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Soil controls on Stand Density of Declining White Oak (Quercus alba L.) Forests across the Eastern United States

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Abstract

Management of white oak (*Quercus alba* L.) stand density is crucial for sustaining forest ecosystems due to its influence on biodiversity, carbon storage, and long-term resilience. Understanding the role of soil properties in shaping stand density is essential for effective oak forest management. This study assessed whether stand density of declining white oaks differs significantly across soil property classes. Multicycle Forest Inventory and Analysis data were compiled to capture white oaks across the eastern United States. Stand density was quantified across plot systems using the number of trees per unit area. Soil variables such as texture, organic matter and total available water were analyzed to assess soil properties. Analysis of variance and Tukey HSD tests revealed that stand density varied significantly with soil tecture ($p < 0.05$), organic matter ($p < 0.01$), and TAW ($p < 0.001$). Among these, TAW emerged as the strongest predictor, highlighting the importance of soil moisture in sustaining forest productivity. The findings indicate that soil attributes are key determinants of forest structure and should be incorporated into silvicutural planning, restoration, and adaptive management programs to mainatin healthy and resilient white oak forest across diverse landscapes.

Introduction

White oak (*Quercus alba* L.) is a keystone species in the oak-dominated forests of the eastern United States, with its significant ecological and economic value (Cabrera et al., 2023). This long-lived, slow-growing species is not just important for its high-quality timber, but also for its contribution to biodiversity by providing habitat and food for a diverse range of wildlife species. However, in recent decades, white oaks in the eastern United States have been experiencing increased mortality, which is evident across much of its natural range (Abbott et al., 2024; Khadka et al., 2024). This decline is associated with a variety of biotic and abiotic factors, including stand density and soil properties, which may significantly influence tree growth, survival, and mortality.

Stand density, which reflects the number of trees per unit area or basal area per unit area (Zeide, 2010), has long been recognized as a crucial factor affecting white oak forest dynamics, especially concerning the competition for essential resources such as sunlight, water, and soil nutrients. High stand densities can exacerbate competition, leading to increased susceptibility to stressors such as drought, pests, and diseases, which may result in tree mortality (Restaino et al., 2019). This can influence the prevalence of fungal diseases such as oak wilt and insect pests such as the spongy moth (*Lymantria dispar*), both of which have been shown to have a negative influence on white oak populations. For instance, insect-pest attacks such as gypsy moths (*Lymantria dispar*) have killed many white oaks with rapid defoliation across the globe, including the United States (Muzika, 2017). Similarly, a study by Khadka et al. (2024) reported that stand competition, topography and edaphic factors are contributing to the localized WOM spatial patterns. Conversely, lower stand densities may reduce competition and promote growth but could also make individual trees more vulnerable to environmental extremes.

White oak is sensitive to soil conditions since it requires well-drained, nutrient-rich soil for maximum growth. Soil texture, including the proportions of sand, silt, and clay, has a direct impact on water retention and drainage, all of which are critical for tree health (Lal, 2020). White oak thrives on loamy soils when there is a balance of moisture and aeration, whereas clay-heavy or poorly drained soils might cause waterlogging, root rot, and other stress-related problems that contribute to higher mortality in oaks (Iverson et al., 2008). Furthermore, coarse-textured soils may exacerbate water shortages during droughts, rendering plants more susceptible to mortality in thick stands where competition for water is increased.

Soil properties such as moisture content, nutrient availability, and texture are also important in determining white oaks tree health and survival. A study by Yu et al. (2023) documented that soil nutrients directly affect the DBH of oak trees that results in the change in basal area. Soils that have low fertility might impede tree growth and recovery, especially in high-density stands where resource competition is strong (Zhao et al., 2024). On the other hand, soils with a high organic matter content and improved nutrient cycling, may support trees, even in thick stands. Soil moisture and organic matter concentration are other important factors in determining the stand density of white oaks (Brockett et al., 2012). Organic matter improves soil structure, increases moisture retention, and provides a delayed release of nutrients, all of which are required for good tree growth. The white oaks with increased organic matter content have lower mortality rates, owing to improved water and nutrient availability (Lyczak et al., 2021). Soils with low water content, which are common in degraded forests, may result in greater death rates due to increased sensitivity to drought stress, especially in higher competitive mixed pine-oak forest (Ferrio et al., 2021).

A notable gap remains in understanding how soil properties influence the stand density of declining white oak forests. Although previous research has generally explored the influence of soil factors on oak growth, the distinct impacts of specific soil textures such as clay loam, fine sandy loam, and loamy fine sand on the stand density of declining white oaks have not been thoroughly examined. Moreover, the interaction between soil texture, soil organic matter, and the total available water (TAW) concerning stand density of declining white oaks remains under-explored. Current research primarily focuses on general factors influencing oak decline, such as climate variability and biotic stressors such as pests and competition (Teshome et al., 2020), but there is insufficient data on how particular soil attributes, especially in combination with moisture availability, directly affect white oak stand density across broader scales. This study aims to (1) assess the stand density of declining white oaks across the eastern US and (2) investigate the relationship between the stand density of declining white oaks and soil properties. Specifically, we hypothesized that the very low total available water and the presence of clay loam soil have a greater influence on the stand density of white oaks.

Materials and Methods

Study Area

Our study area consists of vast areas of oak forests across the eastern United States (Clark & Schweitzer, 2016). The study area contains ten states i.e., Alabama, Arkansas, Illinois, Indiana, Kentucky, Missouri, Ohio, Tennessee, Virginia, and West Virginia (Fig. 1). It has a diverse spectrum of tree species, as well as climate, soil, and topography (Wang et al., 2014). Our study area mostly covers forests followed by cultivated land, urban, water and others. The geographical configuration in the eastern section of our study area is predominantly Appalachian plateaus, with low mountains, small valleys, and sharp edges. The western section ranges from highly flat central till plains to inner low plateaus, as well as the Ozark Highlands. In the south, from Illinois' central till plains Oak-Hickory to Alabama's interior low plateau Highland Riff.

Our study area has a lengthy, hot summer and a cool winter temperature. The mean annual temperature varies from 4 to 18℃ throughout the east-west gradient, with milder temperatures in the south. The precipitation ranges from 500 to 1650 mm. There are various types of soils from alfisols, mollisols, ultisols, and inceptisols. Our study area was historically dominated by oaks, pines, and hickories. Nowadays, agriculture and fast urbanization have displaced most of the forest lands in the eastern U.S.

White oak data

Plot-level data for white oaks were obtained from the USDA Forest Service DataMart, where plots were already classified into strata by the forest inventory program across various states. The weight of each stratum within the plot sampling estimation unit is determined by the proportion of the stratum (Woudenberg et al., 2010). The plot dataset included geographic coordinates (latitudes and longitudes) for a sample area of 0.40 ha, though these coordinates did not account for every tree. To protect landowner privacy, the recorded plot locations by the Forest Service are within one mile of the actual locations (Khadka et al., 2021; Woudenberg et al., 2010). For declining white oak plots, we considered only forested sites that represented a major portion of white oak occurrence across the ten states of the study area.

Our dataset concentrated exclusively on white oaks due to the limited research on the stand density of declining white oaks affected by soil characteristics on a broader scale. Although multiple oak species are present within the sample plots, we restricted our selection to plots containing only white oaks i.e., single species plots and performed our analysis using data from surveys conducted between 1998 to 2019. The data on white oak were obtained from the USDA Forest Service and encompassed various details, including the inventory year (INVYR), which reflects the survey date and the county code (COUNTYCD), designating a specific county; unique plot number (PLOT), assigned to each white oak; species code (SPCD), which identified white oaks in this study; and tree status code (STATUSCD), which denoted live trees (coded as 1) and we used only live trees to calculate white oak decline based on the Forest Inventory and Analysis (FIA) program. Additionally, the dataset included unadjusted trees per acre (TPA_UNADJ), representing the number of trees per acre theoretically represented by the sample tree according to the sample design; and the current diameter (DIA), measured at breast height (4.5 feet

above ground). The dataset also incorporated the cycle (CYCLE), which denotes the set of plots measured over a specific time frame.

Soil Properties Data

We acquired soil variables such as soil texture, soil organic matter, and total available water from the Gridded National Soil Survey Geographic Database (gNATSGO) were resampled to a 1km grid resolution as our study area covers a broader scale analysis, provided by the USDA Natural Resources Conservation Service (Salley et al., 2016). This coarse resolution may generalize localized soil variability; however, it provides a consistent spatial framework for regional scale assessment across multiple states. We acquired these soil variables due to a larger dataset from ten states that requires more time to process and relevant to our study. Therefore, we selected soil texture, organic matter, and total available water as key variables likely to have the greatest influence on stand density in declining white oaks Also, soil texture is vital in soil characteristics which identifies the proportion of sand, silt, and clay affecting organic matter content and water-holding capacity in oak-dominated forests (Slesak et al., 2017; Yang et al., 2021).

The soil texture classifications from SSURGO tabular data were combined with the spatial soil data provided with GIS shapefiles (Table 1). Some regions were null for soil texture classification, which was addressed by obtaining information from the FAO dataset (Pietsch & Lucke, 2008). We used the Soil Texture Triangle as a reference to fill all null values for soil texture by placing SSURGO and FAO spatial soil data into ArcGIS version 10.8.1 (Becker et al., 2022). By doing this, we obtained eighteen types of soil texture classification (including inland water) that were common in our study area. We also calculated soil organic matter and total available water using soil horizon thickness; and classified them into five classes using natural breaks (Jenks).

Table 1. Classification of soil texture, organic matter, and total available water across our study area.

Soil Texture Class I	Soil Texture Class II	Soil Texture Class III	SOM/ Range(%)	TAW/Range (%)
Clay (C)	Loam (L)	Sandy Loam (SL)	No (0)	Very Low (0 - 20)
Clay Loam (CL)	Loamy Fine Sand (LFS)	Silt (SI)	Low (0.01)	Low (21 - 40)
Coarse Sand (COS)	Loamy Sand (LS)	Silt Loam (SIL)	Medium (0.02 - 0.03)	Medium (41 - 60)
Fine Sand (FS)	Sand (S)	Silty Clay (SIC)	High (0.04 -0.1)	High (61 - 80)
Fine Sandy Loam (FSL)	Sandy Clay (SC)	Silty Clay Loam (SICL)	Very High (1.1 - 3.7)	Very High (81 - 100)
Inland Water (WR)	Sandy Clay Loam (SCL)	Very Fine Sandy Loam (VFSL)		

Identification of declining white oaks

The annualized dataset spanning 1998 to 2019 was processed to identify white oak plots (Fig. 2). Following data cleaning and integration from three key tables i.e., plot, forested condition (COND = 1), and tree, we focused on the plot data to isolate criteria for locating white oak plots on accessible forest land (Khadka et al., 2024). For instance, the Virginia plot table provided essential attributes, including unique plot identifiers linked to specific counties and cycles, as well as geographic coordinates corresponding to survey years. Only plots with at least one forested condition deemed accessible were selected for further analysis. The forest condition table contained comparable attributes, minus location data, and was utilized to connect with the plot data. Both the condition and tree tables were processed with the same criteria, prioritizing accessible forest land. The tree table offered crucial information such as unique plot numbers, county codes, species codes, tree diameters, tree density (trees per acre), and survey cycles.

White oaks were identified in the tree dataset using species code 802. From this dataset, we calculated the basal area for white oaks, which serves as an important measure of forest structure and tree health across sampled plots.

$$\text{Basal area } \left(\text{ft}^2\text{ac}^{-1}\right) = 0.005454 * (\text{Current Diameter})^2 * \text{trees per acre unadjusted}$$

1

We linked the forest condition and tree tables by using unique plot identifiers. The combined dataset was then summarized by calculating the basal area (m^2/ha) for each plot. Following this, we joined the summarized basal area with the plot table, again based on unique plot numbers. This produced a comprehensive dataset containing white oak plots, locations, basal area values, and survey cycles. Our dataset, initially annual, was grouped into multi-year cycles following a five-year survey period. For example, Virginia's cycle 7 spanned inventory years from 1998 to 2002, with subsequent cycles covering 2003–2007 (cycle 8), 2008–2012 (cycle 9), 2013–2017 (cycle 10), and 2018–2019 (cycle 11). This same process was applied to other states, extracting white oak plots from cycles for corresponding survey years. Furthermore, we linked individual cycles using a formula that combined county and plot numbers COUNTYCD + (PLOT)/100,000 to identify changes over time. For instance, by subtracting the basal area of cycle 7 from cycle 8, we identified declining plots with negative basal area values. The same procedure was followed to compare cycle 8 to cycle 9, cycle 9 to cycle 10, and cycle 10 to cycle 11. To avoid plot duplications, we summarized all the basal area values in a single plot. Using this method within ArcGIS version 10.8.1, we identified 2,220 declining white oak plots out of 7,405 live white oak plots across ten states.

The decline of white oak was calculated by using basal areas (negative) of surveyed cycles, which were grouped into five years. We did our decline analysis based on plot-level referring to (Khadka et al., 2024), in which we summarized all those basal areas based on plot. Although we extracted all those basal areas from consecutive survey cycles, we calculated basal area decline based on the plot system. A plot was classified as decline if it exhibited a net decrease in basal area. This classification was repeated across all survey cycles within the study period. Some of the white oak plots were remeasured in the

period from 1998 to 2019. Hence, we omitted those repeated plots to have accurate results. However, we summed up all those remeasured plots' basal areas to obtain the true basal area. We extracted all the basal area data from declining white oak plots across all survey years. The declining plots were chosen based on reduced basal area. Reduced basal area refers to the change in basal area (negative) referring to declining white oak plots. For instance, we calculated Virginia's basal area decline from each cycle as:

$$\text{Basal area decline } \left(\text{m}^2\text{ha}^{-1}\right) = \text{Summarized basal area in } (\text{Cycle } 11 - \text{Cycle } 7)$$

2

Calculation of stand density from declining white oaks

From the set of declining white oak plots, we captured the total number of white oak trees corresponding to white oak basal are decline. Based on the total number of trees and area provided in each plot, we calculated the stand density concerning white oaks. For this, we summarized all those stand densities in a single plot so that each declining plot of white oak has a unique number for stand density. To perform this, we captured total number of trees related to the declining basal areas from cycle 7 up through cycle 11 in a plot system and calculated the stand density using the appropriate formula. The stand density can be expressed as:

$$\text{Stand density } (trees/ha) = \frac{\text{Total number of white oak trees}}{\text{Total Area}}$$

3

Data analysis

We applied a logarithmic transformation to the stand density data of declining white oaks to normalize that data distribution and meet statistical assumptions of normality. Total number of white oak trees in a given plot area were utilized to calculate stand density. Soil textures were classified into 18 classes taking a reference from the Food and Agriculture Organization (FAO) Soils Portal based on the World Reference Base (WRB) soil classification system (https://www.fao.org/soils-portal/data-hub/soil-classification/en/). We interpolated soil organic matter and TAW and used the interpolated results to compare them with the stand density of declining white oaks. Soil organic matter and TAW percentage were classified into five classes i.e., very low, low, medium, high, and very high using natural breaks (Jenks) from ArcGIS version 10.8.1. Soil texture and TAW are inherently related due to the influence of soil texture and composition on water availability. Our data were analyzed using R Studio (Kaya et al., 2019), in which we used an ANOVA test with Tukey HSD using significance levels at $p \leq 0.05$. We incorporated 18 soil texture classes into the ANOVA test as one of the independent variables including organic matter and TAW. This allows the model to compare the effect of each soil variables category relative to a reference category. The ANOVA test was performed by:

$$\mathrm{Y_{ijk}} = \mu + \mathrm{A}_i + \mathrm{B_j} + \mathrm{C_k} + (\mathrm{AB})_{\mathrm{ij}} + (\mathrm{AC})_{\mathrm{ik}} + (\mathrm{BC})_{\mathrm{jk}} + (\mathrm{ABC})_{\mathrm{ijk}} + e_{\mathrm{ijk}}$$

4

where Y_{ijk} represents the stand density of declining white oaks; μ is the overall mean, A_i, B_j, C_k are the main effects of the three factors; $(AB)_{ij}$, $(AC)_{ik}$, $(BC)_{jk}$, $(ABC)_{ijk}$ represent interaction effects, and e_{ijk} as the error term.

Results

Overall Relationship between Soil Properties and Stand Density

Analysis of variance demonstrated that soil properties exerted significant effects on the stand density of declining white oaks across the eastern United States (Table 2). Among the main effects, soil texture ($F = 1.85$, $p < 0.02$), organic matter ($F = 3.36$, $p < 0.01$), and total available water ($F = 6.56$, $p < 0.00$) emerged as significant predictors of variation in stand density. Of these, total available water accounted for the largest proportion of explained variance, understanding the importance of soil moisture availability in regulating oak survival and recruitment. Soil texture and organic matter also contributed significantly, suggesting that both physical and chemical properties of soils influence the capacity of white oak stands to persist under declining conditions. Collectively, these findings highlight that water retention capacity and soil fertility play central roles in shaping the distribution and density of declining white oak populations across large spatial scales.

In contrast, interaction terms among soil properties were not statistically significant. Neither the two-way interactions (soil texture x organic matter, soil texture x total available water, organic matter x total available water) nor the three-way interaction (soil texture x organic matter x total available water explained additional variation in stand density (all $p > 0.29$). This lack of interactive effects suggests that soil factors operate largely through independent pathways rather than synergistic or compounding mechanisms. In other words, soil texture, organic matter, and total available water exert distinct influences on stand density of white oaks, but their combined effects do not amplify or diminish one another.

Soil Texture Class Effects on Stand Density

Post-hoc pairwise comparisons using Tukey's HSD test showed that differences in stand density among soil texture classes were generally modest, with most pairwise contrasts exhibiting confidence intervals that overlapped zero, indicating non-significant differences (Fig. 3; Part 1). However, certain soil texture comparisons demonstrated relatively larger mean differences. For instance, white oak stand densities tended to be higher in well drained textures such as VFSL and SIL compared to CL and SICL, though the wide confidence intervals suggest substantial variability across sites. Similarly, soils with coarser textures (e.g., sand S and LS generally supported lower stand densities than finer-textured classes SIL and SL, although these contrasts were not statistically significant at $p = 0.05$.

The Tukey HSD post hoc test (Fig. 4; Part 2) further classified differences in stand density among specific soil texture classes. Across the comparisons, most pairwise contrast exhibited mean differences that were small in magnitude and whose 95% confidence intervals overlapped zero, indicating statistically nonsignificant differences ($p > 0.05$) between most soil texture pairs. This pattern suggests that although soil texture, as a main factor, had an overall significant effect on stand density ($F = 1.85$, $p = 0.02$), individual texture class combinations did not differ markedly in their mean stand densities when compared directly.

Slightly higher mean stand densities were observed in loam (L), silt loam (SIL), and sandy clay loam (SCL) soils relative to coarser textures such as sand (S) and loamy sand (LS), as reflected by the positive mean differences in these pairwise comparisons. Conversely, comparison involving fine-textured soils such as clay and silty clay (SIC) showed more variable responses, with wider confidence intervals extending across both sides of zero, suggesting considerable within-group variability

Organic Matter Class Effects on Stand Density

Analysis of variance indicated that soil organic matter exerted a significant effect on the stand density of declining white oaks across the eastern U.S. ($F = 3.36$, $p = 0.01$). Tukey's HSD post hoc comparisons further elucidated that mean difference in stand density among the organic matter classes were relatively modest, with most pairwise comparisons exhibiting confidence intervals that overlapped zero (Fig. 5). Nonetheless, trends in the data revealed that sites with *medium* to *high* organic matter content generally supported higher stand densities compared to those with very low (Vlow) or low (L) organic matter levels. Specifically, comparisons such as Vlow-Medium and Vlow-low showed positive, albeit statistically nonsignificant, mean differences, suggesting a tendency for stand density to increase with incremental gains in soil organic matter.

The comparisons between *very low-very high* organic matter classes exhibited the largest mean difference, though the wide 95% confidence interval indicated substantial variability among sites. Conversely, comparisons among the higher organic matter categories (e.g., high-very high and medium-high) revealed minimal differences in mean stand density, suggesting that beyond a certain threshold, increases in organic matter confer limited additional benefit to stand density. Collectively, these results demonstrate that organic matter exerts a positive but saturating influence on white oak stand density, with diminishing returns at the upper end of the organic matter gradient.

Available Water Effects on Stand Density

Analysis of variance indicated that total available water (TAW) had a significant influence on the stand density of declining white oaks across study sites ($F = 6.56$, $p < 0.001$). The subsequent Tukey HSD pairwise comparisons revealed distinct patterns along the soil moisture classes (Fig. 6). Overall, sites characterized by medium to high TAW levels tended to support higher stand densities than those with very low or low TAW classes. Mean differences between the very low (Vlow) and higher TAW classes (Medium, High, and Vhigh) were positive, suggesting that incremental increases in soil water availability

corresponded with increases in stand density. However, the wide 95% confidence intervals indicate variability across sites and the absence of statistically significant pairwise differences.

Comparisons among the upper TAW categories (e.g., Medium-High, High-Vhigh) showed smaller mean differences and overlapping confidence intervals, indicating that beyond a moderate level of available water, additional increase in TAW provided limited gains in stand density. Conversely, comparisons involving the lowest water classes (Vlow-Low and Vlow-Medium) consistently displayed lower mean differences, signifying that insufficient soil water availability may constrain stand development. Collectively, these results suggest a positive but nonlinear association between soil water availability and sand density, where improvements in total available water enhance white oak stand structure up to an optimal threshold.

Table 2
Different classes of total available water and soil texture and their respective p-values indicate a significant relationship with the stand density of declining white oaks.

S.N.	Variables	df	Sumsq	Meansq	F statistic	pr (> F)
1	Soil texture	17	49.51	2.91	1.85	0.02*
2	Organic matter	4	21.21	5.30	3.36	0.01**
3	Total available water	4	41.42	10.35	6.56	< 0.00***
4	Soil texture : Organic matter	25	27.07	1.08	0.69	0.88
5	Soil texture : Total available water	34	60.32	1.77	1.12	0.29
6	Organic matter : Total available water	8	13.36	1.67	1.06	0.39
7	Soil texture : Organic matter : Total available water	28	30.89	1.10	0.70	0.88

Significance codes: * p < 0.05; ** p < 0.01; *** p < 0.001.

Discussion

Soil Properties Effects on Stand Density and their Ecological Significance

The results of this study demonstrate that soil properties exert a significant influence on the stand density of declining white oaks across the eastern United States. Total available water emerged as the strongest predictor of variation in stand density, emphasizing the importance of soil moisture availability in regulating oak persistence. This finding is consistent with previous studies showing that soil water availability is a primary determinant of oak regeneration and survival, particularly under conditions of drought stress and increasing climatic variability (Abrams, 1990; Urbieta, 2009). Moisture deficits are known to exacerbate physiological stress, reduce seedling recruitment, and increase susceptibility to

pests and pathogens, all of which contribute to the decline of oak across its natural range (Clark et al., 2016; McEwan et al., 2011).

In addition to water availability, both soil texture and organic matter were also significant predictors of stand density, highlighting the importance of soil physical and chemical properties. Soil texture influences water-holding capacity, root penetration, and nutrient dynamics (Costantini et al., 2016), while organic matter contributes to soil fertility, cation exchange capacity, and microbial activity, thereby supporting oak seedling establishment and long-term stand viability (Giai & Boerner, 2007). These results suggest that white oak stand density is sensitive not only to moisture stress but also to underlying soil fertility that regulates nutrient cycling and productivity.

Interestingly, no significant interactions were observed among soil texture, organic matter, and total available water, suggesting that these factors influence oak stand density through largely independent pathways. These patterns contrast with some localized studies where interactive effects of soil texture and fertility have been reported (Small & McCarthy, 2005). The lack of interaction effects at broad spatial scale of this study may reflect ecological averaging across diverse landscapes, where independent contributions of soil properties dominate over site-specific synergies. These findings reinforce the need to consider soil drivers individually when predicting oak stand decline dynamics at regional scales.

Effects of Soil Texture class on Stand density

Post-hoc pairwise comparisons using Tukey's HSD test indicated that variation in stand density among soil texture classes was generally modest, with most pairwise contrasts exhibiting confidence intervals overlapping zero, signifying non-significant differences. Nevertheless, several texture comparisons exhibited relatively higher mean differences. White oak stands tended to occur at higher densities on well-drained soils such as VFSL and SIL compared to less permeable, fine-textured soils such as CL and SICL. Although these contrasts did not achieve statistical significance, the pattern is ecologically meaningful and aligns with previous findings that moderate drainage enhances root aeration, facilitates mycorrhizal colonization, and reduces waterlogging stress, all of which contribute to oak vigor and persistence (Abrams, 2003; L. Iverson et al., 2008). Conversely, coarser-textured soils such as S and LS generally supported lower stand densities, likely due to limited soil moisture retention and reduced nutrient availability, which constrain seedling establishment and growth (Osman, 2013).

The Tukey HSD results further confirmed that while soil texture exerted a significant overall effect on stand density, individual pairwise differences between texture classes were not statistically distinct. This suggests that soil texture influences stand density through continuous gradients of water-holding capacity, porosity, and nutrient supply rather than discrete categorical effects. Intermediate textures such as L, SIL, and SCL generally supported higher stand densities than coarse S and LS. reflecting an optimal balance between drainage and water availability (Brady & Weil, 2008). In contrast, fine-textured soils such as C and SIC exhibited high within group variability, indicated by wide confidence intervals spanning both sides of zero. Such variability may result from localized differences in soil structure,

compaction, or depth, which can modify root development, moisture availability, and ultimately stand productivity (Clark et al., 2016; Dahlgren, 2003).

These findings provide valuable insight into the soil-based constraints on white oak stand density and potential mechanisms contributing to regional oak decline. The preference of white oak for moderately drained, fertile soils underscores its sensitivity to both drought stress and poor aeration, which are the two factors increasingly influenced by climate change and anthropogenic disturbance (Pederson et al., 2015; Seidl et al., 2017). Soils with balanced hydrologic and physical properties may buffer oaks against episodic droughts, whereas excessively coarse or compacted fine-textured soils could exacerbate water stress or impede root expansion, further reducing stand density and regeneration success. Thus, the spatial heterogeneity of soil properties across the eastern U.S. landscape likely mediates local differences in white oak decline severity and recovery potential.

Effects of Soil Organic Matter Class on Stand Density

The observed trends in the data revealed that stands established on soil with medium to high organic matter content generally supported stem densities compared to those eon soils with very low to low OM levels. Although pairwise comparisons were not statistically significant, the positive direction of the mean differences particularly between the Vlow-Medium and Vlow-Low classe indicates that incremental increases in soil organic matter are associated with higher stan density. These findings align with the growing body of evidence emphasizing the importance of soil organic matter in maintaining forest structure, productivity, and resilience (Lal, 2005; Nave et al., 2009).

The largest mean difference observed between the very low and very high OM categories, despite its wide 95% confidence interval, highlights considerable site-to-site variability in the response of stand density to soil organic matter. Such variability is common in large scale forest studies, as interactions among soil texture, topographic, and local microclimate can modulate the functional influence of organic matter and stand dynamics (Ediş, 2025; Jobbágy & Jackson, 2001). For example, coarse-textured soils with low clay content may exhibit limited benefits from OM accumulation because of reduced water retention capacity (Kaiser & Kalbitz, 2012; Six et al., 2002), while fine-textured soils can amplify the effects of organic enrichment on soil structure and nutrient dynamics (Bronick & Lal, 2005).

Notably, comparisons among higher organic matter categories (e.g., medium-high and high-very high) revealed minimal differences in mean stand density, suggesting that the influence of OM on stand density will no longer cause a significant change beyond a certain threshold. This nonlinear or saturating response has been observed in other temperate forest systems, where excessive OM accumulation can slow decomposition, reduce nutrient mineralization rates, or even create anaerobic microsites that inhibit root respiration (Cotrufo et al., 2013; Prescott, 2010).

Effects of Total Available Water Class on Stand Density

The total available water (TAW) exerted a strong but saturating influence on the stand density of declining white oaks, emphasizing the ecological significance of soil moisture availability in shaping

forest structure across the eastern U.S. The positive association between TAW and stand density aligns with prior research linking soil water status to oak growth, vigor, and regeneration dynamics (Clark & Schweitzer, 2016; Iverson et al., 2008). In particular, white oaks are known to be moderately drought-tolerant yet sensitive to chronic moisture stress, which can lead to reductions in radial growth, root function, and resistance to biotic agents such as borers and fungal pathogens (Haavik et al., 2015; Yang et al., 2021).

The higher stand densities observed in medium and high TAW soils may reflect enhanced rooting depth, nutrient mobility, and overall tree vigor in moderately moist conditions. Adequate water availability facilitates nutrient uptake and supports physiological processess critical for maintaining canopy productivity and resistance to decline (Bréda & Badeau, 2008; McDowell et al., 2008). Moreover, soil moisture indirectly supports microbial activity and organic matter decomposition, improving nutrient cycling and soil structure, which are the factors that further promote stand establishment (Bhattacharyya & Furtak, 2023; Davidson & Janssens, 2006).

The diminishing differences among higher TAW classes suggest that the relationship between water availability and stand density is nonlinear, possibly reflecting a threshold response where additional moisture does not further enhance growth. This saturation effect may result from other site-limiting factors such as aeration, nutrient imbalance, or competition that constrain additional gains in stand density at higher water levels (Miller et al., 2004; Sajedi et al., 2012). In poorly drained or excessively wet soils, oxygen limitation in the root zone may suppress fine root proliferation and increase susceptibility to disease (Priori et al., 2020).

Conversely, very low and low TAW classes likely correspond to coarse-textured or shallow soils, where limited water-holding capacity reduces tree resilience to seasonal drought. These conditions can lead to chronic moisture deficits, predisposing trees to decline through cumulative hydraulic stress (Khadka et al., 2024; O'Brien et al., 2017). As a result, oak mortality tends to be higher in such xeric or marginal habitats (Kabrick et al., 2005; Shifley et al., 2006).

Management Implications

The impacts of extreme TAW levels highlight the vulnerability of white oak stands to both droughts and waterlogging conditions that are expected to become more prevalent with ongoing climate variability. Forest managers may need to adapt silvicultural practices to improve soil water management in regions prone to either extreme, through techniques like thinning, soil management programs, or even hydrological interventions to promote better drainage or water retention (Arthur et al., 2012; Park et al., 2014). These actions not only mitigate oak decline but also enhance forest resilience, carbon retention, and ecological sustainability under increasing climatic variability. Managing white oak stand density in response to these water-related challenges will be key to maintaining healthy white oak populations and their ecological functions, including habitat provision, nutrient cycling, and carbon sequestration, across diverse landscapes in the eastern U.S.

From a management perspective, forest managers can use this information to tailor silvicultural practices based on soil characteristics. For instance, in areas dominated by clay loam or loamy fine sand, practices such as soil amendments, or drainage improvements may be necessary to reduce stress on white oak stand density and mitigate future decline. Furthermore, understanding these soil-oak tree interactions can help guide reforestation efforts, ensuring that oak species need to be planted in specific soil types where they are more likely to thrive (Das et al., 2022f et al., 2012).

Limitations of the Study

The large spatial extent of the study area i.e., eastern US, which spans multiple states, introduces significant variability in climate, land use, and forest management practices, potentially confounding the observed relationships between stand density and soil properties. Our data covers the period from 1998 to 2019, although this period is significant, annual fluctuations in climate (droughts, heatwaves, etc.) and disturbances (insect outbreaks, fire, etc.) could have had strong year-specific effects on the stand density of white oak and its decline. Aggregating data into multiyear cycles may take several processes to study effects on forest dynamics. Although soil variables were derived from national datasets and resampled to 1 km resolution, this scale may mask fine-scale soil heterogeneity. Nevertheless, it offers a valuable regional perspective for assessing soil-related drivers of white oak stand density across diverse ecological gradients.

White oak decline is often influenced by complexities of stand dynamics, such as tree composition, succession, and age structure as well as multiple interacting factors, including biotic stressors like pests and pathogens, which are not fully captured in our analysis and might be a new topic for future researchers. However, the effects of soil characteristics on the stand density of declining white oaks might be useful to forest managers and landowners for a general understanding of white oak stands and their decline in the broader perspective of the eastern U.S.

Conclusions

This study provided robust evidence that soil properties, particularly total available water, soil texture, and organic matter, play a fundamental role in shaping the stand density of declining white oaks across the eastern United States. Among these variables, total available water emerged as the most influential determinant, underscoring the central role of soil moisture in regulating oak persistence, growth, and regeneration. The positive yet nonlinear association between total available water and stand density indicates that moderate soil moisture levels favor white oak establishment and vigor, whereas both drought-prone and waterlogged conditions impose physiological and structural constraints that may accelerate stand decline under changing climatic regimes.

Soil texture and organic matter further modulate these dynamics through their effects on water retention, nutrient availability, and root development. Fine-textured soils and soils with moderate to high organic matter content were generally associated with higher stand densities, reflecting improved soil fertility and moisture-holding capacity. However, beyond certain thresholds, additional fineness or

organic enrichment yielded diminishing returns, suggesting that optimal rather than maximal soil conditions sustain oak stand resilience. The absence of significant interaction effects among the soil variables implies that these edaphic factors operate through largely independent mechanisms that collectively define site suitability for white oak persistence.

At a regional scale, these findings contribute to a growing understanding of the abiotic underpinnings of white oak decline and highlight the need to integrate soil-based indicators into forest health assessments and management frameworks. In the context of increasing climatic variability, maintaining or enhancing soil moisture availability through practices such as minimizing compaction, conserving forest floor organic matter, and promoting mixed species stands may help sustain white oak productivity and ecosystem function. Future research should focus on linking site-level soil attributes with physiological indicators of tree stress and mortality risk to refine predictive models of oak stand density.

Declarations

Author Contributions Saaruj Khadka-Conceptualization; Saaruj Khadka- Methodology; Saaruj Khadka, Sougata Bardhan -Validation, Saaruj Khadka, John Yang, Sougata Bardhan-Writing-review and editing.

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Conflict of Interest The authors declare no conflict of interests.

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Figures

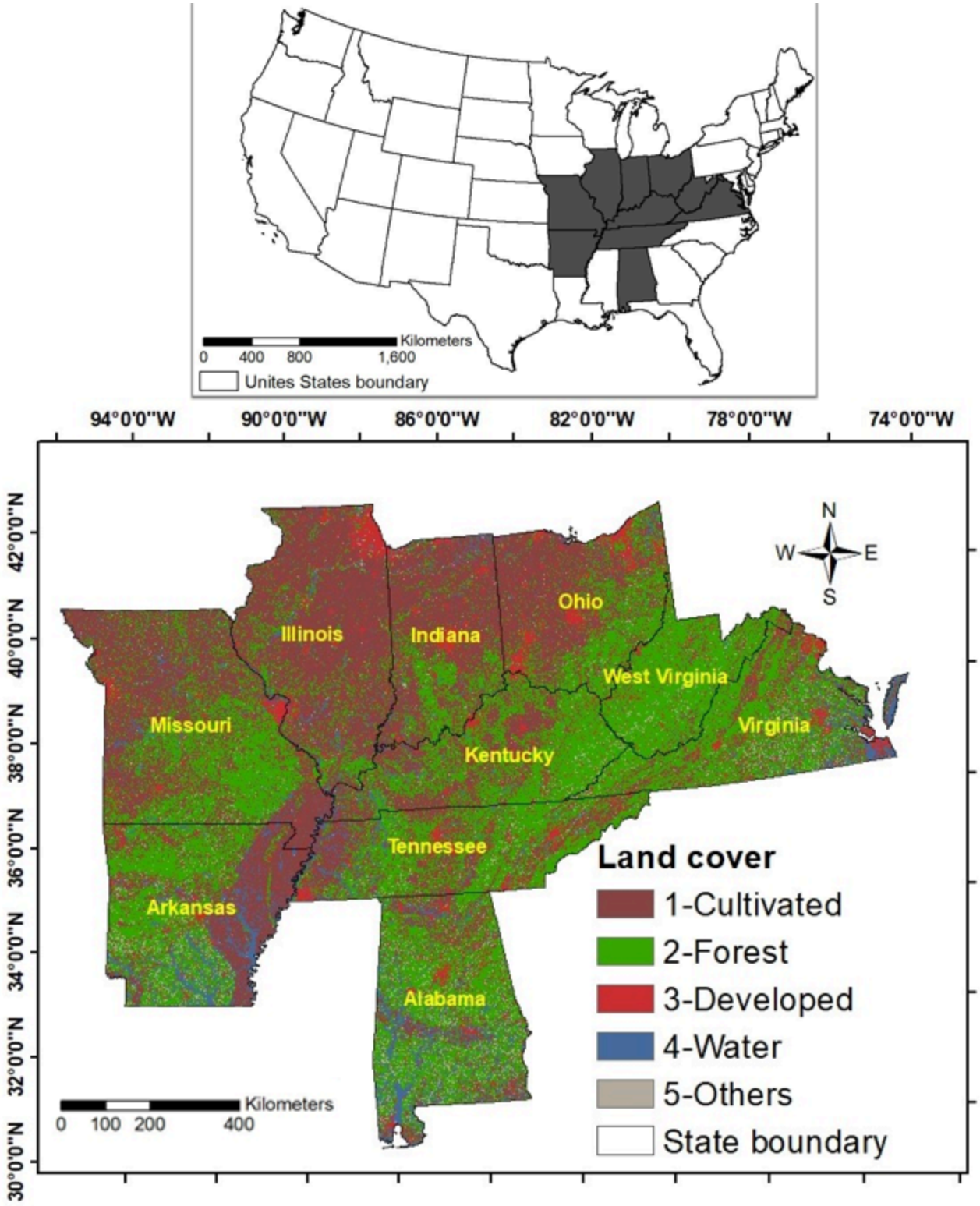


Figure 1

Ten states of the eastern U.S. showing land use land cover including forest area.

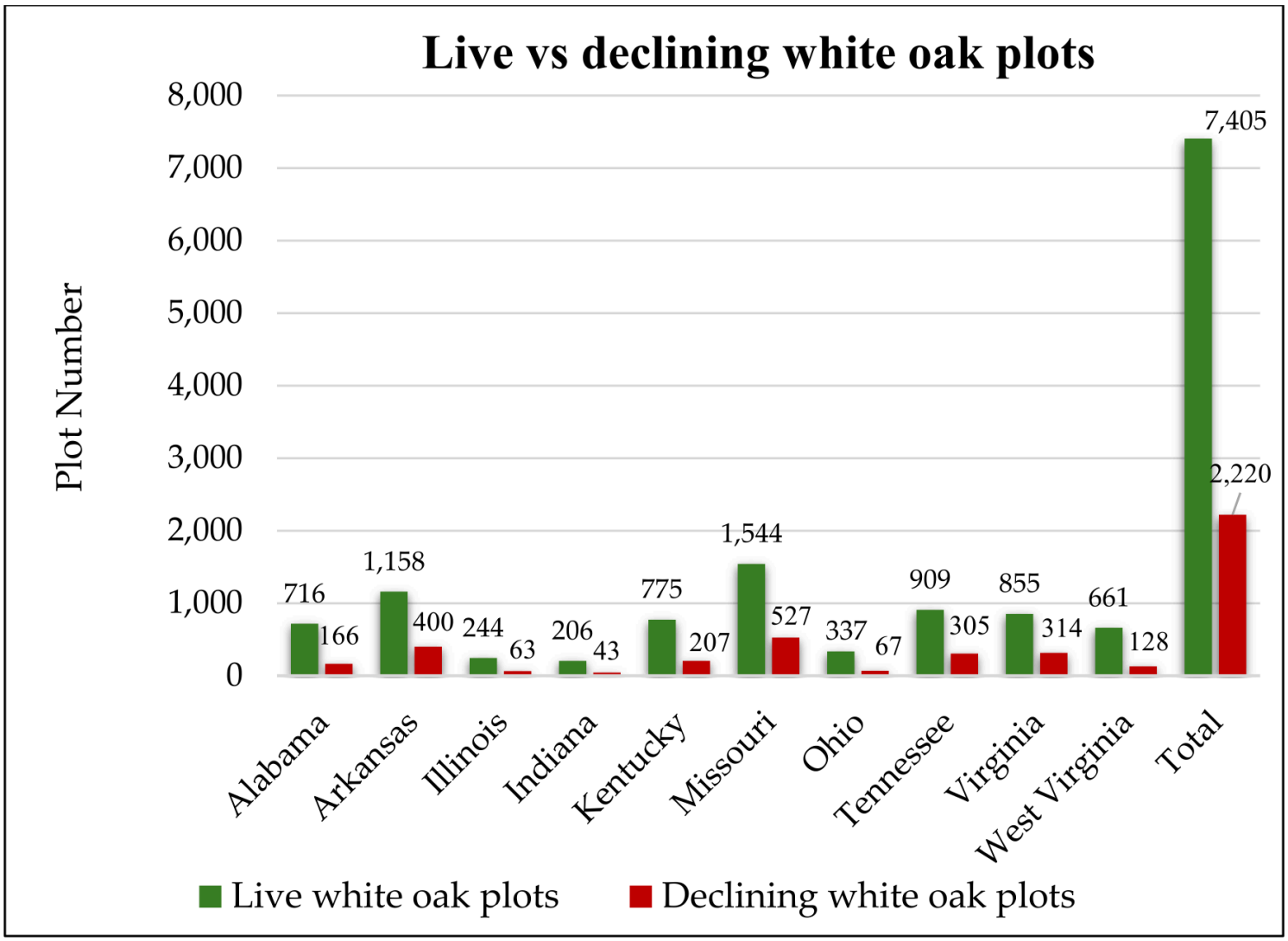


Figure 2

Ten states showing the number of live and declining white oak plots across the eastern US

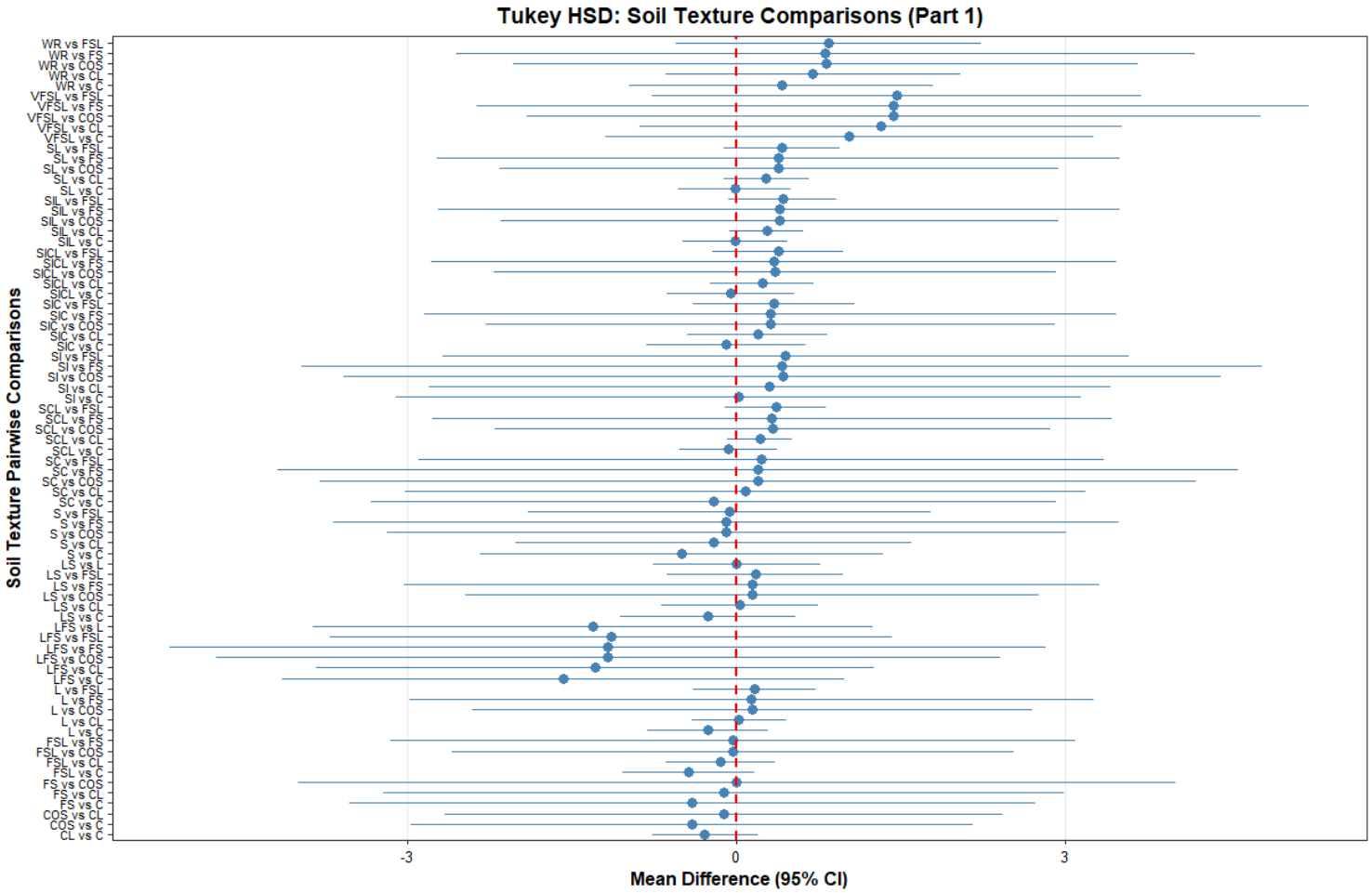


Figure 3

(Part 1): This graph shows the Tukey's HSD pairwise comparisons for soil texture classes in relation to stand density. Each blue point represents the mean difference between two soil texture class levels, and the horizontal lines show the 95% confidence intervals (CIs). The red dashed line at zero indicates no difference between groups.

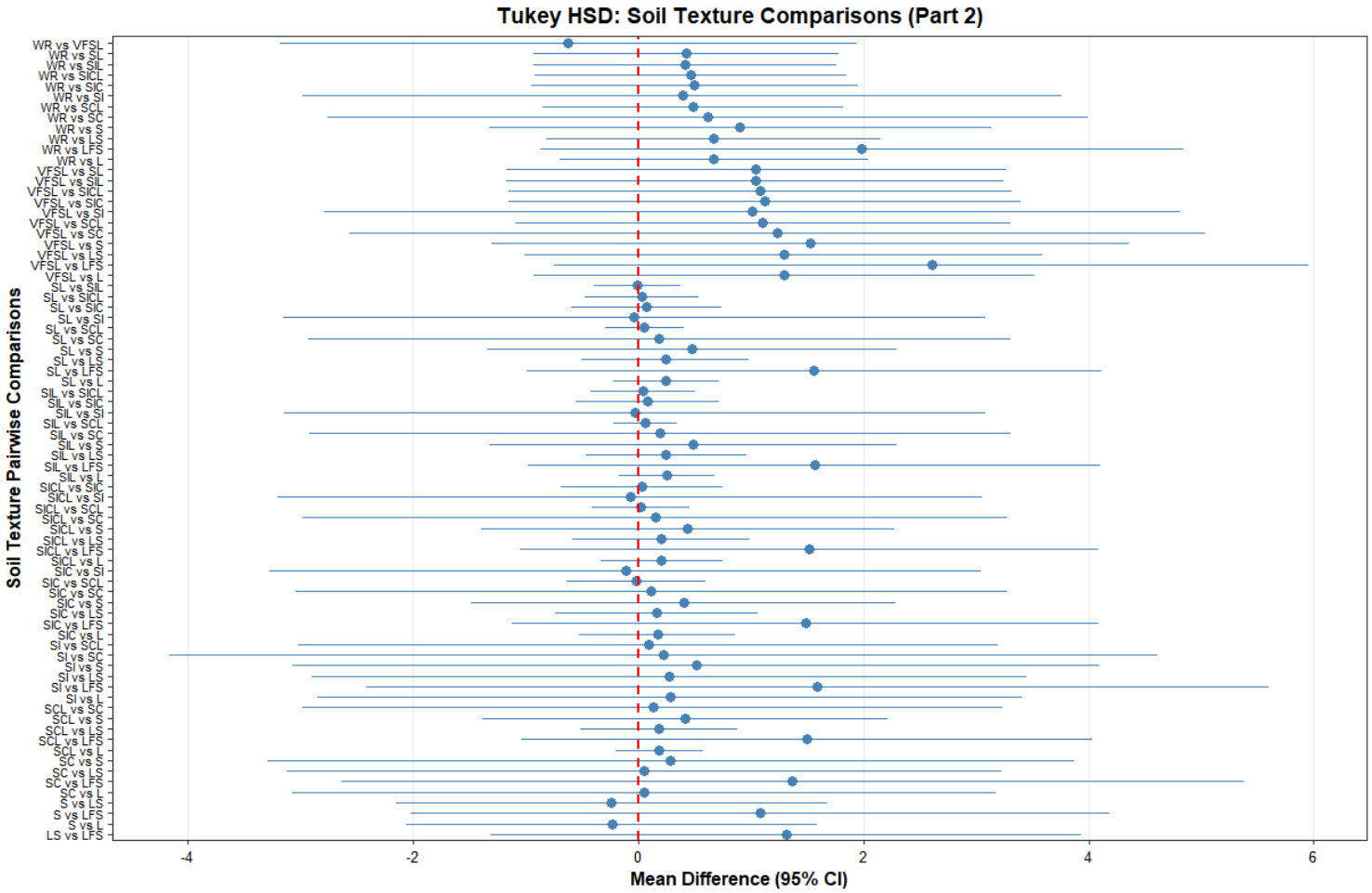


Figure 4

(Part 2): This graph shows Tukey's HSD pairwise comparisons for soil texture classes in relation to stand density. Each blue point represents the mean difference between two soil texture class levels, and the horizontal lines show the 95% confidence intervals (CIs). The red dashed line at zero indicates no difference between groups.

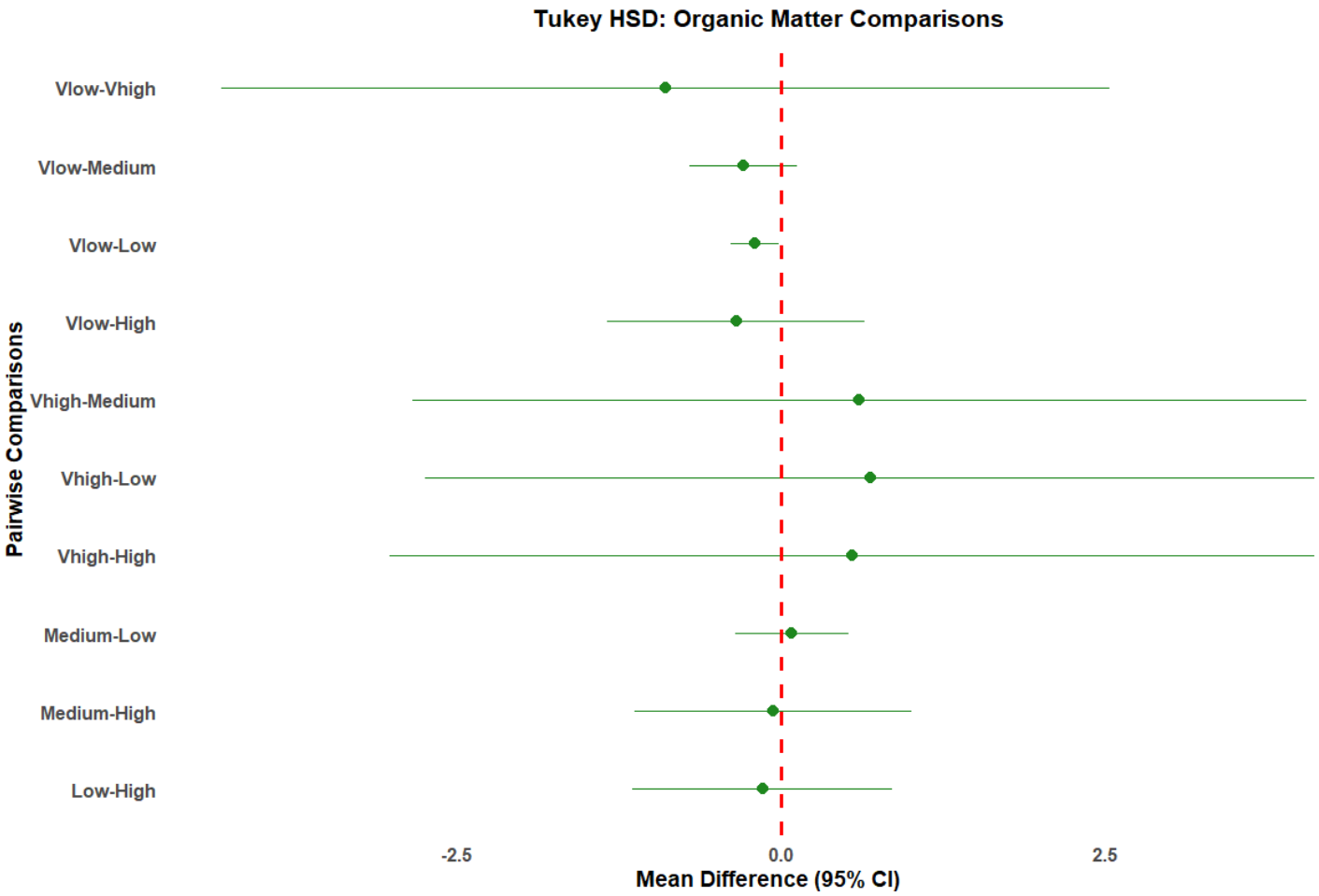


Figure 5

This graph shows Tukey's HSD pairwise comparisons for organic matter classes in relation to stand density. Each green point represents the mean difference between two organic matter class levels, and the horizontal lines show the 95% conf confidence intervals (CIs). The red dashed line at zero indicates no difference between groups.

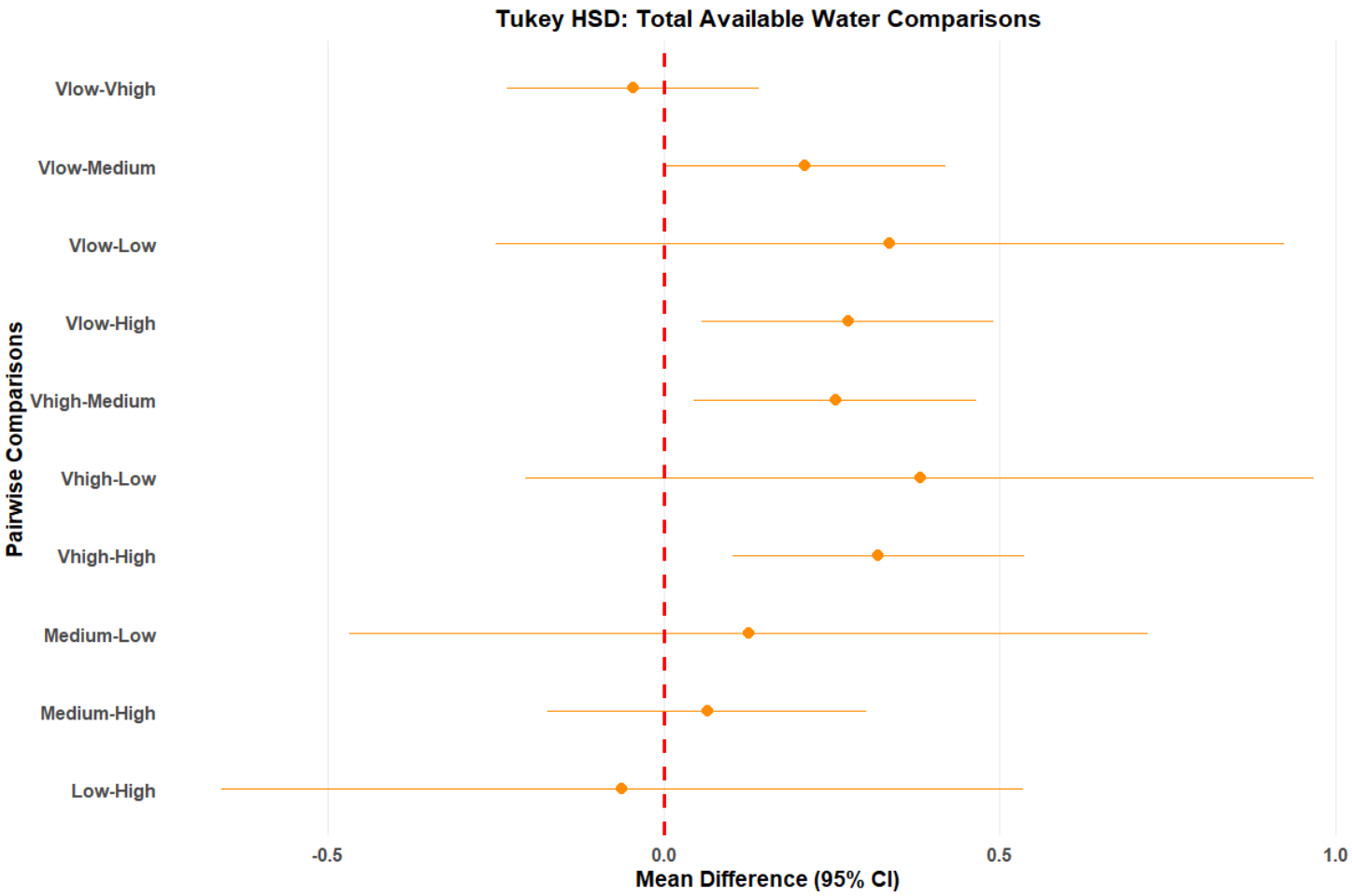


Figure 6

This graph shows the Tukey's HSD pairwise comparisons for total available water classes in relation to stand density. Each light orange point represents the mean difference between two TAW class levels, and the horizontal lines show the 95% confidence intervals (CIs). The red dashed line at zero indicates no diference between groups.