to support the AMF3 installation. Synthesis of this data is needed, especially of historical data and time series data to better understand the following topics:

- Climate, land use, wildfire, land management and burning plans, plant censuses, and disturbance histories
- Soil characteristics, including carbon stocks, depth, nutrients, texture, moisture, temperature, and carbon dioxide (CO_2) and methane (CH_4) fluxes
- Hydrologic budgets, including isotope analysis to understand deep versus shallow sources
- VPDs
- Sap flow and leaf water potential time series
- Land–atmosphere fluxes of water and energy (e.g., eddy covariance data)
- BVOC emissions
- Aerosol chemistry and particle sizes

During synthesis, attention should be paid to relevant time scales since data collection can occur over tremendously variable time frames (e.g., soil data may only be collected once, while atmospheric data may be collected in seconds).

Synthesizing existing data could create opportunities for close engagement with regional schools (e.g., historically Black colleges and universities, minority-serving institutions, state institutions, and Appalachian institutions) to leverage local participation and expertise. Potentially, efforts could involve training students in data collection, assembly, and use. Many of these datasets could provide high-resolution and site-specific companions to the extensive remote sensing catalog across the Southeast (see Appendix A: Remote Sensing Sources, Products, and Platforms, p. 54).

Co-Location Through Sensors at Different Sites

AMF3-BNF can only cover a few land cover types in one geographic location. Therefore, deploying a subset of sensors at sites with different land cover, or similar but different geology and meteorology, could be helpful to supplement and compare data. More detailed measurements of light quality (e.g., diffuse or spectral radiometers) and measurements of aerosol properties (e.g., size distributions, scattering and absorption coefficients, and hydroscopicity) could greatly enhance understanding of land–atmosphere coupling at existing flux tower sites. For example, sites could be leveraged for this purpose at DOE's AmeriFlux Management Project, the U.S. Department of Agriculture – Agricultural Research Service's Long-Term Agroecosystem Research (LTAR) Network, the National Science Foundation's Long Term Ecological Research (LTER) Network and National Ecological Observatory Network (NEON), or at PI-led sites.

Co-Location Through Remote Sensing Techniques

Other space-based remote sensing techniques can provide estimates of column concentrations or emissions of relevant gases, including BVOCs (Palmer et al. 2006), and greenhouse gases, including CH_4 (Jacob et al. 2016) and CO_2 (Eldering et al. 2017). Active remote sensing techniques, such as RADAR and LiDAR, can provide detailed information on vegetation canopy structure (Bergen et al. 2009), which is a critical control on land–atmosphere interactions (Thomas et al. 2008). In all cases, surface, boundary layer, or deeper atmospheric observations provide important training and validation datasets for developing the remote sensing techniques that can help bridge to larger scales.

Co-Location Through Integrated Ecohydrology Data

Another strategy capitalizing on AMF3-BNF would be to co-locate existing ecohydrology data to make it more readily available, especially for model development and testing. Several long-term ecohydrology monitoring facilities are located in the Southeast, but data may not be readily available. Providing an ecohydrology data integrator could assist with data co-location.

9.4 Models and Modeling Frameworks

Models to resolve the questions and issues posed in this report must involve spatially complex and process-rich representations, which can be computationally expensive. Therefore, using AI techniques to develop synthetic datasets and to simplify approaches, such as surrogate models and digital twins, can help generate computationally efficient models. Model simulations could also inform sampling density (both time and space) by testing different levels of landscape heterogeneity. AMF3-BNF and potential future opportunities would be a valuable testbed for evaluating the simplifying assumptions of many land surface models, including plant functional type representations; spatial discretization of variations in topography, plant communities, and soil types; and land use and disturbance history representations. As previously mentioned, remote sensing data will be key for making connections between current observations and past processes.

The diverse types of disturbances affecting the Southeast, including severe storms, droughts, heat waves, prescribed fire, invasive species, and insect pests, could provide opportunities to explore ways to better represent disturbance impacts on ecosystem dynamics and land–atmosphere interactions in models. Opportunities also exist to evaluate the impacts of these different disturbance types on carbon cycling and land–atmosphere interactions. Additionally, the region's diverse and heterogeneous patterns of land use and land management highlight the importance of (1) better representing impacts of human activities on landscape and ecological processes and (2) better incorporating predictions of future changes in land use patterns into predictive models. Simulations of future urbanization trends could also help inform future settlement trajectories and the effects on biogeochemical cycling and land–atmosphere interactions.

9.5 Opportunities for AMF3-BNF to Address Grand Challenges in Land–Atmosphere and Ecological Research

This final section explores how AMF3-BNF can address the grand research challenges identified by participants for each of the six major themes: (1) spatial heterogeneity, (2) climate change, (3) disturbance, (4) land management and land use change, (5) hydroclimate feedbacks, and (6) land–atmosphere coupling and boundary layer dynamics.

Spatial Heterogeneity Grand Challenges

> *How can parameters be identified and scaled to capture and represent processes across scales in a diverse and spatially heterogeneous landscape?*

AMF3-BNF will provide information on aggregated processes in a complex landscape mosaic and will capture the importance of different processes as they shift over seasons, across years, over space, and in response to specific events. Therefore, supplementary measurements could focus on understanding and quantifying individual biological and landscape components and processes at the plot scale under different land uses or landscapes (e.g., sap flow and ET, soil greenhouse gas fluxes, and BVOC emissions). Also needed is additional understanding of how these basic ecosystem processes and system components change in response to seasons and to a variety of stressors common to the Southeast. This plot-level mechanistic information can inform how individual ecosystem components and land use types contribute to the aggregated observations of AMF3-BNF. Furthermore, knowledge of plot-scale mechanisms and land use types can be used to inform and test ecosystem-scale complex model scenarios.

How does landscape heterogeneity influence surface–atmosphere coupling, which in turn affects climate in the Southeast's different physiographic zones?

Studies focusing on surface–atmosphere coupling (i.e., surface fluxes, surface temperature, humidity, and boundary layer formation) in different physiographic regions and in response to seasonal and climatic forcings will be necessary to capture the diversity of responses and to develop predictions of their regional climate impacts. Consideration of size, topography, and characteristics of the landscape mosaic will provide key constraints to understand individual climate contributions of different landscape types across the broader southeast region.

Climate Change Grand Challenges

How will vegetation growth and productivity respond to temperature changes in the Southeast?

In areas where high temperatures occur, timing and location are not predictable, and experimental manipulation is often not practical. AMF3-BNF could address these challenges through a network of common measurements across multiple sites. This networked approach will be more likely to capture both extreme temperatures and co-occurring "reference" conditions, detect timing variabilities of extreme conditions (e.g., hot early spring versus hot late fall conditions), and control for covarying factors (e.g., high temperatures under drought and nondrought conditions). Such an approach should focus on primary productivity as well as respiration and net ecosystem productivity.

How can the effects of climate change be differentiated from other system disturbances?

AMF3-BNF can leverage current and long-term data to help disentangle independent and interactive effects of climate change and disturbance. Large–scale experiments can also be developed that use "natural experiments" created by either actual or simulated disturbances.

How can the predictability of precipitation events and the resulting ecosystem response to increased variability be improved?

AMF3-BNF seeks to target a better understanding of cloud processes that are tied to land–atmosphere interactions. Better parametrizations of land characteristics and their influences on the water cycle can help improve model predictions of precipitation, frequency, intensity, and extreme events. Measurements at sites with co-occurring disturbances, such as droughts and floods, can also promote insight into ecosystem response and resilience to these events. Leveraging groundwater measurements and gauged networks along with ET measurements can enhance knowledge of available water to support southeastern ecosystems.

Disturbance Grand Challenges

How do ecosystem disturbances modify surface fluxes, land–atmosphere interactions, and hydrological and biogeochemical cycles in the Southeast?

AMF3-BNF would address this challenge by leveraging emerging high-spatial and- temporal frequency observations of vegetation obtained from remote sensing and cloud radars. When combined with atmospheric measurements (e.g., BVOC and aerosols, ET, and carbon [CO_2 and CH_4] fluxes), measurements of vegetation change (e.g., phenology, composition, and structure) and soil moisture can provide a more detailed understanding of the cascade effects of disturbance-driven changes in land–atmosphere interactions on hydrological and biogeochemical cycles.

How does the trajectory of ecosystem response to varying disturbance severity in the Southeast compare to other regions?

Understanding how disturbance severity affects the response trajectory of southeastern ecosystems requires integration of long-term, high-spatial resolution and temporal frequency observations of plant phenology, land–atmosphere flux exchange, and hydrological cycles. Such an integration necessitates stronger partnerships with agencies, universities, and other organizations in the Southeast, such as the U.S. Forest Service. Long-term ecosystem observation networks can provide pre- and post-disturbance datasets needed to successfully achieve integration with these observations.

Land Management and Land Use Change Grand Challenges

How does urbanization impact land–atmosphere interactions and ecosystem processes?

Paired studies in Southeast urban and suburban environments could be conducted to compare and contrast the rural environment of the AMF-BNF3 with more developed areas. Land–atmosphere interactions are affected by differences in surface radiation, tree canopy and density, urban infrastructure, atmospheric composition, rainfall and runoff, and microclimate. New investigations and data collection can be used to better understand how urbanization affects ecosystem processes, such as energy balance and partitioning of ET, biogeochemical cycling, and land–atmosphere exchange of pollutants. Furthermore, such studies would aid in improving model representation of urban environments, with applications well beyond the southeastern United States. The effects of urban microclimate on diverse human populations are also an important concern due to the prevalence of high poverty rates and the suitability of residential infrastructure to withstand heat waves and other extreme events.

How do diverse forest management practices influence energy, hydrology, and biogeochemistry across a landscape?

Bankhead National Forest is managed for multiple objectives and represents many management practices common throughout the Southeast, including timber harvesting, wildlife management, and prescribed fire. Because of the diverse, highly fragmented mosaic of forests in the Southeast, strong partnerships with universities (particularly land-grant), federal and state agencies, Tribes, nongovernmental organizations (e.g., land trusts and conservation organizations), and industry will be required to assemble the data necessary to address these questions. The data required for an effective approach will need to not only consider multiple disciplines of the natural sciences but also incorporate social sciences, which can help to identify changing socioeconomic drivers and impacts of management decisions.

Hydroclimate Feedback Grand Challenges

How sensitive are plant transpiration and ecosystem ET to changing climatic conditions, and how will compositional changes to vegetation in future ecosystems alter these dynamics?

Throughout the Southeast, climate change is expected to increase temperature, VPD, as well as the frequency and/or intensity of both drought and flooding. Thus, the AMF3-BNF deployment should help to facilitate coordinated monitoring of the components of ET (via eddy covariance, sap flow, and other methods). In some cases, substitutions of space for time may be possible by monitoring similar species and ecosystems among sites with climate variations. Research will also need to account for novel forest conditions caused by changes in key species (e.g., loss of ash or expansion of invasive species), restored ecosystems (e.g., longleaf pine savannas), and changing management regimes.

How can high-resolution data from AMF3-BNF contribute to understanding convective storm impacts on hydrological cycles in a watershed?

Because convective storm effects are highly spatially and temporally variable, high-resolution data will be required to identify affected areas. This information can be leveraged to select sites spanning a range of intensities as a natural experimental treatment. However, such an approach will require a network of coordinated sites with common sets of measurements.

Land–Atmosphere Coupling and Boundary Layer Dynamics Grand Challenges

What feedbacks occur between the atmospheric boundary layer and terrestrial ecosystems, and how will those interactions change in the future?

Surface turbulence is a strong driver of boundary layer dynamics. The role that different types of vegetation canopy play on mass and momentum fluxes can be explored by coupling AMF3-BNF monitoring measurements with additional remote sensing observations across a variety of ecosystem types over a range of topography. Ultimately, land cover influence on cloud and convective processes can be informed by (1) linking across scales to resolve the spatiotemporal disconnect between flux towers and larger meso- and synoptic-scale features and (2) determining how these features change across gradients (e.g., rural to urban), seasons, and capture when they become uncoupled.

Which factors control BVOC emissions and SOA formation, and how do they differ among different land uses and landscapes?

The southeastern U.S. is a hotspot for BVOC emissions, and research could investigate how BVOC emissions from trees respond to stress and local environmental conditions (e.g., CO_2 concentrations, heat, insect pathogens, and drought). BVOCs vary according to species, with the common southern species *Quercus* emitting isoprenes and *Pinus* species emitting terpenes. A tremendous level of unexplored complexity exists within and beyond these two common species and their marker compounds. A dichotomy of VOCs is emitted in urban versus rural spaces, with the former involving anthropogenic compounds like benzene and toluene. However, because the technology for discrimination is expensive and complex, these topics remain relatively unexplored.

Furthermore, BVOCs can interact with oxidized atmospheric compounds (e.g., nitrates and sulfates) to create ozone, which can further damage plants and impact human health. BVOCs can also contribute to the formation of secondary organic aerosols, which can alter light transmission and photosynthesis and affect cloud condensation and precipitation. These topics could also benefit from greater exploration. For example, studies could involve investigations of BVOC formation, emissions, downstream transport and reactions, and attendant effects upon human and tree health and on atmospheric processes.

The spatial heterogeneity, intensive land management, disturbances, and land use change that characterize the Southeast are important controls on land–atmosphere interactions. Leveraging and expanding the research focus of the AMF3 deployment can (1) expand the types of landscapes and processes in the domain as well as the study processes across spatial and temporal scales and (2) develop new methods and techniques for simulating and understanding the Southeast. Ultimately, this integrative new effort can provide improved predictability through better representation of the Southeast in Earth system models, connect system components across spatial and temporal scales, and advance understanding of local and regional changes to impacts in a vulnerable, highly populated, and dynamic region.

Grand Challenges in Land–Atmosphere and Ecological Research

Spatial Heterogeneity Grand Challenges

- How can parameters be identified to capture and represent processes across scales in a diverse and spatially heterogeneous landscape?"
- How does landscape heterogeneity influence surface–atmosphere coupling (i.e., surface fluxes, surface temperature, humidity, and boundary layer formation), which in turn affects climate in the Southeast's different physiographic zones?

Climate Change Grand Challenges

- How will vegetation growth and productivity respond to temperature changes in the Southeast?
- How can the effects of climate change be differentiated from other system disturbances?
- How can the predictability of precipitation events and the resulting ecosystem response to increased variability be improved?

Disturbance Grand Challenges

- How do ecosystem disturbances modify surface fluxes, land–atmosphere interactions, and hydrological and biogeochemical cycles in the Southeast?
- How does the trajectory of ecosystem response to varying disturbance severity in the Southeast compare to other regions?

Land Management and Land Use Change Grand Challenges

- How does urbanization impact land–atmosphere interactions and ecosystem processes?
- How do diverse forest management practices influence energy, hydrology, and biogeochemistry across a landscape?

Hydroclimate Feedback Grand Challenges

- How sensitive are plant transpiration and ecosystem evapotranspiration to changing climatic conditions, and how will compositional changes to vegetation in future ecosystems alter these dynamics?
- How can high-resolution data from AMF3-BNF contribute to understanding convective storm impacts on hydrological cycles in a watershed?

Land–Atmosphere Coupling and Boundary Layer Dynamics Grand Challenges

- What feedbacks occur between the atmospheric boundary layer and terrestrial ecosystems, and how will those interactions change in the future?
- Which factors control biogenic volatile organic compound emissions and secondary organic aerosol formation, and how do they differ among different land uses and landscapes?

Appendix A
Remote Sensing Sources, Products, and Platforms

This list was gathered from workshop participants and is not intended to be exhaustive.

Aerial Imagery

Image: *Agricultural Aircraft [Courtesy Adobe Stock]*

Airborne Observation Platform (AOP)

neonscience.org/data-collection/airborne-remote-sensing

Product
LiDAR, spectrometers and hyperspectral instruments focused on National Ecological Observatory Network (NEON) sites

Spatial Resolution
Hyperspectral images: 1 m
Gridded LiDAR: 1 m
Digital photography: 0.25 m
High-resolution RGB camera: 0.1 m

Frequency of Measurements
Flights scheduled during growing season

Dates of Data Collected
2013–present

Origin
Battelle Memorial Institute, United States

Types of Data Collected
Quantitative information on land cover and changes to ecological structure and chemistry, including the presence and effects of invasive species

National Agricultural Imagery Program (NAIP)

naip-usdaonline.hub.arcgis.com

Product
Aerial imagery via aircraft or satellite

Spatial Resolution
2 m, 1 m, 2 ft

Frequency of Measurements
Refreshed on a 3-year cycle; one-third of the continental U.S. flown each year

Dates of Data Collected
2003–present

Origin
U.S. Department of Agriculture

Types of Data Collected
Leaf-on aerial imagery during the peak growing season

Instruments on the International Space Station

***Image**: International Space Station [Courtesy Adobe Stock]*

Earth Surface Mineral Dust Source Investigation (EMIT)

earth.jpl.nasa.gov/emit

Product
Imaging spectrometer on an Earth Ventures-Instrument-4 (EVI-4) mission to map the mineral composition of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared range

Spatial Resolution
60 m

Spectral resolution
7.5 nm

Dates of Data Collected
2022–present

Origin
NASA

Types of Data Collected
Atmospheric aerosols, specifically the mineral composition of aerosols to identify cooling or heating effects of aerosols on the climate

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

ecostress.jpl.nasa.gov

Product
Thermal radiometer

Spatial Resolution
38 m in-track x 69 m cross-track

Dates of Data Collected
2018–present

Origin
NASA

Types of Data Collected
Research-grade methane plume complexes from point-source emitters and measurement of plant canopy biochemistry processes; studies how plants use water and respond to stress by measuring their temperature

DLR Earth Sensing Imaging Spectrometer (DESIS)

tbe.com/what-we-do/markets/geospatial-solutions/desis

Product
Hyperspectral imager

Spatial Resolution
30 m

Dates of Data Collected
Launched in 2018

Origin
German Aerospace Center (DLR), Germany; Teledyne Brown Engineering, United States

Types of Data Collected
Estimated ecosystem and forest structure, as well as aboveground biomass

Global Ecosystem Dynamics Investigation (GEDI)

earthdata.nasa.gov/sensors/gedi

Product
High-resolution LiDAR

Spatial Resolution
25 m

Dates of Data Collected
2018–present

Origin
NASA; University of Maryland

Types of Data Collected
Estimated ecosystem and forest structure, as well as aboveground biomass

Orbiting Carbon Observatory-3 (OCO-3)

ocov3.jpl.nasa.gov

Product
Highly accurate three-channel spectrometer

Spatial Resolution
2.25 km x 0.7 km

Dates of Data Collected
2019–present

Origin
NASA

Types of Data Collected
Estimated CO_2 concentrations in the atmosphere as well as an albedo and aerosol product; potential for measuring solar-induced fluorescence

Instruments on a Satellite

Image: *Landsat Thematic Mapper [Courtesy NASA]*

Global Ozone Monitoring Experiment-2 (GOME-2)

esa.int/Applications/Observing_the_Earth/Meteorological_missions/MetOp/About_GOME-2

Product
Spectrometers on three Meteorological Operational (MetOp) satellites

Spatial Resolution
80 km x 40 km; GOME-2A also has a 40 km x 40 km^2 resolution

Frequency of Measurements
1.5 days for global coverage

Dates of Data Collected
GOME-2A: 2007-2021
GOME-2B: 2012-present
GOME-2C: 2019-present

Origin
European Space Agency

Types of Data Collected
Atmospheric ozone, trace gases, and ultraviolet radiation

Landsat Thematic Mapper (TM)

landsat.gsfc.nasa.gov/thematic-mapper

Product
Multispectral scanner on the Landsat satellite

Spatial Resolution
30 m

Thermal Resolution
120 m

Frequency of Measurements
16 days

Dates of Data Collected
First version launched in 1982

Origin
NASA

Types of Data Collected
Maps of surface reflectance, surface temperature, spectral indices, surface water extent, fractional snow cover, and burned area

Landsat Operational Land Imager (OLI)

landsat.gsfc.nasa.gov/satellites/landsat-8/spacecraft-instruments/operational-land-imager

Product
Imager on the Landsat satellite

Spatial Resolution
Panchromatic: 15 m
Multispectral: 30 m
Scene size: 185 km

Frequency of Measurements
16 days for global coverage

Dates of Data Collected
Launched in 2013

Origin
Ball Aerospace & Technologies Corporation, United States

Types of Data Collected
Measures in the visible, near infrared, and shortwave infrared portions of the spectrum; spectral bands tailored especially for cirrus cloud detection (with the new, near infrared band 9) and coastal zone observations (with the new, deep-blue visible band 1)

Moderate Resolution Imaging Spectroradiometer (MODIS)

modis.gsfc.nasa.gov/about

Product
Spectroradiometer on the Terra and Aqua satellites

Spatial Resolution
250 m, 500 m, 1,000 m

Frequency of Measurements
1–2 days

Dates of Data Collected
Launched in 1999

Origin
NASA

Types of Data Collected
Aerosols, cloud cover, atmospheric profiles, surface reflectance and emissivity, land cover, spectral indices, gross primary productivity, leaf area, and evapotranspiration

Tropospheric Emissions: Monitoring of Pollution (TEMPO)

tempo.si.edu

Product
UV-visible spectrometer located on the Intelsat 40E commercial communication satellite

Spatial Resolution
2.1 x 4.5 km^2

Frequency of Measurements
Hourly during daylight

Dates of Data Collected
2023–present

Origin
NASA

Types of Data Collected
North American lower tropospheric ozone, formaldehyde and nitrogen dioxide as primary pollutant gases, sulfur dioxide, glyoxal, water vapor, halogen oxides, aerosols, clouds, ultraviolet B radiation, and foliage properties

TROPOspheric Monitoring Instrument (TROPOMI)

tropomi.eu

Product
Instrument on the Copernicus Sentinel-5 Precursor satellite

Spatial Resolution
5.5 km x 3.5 km

Frequency of Measurements
Daily

Dates of Data Collected
Launched in 2017

Origin
Netherlands Space Office; European Space Agency

Types of Data Collected
Climate monitoring including a variety of trace gases and information about aerosols, cloud height, and cloud coverage

Satellites

Image: *Satellite [Courtesy Adobe Stock]*

Geostationary Operational Environmental Satellite–R Series (GOES-R)

goes-r.gov

Product
Group of weather satellites orbiting the equator at speeds matching Earth's rotation

Spatial Resolution
Varies

Dates of Data Collected
2016–present

Origin
NASA; National Oceanic and Atmospheric Administration

Types of Data Collected
Primary instrument for imaging Earth's weather, oceans, and environment; used for a wide range of applications related to severe weather, hurricanes, aviation, natural hazards, the atmosphere, oceans, and the cryosphere

Global Change Observation Mission (GCOM)

global.jaxa.jp/projects/sat/gcom_w

Product
Two-satellite mission that includes GCOM-W and GCOM-C1

Spatial Resolution
GCOM-W: 10km
GCOM-C1: 250 m and 1000 m

Frequency of Measurements
Global data every 2–3 days

Dates of Data Collected
2012–present (W) and 2017–present (C1)

Origin
Japan Aerospace Exploration Agency

Types of Data Collected
GCOM-W has an advanced microwave scanning radiometer (passive-microwave) that monitors changes in precipitation, water vapor fluxes, and water levels over land. GCOM-C1 has two multiband radiometers for monitoring aerosols, clouds, vegetation, and temperature: (1) visible near infrared and (2) infrared scanning.

Ice, Cloud and Land Elevation Satellite-2 (ICESat-2)

icesat-2.gsfc.nasa.gov

Product
Environmental science satellite

Spatial Resolution
Varies

Dates of Data Collected
Launched in 2018

Origin
NASA

Types of Data Collected
Initially instrumented toward a focus on the cryosphere, researchers have found the instrument also works well to estimate forest and ecosystem structure.

Orbiting Carbon Observatory-2 (OCO-2)

ocov2.jpl.nasa.gov

Product
Environmental science satellite

Spatial Resolution
Cross-track: 1.29 km
Along-track at nadir: 2.25 km

Frequency of Measurements
16 days

Dates of Data Collected
2014–present

Origin
NASA

Types of Data Collected
Collects space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize sources and sinks and quantify its seasonal variability

PlanetScope

planet.com/products/satellite-monitoring

Product
Constellation of nanosatellites
(not open-source data)

Spatial Resolution
3 m

Frequency of Measurements
Near-real-time

Dates of Data Collected
2014–present

Origin
Planet Labs, Inc., United States

Types of Data Collected
Available through a subscription model, daily images of the entire Earth can be scaled to meet analysis and application needs.

Soil Moisture Active Passive (SMAP) Observatory

jpl.nasa.gov/missions/soil-moisture-active-passive-smap

Product
Radiometer

Spatial Resolution
36 km

Frequency of Measurements
Every 2–3 days

Dates of Data Collected
2015–present

Origin
NASA

Types of Data Collected
Soil moisture and liquid water.

TerraSAR-X Add-on for Digital Elevation Measurement (TanDEM-X)

earth.esa.int/eogateway/missions/terrasar-x-and-tandem-x

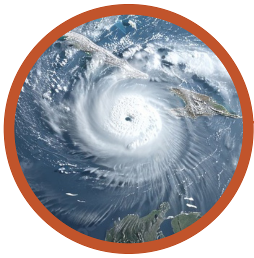
Product
Synthetic aperture radar (SAR) satellites that fly in close formation to simultaneously image Earth's terrain from different angles

Spatial Resolution
Relative: 2 m
Absolute: 4 m

Dates of Data Collected
2007–present

Origin
German Aerospace Center

Types of Data Collected
Accurate digital elevation models, useful for interpolating other data sources such as GEDI and ICESat-2 for creating continuous maps



Other Data Sources

***Image**: Weather Satellite [Courtesy Adobe Stock]*

PhotoSpec

climatesciences.jpl.nasa.gov/sif/download-data/tower

Product
Ground-based spectrometer system

Frequency of Measurements
Real-time

Dates of Data Collected
2016–present

Origin
California Institute of Technology; NASA; University of California–Los Angeles

Types of Data Collected
Spatially distributed solar-induced chlorophyll fluorescence in the red (670-732 nm) and far-red (729–784 nm) wavelength ranges; canopy reflectance (400–900 nm)

Short-term Prediction Research and Transition (SPoRT)

weather.ndc.nasa.gov/sport

Product
A research-to-operations/operations-to-research endeavor that has transitioned NASA capabilities, including over 50 satellite products, to stakeholders

Frequency of Measurements
Real-time

Dates of Data Collected
2002–present

Origin
NASA

Types of Data Collected
Data products focus on weather forecasting, land surface, and atmospheric processes

Appendix B
Workshop Agenda

All Times U.S. Eastern

Wednesday, August 23, 2023

Welcome and Introductory Comments

11:00 a.m. — ***Welcome***
Beth Drewniak (U.S. Department of Energy)

11:05 a.m. — ***Environmental System Science (ESS) Program***
Gil Bohrer (U.S. Department of Energy)

11:15 a.m. — ***Atmospheric Radiation Measurement User Facility***
Sally McFarlane (U.S. Department of Energy)

11:25 a.m. — ***Workshop Structure and Charge***
Andrew Christopher Oishi (U.S. Forest Service), C. Ross Hinkle (University of Central Florida), Nina Wurzburger (University of Georgia)

Plenary Sessions

11:35 a.m. — ***AMF3 Deployment***
Nicki Hickmon, Michael Ritsche, Adam Theisen (Argonne National Laboratory); Scott Giangrande, Chongai Kuang, Shawn Serbin (Brookhaven National Laboratory)

12:20 p.m. — ***ESS Strategic Interests in the Southeast***
Brian Benscoter (U.S. Department of Energy)

12:30 p.m. — ***Break***

Breakout Session 1. Identify Knowledge Gaps in Key Processes

12:45 p.m. — ***Breakout Logistics***
Workshop Organizers

12:50 p.m. — ***Group A. Flux/Land–Atmosphere Interactions***
Lead: Asko Noormets (Texas A&M University)
Rapporteur: Camilo Rey-Sanchez (North Carolina State University)

Group B. Ecology/Disturbance/Biogeochemistry
Lead: Vanessa Bailey (Pacific Northwest National Laboratory)
Rapporteur: Tammy Foster (University of Central Florida and NASA)

Group C. Hydrology/Ecohydrology/Terrestrial–Aquatic Interface
Lead: Carl Trettin (U.S. Forest Service)
Rapporteur: Betsey Boughton (MacArthur Agroecology Research Center)

2:15 p.m.	***Break***
2:30 p.m.	***Report Back from Session 1 and Discussion***

Breakout Session 2. Identify Gaps for Research and Modeling to Advance Predictability

3:00 p.m.	***Group A. Flux/Land–Atmosphere Interactions*** *Lead:* Gregory Starr (University of Alabama) *Rapporteur:* Tom O'Halloran (Clemson University)
	Group B. Ecology/Disturbance/Biogeochemistry *Lead:* Margaret Torn (Lawrence Berkeley National Laboratory) *Rapporteur:* Jeff Atkins (U.S. Forest Service)
	Group C. Hydrology/Ecohydrology/Terrestrial–Aquatic Interface *Lead:* Georgianne Moore (Georgia Southern University) *Rapporteur:* Ashley Matheny (University of Texas–Austin)
4:30 p.m.	***Break***
4:35 p.m.	***Report Back from Session 2 and Discussion***
5:00 p.m.	***Adjourn***

Thursday, August 24, 2023

Welcome and Reconvening Comments

11:00 a.m.	***Welcome***
11:05 a.m.	***Summary from Day 1 and Open Discussion***

Plenary Sessions

12:05 p.m.	***Experiences with Surface Atmosphere Integrated Field Laboratory (SAIL) Campaign*** Dan Feldman (University of California–Berkeley)
12:30 p.m.	

Breakout Session 3. Identify Potential ESS-Relevant ModEx-Driven Opportunities

12:45 p.m.	***Break***
	Group A. Flux/Land–Atmosphere Interactions *Lead:* Andrew Christopher Oishi (U.S. Forest Service) *Rapporteur:* Yun Yang (Mississippi State University)
	Group B. Ecology/Disturbance/Biogeochemistry *Lead:* Melanie Mayes (Oak Ridge National Laboratory) *Rapporteur:* Debjani Sihi (Emory University)
	Group C. Hydrology/Ecohydrology/Terrestrial–Aquatic Interface *Lead:* Doug Aubrey (University of Georgia) *Rapporteur:* Eric Pierce (Oak Ridge National Laboratory)

2:15 p.m.	***Break***
2:30 p.m.	***Report Back from Breakout Session 3***
3:00 p.m.	***Open Discussion***
4:00 p.m.	***Synthesizing the Major Themes*** Identify writing leads, groups, and assignments
4:45 p.m.	***Summary and Closing***

Appendix C
Breakout Questions

During the workshop, participants were divided into breakout groups and asked a series of questions, which are listed here in the order that the groups occurred.

Breakout 1: Identify Knowledge Gaps in Key Processes

> *Objective: Identify the physical processes and dynamics that are important to capture land–atmosphere interactions in the Southeast.*

- What are the agents (e.g., heat, storms, fire, forestry, invasives and diseases, urbanization, and agriculture), drivers, and feedbacks of change?
- How does local- and landscape-scale heterogeneity of vegetation and land surface influence land–atmosphere coupling?
- What influences do surface dynamics exert on regional biogeochemistry and aerosol formation?
- What is the role of disturbance as a driver of change in land–atmosphere interactions, biogeochemistry, and the water cycle? What are the expected changes in frequency and intensity of these events?
- Which human activities affect ecological, hydrological, and biogeochemical processes in the Southeast?
- How do land use and land cover changes affect energy, carbon, chemical, and water fluxes to the atmosphere?

Breakout 2: Identify Gaps for Research and Modeling to Advance Predictability

> *Objective: Identify the biggest challenges, gaps, and uncertainties in modeling land–atmosphere interactions in the Southeast.*

- What are the most important processes and dynamics needed to model land–atmosphere interactions in the Southeast?
- What drivers are the least understood or poorly represented?
- What spatial and temporal scales are needed to capture surface–atmosphere processes in models?
- What observations and data are needed to parameterize these models?
- What level of heterogeneity is needed for models to capture these processes?
- Which ecosystems or land cover types are underrepresented in observations or models?
- What are the current gaps and priorities for capturing short- and long-term disturbance responses in models?
- How can we use current model tools and techniques to inform the future of observations and applications?

Breakout 3: Identify Potential ESS-Relevant ModEx-Driven Opportunities

> *Objective: Identify priorities and opportunities where the Southeast can be used as a study region and where the ARM-Mobile Facility (AMF3) deployment in Alabama can be leveraged.*

- What are the high-priority, poorly understood processes that would benefit from leveraging the AMF3 observations?
- Which measurements should take priority to maximize advancement in the understanding and application of land–atmospheric processes in this system, and where should those measurements be focused?
- How can measurements benefit from and augment the AMF3 campaign?
- How can ModEx be streamlined to ensure data availability and accessibility for model benchmarking and validation?
- How can understanding of land–atmosphere interactions be improved in an area of the United States where data are limited?"

Appendix D
Workshop Participants

Co-Chairs

C. Ross Hinkle
University of Central Florida

Andrew Christopher Oishi
U.S. Forest Service

Nina Wurzburger*
University of Georgia

Participants

Kerry Ard
The Ohio State University

Jeff Atkins**
U.S. Forest Service

Doug Aubrey*
University of Georgia

Vanessa Bailey*
Pacific Northwest National Laboratory

Ben Bond-Lamberty
Pacific Northwest National Laboratory

Betsey Boughton**
MacArthur Agroecology Research Center

Rosvel Bracho
University of Florida

Steven Brantley
The Jones Center at Ichauway

Tammy Foster**
University of Central Florida and NASA

Scott Giangrande
Brookhaven National Laboratory

Johnny Grace
U.S. Forest Service

Nicki Hickmon
Argonne National Laboratory

April Hiscox
University of South Carolina

Chongai Kuang
Brookhaven National Laboratory

Jeff Luvall
NASA

Katherine Martin
North Carolina State University

Roser Matamala
Argonne National Laboratory

Ashley Matheny**
University of Texas–Austin

Melanie Mayes*
Oak Ridge National Laboratory

Georgianne Moore*
Georgia Southern University

Asko Noormets*
Texas A&M University

Richard Norby
University of Tennessee

Tom O'Halloran**
Clemson University

Eric Pierce**
Oak Ridge National Laboratory

Thomas Powell
The University of the South (Sewanee)

Laura Reed
Archbold Biological Station

* Breakout Session Lead; ** Breakout Session Rapporteur

Camilo Rey-Sanchez**
North Carolina State University

Daniel Ricciuto
Oak Ridge National Laboratory

Michael Ritsche
Argonne National Laboratory

Fernanda Santos
Oak Ridge National Laboratory

Paul Schmalzer
University of Central Florida and NASA

Shawn Serbin
Brookhaven National Laboratory

Debjani Sihi**
Emory University

Gregory Starr*
University of Alabama

Benjamin Sulman
Oak Ridge National Laboratory

David Sumner
U.S. Geological Survey

Hilary Swain
Archbold Biological Station

Adam Theisen
Argonne National Laboratory

Margaret Torn*
Lawrence Berkeley National Laboratory

Carl Trettin*
U.S. Forest Service

Charuleka Varadharajan
Lawrence Berkeley National Laboratory

Jorge Villa
University of Louisiana–Lafayette

Yun Yang**
Mississippi State University

Observers

Paul Bayer
U.S. Department of Energy

Brian Benscoter
U.S. Department of Energy

Gil Bohrer
U.S. Department of Energy

Beth Drewniak
U.S. Department of Energy

Sally McFarlane
U.S. Department of Energy

Daniel Stover
U.S. Department of Energy

* Breakout Session Lead; ** Breakout Session Rapporteur

Appendix E
References

Alexander, H. D., C. Siegert, J. S. Brewer, J. Kreye, M. A. Lashley, J. K. McDaniel, A. K. Paulson, H. J. Renninger, and J. M. Varner. 2021. "Mesophication of Oak Landscapes: Evidence, Knowledge Gaps, and Future Research," *BioScience* **71**(5), 531–542. DOI:10.1093/biosci/biaa169

Allegrini, J. 2018. "A Wind Tunnel Study on Three-Dimensional Buoyant Flows in Street Canyons with Different Roof Shapes and Building Lengths," *Building and Environment* **143**, 71–88. DOI:10.1016/j.buildenv.2018.06.056

Archibald, S. C. E. R. Lehmann, J. L. Gómez-Dans, ans R. A. Bradstock. 2013. "Defining Pyromes and Global Syndromes of Fire Regimes," *PNAS* **110**(16), 6442–6447. DOI:10.1073/pnas.121146611

Bachelet, D., R. P. Neilson, J. M. Leniham, and R. J. Drapek. 2001. "Climate Change Effects on Vegetation Distribution and Carbon Budget in the United States," *Ecosystems* **4**, 164–185. DOI:10.1007/s10021-001-0002-7

Bai, K., K. Li, M. Ma, K. Li, Z. Li, J. Guo, N.-B. Chang, Z. Tan, and D. Han. 2022. "LGHAP: The Long-Term Gap-Free High-Resolution Air Pollutant Concentration Dataset, Derived via Tensor-Flow-Based Multimodal Data Fusion," *Earth System Science Data* **14**(2). 907–927. DOI:10.5194/essd-14-907-2022

Balch, J. K., B. A. Bradley, J. T. Abatzoglou, and A. L. Mahood. 2017. "Human-Started Wildfires Expand the Fire Niche Across the United States," *PNAS* **114**(11), 2946–2951. DOI:10.1073/pnas.1617394114

Batibeniz, F., M. Ashfaq, N. S. Diffenbaugh, K. Key, K. J. Evans, U. U. Turuncoglu, and B. Önol. 2020. "Doubling of U.S. Population Exposure to Climate Extremes by 2050," *Earth's Future* **8**(4), e2019EF001421. DOI:10.1029/2019EF001421

Bergen, K. M., S. J. Goetz, R. O. Dubayah, G. M. Henebry, C. T. Hunsaker, M. L. Imhoff, R. F. Nelson, G. G. Parker, V. C. Radeloff. 2009. "Remote Sensing of Vegetation 3-D Structure for Biodiversity and Habitat: Review and Implications for Lidar and Radar Spaceborne Missions," Journal of Geophysical Research: Biogeosciences 114, G00E06. DOI:10.1029/2008JG000883

Bigelow, D. P., and A. Borchers. 2017. *Major Uses of Land in the United States*. EIB-178, U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/webdocs/publications/84880/eib-178.pdf?v=2300.9

Bornstein, R., and Q. Lin. 2000. "Urban Heat Islands and Summertime Convective Thunderstorms in Atlanta: Three Case Studies," *Atmospheric Environment* **34**(3), 507–516. DOI:10.1016/S1352-2310(99)00374-X

Brey, S. J., E. A. Barnes, J. R. Pierce, C. Wiedinmyer, and E. V. Fischer. 2018. "Environmental Conditions, Ignition Type, and Air Quality Impacts of Wildfires in the Southeastern and Western United States," *Earth's Future* **6**(10), 1442–1456. DOI:10.1029/2018EF000972

Caldwell, P., C. Muldoon, C. Ford-Miniat, E. Cohen, S. Krieger, G. Sun, S. McNulty, and P. V. Bolstad. 2014. *Quantifying the Role of National Forest System Lands in Providing Surface Drinking Water Supply for the Southern United States,* SRS-197. U.S. Department of Agriculture Forest Service, Southern Research Station. DOI:10.2737/SRS-GTR-197

Caldwell, P. V., C. F. Miniat, K. J. Elliott, W. T. Swank, S. T. Brantley, and S. H. Laseter. 2016. "Declining Water Yield from Forested Mountain Watersheds in Response to Climate Change and Forest Mesophication," *Global Change Biology* **22**(9), 2997–3012. DOI:10.1111/gcb.13309

Carter, L., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm. 2018. "Chapter 19: Southeast," *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Eds. D.R. Reidmiller, C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart. U.S. Global Change Research Program. 743–808. doi:10.7930/NCA4.2018.CH19

Chambers J. Q., J. I. Fisher, H. Zeng, E. L. Chapman, D. B. Baker, and G. C. Hurtt. 2007. "Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests," *Science* **318**(5853), 1107. DOI:10.1126/science.114891

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, Jr., J. E. Hansen, and D. J. Hofmann. 1992. "Climate Forcing by Anthropogenic Aerosols," *Science* **255**(5043), 423–430. DOI:10.1126/science.255.5043.423

Clarke, N., L. P. Kiær, O. J. Kjønaas, T. G. Bárcena, L. Vesterdal, I. Stupak, L. Finér, S. Jacobson, K. Armolaitis, D. Lazdina, H. M. Stefánsdóttir, and B. D. Sigurdsson. 2021. "Effects of Intensive Biomass Harvesting on Forest Soils in the Nordic Countries and the UK: A Meta-Analysis," *Forest Ecology and Management* **482**, 118877. DOI:10.1016/j.foreco.2020.118877.

Costanza, J., S. Beck, M. Pyne, A. Terando, M. J. Rubino, R. White, and J. Collazo. 2016. *Assessing Climate-Sensitive Ecosystems in the Southeastern United States*. U.S. Geological Survey. DOI:10.3133/ofr20161073

Dangendorf, S., N. Hendricks, Q. Sun, J. Klinck, T. Ezer, T. Frederikse, F. M. Calafat, T. Wahl, and T. E. Törnqvist. 2023. "Acceleration of U.S. Southeast and Gulf Coast Sea-Level Rise Amplified by Internal Climate Variability," Nature Communications **14**, 1935. DOI:10.1038/s41467-023-37649-9

Dixon, P. G., and T. L. Mote. 2003. "Patterns and Causes of Atlanta's Urban Heat Island–Initiated Precipitation," *Journal of Applied Meteorology and Climatology* **42**(9), 1273–1284. DOI: 10.1175/1520-0450(2003)042<1273:PACOAU>2.0.CO;2

Drewniak, B., R. Kotamarthi, R. Jacob, F. Chen, and C. Catlett. 2014. *Urban Landscape and Climate Change Workshop Summary*, ANL-18/13. Argonne National Laboratory. DOI:10.2172/1480521

Dudareva, N., A. Klempien, J. K. Muhlemann, and I. Kaplan. 2013. "Biosynthesis, Function and Metabolic Engineering of Plant Volatile Organic Compounds," *New Phytologist* **198**(1), 16–32. DOI:10.1111/nph.12145

Earth@Home. "Climate of the Southeastern United States." Accessed July 2024. Paleontological Research Institution. https://earthathome.org/hoe/se/climate/

Eldering, A., P. O. Wennberg, D. Crisp, D. S. Schimel, M. R. Gunson, A. Chatterjee, J. Liu, F. M. Schwandner, Y. Sun, C. W. O'Dell, C. Frankenberg, T. Taylor, B. Fisher, G. B. Osterman, D. Wunch, J. Hakkarainen, J. Tamminen, and B. Weir. 2017. "The Orbiting Carbon Observatory-2 Early Science Investigations of Regional Carbon Dioxide Fluxes," *Science* **358**(6360), eaam5745. DOI:10.1126/science.aam5745

Elliott, K. J., C. F. Miniat, N. Pederson, and S. H. Laseter. 2015. Forest Tree Growth Response to Hydroclimate Variability in the Southern Appalachians," *Global Change Biology* **21**(12), 4627–4641. DOI:10.1111/gcb.13045

Elmore, B. 2010. "Hydrology and Residential Segregation in the Postwar South: An Environmental History of Atlanta, 1865-1895," *The Georgia Historical Quarterly* **94**(1), 30–61. http://www.jstor.org/stable/40585153.

Fisher, R. A., S. Muszala, M. Verteinstein, P. Lawrence, C. Xu, N. G. McDowell, R. G. Knox, C. Koven, J. Holm, B. M. Rogers, A. Spessa, D. Lawrence, and G. Bonan. 2015. "Taking Off the Training Wheels: The Properties of a Dynamic Vegetation Model Without Climate Envelopes, CLM4.5(ED)," *Geoscientific Model Development* **8**, 3593–3619. DOI:10.5194/gmd-8-3593-2015

Gardner, L. R., W. K. Michener, T. M. Williams, E. R. Blood, B. Kjerve, L. A. Smock, D. J. Lipscomb, and C. Gresham. 1992. "Disturbance Effects of Hurricane Hugo on a Pristine Coastal Landscape: North Inlet, South Carolina, USA," *Netherlands Journal of Sea Research* **30**, 249–263. DOI:10.1016/0077-7579(92)90063-K

Griffith, J. A., S. V. Stehman, and T. R. Loveland. 2003. "Landscape Trends in Mid-Atlantic and Southeastern United States Ecoregions," *Environmental Management* **32**(5), 572–588. DOI:10.1007/s00267-003-0078-2

Gu, L., P. J. Hanson, W. M. Post, D. P. Kaiser, B. Yang, R. Nemani, S. G. Pallardy, and T. Meyers. 2008. "The 2007 Eastern U.S. Spring Freeze: Increased Cold Damage in a Warming World?," *BioScience* **58**(3), 253–262. DOI:10.1641/B580311

Guyette, R. P., M. C. Stambaugh, D. C. Dey, and R.-M. Muzika. 2012. "Predicting Fire Frequency with Chemistry and Climate," *Ecosystems* **15**, 322–335. DOI: 10.1007/s10021-011-9512-0

Hadeeb, D., J. Vargo, and B. Stone. 2015. "Rising Heat Wave Trends in Large US Cities," *Natural Hazards* **76**, 1651–1665. DOI:10.1007/s11069-014-1563-z

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change," *Science* **342**(6160), 850–853. DOI:10.1126/science.1244693

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen., and T. Houser. 2017. "Estimating Economic Damage from Climate Change in the United States," *Science* **356**(6345), 1362–1369. DOI:10.1126/science.aal4369

Jacob, D. J., A. J. Turner, J. D. Maasakkers, J. Sheng, K. Sun, X. Liu, K. Chance, I. Aben, J. McKeever, and C. Frankenberg. 2016. "Satellite Observations of Atmospheric Methane and Their Value for Quantifying Methane Emissions," *Atmospheric Chemistry and Physics* **16**(22), 14371–14396. DOI:10.5194/acp-16-14371-2016

Javanroodi, K., V. M. Nik, M. G. Giometto, and J.-L. Scartezzini. 2022. "Combining Computational Fluid Dynamics and Neural Networks to Characterize Microclimate Extremes: Learning the Complex Interactions Between Meso-Climate and Urban Morphology," *Science of the Total Environment* **829**, 154223. DOI:10.1016/j.scitotenv.2022.154223

Jiao, Y., A. Ruecker, M. J. Deventer, A. T. Chow, and R. C. Rhew. 2018. "Halocarbon Emissions from a Degraded Forested Wetland in Coastal South Carolina Impacted by Sea Level Rise," *ACS Earth and Space Chemistry*, **2**(10), 955–967. DOI:10.1021/acsearthspacechem.8b00044

Keellings. D., and J. Engström. 2019. "The Future of Drought in the Southeastern U.S.: Projections from Downscaled CMIP5 Models," *Water* **11**(2): 259. DOI:10.3390/w11020259.

Keppel-Aleks, G., and R. A. Washenfelder. 2016. "The Effect of Atmospheric Sulfate Reductions on Diffuse Radiation and Photosynthesis in the United States During 1995–2013," *Geophysical Research Letters* **43**(18), 9984–9993. DOI:10.1002/2016GL070052.

Kleinman, J. S., J. D. Goode, J. L. Hart, and D. C. Dey. 2020. "Prescribed Fire Effects on Pinus Palustris Woodland Development after Catastrophic Wind Disturbance and Salvage Logging," *Forest Ecology and Management* **468**(15), 118173. DOI:10.1016/j.foreco.2020.118173

Kuang, C., S. Giangrande, S. Serbin, G. Elsaesser, P. Gentine, T. Heus, M. Oue, J. Peters, J. Smith, A. Steiner, A. McComiskey, M. Jensen, A. Sedlacek, P. Kollias, A. Vogelmann, H. Morrison, M. Petters, and D. Turner. 2023. *Science Plan for the Deployment of the Third ARM Mobile Facility to the Southeastern United States at the Bankhead National Forest, Alabama (AMF3 BNF)*, DOE/SC-ARM-23-035. U.S. Department of Energy Office of Science. DOI:10.2172/2280575

Kupfer, J. A., A. J. Terando, P.,Gao, C. Teske, and J. K. Hiers. 2020. "Climate Change Projected to Reduce Prescribed Burning Opportunities in The Southeastern United States," *International Journal of Wildland Fire* **29**(9), 764-778. DOI:10.1071/WF19198

Lacke, M. C., T. L. Mote, and J. M. Shepherd. 2009. "Aerosols and Associated Precipitation Patterns in Atlanta," *Atmospheric Environment* **43**(28), 4359–4373. DOI:10.1016/j.atmosenv.2009.04.022

Li, L., and P. Chakraborty. 2020. "Slower Decay of Landfalling Hurricanes in a Warming World," *Nature* **587**(7833), 230-234. DOI:10.1038/s41586-020-2867-7

Loescher, H. W., and C. L. Staudhammer. 2011. "Disturbance and Climate Feedbacks in the Southeastern United States," *Forest Ecology and Management* **261**(8), 1353–1360. DOI:10.1016/j.foreco.2010.12.036

McLeod, J., M. Shepherd, and C. E. Konrad II. 2017. "Spatio-Temporal Rainfall Patterns Around Atlanta, Georgia and Possible Relationships to Urban Land Cover," *Urban Climate* **21**, 27–42. DOI:10.1016/j.uclim.2017.03.004

Muse, N., K. J. Mach, D. M. Iwaniec, C. Wyczalkowski. 2022. "Heat Exposure and Resilience Planning in Atlanta, Georgia," *Environmental Research: Climate* **1**, 015004. https://iopscience.iop.org/article/10.1088/2752-5295/ac78f9/ampdf.

Nagy, R. C., and B. G. Lockaby. 2011. "Urbanization in the Southeastern United States: Socioeconomic Forces and Ecological Responses Along an Urban–Rural Gradient," *Urban Ecosystems* **14**, 71–86. DOI:10.1007/s11252-010-0143-6

Nedd, R., and A. Anandhi. 2022. "Land Use Changes in the Southeastern United States: Quantitative Changes, Drivers, and Expected Environmental Impacts," *Land* **11**(12), 2246. DOI:10.3390/land11122246

NOAA NCEI. 2018. "Billion-Dollar Weather and Climate Disasters," National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/.

Noss, R. F., W. J. Platt, B. A. Sorrie, A. S. Weakley, D. B. Means, J. Costanza, and R. K. Peet. 2015. "How Global Biodiversity Hotspots May Go Unrecognized: Lessons from the North American Coastal Plain," *Diversity and Distributions*, **21**(2), 236–244. DOI:10.1111/ddi.12278

Novick, K. A., D. L. Ficklin, P. C. Stoy, C. A. Williams, G. Bohrer, A. C. Oishi, S. A. Papuga, P. D. Blanken, A. Noormets, B. N. Sulman, R. L. Scott, L. Wang, and R. P. Phillips. 2016. "The Increasing Importance of Atmospheric Demand for Ecosystem Water and Carbon Fluxes," *Nature Climate Change* **6**, 1023–1027.

Nowacki, G. J., and M. D. Abrams. 2015. "Is Climate an Important Driver of Post-European Vegetation Change in the Eastern United States?," *Global Change Biology* **21**(1), 314–334. DOI:10.1111/gcb.12663

Nowacki, G. J., and M. D. Abrams. 2008. "The Demise of Fire and 'Mesophication' of Forests in the Eastern United States," *BioScience* **58**(2), 123–138. DOI:10.1641/B580207

O'Halloran, T. L., B. E. Law, M. L. Goulden, Z. Wang, J. G. Barr, C. Schaaf, M. Brown, J. D. Fuentes, M. Göckede, A. Black, and V. Engel. 2012. "Radiative Forcing of Natural Forest Disturbances," *Global Change Biology* **18**(2), 555–565. DOI:10.1111/j.1365-2486.2011.02577.x

Oishi, A. C., C. F. Miniat, K. A. Novick, S. T. Brantley, J. M. Vose, and J. T. Walker. 2018. "Warmer Temperatures Reduce Net Carbon Uptake, But Do Not Affect Water Use, in a Mature Southern Appalachian Forest," *Agricultural and Forest Meteorology* **252**, 269–282. DOI:10.1016/j.agrformet.2018.01.011

Oswalt, S. N., W. B. Smith, P. D. Miles, and S. A. Pugh. 2014. *Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2010 Update of the RPA Assessment,* WO-91. U. S. Department of Agriculture, Forest Service. DOI:10.2737/WO-GTR-91

Palmer, P. I., D. S. Abbot, T.-M. Fu, D. J. Jacob, K. Chance, T. P. Kurosu, A. Guenther, C. Wiedinmyer, J. C. Stanton, M. J. Pilling, S. N. Pressley, B. Lamb, and A. L. Sumner. 2006. "Quantifying the Seasonal and Interannual Variability of North American Isoprene Emissions Using Satellite Observations of the Formaldehyde Column," *Journal of Geophysical Research: Atmospheres* **111**, D1215. DOI: 10.1029/2005JD006689

Pedersen, N., A. W. D'Amato, J. M. Dyer, D. R. Foster, D. Goldblum, J. L. Hart, A. E. Hessl, L. R. Iverson, S. T. Jackson, D. Martin-Benito, B. C. McCarthy, R. W. McEwan, D. J. Mladenoff, A. J. Parker, B. Shuman, and J. W. Williams. 2015. "Climate Remains an Important Driver of Post-European Vegetation Change in the Eastern United States," *Global Change Biology*, **21**(6), 2105–2110. DOI:10.1111/gcb.12779

Perica, S., D. Martin, S. Pavlovic, I. Roy, M. S. Laurent, C. Trypaluk, D. Unruh, M. Yekta, and G. Bonnin. 2013. *NOAA Atlas 14: Precipitation-Frequency Atlas of the United States, Vol. 9 Version 2.0: Southeastern States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi).* U. S. National Weather Service. https://repository.library.noaa.gov/view/noaa/22617.

PRISM Climate Data. 2014. Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group, Oregon State University. https://prism.oregonstate.edu, accessed 16 Dec 2020.

Rady, J. and the FATES Development Team. 2022. The Functionally Assembled Terrestrial Ecosystem Simulator (FATES) with the Vegetation Management Module (VM). Version 1.0.0. Zenodo. DOI:10.5281/zenodo.6536487

Reitz, M., W. E., Sanford, and S. Saxe. 2023. "Ensemble Estimation of Historical Evapotranspiration for the Conterminous U.S.," *Water Resources Research*, **59**(6), e2022WR034012.

Schleeweis, K. G., G. G. Moisen, T. A. Schroeder, C. Toney, E. A. Freeman, S.l N. Goward, C. Huang, and J. L. Dungan. 2020. "U.S. National Maps Attributing Forest Change: 1986–2010," *Forests* **11**(6), 653. DOI:10.3390/f11060653

Schweitzer, C. J., D. C. Day, and Y. Wang. 2019. "White Oak (Quercus alba) Response to Thinning and Prescribed Fire in Northcentral Alabama Mixed Pine–Hardwood Forests," *Forest Science* **65**(6), 758–766. DOI:10.1093/forsci/fxz031

Shen, L., L. J. Mickley, and E. Gilleland. 2016. "Impact of Increasing Heat Waves on U.S. Ozone Episodes in the 2050s: Results from a Multimodel Analysis Using Extreme Value Theory," *Geophysical Research Letters* **43**(8), 4017–4025. DOI:10.1002/2016GL068432

Shepherd, J. M., H. Pierce, and A. J. Negri. 2002. Rainfall Modification by Major Urban Areas: Observations from Spaceborne Rain Radar on the TRMM Satellite," *Journal of Applied Meteorology and Climatology* **41**(7), 689–701. 10.1175/1520-0450(2002)041<0689:RMBMUA>2.0.CO;2

Song, X., H. Tian, X. Xu, D. Hui, G. Chen, G. Sommers, L. Marzen, and M. Liu. 2013. "Projecting terrestrial carbon sequestration of the southeastern United States in the 21st century," *Ecosphere* **4**(7), 1–18.

Spielman, S.E., J. Tuccillo, D.C. Folch, A. Schweikert, R. Davies, N. Wood, and E. Tate. 2020. "Evaluating Social Vulnerability Indicators: Criteria and Their Application to the Social Vulnerability Index," *Natural Hazards* **100**, 417–436. DOI:10.1007/s11069-019-03820-z

Swain, D. L., O. E. J. Wing, P. D. Bates, J. M. Done, K. A. Johnson, and D. R. Cameron. 2020. "Increased Flood Exposure Due to Climate Change and Population Growth in the United States," *Earth's Future* **8**(11), e2020EF001778. DOI:10.1029/2020EF001778

Tegen, I., and K. Schepanski. 2018. "Climate Feedback on Aerosol Emission and Atmospheric Concentrations," *Current Climate Change Reports* **4**, 1–10. DOI:10.1007/s40641-018-0086-1

Terando A. J., J. Costanza, C. Belyea, R. R. Dunn, A. McKerrow, and J. A. Collazo. 2014. "The Southern Megalopolis: Using the Past to Predict the Future of Urban Sprawl in the Southeast U.S.," *PLoS ONE* **9**(7), e102261. DOI:10.1371/journal.pone.0102261

Thomas, R. Q., G. C. Hurtt, R. Dubayah, and M. H. Schilz. 2008. "Using Lidar Data and A Height-Structured Ecosystem Model to Estimate Forest Carbon Stocks and Fluxes Over Mountainous Terrain," *Canadian Journal of Remote Sensing* **34**(sup2), S351–S363. DOI:10.5589/m08-036

Tuccillo, J.V., and S. E. Spielman. 2022. "A Method for Measuring Coupled Individual and Social Vulnerability to Environmental Hazards," *Annals of the American Association of Geographers* **112**(6), 1702–1725. DOI:10.1080/24694452.2021.1989283

U.S. Climate Resilience Toolkit. "Southeast." Accessed July 2024. U.S. Global Change Research Program. https://toolkit.climate.gov/regions/southeast

U.S. EPA. 1963. Clean Air Act. United States Environmental Protection Agency. https://www.epa.gov/laws-regulations/summary-clean-air-act

U.S. EPA. 2024. "Heat Island Effect," U.S. Environmental Protection Agency. Accessed 23 August 2024. https://www.epa.gov/heatislands

U.S. GCRP. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Eds. D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart. U.S. Global Change Research Program. DOI:10.7930/NCA4.2018.

van Dijk, A. I. J. M., J. H. Gash, E. van Gorsel, P. D. Blanken, A. Cescatti, C. Emmel, B. Gielen, I. N. Harman, G. Kiely, L. Merbold, L. Montagnani, E. Moors, M. Sottocornola, A. Varlagin, C. A. Williams, and G. Wohlfahrt. 2015. "Rainfall Interception and the Coupled Surface Water and Energy Balance," *Agricultural and Forest Meteorology* **214–15**, 402-15.

Van Metre, P. C., I. R. Waite, S. Qi, B. Mahler, A. Terando, M. Wieczorek, M. Meador, P. Bradley, C. Journey, T. Schmidt, and D. Carlisle. 2019. "Projected Urban Growth in the Southeastern USA Puts Small Streams at Risk," *PLoS ONE* **14**(10), e0222714. DOI:10.1371/journal.pone.0222714

Varner, J. M., J. M. Kane, J. K. Kreye, and T. M. Shearman. 2021. "Litter Flammability of 50 Southeastern North American Tree Species: Evidence for Mesophication Gradients Across Multiple Ecosystems," *Frontiers in Forests and Global Change* **4**, 727042. DOI:10.3389/ffgc.2021.727042

Vigil, J. F., R. J. Pike, and D. G. Howell. 2000. "A Tapestry of Time and Terrain." Pamphlet to accompany U.S. Geological Survey Geologic Investigations Series I-2720. https://pubs.usgs.gov/imap/i2720/i2720_pamphlet.pdf

Williams, C. A., H. Gu, R. MacLean, J. G. Masek, and G. J. Collatz. 2016. "Disturbance and the Carbon Balance of U.S. Forests: A Quantitative Review of Impacts from Harvests, Fires, Insects, and Droughts," *Global and Planetary Change* **143**, 66–80. DOI:10.1016/j.gloplacha.2016.06.002

Williams, A. P., B. I. Cook, J. E. Smerdon, D. A. Bishop, R. Seager, and J. S. Mankin. 2017. "The 2016 Southeastern U.S. Drought: An Extreme Departure from Centennial Wetting and Cooling," *Journal of Geophysical Research: Atmospheres* **122**(20), 10,888–10,905. DOI:10.1002/2017JD027523

Winbourne, J. B., T. S. Jones, S. M. Garvey, J. L. Harrison, L. Wang, D. Li, P. H. Templer, and L. R. Hutyra. 2020. "Tree Transpiration and Urban Temperatures: Current Understanding, Implications, and Future Research Directions," *BioScience* **70**(7), 576–588. DOI:10.1093/biosci/biaa055

Xu. L., H. Guo, C. M. Boyd, M. Klein, A. Bougiatioti, K. M. Cerully, J. R. Hite, G.Isaacman-VanWertz, N. M. Kreisberg, C. Knote, K. Olson, A. Koss, A. H. Goldstein, S. V. Hering, J. de Gouw, K. Baumann, S.-H. Lee, A. Nenes, R. J. Weber, and N. L. Ng. 2015a. "Effects of Anthropogenic Emissions on Aerosol Formation from Isoprene and Monoterpenes in the Southeastern United States," *PNAS* **112**(1), 37–42. DOI: 10.1073/pnas.14176091

Xu, L., S. Suresh, H. Guo, R. J. Weber, and N. L. Ng. 2015b. "Aerosol Characterization Over the Southeastern United States Using High-Resolution Aerosol Mass Spectrometry: Spatial and Seasonal Variation of Aerosol Composition and Sources with a Focus on Organic Nitrates," *Atmospheric Chemistry and Physics* **15**(13), 7307–7336. DOI:10.5194/acp-15-7307-2015

Appendix F
Acronyms and Abbreviations

AMF3	third Atmospheric Radiation Measurement mobile facility
ARM	Atmospheric Radiation Measurement research facility
AVOC	anthropogenic volatile organic carbon
BER	Biological and Environmental Research program
BNF	Bankhead National Forest
BVOC	biogenic volatile organic carbon
C	carbon
CCN	cloud condensation nuclei
CO_2	carbon dioxide
CH_4	methane
CMIP5	Coupled Model Intercomparison Project Phase 5
DESIS	DLR Earth Sensing Imaging Spectrometer
DOE	U.S. Department of Energy
E	evaporation
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ESS	Environmental System Science
ET	evapotranspiration
FATES	Functionally Assembled Terrestrial Ecosystem Simulator
LiDAR	light detection and ranging
ModEx	model-experiment approach
NASA	National Aeronautics and Space Administration
NCA4	Fourth National Climate Assessment
NOAA	National Oceanic and Atmospheric Administration
RADAR	radio detection and ranging
RCP	representative concentration pathway
SELARO	Southeast Land–Atmosphere Research Opportunities
SOA	secondary organic aerosol
SLR	sea level rise
T	transpiration
UHI	urban heat island
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VPD	vapor pressure deficit

Back Cover Images

Top to bottom: **(1)** Fall in the southern Appalachian Mountains. Courtesy Getty Images. **(2)** Mature longleaf pine forest in South Carolina. Courtesy U.S. Forest Service. **(3)** Tornado damage in Sawyerville, Ala. Courtesy National Oceanic and Atmospheric Administration. **(4)** Last Resort Fire in Tyrrell County, N.C. Courtesy N.C. Forest Service. **(5)** Mississippi Delta. Courtesy U.S. Geological Survey. **(6)** Rock slide on Little River Road, Tenn. Courtesy National Park Service.