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Endeavors

Life Sciences

Impacts of southern pine beetle (*Dendroctonus frontalis*) on loblolly pine (*Pinus taeda*) canopy and water use in the Homochitto National Forest, Mississippi, USA

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Abstract

Forest disturbances can have many impacts on forest ecosystem services, including forest water use. Studies on impacts to forest evapotranspiration have been conducted on the mountain pine beetle (*Dendroctonus ponderosae*) in western North America, but not on the southern pine beetle (*Dendroctonus frontalis*), a native pest of loblolly pine (*Pinus taeda*) and shortleaf pine (*Pinus echinata*) in the southeastern United States. Stressed pine trees produce pheromones that attract southern pine beetles and, with enough stressed trees, beetle populations can quickly grow to epidemic levels and attack healthy trees, resulting in widespread tree mortality. Here, we examined the impact of southern pine beetle spots on canopy density and evapotranspiration in loblolly pine stands in the Homochitto National Forest from 2012-2021. USDA Forest Service beetle spot locations were used to extract normalized difference vegetation index (NDVI) values using Landsat satellite observations on Google Earth Engine, and evapotranspiration data at stand-level from the OpenET platform for two years pre- and post-southern pine beetle detection for comparative analysis. Southern pine beetle outbreaks reduced NDVI and evapotranspiration, though other factors (e.g., understory vegetation) may result in stand-by-stand variation in hydrologic cycle impacts. This study demonstrates that satellite observations can provide critical environmental data on the impacts of forest pests. By understanding the relationships between biotic disturbance agents and forest water use capability in forest ecosystems, we can improve our understanding of the impacts of forest disturbance agents on ecosystem services and possibly help direct management of forest stands impacted by these disturbances.

Introduction

The southern pine beetle (*Dendroctonus frontalis* Zimmerman) is an economically important pest of southern pine species, such as loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), and Virginia pine (*P. virginiana*) (Pye et al., 2011; Clarke et al., 2016). Female southern pine beetles fly in search of a host tree that has weakened defenses. Upon finding a host, they release aggregation pheromones to attract other female and male southern pine beetles that then release pheromones that have a synergizing effect with the aggregation pheromones released by the colonizing female beetles (Renwick and Vité, 1969; Sullivan, 2011). Adult beetles construct galleries, and mated females will deposit eggs along the gallery. The eggs then hatch and larvae develop in short larval galleries before moving to the outer bark to pupate and emerge as an adult that disperses to another tree (Hain et al., 2011). When the environment is conducive for southern pine beetle population growth and multiple, suitable host trees are available, increased beetle population density can ultimately result in an outbreak (Gara and Coster, 1968; Price et al., 1998). During an outbreak, beetles can mass-attack healthy host trees, and infestations of beetles can grow rapidly, resulting in the mortality of thousands of hectares of pine trees (Gara and Coster, 1968; Ayres et al., 2011).

The southern pine beetle has, historically, been an eruptive pest in pine stands located in the southeastern United States (Clarke et al., 2016). However, some studies have documented reductions in southern pine beetle populations in the southeastern United States, possibly due to changes in forest management practices, use of genetically improved tree stock in planted forest settings, or climatic variables, such as drought or heat (e.g., Asaro et al., 2017; Lombardo et al., 2022). Simultaneously, sustained outbreaks have been documented in the northeastern United States, suggesting that the southern pine beetle is expanding its range to areas previously considered to have unsuitable climates due to recent warming in these areas (Aoki et al., 2018; Kanaskie et al., 2023). Changes in climate, such as increased heat and drought, can also exacerbate tree stress, promote southern pine beetle populations, increase risk to other abiotic and biotic disturbances, and negatively impact primary production, nutrient cycling, forest composition, and succession (Tchakerian and Coulson, 2011; Chen et al., 2018; Gandhi et al., 2022). Southern pine beetle outbreaks can also significantly increase the amount of fuels for eight years post-outbreak, which can increase wildfire risk (Xie et al., 2020).

In the last decade, several studies have assessed the ability of remote sensing systems to detect bark beetle damage within forest stands. Many remote sensing studies have focused on utilizing the Normalized Difference Vegetation Index (NDVI), which compares the visible red and near infrared spectral bands to estimate photosynthetic activity in vegetation (Tucker, 1979). For example, Assal et al., (2014) modeled historical mountain pine beetle outbreaks using the Landsat Multispectral Scanner System. Tree mortality caused by mountain pine beetle has also been mapped using NDVI products from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Spruce et al., 2019). Verbesselt et al., (2009) used MODIS NDVI to predict insect-induced tree mortality. Wulder et al., (2022) reviewed using Landsat observations for various studies, including insect damage. Southern pine beetle infestations have also been detected in Florida using Sentinel-2 and MODIS NDVI (Gomez et al., 2020). In the past, the NDVI of southern pine beetle spots was derived from images acquired from light aircrafts (e.g., Carter et al., 1998). Now, low to high resolution images acquired from satellites are more commonly used to pick up on yellow, orange, or red-brown coloration (i.e., the color of dying pine trees), though further research using imagery with higher spatial and temporal resolution is required to more precisely map southern pine beetle spots over time (e.g., Gomez et al., 2020).

While there are some studies on the impacts of southern pine beetle to forest ecosystem services, there are very few studies of the impacts of southern pine beetle outbreaks on hydrologic cycles of forested systems, such as impacts on forest evapotranspiration (Tchakerian and Coulson, 2011). Evapotranspiration is an important function within forest ecosystems that helps move water from soil and vegetation into the atmosphere (Jasechko et al., 2013). Studies of the impacts of forest pests on forest evapotranspiration have been conducted with the mountain pine beetle (*Dendroctonus ponderosae*). Edburg et al., (2012) provided a conceptual framework of the impacts of mountain bark beetles on biogeochemical processes, including evapotranspiration, and showed that evapotranspiration rates can reduce and vary across the different stages of mountain pine beetle outbreaks. Brown et al., (2014) found a reduction in evapotranspiration in lodgepole pine (*Pinus contorta*) stands killed by mountain pine beetle. However, the reduction was offset by an increase in evapotranspiration from accelerated growth of surviving species in the sub-canopy (Brown et al., 2014). Vanderhoof and Williams, (2015) found that, in some cases, mountain pine beetle outbreaks reduce summer evapotranspiration, but intermediate-aged stands experienced an increase in summer evapotranspiration for a few decades post-disturbance in lodgepole pine stands. Similarly, Knowles et al., (2023) found that mountain pine beetle outbreaks reduced evapotranspiration by 2 - 25%, and it took several years for evapotranspiration recovery to begin in stands of mixed coniferous forest.

Despite extensive knowledge of impacts of bark beetle on evapotranspiration in the western United States, novel combinations of forest types and their unique hydrologic cycles and disturbances may produce unique outcomes that are not demonstrated by existing research (Jones et al., 2020). In the eastern United States, evapotranspiration is generally less limited by precipitation and soil moisture than in the western United States (Teuling et al., 2009; Kramer et al., 2015), so impacts of southern pine beetle on forest evapotranspiration may be different than that of mountain pine beetle on forest evapotranspiration in the western United States. Further, past studies of southern pine beetle, in particular, have used imagery with lower spatial or temporal resolution to assess NDVI or have not evaluated all currently available technologies, so there is a need to explore more remote sensing technologies for assessing impacts of southern pine beetle outbreaks on canopy density. Here, we aimed to examine the impact of southern pine beetle spots on canopy density and evapotranspiration in loblolly pine stands in the Homochitto National Forest from 2012-

2021. We hypothesized that the NDVI and evapotranspiration would decrease at southern pine beetle detection and post-detection compared to pre-detection.

Materials and Methods

Study Site

The Homochitto National Forest covers seven counties and contains 77,634.5 hectares between latitude 31°30 N and longitude 90°59 W in southwestern Mississippi (Figure 1; Nowak et al., 2015). Like many other southern National Forests, the Homochitto National Forest's lands are arranged in a patchwork of mixed ownership (i.e., National Forest land among industrial timber lands, private agricultural lands, and private residences) (USFS, 2025). Historically, the area was dominated by longleaf pine (*Pinus palustris*), but extensive harvesting, land clearing for agriculture, and fire prevention significantly reduced longleaf pine populations in the region (USFS, 2025). When the USDA Forest Service initially acquired the land in 1936, most remaining longleaf pine trees were replaced with loblolly pine stands (USFS, 2025). However, after over 75 years of management, the Homochitto National Forest is now home to over 850 species of vascular plant species, including loblolly pine, longleaf pine, mockernut hickory (*Carya tomentosa*), red maple (*Acer rubrum*), shortleaf pine, sweetgum (*Liquidambar styraciflua*), water oak (*Quercus nigra*), white oak (*Q. alba*), willow oak (*Q. phellos*), and various herbaceous plants [e.g., bluestems (*Andropogon* spp.), goldenrods (*Solidago* spp.), milkweeds (*Asclepias* spp.)] that can be found in the upland pine, pine-hardwood, and/or bottomland hardwood forested areas (Havran, 2004; McFarland et al., 2020).

There is a diverse array of soils in the Homochitto National Forest, but some common soils include Susquehanna-Smithdale association, Lorman silt loam, Gillsburg silt loam, and Smithdale silt loam (NRCS, 2025). The topography is variable, ranging from relatively flat to rolling hills and steep slopes. The mean annual temperature is 18.8°C with an annual precipitation of approximately 1,368 mm (Nowak et al., 2015).

Although some studies have documented reductions in southern pine beetle populations in the southeastern United States (Asaro et al., 2017; Lombardo et al., 2022), the Homochitto National Forest has experienced a series of southern pine beetle outbreaks in the past (Clarke and Hartshorn, 2021). One of the most recent outbreaks began in 2015 and peaked in 2017 - 2018, resulting in over 4,856 hectares of pine damage with 809 hectares of trees that were cut and removed, 1,133 hectares of trees that were cut and left on site, and the remaining 2,800+ hectares that were left as dead, standing trees (USFS, 2025). This outbreak was likely fueled by the dry summers followed by high temperature winters before the outbreak, and an abundance of moderate to high density pine stands that provide suitable conditions for southern pine beetle infestation due to a lack of thinning from poor timber markets in some areas (USFS, 2017).

To study the impacts of southern pine beetle on NDVI and evapotranspiration, we selected an approximately 30.55 km^2 area of interest of the Homochitto National Forest southwest of Meadville, Mississippi, USA. Most of the area is comprised of loblolly pine and mixed species forest, but there are some residences, churches, small ponds, and roads that create insignificant clearings in the mostly contiguous forested area. This area was selected because it had several southern pine beetle spots detected during the time frame included in this study.

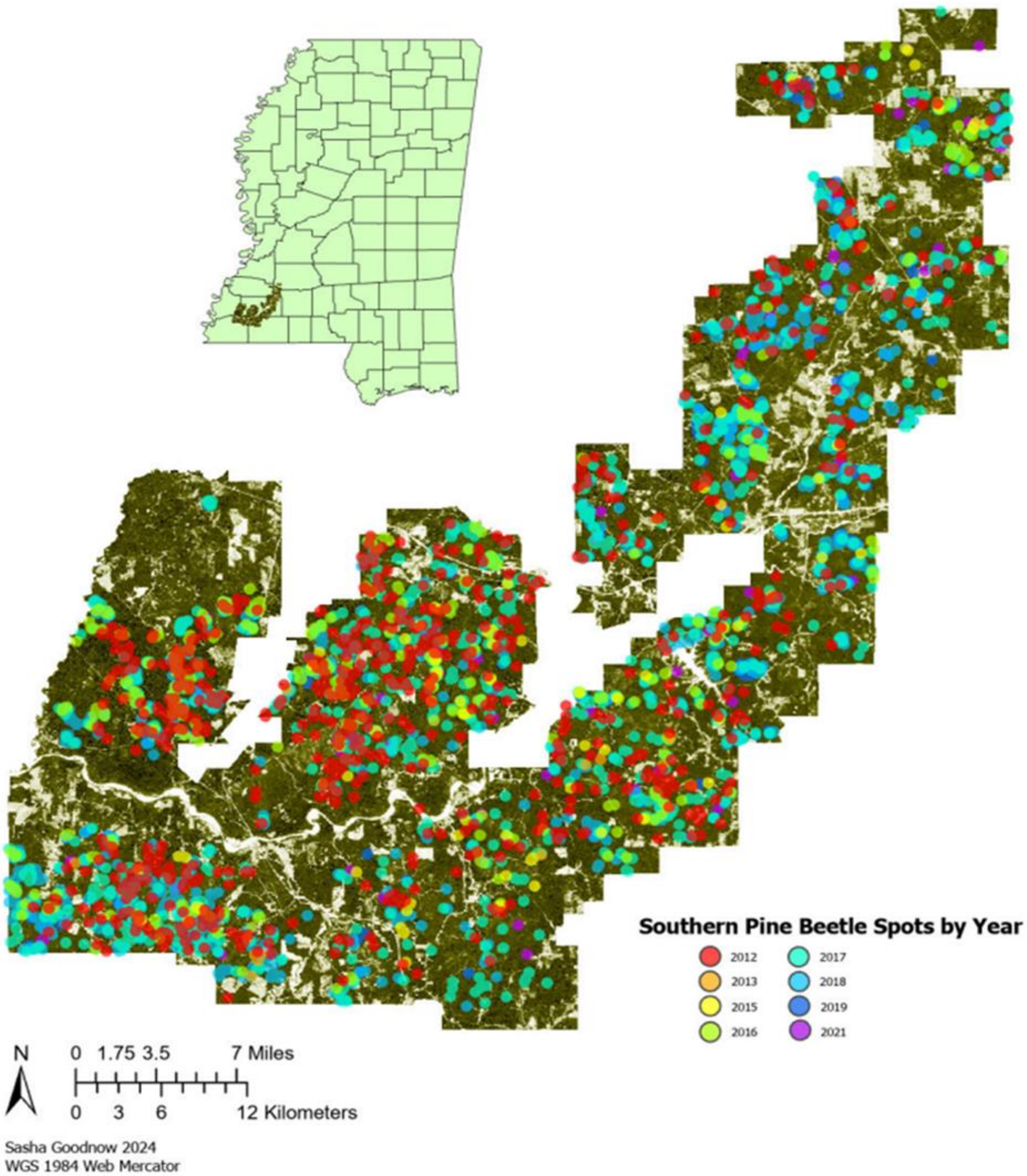

Figure 1. Location of the Homochitto National Forest in southwestern Mississippi, with southern pine beetle spots by year.

USDA Forest Service Southern Pine Beetle Spot Data

The USDA Forest Service documented southern pine beetle spot aerial and ground truth data from the Homochitto National Forest from 2012 - 2021, which encompasses the 2015 - 2018 outbreak. Data were cleaned and provided by Dr. James Meeker with the USDA Forest Service, though historical data can now also be found via the Southern Pine Beetle Information Center (https://spb.clemson.edu/). The southern pine beetle spot data consisted of latitude and longitude, the date of detection, size of each southern pine beetle spot, total affected area, treated area, number of green trees, number of red trees, number of dead trees, number of infested trees, pine basal area, and total basal area from 2012 - 2021. No southern pine beetle spots were detected in 2014 and no data were collected in 2020 due to COVID-19, thus, the years 2014 and 2020 were excluded from this study. A shapefile was created in ESRI ArcGIS Pro 3.4 with the Homochitto National Forest base map (USFS, 2024) and southern pine beetle spot locations using the coordinates (i.e., latitudes and longitudes) for each spot provided by the USDA Forest Service.

Google Earth Engine and OpenET Analyses

We integrated the southern pine beetle information into Google Earth Engine as point data. We then used their coordinates to analyze the dynamics of NDVI, a measurement of the amount and vigor of terrestrial vegetation that is calculated as (NIR – Red)/(NIR + Red), where NIR is the near-infrared radiation and Red is the visible radiation (Tucker, 1979). The NDVI calculations on land surfaces always result in a number between 0 and 1, where barren areas produce very low NDVI values, unhealthy vegetation produces a value close to zero, and healthy, dense vegetation results in values close to one. Analyses of NDVI were conducted using Landsat satellite observations in Google Earth Engine (Gorelick et al., 2017). Landsat 7 was used to analyze NDVI from April to October in 2010 - 2012, and Landsat 8 was used to analyze NDVI from April to October in 2013 - 2023. Cloud contaminated pixels were removed using the cloud coverage information in Landsat observations.

Using the southern pine beetle spot locations, evapotranspiration data were extracted at stand level from the 30-meter OpenET ensemble monthly evapotranspiration v2.0, which provides the average value of six evapotranspiration models in OpenET after removing the outliers (Melton et al., 2022). These monthly ensemble evapotranspiration data from 2013 to 2023 were used in this study. For both NDVI and evapotranspiration, we calculated the average value for the southern pine beetle detection year, two years prior to the detection year, and two years after the detection year for comparative analysis. Since the OpenET platform can only provide evapotranspiration data back to 2013 at the time of this study, we started at 2015 to assess the southern pine beetle pre-detection years of 2013 and 2014, which could not be conducted for 2012 or 2013. Monthly precipitation values (in mm) for the Homochitto National Forest area were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), a high-resolution spatial climate dataset (Daly et al., 1997; PRISM Climate Group, 2025).

Statistical Analyses

Summary statistics for the total affected hectares, NDVI, and evapotranspiration data were calculated in Microsoft Excel. An analysis of variance with post-hoc Tukey's HSD test was conducted at a significance level of $\alpha = 0.05$ in R v. 4.3.1 (R Core Team, 2023) to compare NDVI and evapotranspiration among the five times to detection (i.e., two years prior, one year prior, detection year, one year post, two years post). Evapotranspiration and NDVI analyses were conducted using aerial forest imagery derived from Landsat 8 for the years 2016 - 2018, which included forest coloration just before, during, and after the peak of the outbreak in 2017. The NDVI and evapotranspiration values for the area were mapped in ESRI ArcGIS Pro 3.3. A 10 m buffer was placed around each southern pine beetle spot. After the NDVI and evapotranspiration maps were produced, we visually categorized the southern pine beetle spots into one of three categories (increased, no change in, or decreased NDVI/ET) based on the color of the pixels around the spots. For example, if the area around the spot was purple or blue, it was categorized as an increase in NDVI or evapotranspiration, while green would demonstrate that there was no change, and yellow, orange, and red would indicate a decrease in NDVI or evapotranspiration.

Results

Over the nine-year period, 3,536 southern pine beetle spots were detected via aerial and ground surveys of the Homochitto National Forest, averaging to 54.3 spots per acre (Figure 1). Of these spots, 3,142 were measured by the USDA Forest Service to identify the total size of the area affected by southern pine beetles. The total affected hectares for one southern pine beetle spot ranged from ≤ 0.01 to 25 hectares. The mean (±SE) affected hectares was highest in 2017, with the average southern pine beetle spot being 1.01 ± 0.06 hectares in size (Figure 2).

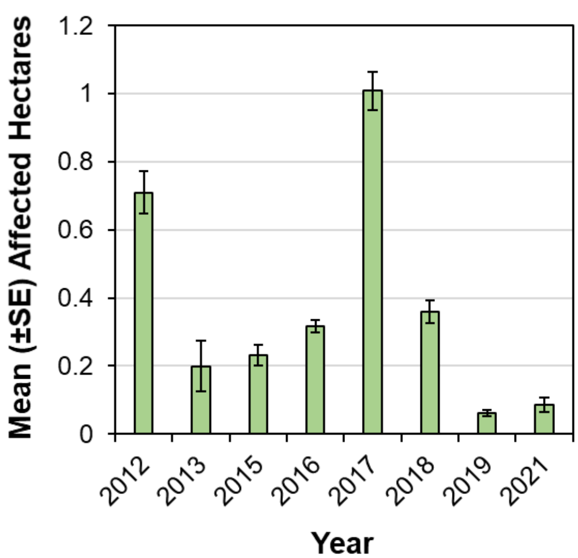

Figure 2. Mean (±SE) area (in hectares) affected by southern pine beetles each year from 2012 - 2021.

The NDVI outputs varied between 0 and 1 (green vegetation = 0.8 – 0.9). The mean (±SE) NDVI for spots two years before southern pine beetle detection was 0.82 ± 0.0006, 0.83 ± 0.001 for spots one year before detection, 0.8 ± 0.0008 for the detection year, 0.79 ± 0.001 for one year after detection, and 0.82 ± 0.0008 for two years after detection (Figure 3A). There was at least one statistically significant difference in NDVI among the five times to detection ($F(4) = 308$, $p < 0.001$). The post-hoc Tukey's HSD test showed significant differences in all time points except the two years prior to detection and two years post detection ($p = 0.54$) and one year prior to detection ($p = 0.54$) (Figure 3A). In all years except 2013, the NDVI of the detection year and one year post detection were less than the years prior to detection. In 2013, the NDVI was higher in the year of southern pine beetle detection than in the two years before detection. In three of the years that were assessed (37.5%), the NDVI started to increase again in the year after southern pine beetle detection. In six of the years assessed (75%), the NDVI more significantly increased two years after southern pine beetle detection, with some NDVI values reaching or exceeding the NDVI values observed prior to southern pine beetle detection (Figure 4A).

Evapotranspiration for spots from 2015 – 2017 ranged from 57.4 to 181.2 mm. The mean (±SE) evapotranspiration for spots two years before southern pine beetle detection was 154.5 ± 0.16 mm, 150.5 ± 0.16 mm for spots one year before detection, 148.6 ± 0.2 mm for the detection year, 146.46 ± 0.27 mm for one year after detection, and 148.47 ± 0.22 mm for two years after detection (Figure 3B). There was at least one statistically significant difference in evapotranspiration among the five times to detection ($F(4) = 219.9$, $p < 0.001$), with significant differences in all time points except the detection year and two years post detection ($p = 0.99$) (Figure 3B). From year

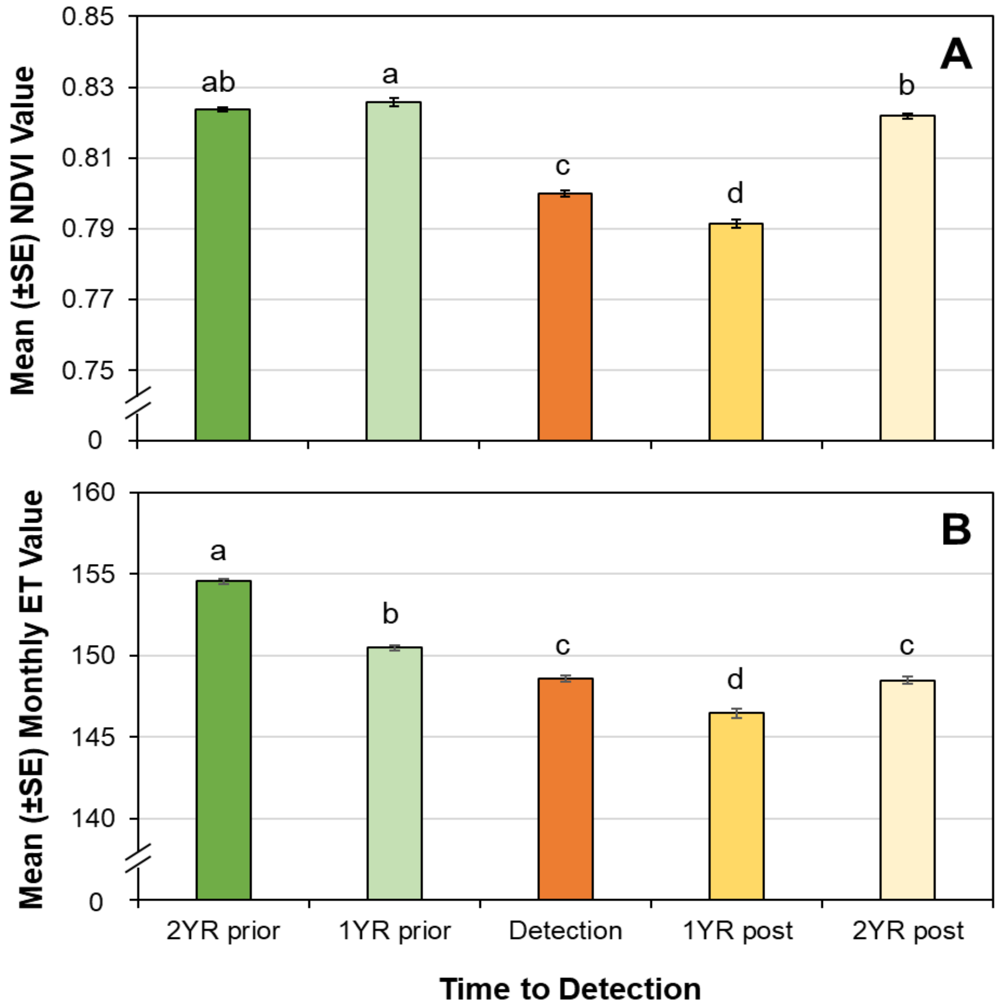

Figure 3. Mean (±SE) (**A**) normalized difference vegetation index (NDVI) and (**B**) monthly evapotranspiration (ET; mm) by time to detection for the pine stands affected by southern pine beetles in the Homochitto National Forest. Bars with different letters are significantly different from one another ($P < 0.05$).

to year, evapotranspiration levels tended to decrease in years of southern pine beetle detection and in subsequent years compared to the years prior to detection, but evapotranspiration in detection year 2018 was higher relative to the two years before and two years after detection (Figure 4B). In three of the six years assessed (50%), the evapotranspiration levels began to increase again in the year or two after southern pine beetle detection to the point of reaching or exceeding the levels at the year of detection (Figure 4B).

Total annual precipitation ranged from 1,563.4 mm in 2018 to 1,705.9 mm in 2015, with a mean (±SE) of 1,631.48 ± 24.18 (Figure 4B). Prior to 2015, total annual precipitation was 1,372.8 mm in 2011, 1,869.5 mm in 2012, 1,737.4 mm in 2013, and 1,693.1 mm in 2014 (Figure 5). There was a decrease in winter and fall precipitation in 2014 compared to previous years; however, the total spring and summer precipitation was slightly higher in 2014 than in previous years. In 2015, the winter was dry and the spring was wet, similar to what was

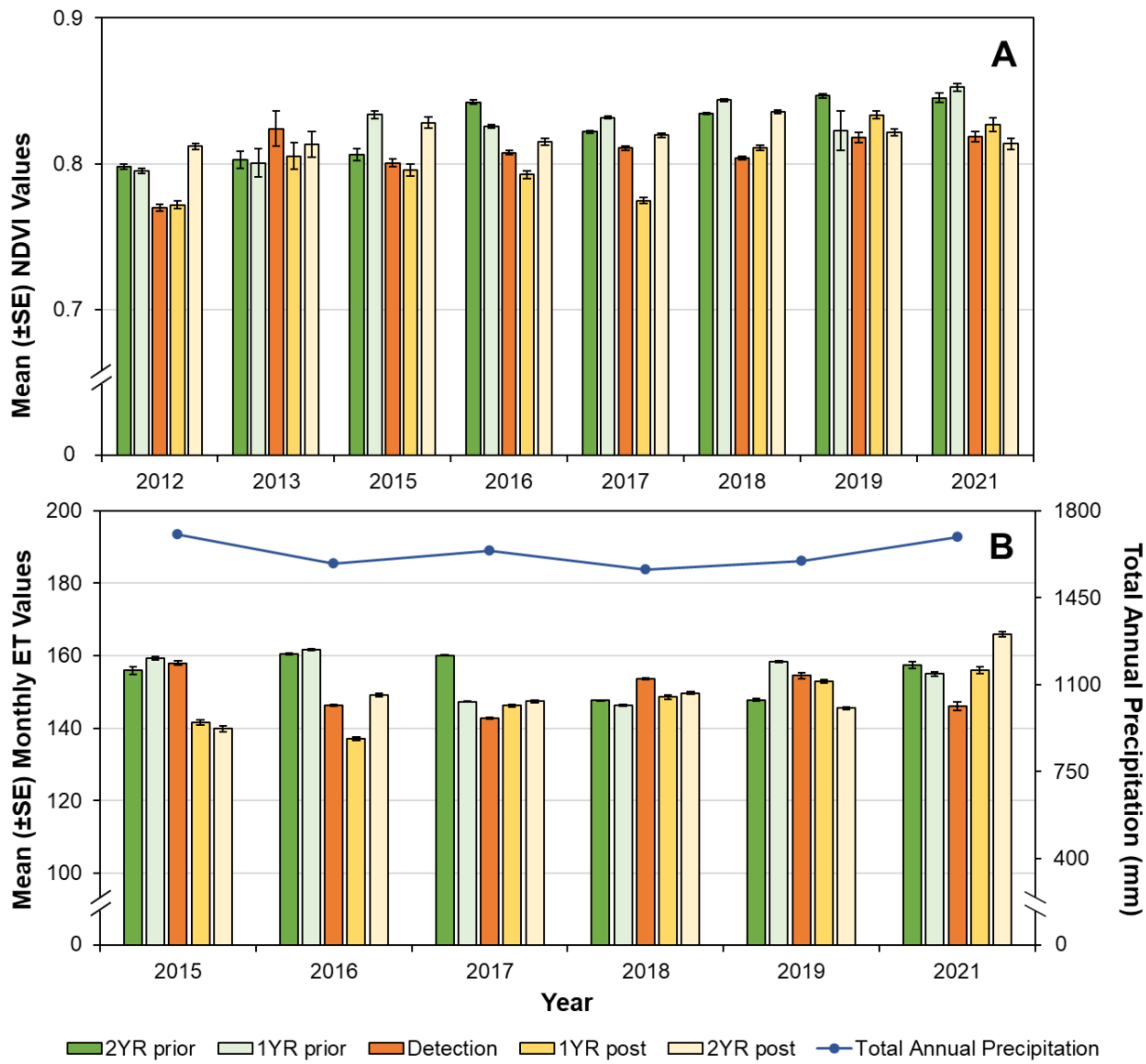

Figure 4. Mean (±SE) (**A**) normalized difference vegetation index (NDVI) and (**B**) evapotranspiration (ET; mm) by southern pine beetle spots per year. Total annual precipitation (mm) for each year is denoted by the blue line (**B**).

observed in 2014. Summer precipitation was reduced compared to previous years, which may have exacerbated the outbreak that started that year. Total annual precipitation was slightly lower in 2014 and 2015 compared to 2012 and 2013, though 2011 had the lowest and 2012 had the highest total annual precipitation of all years included in this study (Figure 5).

There was a total of 90 southern pine beetle spots detected within the area of interest near Meadville, Mississippi (Figure 6), including 20 spots in 2012, two spots in 2015, 14 spots in 2016, 46 spots in 2017, seven spots in 2018, one spot in 2021, and no spots in 2013 and 2019. From 2016 – 2018, the NDVI increased for five southern pine beetle spots (5.6%), remained unchanged for 38 spots (42.2%), and decreased for 47 spots

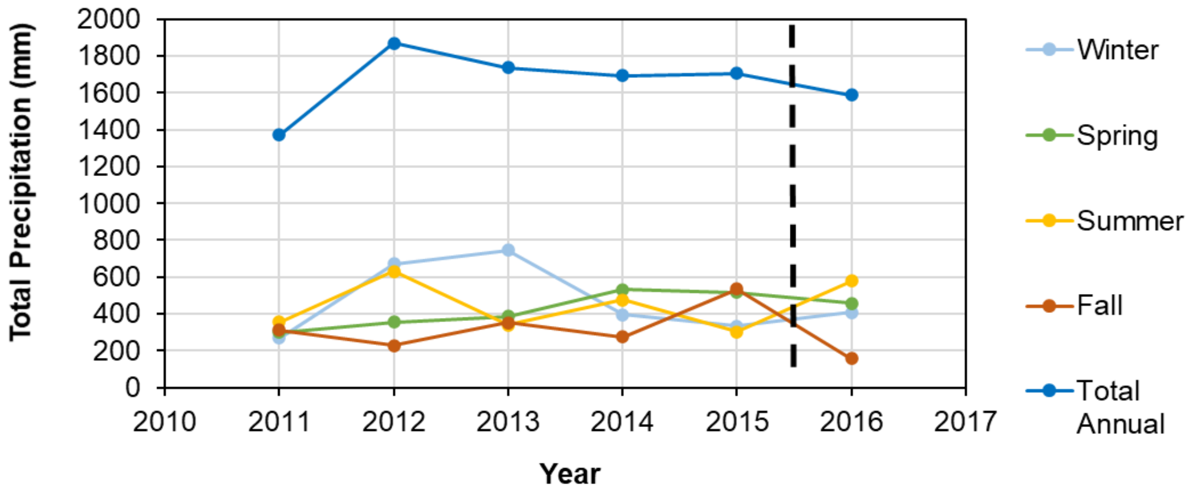

Figure 5. Total seasonal and annual precipitation (mm) for the years prior to the start of the southern pine beetle outbreak, denoted by the black dashed line. Total seasonal precipitation is categorized as winter (December of the previous year, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November).

(52.2%). Evapotranspiration increased for 12 southern pine beetle spots (13.3%), remained unchanged for 29 spots (32.2%), and decreased for 49 spots (54.5%).

Discussion

The primary contribution of this study to the scientific literature is our assessment of the change in loblolly pine canopy and evapotranspiration following southern pine beetle outbreaks through two years post-disturbance and tracking back two years pre-disturbance. Our analysis of the USDA Forest Service southern pine beetle spot detection data revealed that the area assessed in the Homochitto National Forest had the most impacted area in 2017 (Figure 2). This supports the timeline documented by USFS, (2025), which suggests that the outbreak began around 2015 and peaked in 2017 - 2018. In the couple of years prior to 2015, the southern pine beetle populations were thought to be in their endemic phase, as opposed to the epidemic phase seen during outbreaks (Coulson et al., 1999).

We found that NDVI significantly decreased in the year of southern pine beetle detection and in the year following detection, but NDVI tended to increase again two years post-detection (Figure 3A). Except for 2013, each of the years analyzed showed a decrease in NDVI in the year of detection and year post-detection when compared to two years prior to detection (Figure 4A). These results are as expected because NDVI values tend to decrease as trees stop transmitting healthy spectral radiance when they transition from stage one (i.e., southern pine beetle adults bore into trees; green crowns) to stage two (i.e., roughly when the trees contain southern pine beetle eggs, larvae, or pupae; yellowing foliage) and especially stage three (i.e., roughly when the next generation of southern pine beetles emerge from trees; red foliage) (Billings and Herbert, 1979; Carter et al., 1998). It should be noted that NDVI cannot detect early southern pine beetle attack (i.e., stage one), as the foliage is typically still green and does not show signs of dieback (Kanaskie et al., 2024). As such, detectable changes in crown color usually indicate that the forest stand is in a later stage of beetle colonization with crowns turning red-brown over time (Gomez et al., 2020). Further, if an

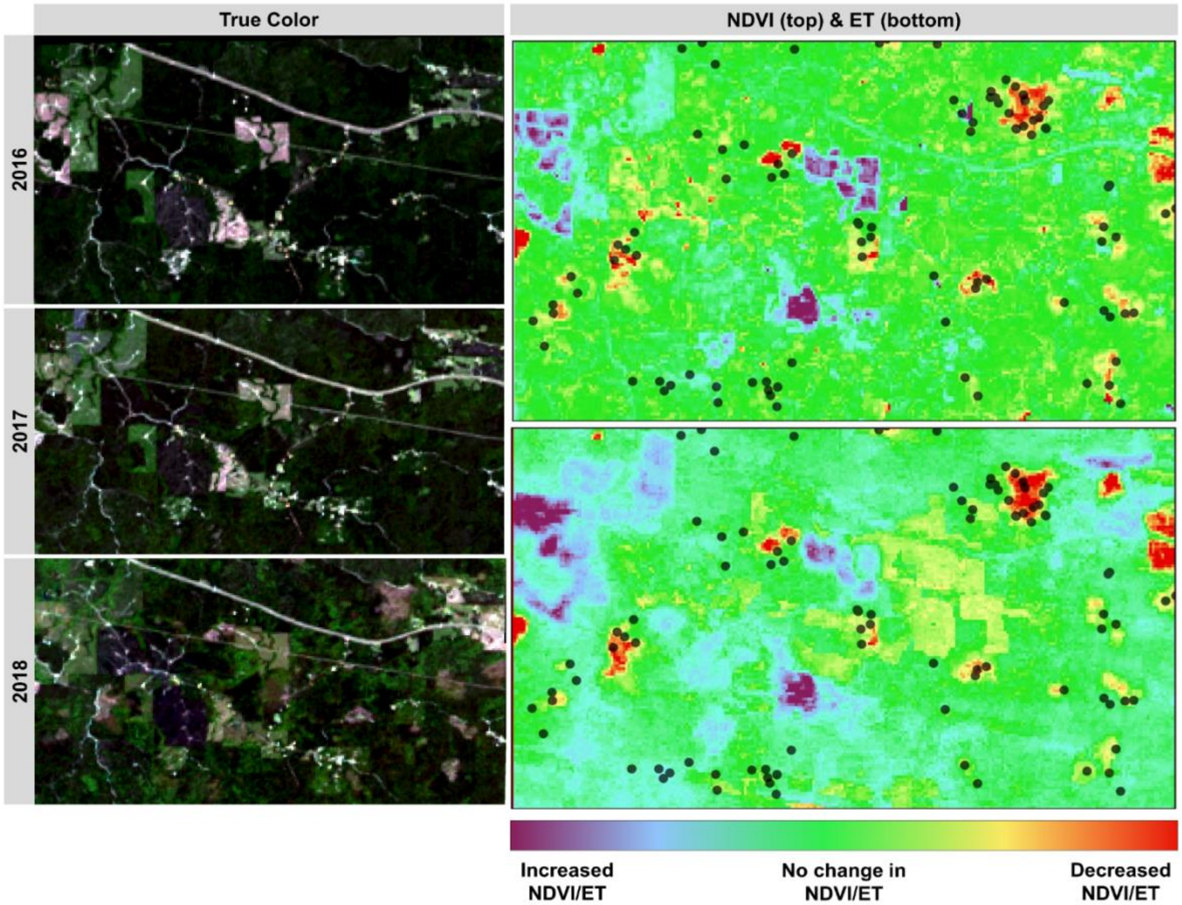

Figure 6. True color (left), NDVI (**top right**), and evapotranspiration (ET, **bottom right**) maps for the area of interest located near Meadville, MS. The color scale at the bottom represents the amount of change in NDVI and ET from 2016 - 2018, where purple represents an increase and red represents a decrease in NDVI and ET. The black circles represent southern pine beetle spot locations.

area comprises both dead and live trees, NDVI may not change as significantly as it would in an area with all trees in a stand displaying symptoms of dieback (Carter et al., 1998; Assal et al., 2014). Some of the stands with increased or without significant changes in NDVI may have had other species in the stand, including mixed hardwood species in the dominant or codominant crown classes or understory that may have softened the change in NDVI over time (Figure 6). While NDVI is valuable for assessing the presence of healthy vegetation, it cannot distinguish among woody plant species or other vegetation that can be found within a forest stand (Iglesia Martinez and Labib, 2023). For example, as overstory pine trees die and/or are removed through salvage logging, dense vegetation in the understory could register as green on the NDVI color spectrum compared to the yellow, red, or brown coloration of a dying or dead pine crown (e.g., Figure 7) or the soil without much understory vegetation (Tucker, 1979). As shown in Figure 8, some loblolly pine stands within the Homochitto National

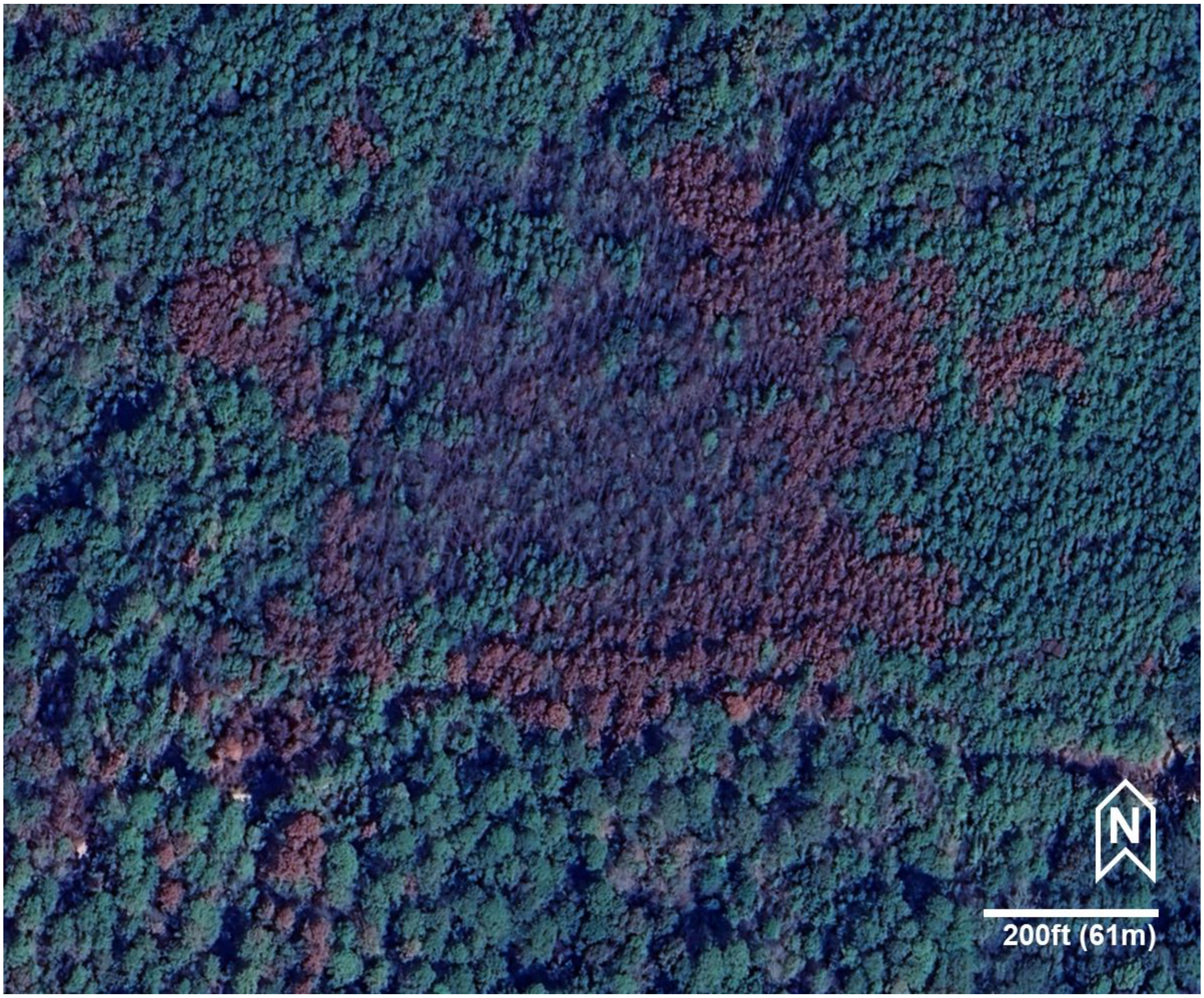

Figure 7. Southern pine beetle spot (31.241315, -91.055202) in Wilkinson County, MS in the southern section of the Homochitto National Forest. Figure courtesy of Google Earth.

Forest have dense understory vegetation that could buffer changes in NDVI in stands impacted by southern pine beetles.

Our results also demonstrate a significant decrease in evapotranspiration values in the southern pine beetle detection year and in the years post-detection compared to the years prior to detection (Figure 3B). Overall, this trend is similar to past studies that found a decrease in evapotranspiration after pines were impacted by mountain pine beetles in the western United States (Edburg et al., 2012; Vanderhoof and Williams, 2015; Knowles et al., 2023). In the eastern United States, some studies have also found that forest disturbances can negatively impact evapotranspiration. For example, Yang et al., (2020) found that drought decreased evapotranspiration, especially in young pine stands with more shallow root systems, and Krzemien et al., (2024) observed reduced evapotranspiration in ash (*Fraxinus* spp.) stands impacted by emerald ash borer, an invasive, phloem-feeding insect that bores into the stems of ash trees. There are many factors impacting evapotranspiration dynamics, including temperature,

Figure 8. Example of a loblolly pine stand in the Homochitto National Forest.

precipitation, wind speed, etc. However, comparing the evapotranspiration data from the same year for different attack stages demonstrates the water use changes of trees impacted by southern pine beetle attack. It should also be noted that, in select cases, evapotranspiration was observed to increase or remain unchanged in the detection year and post-detection years compared to pre-detection (e.g., 2018 in Figure 4B, 45.5% of spots in the area of interest in Figure 6). While it is unknown if these spots were salvage logged, it is possible that the change in evapotranspiration was offset by rapid growth of understory plant species, as was found by Brown et al., (2014). Rapid recovery from abiotic, biotic, and anthropogenic disturbances is common in southeastern forests, as sites can quickly revegetate in response to disturbance and impact post-disturbance hydrologic cycles (Jackson et al., 2004). While our study focused on annual analysis, the month of when the southern pine beetle attack started could also impact the evapotranspiration dynamics. Further analysis at a monthly time scale could be helpful to clarify the impacts of the timing of attack onset on evapotranspiration changes.

We found that, overall, total annual precipitation was lowest in 2011 and highest in 2012, and there were seasonal fluctuations in precipitation leading up to the start of the southern pine beetle outbreak in 2015 (Figure 4B; Figure 5). A report by USFS, (2017) indicated that the southern pine beetle outbreak during the time period of this study was likely fueled by the dry summers before the outbreak. Past research has found that southern pine beetle outbreaks occurred after high winter rainfall, high spring rainfall, and low summer rainfall (King, 1972), prolonged periods of low precipitation (Hansen et al., 1973), increased moisture and late winter potential evapotranspiration (Kalkstein, 1976), high summer rainfall (Kroll and Reeves, 1978), or decreases in spring and winter precipitations (An and Gan, 2022). For this study, the precipitation in the winters leading up to the outbreak were lower than in previous years, which is supported by An and Gan, (2022), and the wet spring and summer prior to the detection of the outbreak in 2015 is supported by King, (1972) and Kroll and Reeves, (1978), respectively.

This study is intended to provide a foundation for further research on the impacts of the southern pine beetle and other forest disturbances on hydrologic cycles of forest ecosystems in the eastern United States. There are some limitations to our study, as well as many possible future studies that could stem from this analysis. For example, although we use OpenET to derive Landsat-scale evapotranspiration data, which has been demonstrated to be an effective tool for assessing impacts of forest disturbances on evapotranspiration (Yang et al., 2021), future research could examine impacts using ground-based eddy-covariance techniques to compare to impacts derived from satellite-based methods, like OpenET, to ensure consistency in results. This study also only focused on the Homochitto National Forest, with a much smaller area of interest included as a case study to map NDVI and evapotranspiration changes over time. Future research should consider expanding the area of interest and/or include other areas that might be impacted by southern pine beetle, including other National Forests, private forest land, or areas impacted by southern pine beetle range expansion in the northeastern United States (Aoki et al., 2018; Kanaskie et al., 2023). With some additional data collection, further analyses could include more refined assessments of impacts of salvage logging and understory vegetation on evapotranspiration in forest stands impacted by southern pine beetles. Results from these studies could help inform management practices that could reduce impacts of southern pine beetles to hydrologic cycles in forest ecosystems of the eastern United States.

Conclusions

The Homochitto National Forest is one of many areas in Mississippi and the southeastern United States region that has been impacted by southern pine beetle outbreaks in the past. Our study demonstrates the overall negative impact of southern pine beetle outbreaks on forest canopy and evapotranspiration. This study also highlights that other factors, including rapid growth of understory vegetation, can contribute to stand-by-stand variation in forest biophysical characteristics. By understanding the relationships between disturbance agents and forest canopy and water use capability, we can improve our understanding of the short- and long-term impacts of forest disturbances on ecosystem services and possibly help direct management of these sites.

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069550. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture. Data supporting the results are publicly available through the Southern Pine Beetle Information Center (https://spb.clemson.edu/) and OpenET platform.

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