A Statistical Analysis of Surface Roughness Influences on Tornadogenesis and Tornado Decay within the Southeastern United States

Research Thesis

Presented in partial fulfillment of the requirements for graduation *with Research Distinction* in Atmospheric Sciences in the undergraduate colleges of The Ohio State University

by

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Abstract

As tornadic activity increases in the Southeastern United States (Agee et al. 2016), it becomes imperative to investigate tornadic activity in this region. Given that patterns of land cover greatly differ between the Southeast and the traditional Tornado Alley and that surface roughness has been well documented to affect the structure and behavior of tornadoes (Bode et al. 1975; Dessens 1972; Kuai et al. 2008; Matsui and Tamura 2009; Natarajan and Hangan 2009, 2012; Neakrase and Greeley 2010; Wang et al. 2017; Zhang and Sarkar 2008), investigating the relationship between surface roughness and tornadic activity in the Southern U.S. would be a worthwhile enterprise. A hotspot analysis of tornadogenesis and tornado decay points, was performed within four states within the region with high tornadic activity (Alabama, Georgia, Mississippi, and Tennessee). Additionally, statistical comparisons of the frequency of tornadogenesis and decay within each of the categories of land cover as defined by the National Land Cover Database (NLCD) were made in each of the four states of study. Finally, the average surface roughness length in the immediate areas surrounding the tornadogenesis and decay points were statistically compared to the surface roughness lengths in the surrounding environments. Results indicated that tornadoes were more likely to form and dissipate in developed areas and at sites in which the average surface roughness greatly differed from the average surface roughness in the immediate environment. While some studies (Cusack 2014) have indicated the potential that urban environments are more likely to produce tornadogenesis, it is impossible to come to a firm conclusion of causation given the possibility of damage indicator reporting bias when it comes to tornado tracks and spatial correlation bias when it comes to land cover analysis.

Introduction

The Southeastern United States is well-known to have a high number of tornadoes with several states in the region averaging at least 30 tornadoes per year and peak activity occurring in the spring (Storm Prediction Center). In fact, it has been demonstrated that increasing tornadic activity in the Southeast is coinciding with a decrease in tornadic activity in the Great Plains region (Agee et al. 2016). Figure 2a (2023) shows the areas determined by FEMA where tornadoes are most likely to have the greatest impact based on a combination of tornado frequency and potential for tornado damage, with high tornado risk areas found across both Tornado Alley and the Southeast. However, unlike Tornado Alley, much of the Southeast is characterized by low overall risk to natural disasters as shown in Figure 2b (FEMA 2023), demonstrating the outsized hazard that tornadoes pose to this region. This outsized risk posed by tornadoes in the Southeast is demonstrated by Ashley (2007) where it is found that this region contains the highest density of tornado-related deaths, theorized to be as a result of a high density of mobile homes, a type of structure known to be notoriously vulnerable to high winds and tornadoes, with only a minimum of 110 mph winds required for complete destruction compared to the minimum 165 mph winds required for complete destruction of a site-built house (Ashley 2007; Storm Prediction Center).

One key physical difference between Tornado Alley and the Southeast is the distribution of the types of land cover across each region as shown in Figure 2. Tornado Alley land cover is largely defined by a transition from grasslands and croplands in the west to deciduous forests in the east. However, with the exception of a significant region of croplands near the Mississippi River, the land cover in the Southeast is mostly characterized by a mix of forests and developed areas. The reason why differences in land cover are relevant is because of surface roughness.

Surface roughness is defined as, "the geometric characteristic of a surface associated with its efficiency as a momentum sink for turbulent flow, due to the generation of drag forces and increased vertical wind shear" (Stull 1988). The presence of surface roughness greatly affects flow in the boundary layer, the lowest layer of the atmosphere most directly affected by the Earth's surface, due the aforementioned drag and friction forces it provides (Houser et al. 2020; Stull 1988). Many laboratory studies have demonstrated that variations in surface roughness have significant effects on tornado structure. (Bode et al. 1975; Kuai et al. 2008; Neakrase and Greeley 2010; Zhang and Sarkar 2008; Wang et al. 2017; Dessens 1972; Matsui and Tamura 2009; Natarajan and Hangan 2012). Bode et al. (1975), Natarajan and Hangan (2009), and Wang et al. (2017) found increasing surface roughness increased tangential velocities of tornadoes while Kuai et al. (2008), Natarajan and Hangan (2012), Neakrase and Greeley (2010), and Zhang and Sarkar (2008) found increasing surface roughness decreased tangential velocities. Natarajan and Hangan (2009) and Zhang and Sarkar (2008) found that increasing surface roughness increased the radial velocities of tornadoes while Bode et al. (1975) found increasing surface roughness decreased radial velocities. Cusack (2014), Dessens (1972), and Zhang and Sarkar (2008) found that increasing surface roughness increased the vertical velocities of tornadoes while Bode et al. (1975) found that increasing surface roughness decreased the vertical velocities. Finally, Dessens (1972), Kuai et al. (2008), Natarajan and Hangan (2012), and Neakrase and Greeley (2010) found that increasing surface roughness increased the core radius of a tornado while Bode et al. (1975) and Wang et al. (2017) found that increasing surface roughness decreased the core radius. None of these aforementioned studies could come to a conclusion about whether changing the surface roughness would change the overall likelihood or intensity of a tornado, likely due the contradictory results that were found about the changes in tornado structure.

Some studies have also been performed to analyze effects of surface roughness on spatial distributions of tornadic events. Kellner and Niyogi (2014) found that surface roughness was a significant regressor in determining historical frequency in the state of Indiana while Markert et al. (2019) found that statistically significant gradients in surface roughness were present at the tornadogenesis sites of weak tornadoes in northern Alabama. However, unlike laboratory simulations, there are far less studies concerning effects of surface roughness on climatological spatial patterns of tornado occurrence. Muncy (2021) attempted to address this by looking into the patterns of tornadogenesis and decay as it related to surface roughness in the states of Oklahoma and Arkansas. This study seeks to build upon Muncy (2021) by applying modified version of some of the methodologies used in Oklahoma and Arkansas to other states located in the Southeast with the main end goal of answering an important research question: do differences in land cover and/or surface roughness affect the likelihood of tornadogenesis and/or tornado decay within the Southeast?

Data and Methodology

Four states (Alabama, Georgia, Mississippi, and Tennessee) with high amounts of tornadoes (Storm Prediction Center 2023b) and commonly defined to be located within the Southeast were chosen as the geographic region of analysis. Every tornadogenesis and tornado decay point occurring between 2000 and 2021 were included as part of the analysis with points being sourced from the Storm Prediction Center's SeverePlot database (2023a). The 2011 National Land Cover Database map with a 30 m resolution was used to determine the category of land cover at exact coordinate points and the AERSURFACE transitional spring, non-airport, non-arid surface roughness length values were applied to each NLCD pixel (U.S. Geological

Survey 2011; U.S. Environmental Protection Agency 2020). This study was comprised of three main parts: a hotspot analysis of tornadogenesis and tornado decay points, in order to provide geographic and spatial context of tornado activity within each state, a categorical land cover significance comparison, in order to answer whether land cover affects tornadogenesis/decay, and a surface roughness length bootstrap comparison, in order to answer whether surface roughness affects tornadogenesis/decay. For the hotspot analysis, the “Optimized Hot Spot Analysis” tool within ArcGIS Pro used the Getis-Ord Gi* statistic to generate maps in each of the four states of areas of statistically significant high and low densities of genesis and decay points. The Gi* statistic works by detecting areas of statistically significant high or low values surrounded by other areas of statistically significant high or low values (Getis and Ord 1992). In order to calculate this statistic, each state was divided into grids with resolutions varying depending on the state’s size and shape (~8.25 km for Alabama, ~11 km for Georgia, ~7.25 km for Mississippi, and ~9.75 km for Tennessee). For the categorical land cover significance comparison, binomial tests were run comparing the proportion of genesis and decay points occurring within each land cover category to the proportion of the total area of each land cover category in each of the four states. It is assumed in this scenario that tornadoes have equal chance of forming and dissipating in each land cover types meaning that significant divergence of the proportion of these tornado points by category from the proportion of the total area of each state would indicate tornadoes being “overrepresented”, having more tornado points that what would be expected, or “underrepresented”, having less tornado points than what would be expected. Finally, for the surface roughness bootstrap comparison, the estimated values of surface roughness length around the spot of genesis/decay were compared to the estimated surface roughness length of the immediate environment. Using the AERSURFACE surface roughness length values and the pixels with the 2011 NLCD map, the mean surface roughness value in a 250 m radius around each genesis/decay point was calculated and statically compared to a 1000-sample bootstrap sampling an equivalent number of pixels within a 2 km radius of each point and calculating the mean. The percentile of each "true" 250 m sample within the bootstrap mean dataset was calculated for each point. Figure 3 shows an example of how the 250m and 2km radii around each point were set up while Table 1 shows the AERSURFACE estimated surface roughness length for each land cover category.

Results

Hotspot Analysis

As shown in Figures 4 – 7, regions of high and low density of tornadogenesis and tornado decay points are visually similar within states, likely demonstrating the high prevalence of short-lived tornadoes within the overall tornado record. In Alabama, the high prevalence of tornadoes across north-central Alabama is consistent with the findings of Markert et al. who found a high prevalence of tornado tracks near the Huntsville metropolitan area (Markert et al. 2019). Additional hotspots can be found around Montgomery and Dothan while cold spots are found near the Talladega National Forest and rural areas north of Mobile. Hotspots can also be found along the Gulf coast in Mississippi and Alabama, likely owing to the prevalence of tornadoes induced by landfalling tropical cyclones in the region. Further north in Mississippi, tornadic activity is concentrated around the city of Jackson and the rural Pine Belt region between Jackson and Hattiesburg. Areas of low tornado activity can be found in the Mississippi Delta region where croplands are prevalent, as previously mentioned. In Georgia, tornadic activity in mainly concentrated in a region bounded by the Atlanta, Macon/Warner Robbins, and Columbus metropolitan areas, mostly characterized by suburban and rural areas, with an additional hotspot found southwest of Albany. Most of the cold spots within Georgia can be found in the state's Coastal Plains region. Finally, tornadic activity in Tennessee is mostly concentrated in Middle Tennessee with an additional hotspot found near Chattanooga, just west of the Cumberland Plateau. Cold spots are found in the Appalachian Mountains of East Tennessee as well as far-north Georgia. While this provides a nice geographic and spatial frame of reference for this study, no conclusions about the effects of surface roughness on tornadogenesis or tornado decay given the ambiguity of land cover in most of the hot and cold spots and the divergent conflicting trends in the areas of cropland in Northwest Mississippi and Southwest Georgia.

Categorical Land Cover Analysis

Tables 2 – 9 display the results of the categorical land cover analysis. In all four states, all four "developed" categories were overrepresented by both tornadogenesis and tornado decay points by a statistically significant amount, with the "open space" and "low intensity categories tending be the most overrepresented given the lower p-values calculated during the binomial tests. Additionally, pastures were overrepresented by genesis and decay points in Alabama, Mississippi, and Tennessee while croplands in Georgia were overrepresented by genesis points. These overrepresentations were mostly made up for by underrepresentations in the forests and woody wetlands. Deciduous and evergreen forests were underrepresented by tornado genesis and decay points in all four states while mixed forests were underrepresented by tornadogenesis point in Alabama, Georgia, and Tennessee and by tornado decay points in Georgia and Tennessee. Shrubs were underrepresented by tornadogenesis points in Alabama and tornado decay points in Alabama and Mississippi while grasslands were underrepresented by tornadogenesis and tornado decay points. Woody wetlands were underrepresented by tornadogenesis and tornado decay points in all four states while emergent herbaceous wetlands were underrepresented by tornado tornadogenesis points in Alabama and Georgia. Finally, open water was underrepresented by tornadogenesis points in Alabama while croplands were underrepresented by tornadogenesis and decay points in Mississippi. Barren land was not observed to be over or underrepresented by tornado points in any of the four states, likely due to the fact that this category accounts for the smallest proportion of area in each of the four states. Results were relatively consistent from state to state with the notable exception of divergent trends in croplands in Georgia vs Mississippi (i.e., tornadogenesis points being overrepresented in Georgia and underrepresented in Mississippi in this category). Additionally, there does not to be any clear pattern emerging based on surface roughness lengths alone as developed areas being consistently overrepresented is counterbalanced with land cover types of equivalent surface roughness lengths being consistently underrepresented (i.e., shrubs and grasslands vs open space developed, woody and emergent wetlands vs medium and high intensity developed, etc.). This could imply that land cover type is a more important factor in tornadogenesis and decay; however, we need the results of the quantitative surface before any conclusions of this nature can potentially be made.

Quantitative Surface Roughness Analysis

Within all four states, the vast majority of genesis and decay points in each of the four states had their "true" mean surface roughnesses within a 250m radius well outside the confidence intervals of their respective bootstrapped 2km radius mean surface roughnesses, as shown in Figures 8 – 11. In every case, the highest frequency of percentiles was contained in the lowest 1% while the second highest frequency of percentiles were contained in the highest 1% of their respective confidence intervals. Out of the remaining points, the majority had their percentiles within their respective bootstraps concentrated in the lowest and highest 20% of percentiles, indicating further tendencies of "true" means to diverge from their bootstrapped counterparts.

Discussion

The categorical land cover analysis produced results suggesting that developed areas are more conducive for tornadogenesis and tornado decay while the results of the of the quantitative surface roughness analysis would suggest that tornadoes are more likely to form and dissipate at points where the surface roughness greatly differs from its surrounding environment, a statement that would be backed up by the findings of Markert et al. (2019) and Muncy (2021). However, it is also possible that there are other confounding variables influencing these results. Looking to Figure 3 as an example, land cover types are often spatially correlated with one another (i.e., different land cover types occur in clusters rather than a true random distribution). This means that if the mean surface roughness length is taken over a small continuous area, such as what was what done in a 250m radius around each of the tornado points, the result is likely to be similar to the mode of the surface roughness lengths within that area. However, if the mean surface roughness length is taken from random points over a larger area, such as what was done in a 2km radius around each tornado point, the result would likely be similar to the median surface roughness length of the dataset. Figure 12, using the 2km radii around the tornadogenesis points in Alabama, shows an example of how surface roughness length distributions are mostly clustered near the ends of the spectrum with the median of the dataset, shown by the blue dotted line, is towards the center where there are less pixels with equivalent surface roughness lengths. This could explain why the vast majority of mean surface roughness values in the 250m radii greatly differed from the bootstrap samples in the 2km radii. Additionally, all the categories of land cover that were overrepresented by tornado points were anthropogenic while nearly all of the categories that were underrepresented were natural. Figure 13 shows that 26 of the 28 categories of tornado damage indicators involve structures that would be considered developed land cover by the NLCD. Given that it is more difficult to access non-developed sites compared to developed sites, it is possible that there exists a bias in the record of tornadogenesis and decay points towards urban sites. However, it is also possible that urban areas are more likely to be conducive for tornadogenesis due to unique boundary layer effects such as the "urban heat island" as explained by Cusack (2014). More work will need to be done in order to reach firmer conclusions.

Conclusions

This study produced a variety of interesting results with few firm conclusions to be made. Firstly, the hotspot analysis indicated that certain land cover types may not be a pure determiner in tornadogenesis/decay likelihood as shown by the diverging results with the hotspot in the croplands of southwest Georgia and the coldspot in the similar croplands of northwest Mississippi. Secondly, the land cover analysis indicated that developed land cover may be more likely to produce tornadogenesis/decay and forested land cover may be less likely to produce tornadogenesis/decay in the Southeast. However, given the possibility of tornado track reposting bias and inaccuracies, this may not necessarily be the case. Finally, the surface roughness analysis indicated that tornadoes were more likely to form/dissipate at points where the surface roughness lengths greatly differed from those of their surrounding environments. However, these results may have been the result of a flaw in the methodology not taking into account the tendency of land cover types, and their associated surface roughness lengths, to be clustered.

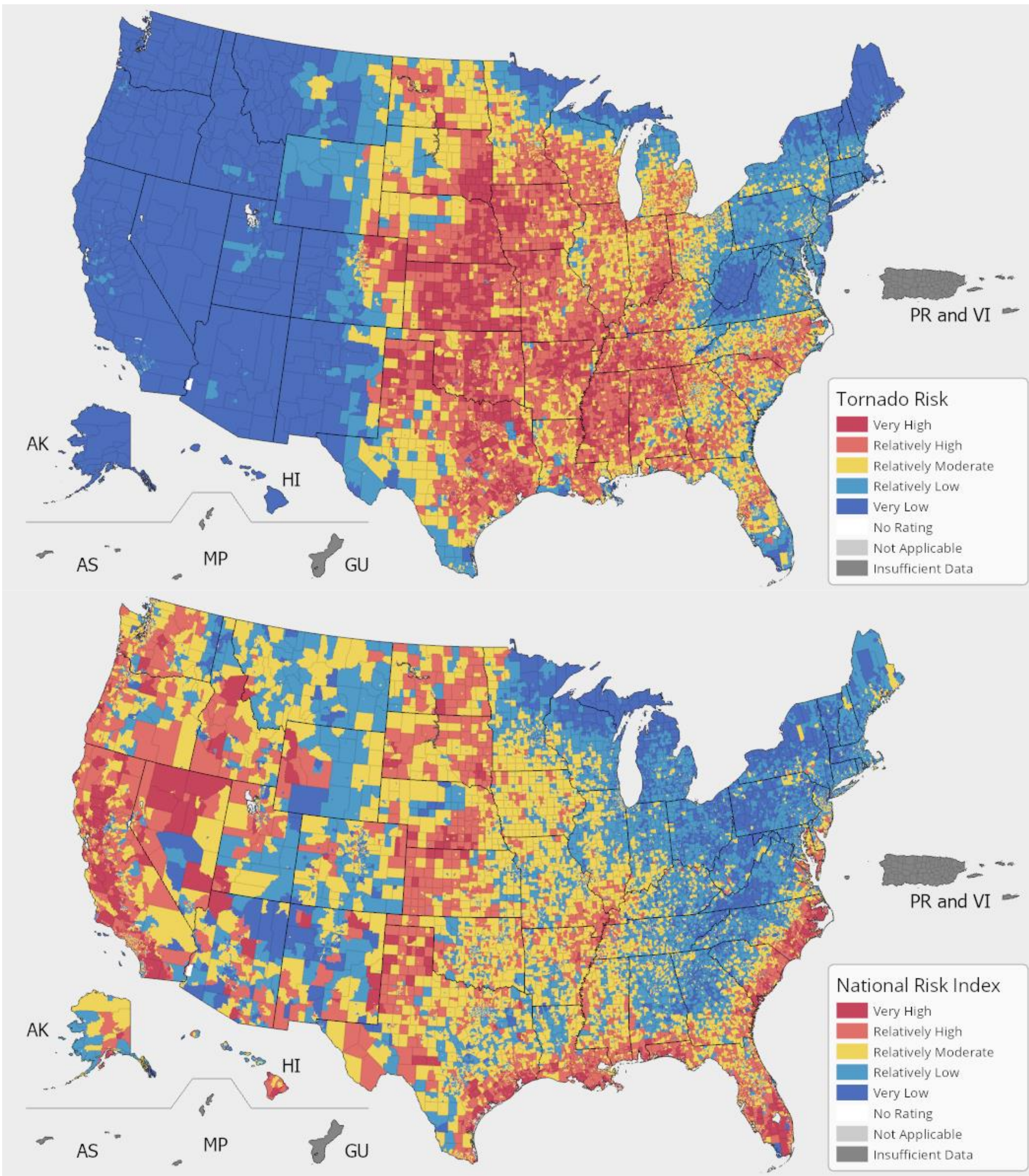
Future Work

This study demonstrates the difficulty and uncertainty in establishing conclusive relationships between tornadoes and surface roughness. First off, a better methodology for comparing surface roughness lengths in immediate tornado environments vs the surrounding environments likely needs to be determined. Future work could also apply some of these analysis methods to other states, such as performing the categorical land cover analysis in states with less widespread development in the Plains and Midwest regions. Additionally, future work would be recommended to investigate potential urban biases in the records of tornado tracks in order to further improve the accuracy of the overall tornado record. Finally, future work could also investigate whether changes in land cover and surface roughness over time make regions more or less conducive for tornadogenesis and/or tornado decay since this study was performed using a static land cover record.

Figures

Figures 1a (top) and 1b (bottom)

FEMA Tornado Risk and Overall Natural Disaster Risk by Census Tract (FEMA 2023)



Figures 2a (top) and 2b (middle)

Tornado Alley and Southeastern United States NLCD Land Cover

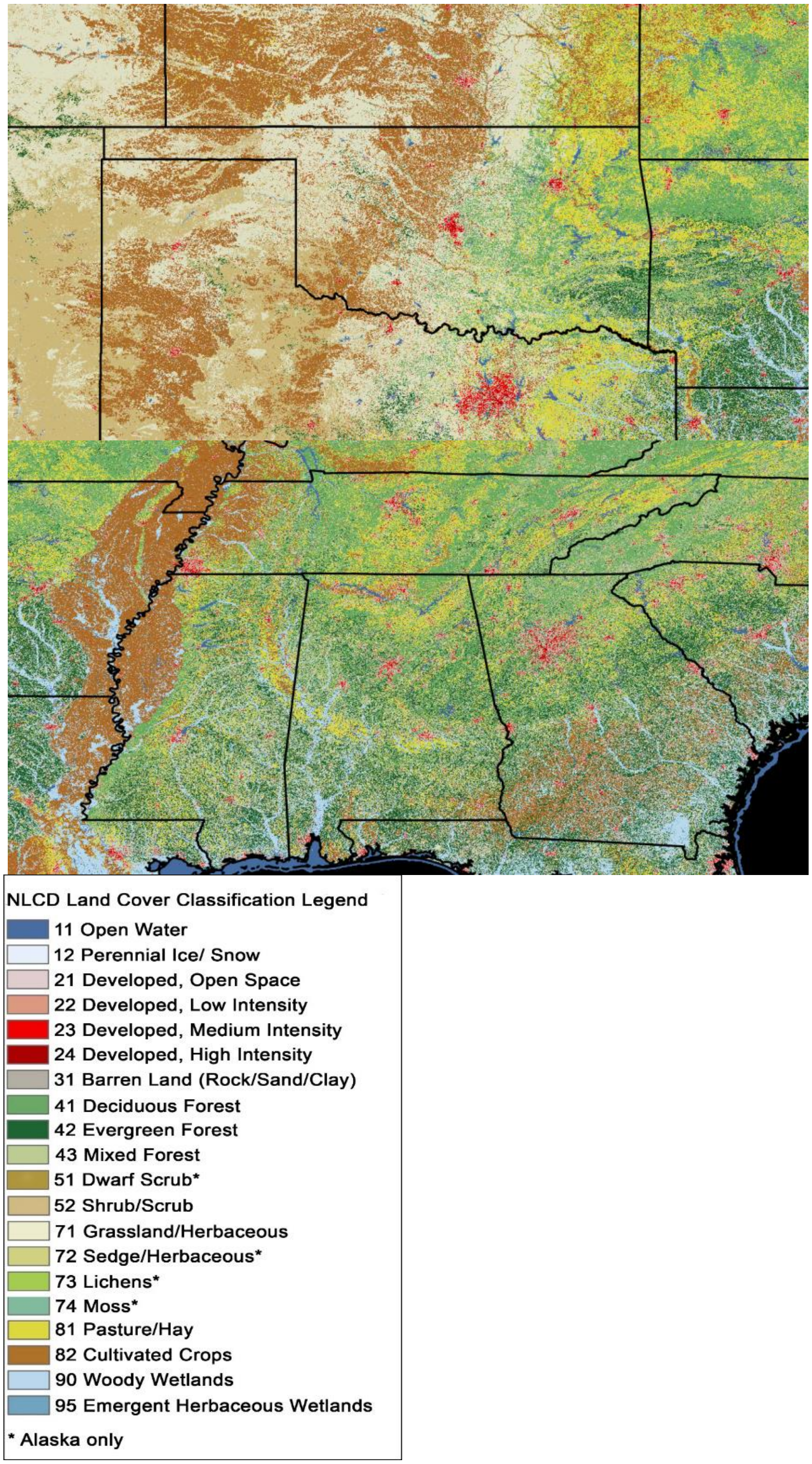
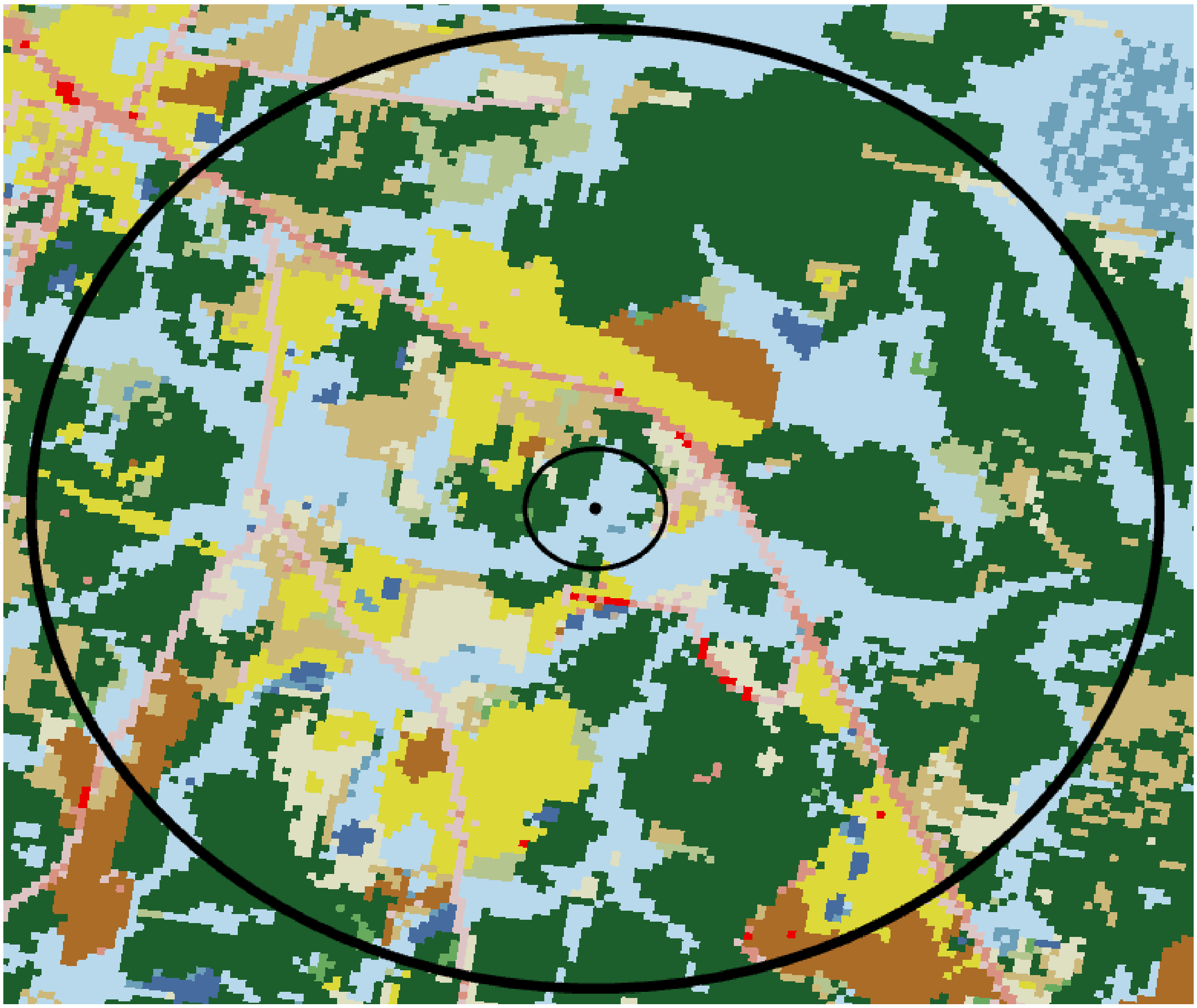


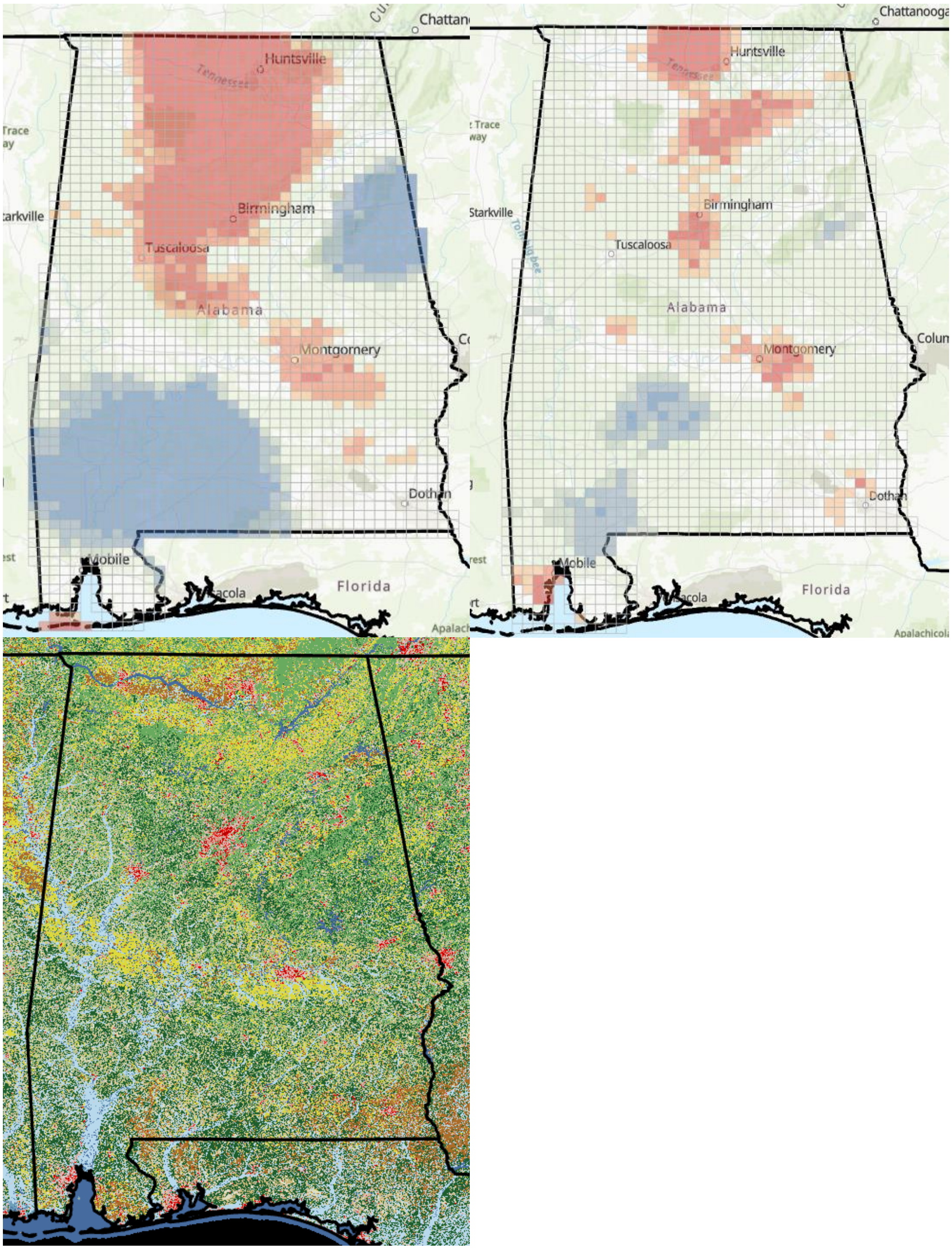
Figure 3

250m and 2km radii Around Example Tornado Decay Point



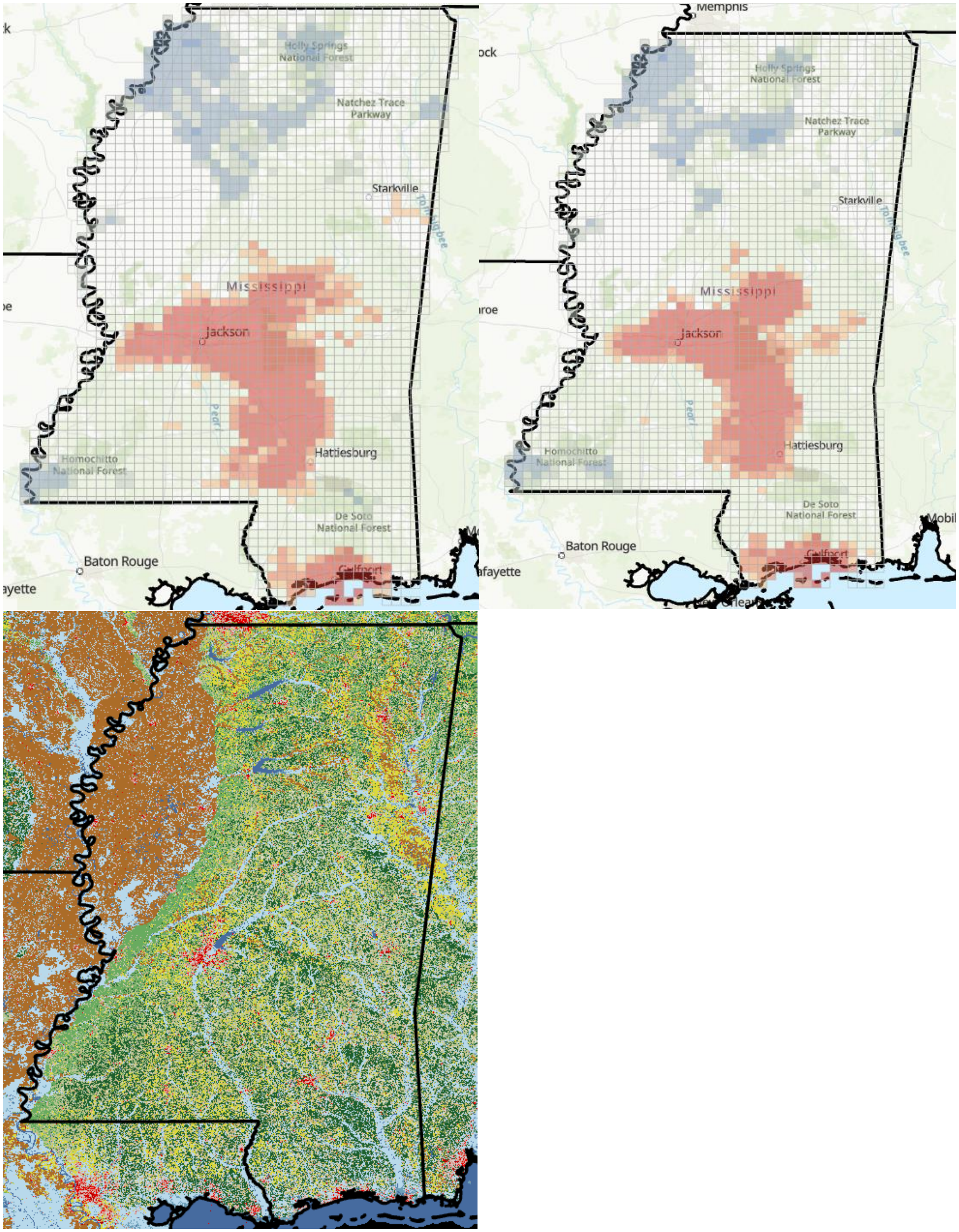
Figures 4a (top left), 4b (top right), and 4c (bottom left)

Hotspot Analysis of Tornadogenesis and Tornado Decay Points in Alabama Compared with NLCD Land Cover



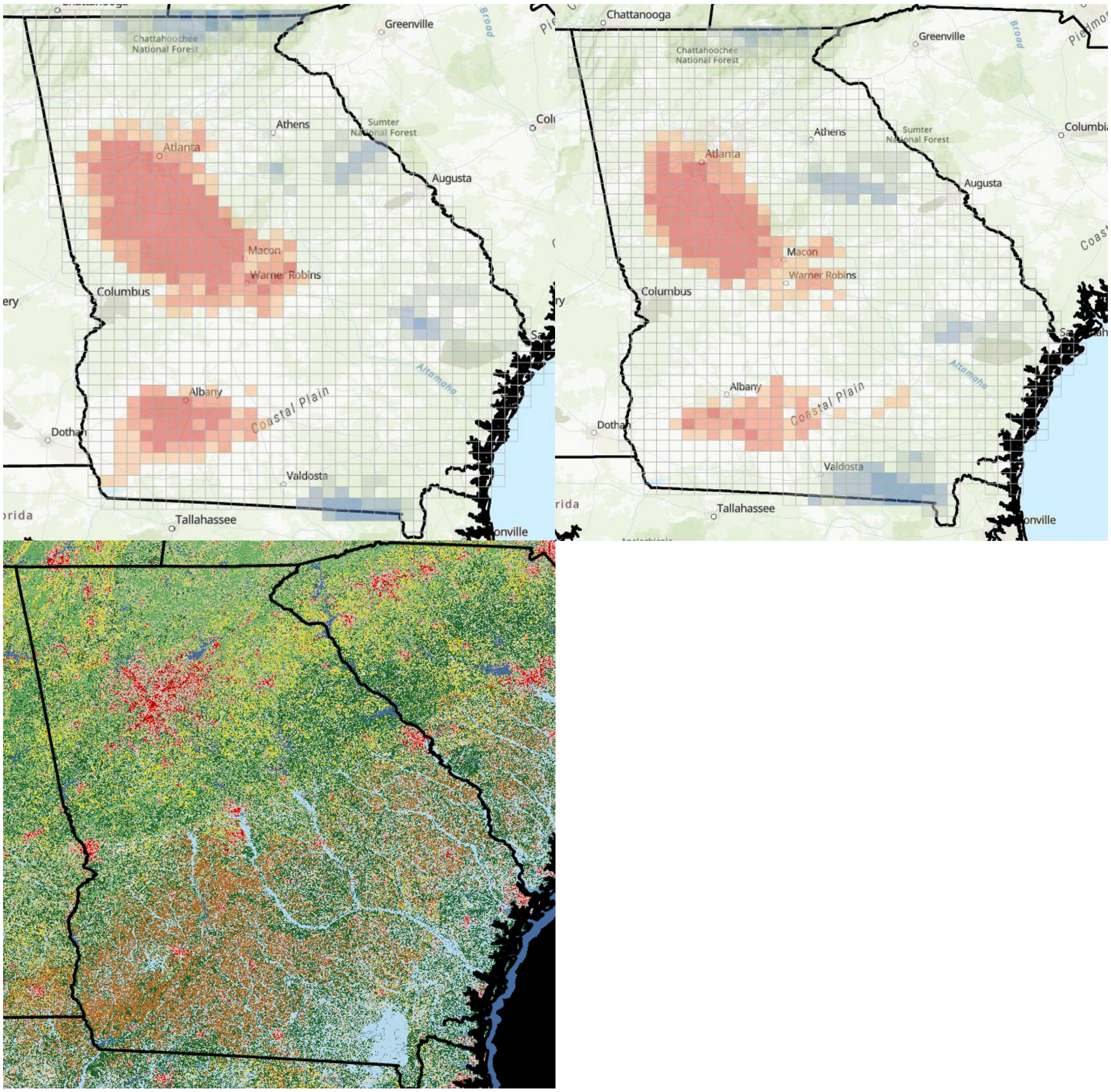
Figures 5a (top left), 5b (top right), and 5c (bottom left)

Hotspot Analysis of Tornadogenesis and Tornado Decay Points in Mississippi Compared with NLCD Land Cover



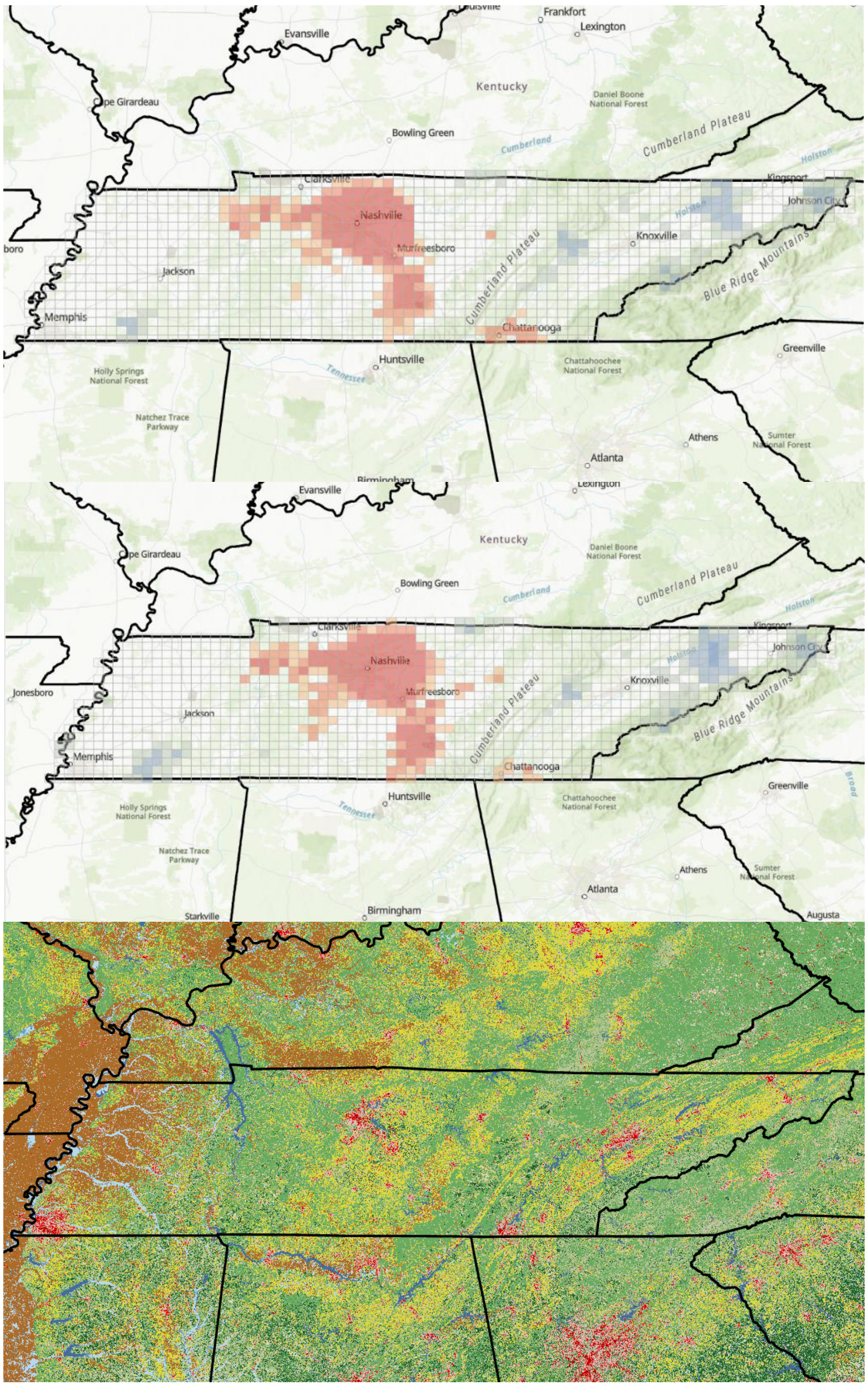
Figures 6a (top left), 6b (top right), and 6c (bottom left)

Hotspot Analysis of Tornadogenesis and Tornado Decay Points in Georgia Compared with NLCD Land Cover

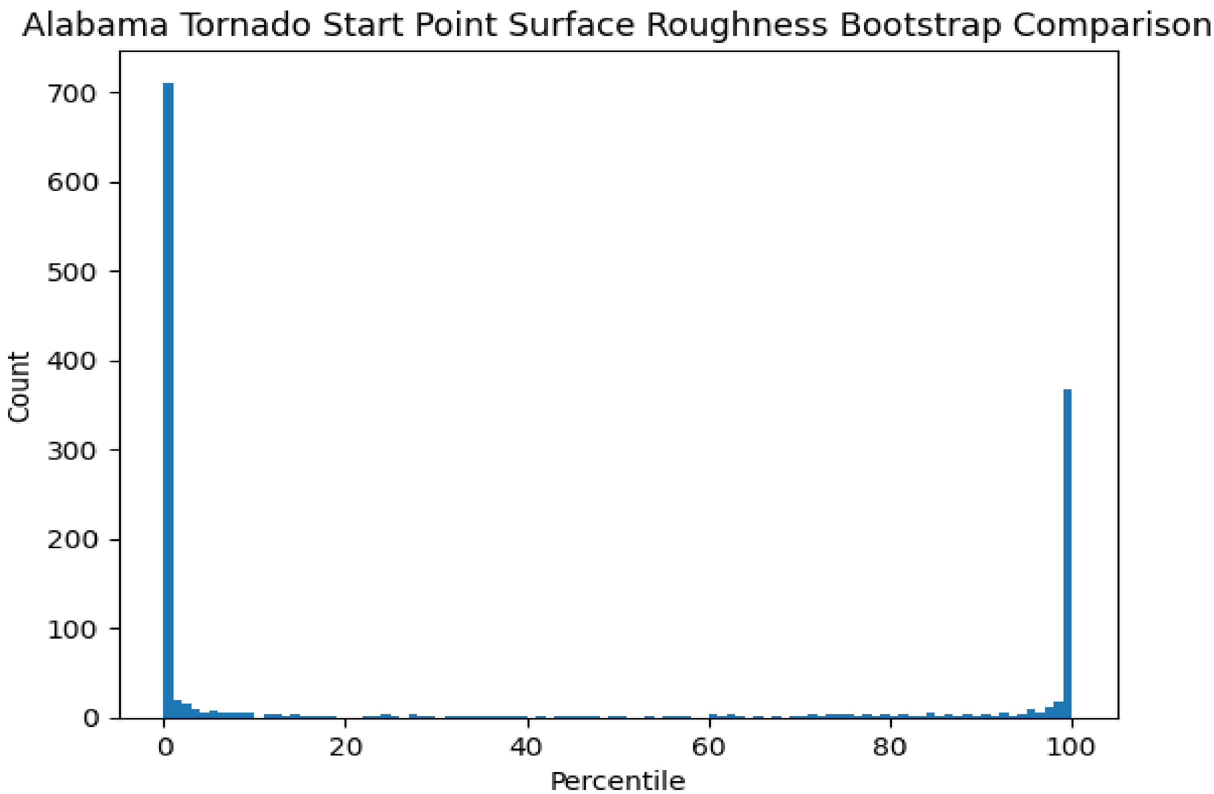


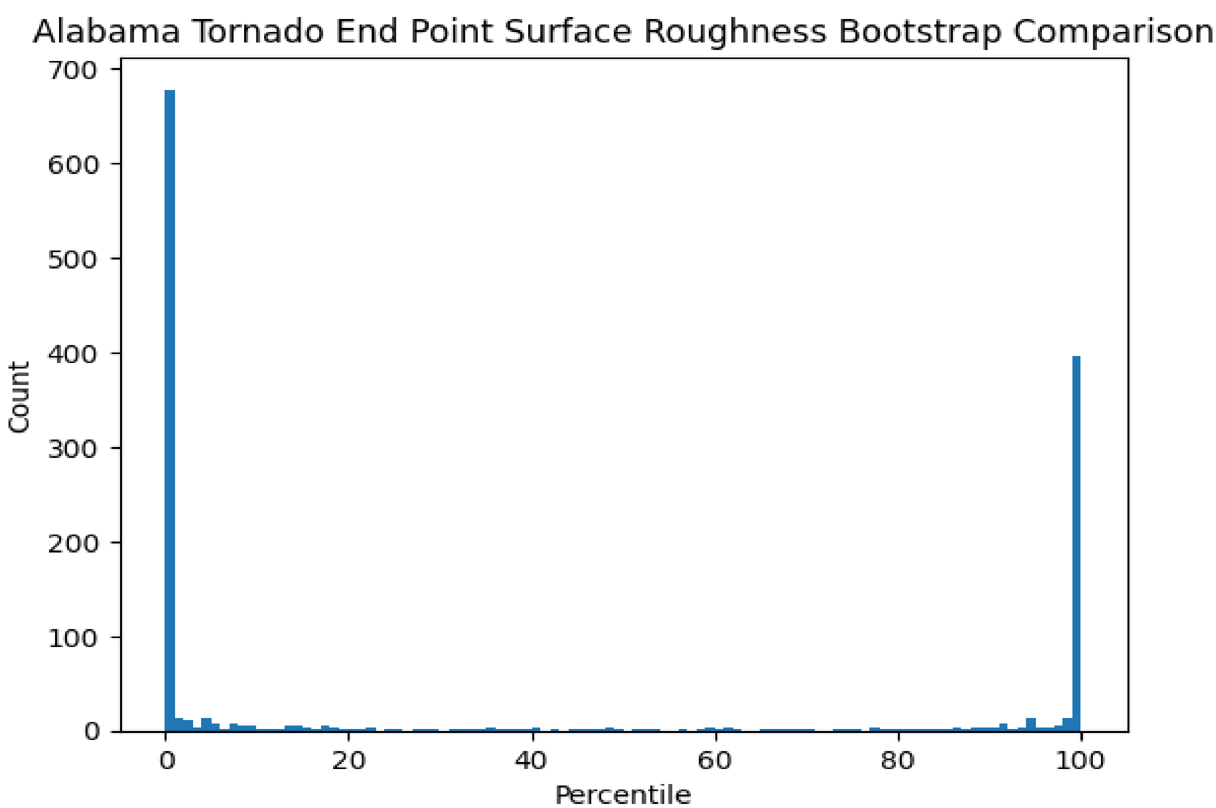
Figures 7a (top), 7b (middle), and 7c (bottom)

Hotspot Analysis of Tornadogenesis and Tornado Decay Points in Tennessee Compared with NLCD Land Cover

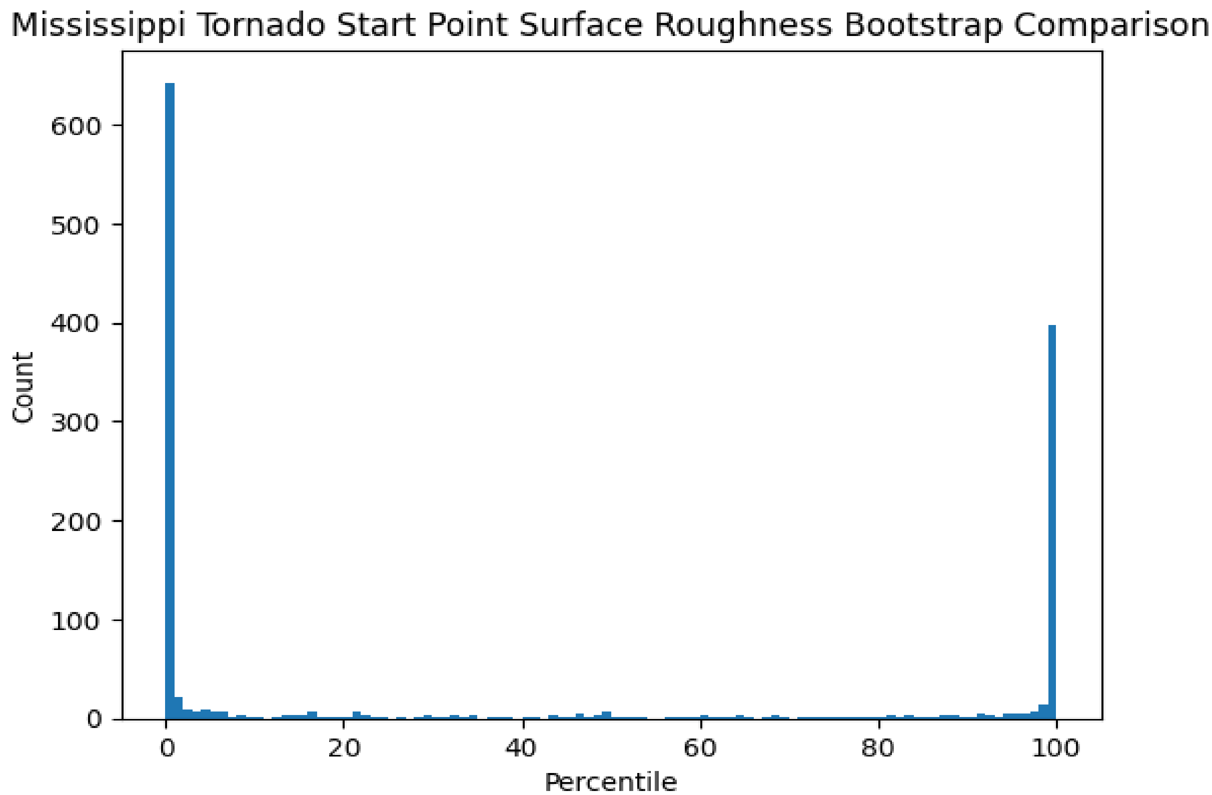


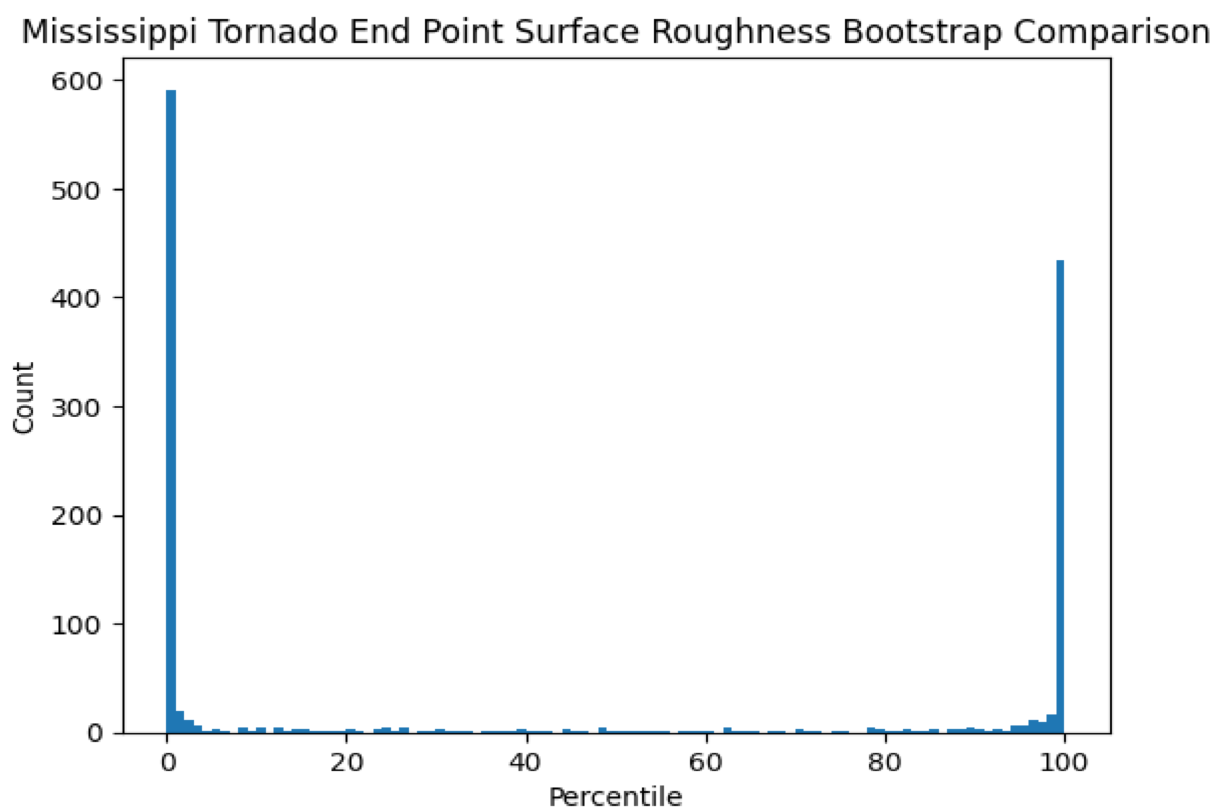
Figures 8a (top) and 8b (bottom)



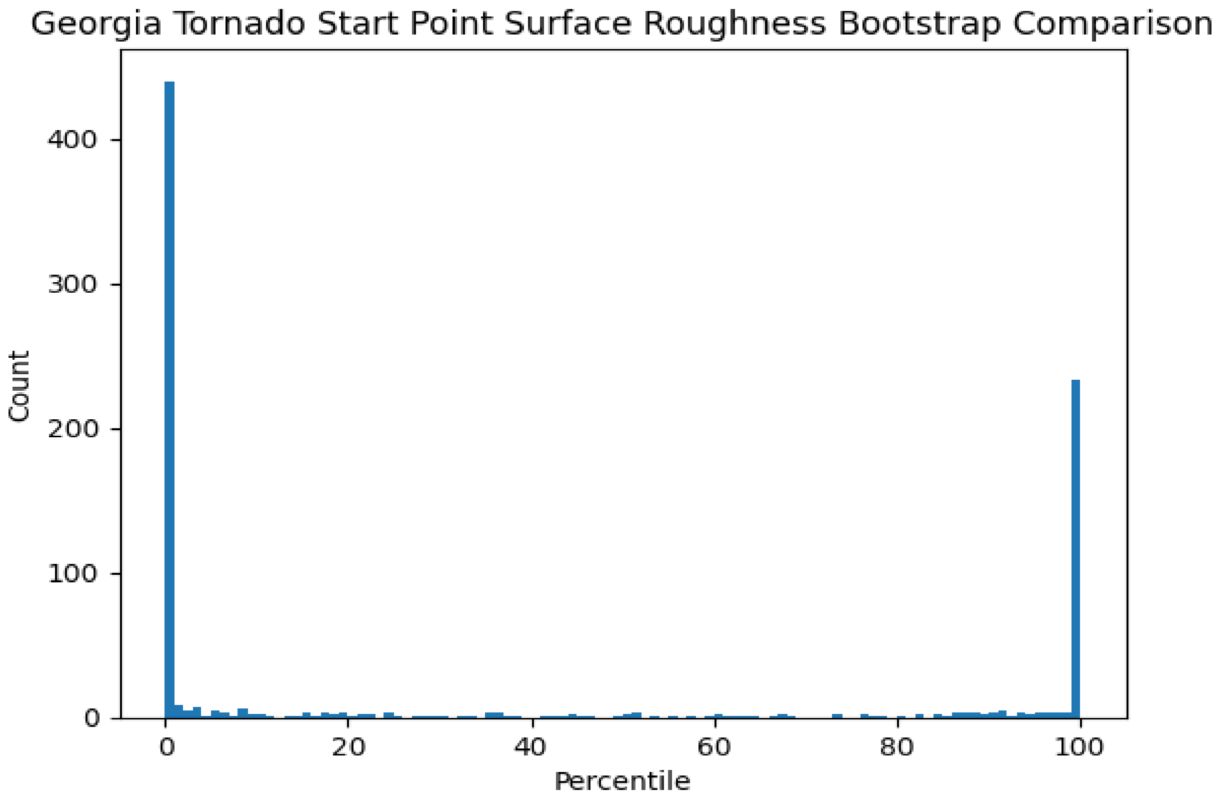


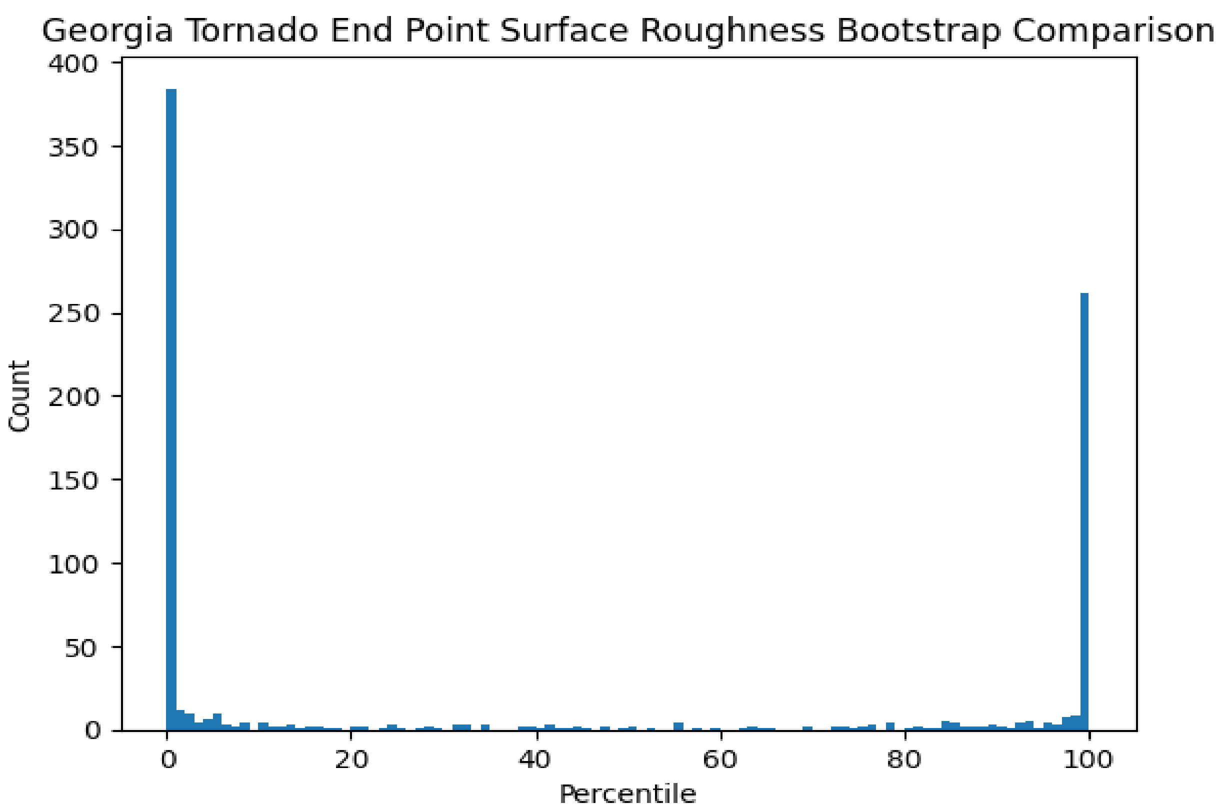
Figures 9a (top) and 9b (bottom)



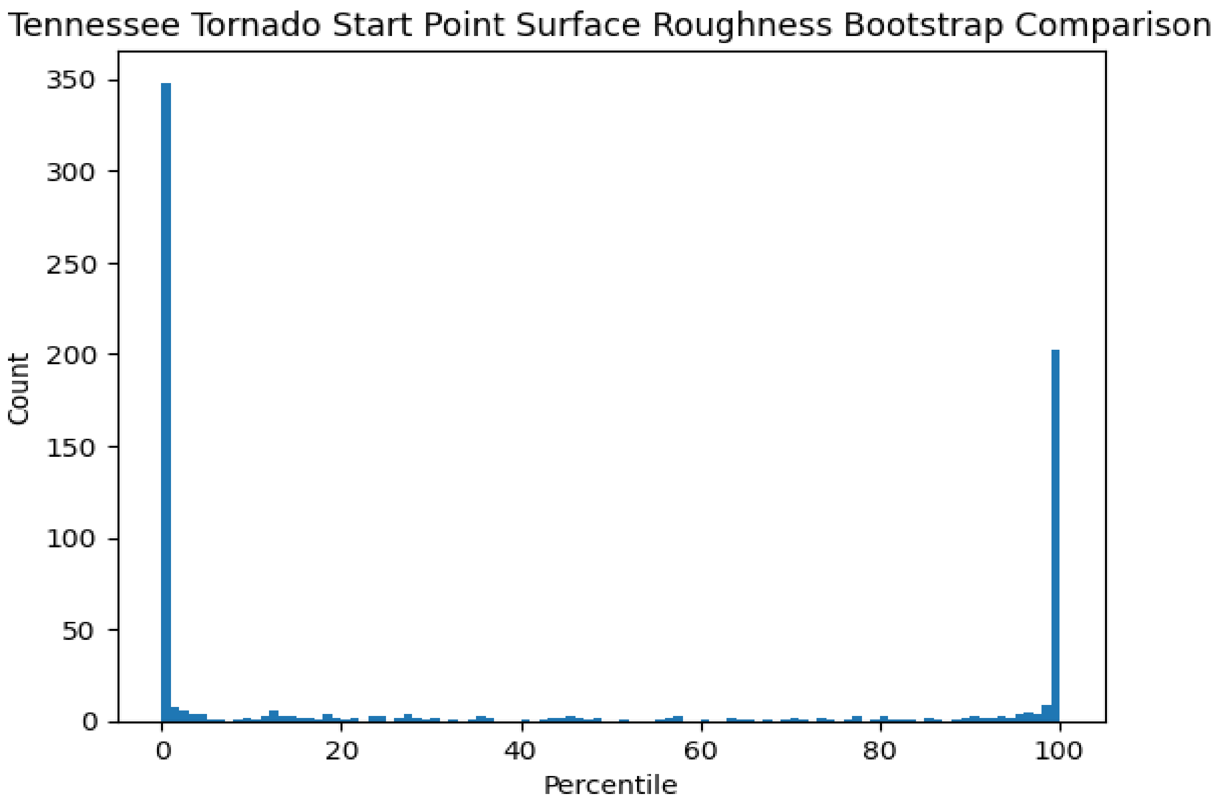


Figures 10a (top) and 10b (bottom)





Figures 11a (top) and 11b (bottom)



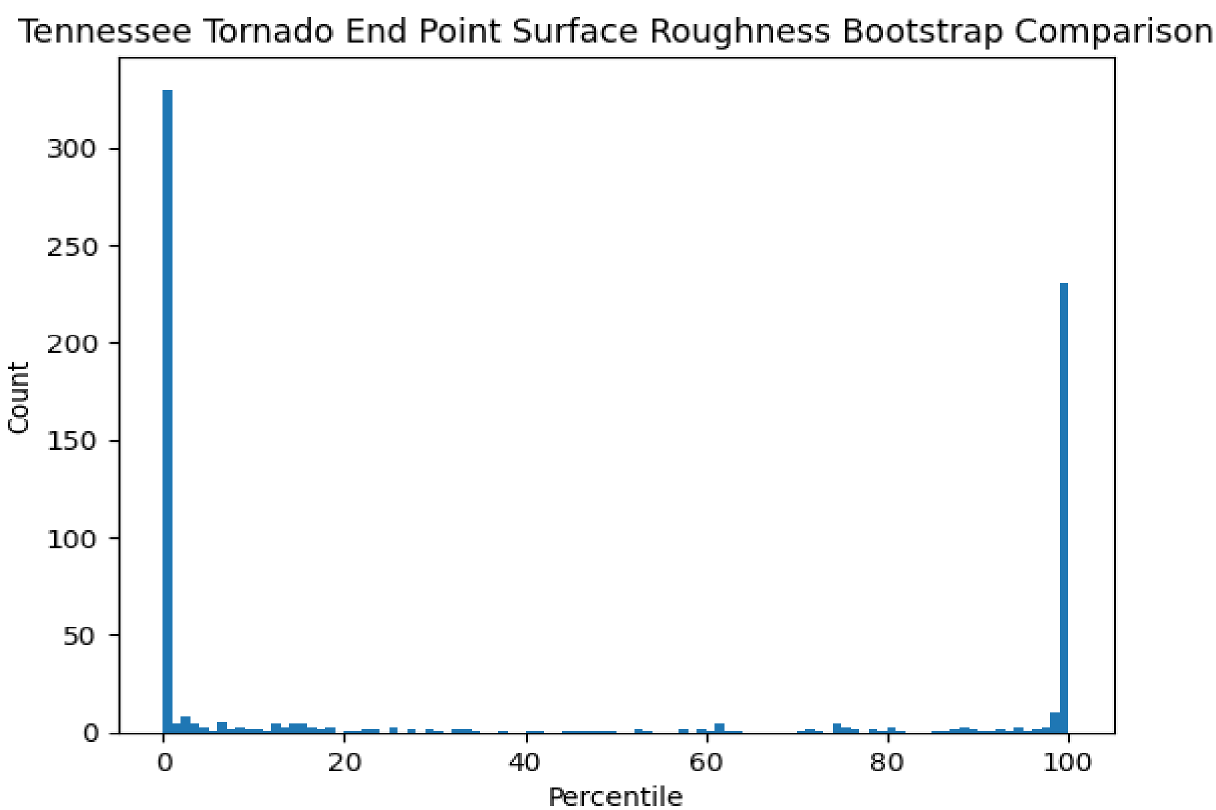


Figure 12

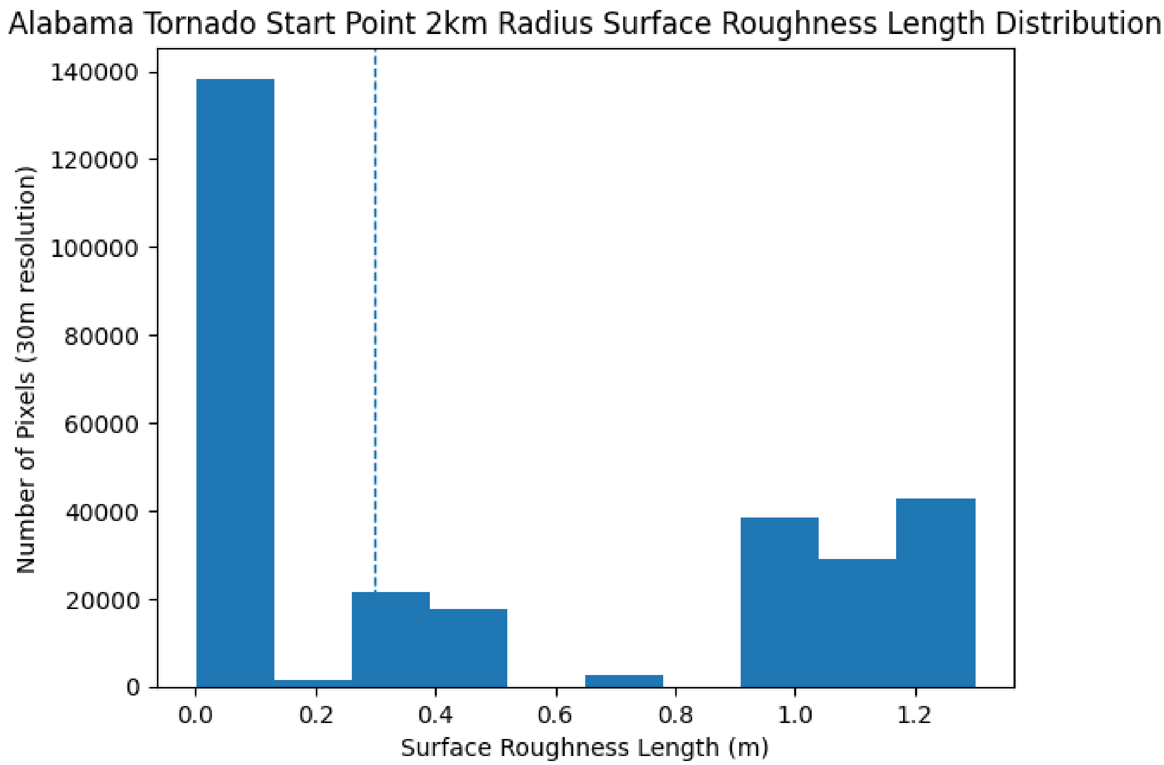


Figure 13

Table of Damage Indicators Used by National Weather Service to Determine Enhanced Fujita Rating (Storm Prediction Center 2023c)

Enhanced F Scale Damage Indicators

NUMBER (Details Linked)	DAMAGE INDICATOR	ABBREVIATION
1	Small barns, farm outbuildings	SBO
2	One- or two-family residences	FR12
3	Single-wide mobile home (MHSW)	MHSW
4	Double-wide mobile home	MHDW
5	Apt, condo, townhouse (3 stories or less)	ACT
6	Motel	M
7	Masonry apt. or motel	MAM
8	Small retail bldg. (fast food)	SRB
9	Small professional (doctor office, branch bank)	SPB
10	Strip mall	SM
11	Large shopping mall	LSM
12	Large, isolated ("big box") retail bldg.	LIRB
13	Automobile showroom	ASR
14	Automotive service building	ASB
15	School - 1-story elementary (interior or exterior halls)	ES
16	School - jr. or sr. high school	JHSH
17	Low-rise (1-4 story) bldg.	LRB
18	Mid-rise (5-20 story) bldg.	MRB
19	High-rise (over 20 stories)	HRB
20	Institutional bldg. (hospital, govt. or university)	IB
21	Metal building system	MBS
22	Service station canopy	SSC
23	Warehouse (tilt-up walls or heavy timber)	WHB
24	Transmission line tower	TLT
25	Free-standing tower	FST
26	Free standing pole (light, flag, luminary)	FSP
27	Tree - hardwood	TH
28	Tree - softwood	TS

Tables

Table 1

NLCD AERSURFACE Surface Roughness Lengths (U.S. Environmental Protection Agency 2020)

NLCD Land Cover Category	**AERSURFACE Surface Roughness Length (m)**
Open Water	0.001
Developed, Open Space	0.03
Developed, Low Intensity	0.09
Developed, Medium Intensity	0.3
Developed, High Intensity	0.7
Barren Land	0.05
Deciduous Forest	1.0
Evergreen Forest	1.3
Mixed Forest	1.1
Shrub/Scrub	0.05
Grasslands/Herbaceous	0.05
Pasture/Hay	0.03
Cultivated Crops	0.04
Woody Wetlands	0.5
Emergent Herbaceous Wetland	0.2

Table 2

Tornadogenesis Points in Alabama by NLCD Land Cover Category

NLCD Land Cover Category	**AERSURFACE Surface Roughness Length (m)**	**Area Proportion (%)**	**Tornado Point Proportion (%)**	**Binomial Test P-Value**
Open Water	0.001	2.06	1.72	0.441
Developed, Open Space	0.03	4.51	16.74	<0.001
Developed, Low Intensity	0.09	2.20	9.12	<0.001
Developed, Medium Intensity	0.3	0.86	2.99	<0.001
Developed, High Intensity	0.7	0.28	0.82	0.002
Barren Land	0.05	0.21	0.30	0.368
Deciduous Forest	1.0	16.90	10.24	<0.001

Evergreen Forest	1.3	22.17	11.88	<0.001
Mixed Forest	1.1	11.03	8.37	0.001
Shrub/Scrub	0.05	5.84	4.19	0.009
Grasslands/Herbaceous	0.05	4.71	3.29	0.012
Pasture/Hay	0.03	13.15	20.93	<0.001
Cultivated Crops	0.04	4.25	3.81	0.456
Woody Wetlands	0.5	10.87	5.31	<0.001
Emergent Herbaceous Wetland	0.2	0.95	0.30	0.01

Table 3

Tornado Decay Points in Alabama by NLCD Land Cover Category

NLCD Land Cover Category	AERSURFACE Surface Roughness Length (m)	Area Proportion (%)	Tornado Point Proportion (%)	Binomial Test P-Value
Open Water	0.001	2.06	1.51	0.206
Developed, Open Space	0.03	4.51	15.37	<0.001
Developed, Low Intensity	0.09	2.20	8.86	<0.001
Developed, Medium Intensity	0.3	0.86	2.12	<0.001
Developed, High Intensity	0.7	0.28	1.44	<0.001
Barren Land	0.05	0.21	0.30	0.362
Deciduous Forest	1.0	16.90	12.79	<0.001
Evergreen Forest	1.3	22.17	13.17	<0.001
Mixed Forest	1.1	11.03	9.39	0.059
Shrub/Scrub	0.05	5.84	3.79	<0.001
Grasslands/Herbaceous	0.05	4.71	2.95	0.002
Pasture/Hay	0.03	13.15	18.09	<0.001
Cultivated Crops	0.04	4.25	3.48	0.194
Woody Wetlands	0.5	10.87	5.98	<0.001
Emergent Herbaceous Wetland	0.2	0.95	0.76	0.57

Table 4

Tornadogenesis Points in Mississippi by NLCD Land Cover Category

NLCD Land Cover Category	**AERSURFACE Surface Roughness Length (m)**	**Area Proportion (%)**	**Tornado Point Proportion (%)**	**Binomial Test P-Value**
Open Water	0.001	2.15	1.23	0.021
Developed, Open Space	0.03	3.70	11.61	<0.001
Developed, Low Intensity	0.09	1.82	7.61	<0.001
Developed, Medium Intensity	0.3	0.69	2.38	<0.001
Developed, High Intensity	0.7	0.20	1.23	<0.001
Barren Land	0.05	0.17	0.31	0.297
Deciduous Forest	1.0	9.28	6.92	0.003
Evergreen Forest	1.3	19.01	14.14	<0.001
Mixed Forest	1.1	12.21	10.68	0.099
Shrub/Scrub	0.05	4.57	3.77	0.184
Grasslands/Herbaceous	0.05	3.18	3.00	0.812
Pasture/Hay	0.03	12.21	15.99	<0.001
Cultivated Crops	0.04	13.29	8.69	<0.001
Woody Wetlands	0.5	15.97	11.53	<0.001
Emergent Herbaceous Wetland	0.2	1.55	0.92	0.71

Table 5

Tornado Decay Points in Mississippi by NLCD Land Cover Category

NLCD Land Cover Category	AERSURFACE Surface Roughness Length (m)	Area Proportion (%)	Tornado Point Proportion (%)	Binomial Test P-Value
Open Water	0.001	2.15	1.57	0.176
Developed, Open Space	0.03	3.70	12.31	<0.001
Developed, Low Intensity	0.09	1.82	6.04	<0.001
Developed, Medium Intensity	0.3	0.69	2.43	<0.001
Developed, High Intensity	0.7	0.20	0.94	<0.001
Barren Land	0.05	0.17	0.16	1.0
Deciduous Forest	1.0	9.28	6.75	0.001
Evergreen Forest	1.3	19.01	16.08	0.007
Mixed Forest	1.1	12.21	11.37	0.392
Shrub/Scrub	0.05	4.57	4.08	0.46
Grasslands/Herbaceous	0.05	3.18	3.37	0.69
Pasture/Hay	0.03	12.21	14.35	0.023
Cultivated Crops	0.04	13.29	8.08	<0.001
Woody Wetlands	0.5	15.97	11.45	<0.001
Emergent Herbaceous Wetland	0.2	1.55	1.02	0.14

Table 6

Tornadogenesis Points in Georgia by NLCD Land Cover Category

NLCD Land Cover Category	**AERSURFACE Surface Roughness Length (m)**	**Area Proportion (%)**	**Tornado Point Proportion (%)**	**Binomial Test P-Value**
Open Water	0.001	1.60	1.20	0.487
Developed, Open Space	0.03	5.55	14.77	<0.001
Developed, Low Intensity	0.09	3.25	9.24	<0.001
Developed, Medium Intensity	0.3	1.24	3.00	<0.001
Developed, High Intensity	0.7	0.53	1.20	0.016
Barren Land	0.05	0.21	0.36	0.259
Deciduous Forest	1.0	12.70	10.32	0.042
Evergreen Forest	1.3	23.99	16.69	<0.001
Mixed Forest	1.1	6.53	4.20	0.005
Shrub/Scrub	0.05	3.34	2.40	0.147
Grasslands/Herbaceous	0.05	4.57	4.08	0.561
Pasture/Hay	0.03	6.88	7.68	0.338
Cultivated Crops	0.04	11.79	14.41	0.021
Woody Wetlands	0.5	15.90	9.48	<0.001
Emergent Herbaceous Wetland	0.2	1.91	0.96	0.042

Table 7

Tornado Decay Points in Georgia by NLCD Land Cover Category

NLCD Land Cover Category	AERSURFACE Surface Roughness Length (m)	Area Proportion (%)	Tornado Point Proportion (%)	Binomial Test P-Value
Open Water	0.001	1.60	1.07	0.27
Developed, Open Space	0.03	5.55	13.08	<0.001
Developed, Low Intensity	0.09	3.25	10.11	<0.001
Developed, Medium Intensity	0.3	1.24	2.14	0.027
Developed, High Intensity	0.7	0.53	1.55	<0.001
Barren Land	0.05	0.21	0.36	0.263
Deciduous Forest	1.0	12.70	11.89	0.501
Evergreen Forest	1.3	23.99	16.77	<0.001
Mixed Forest	1.1	6.53	4.28	0.006
Shrub/Scrub	0.05	3.34	2.02	0.034
Grasslands/Herbaceous	0.05	4.57	3.92	0.409
Pasture/Hay	0.03	6.88	6.30	0.585
Cultivated Crops	0.04	11.79	13.44	0.148
Woody Wetlands	0.5	15.90	11.18	<0.001
Emergent Herbaceous Wetland	0.2	1.91	1.90	1.0

Table 8

Tornadogenesis Points in Tennessee by NLCD Land Cover Category

NLCD Land Cover Category	**AERSURFACE Surface Roughness Length (m)**	**Area Proportion (%)**	**Tornado Point Proportion (%)**	**Binomial Test P-Value**
Open Water	0.001	2.26	1.97	0.705
Developed, Open Space	0.03	5.71	13.06	<0.001
Developed, Low Intensity	0.09	3.01	6.88	<0.001
Developed, Medium Intensity	0.3	1.35	3.37	<0.001
Developed, High Intensity	0.7	0.52	1.12	0.036
Barren Land	0.05	0.13	0.14	0.607
Deciduous Forest	1.0	37.41	26.97	<0.001
Evergreen Forest	1.3	3.74	1.97	0.01
Mixed Forest	1.1	8.54	6.18	0.022
Shrub/Scrub	0.05	1.66	0.98	0.186
Grasslands/Herbaceous	0.05	1.91	1.12	0.168
Pasture/Hay	0.03	20.32	25.00	0.002
Cultivated Crops	0.04	10.10	9.69	0.756
Woody Wetlands	0.5	3.11	1.54	0.013
Emergent Herbaceous Wetland	0.2	0.23	0.00	0.421

Table 9

Tornado Decay Points in Tennessee by NLCD Land Cover Category

NLCD Land Cover Category	AERSURFACE Surface Roughness Length (m)	Area Proportion (%)	Tornado Point Proportion (%)	Binomial Test P-Value
Open Water	0.001	2.26	0.56	<0.001
Developed, Open Space	0.03	5.71	13.15	<0.001
Developed, Low Intensity	0.09	3.01	7.27	<0.001
Developed, Medium Intensity	0.3	1.35	3.36	<0.001
Developed, High Intensity	0.7	0.52	1.12	0.037
Barren Land	0.05	0.13	0.00	1.0
Deciduous Forest	1.0	37.41	27.97	<0.001
Evergreen Forest	1.3	3.74	2.24	0.038
Mixed Forest	1.1	8.54	6.43	0.045
Shrub/Scrub	0.05	1.66	1.12	0.306
Grasslands/Herbaceous	0.05	1.91	1.54	0.584
Pasture/Hay	0.03	20.32	24.90	0.003
Cultivated Crops	0.04	10.10	8.53	0.172
Woody Wetlands	0.5	3.11	1.68	0.023
Emergent Herbaceous Wetland	0.2	0.23	0.14	1.0

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