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Exploring the influence of natural physical variables on wood specific gravity in oak across a broad geographic range

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Abstract

Wood specific gravity (SG) is an essential indicator of wood quality, carbon stock, and the universality of tree functional traits influenced by both genetic and environmental factors. This study investigates the influence of natural physical variables, topography, water availability, and wind exposure on the specific gravity of the *Quercus* genus across a wide geographic range. Using a Bayesian regression model, we analyzed the relationships between SG and the selected physical variables. Our results indicate that these variables explain a significant proportion of the variation in SG among oak species. Increased topographic complexity leads to higher SG, likely due to stability and resource acquisition challenges in rugged terrain. Water availability is negatively correlated with SG, as higher precipitation or proximity to a river reduces water stress. Wind exposure was also associated with higher SG, likely due to the structural adaptations required to withstand mechanical forces. Our findings align with previous studies on SG variation in other tree species, supporting the hypothesis that environmental stressors drive increases in wood density. These results contribute to a broader understanding of how climate and landscape shape wood properties in the *Quercus* genus, a keystone component in eastern deciduous forest ecosystems in the United States.

Keywords Keystone species, Wood density, PyMC3

1 Introduction

Oak trees (*Quercus spp.*) are considered keystone species due to their critical role in maintaining ecological structure and function [33]. The acorns produced by these trees are a fundamental food resource for a wide range of animals, with up to 96 species relying on them [54]. This includes numerous bird species, such as the ruffed grouse (*Bonasa umbellus*) and northern bobwhite (*Colinus virginianus*), as well as mammals like the black bear (*Ursus americanus*) and various species of squirrels, including the gray squirrel (*Sciurus carolinensis*) and fox squirrel (*Sciurus niger*) [33]. Additionally, oak trees play a pivotal role in seed dispersal, with species like the blue jay (*Cyanocitta cristata*) actively transporting acorns. This facilitates the regeneration of oak populations

and the dispersion of other plant species [103]. A reduction in acorn production, therefore, not only limits food availability for these species but also disrupts the broader ecological processes of seed dispersal and forest regeneration [57]. The cascading effects of diminished acorn availability contribute to a decline in biodiversity, as herbaceous plants, understory species, and even larger animals that depend on oak-related ecosystems face severe habitat disturbances [9]. These interconnected relationships emphasize the role of oak trees as keystone species that sustain a diverse array of organisms and ecosystem functions.

Globally, oak remains one of the most economically and culturally important hardwood genera. In 2017, U.S. red oak exports alone exceeded 374,000 $m.^3$, with significant demand from Asian and European markets [14]. Although comprehensive global estimates of oak forest coverage are limited, regional studies highlight their ecological importance across diverse landscapes, including Mediterranean ecosystems [19] and the central Himalayas [62]. In the southeastern U.S., oaks are dominant in both volume and area within upland hardwood forests, often comprising 40–50% of trees or more in these ecosystems [37]

This region hosts a high diversity of oak species, including *Quercus alba*, *Q. falcata*, *Q. stellata*, *Q. nigra*, and *Q. laevis*, all of which play essential roles in shaping forest structure and successional dynamics [15]. Rather than emphasizing individual species, oaks as a genus function as ecological keystones due to their widespread distribution, structural dominance, and critical functional traits in temperate deciduous forests [33].

The long-term prognosis for oak trees across the United States particularly in the Southeast has raised growing concern among ecologists and forest managers. Although oaks remain ecologically and economically dominant in many upland forests, decades of fire suppression, intensive land-use change, and expanding populations of mesophytic competitors (e.g., red maple, American beech) have reduced their ability to regenerate naturally [64]. In the Southeast, these pressures are compounded by habitat fragmentation, invasive species, overbrowsing by deer, and climate-related stressors such as increasing drought frequency and temperature extremes [33, 40, 57, 77]. Despite these challenges, evidence suggests that active management strategies especially prescribed burning, selective thinning, and midstory control can restore the disturbance regimes necessary for sustaining oak-dominated systems over time [13]. Without such interventions, many oak forests risk transitioning into alternative, non-oak-dominated states.

Wood specific gravity (SG) is an essential ecological trait that affects forest resilience and ecosystem functioning. The moisture content of wood varies greatly; therefore, researchers and foresters have used different methods to determine the specific density of different wood species. Williamson and Wiemann [100] have recognized three main ways of calculating wood density and its counterpart, specific gravity. These are listed below:

1. Basic wood density and specific gravity:

$$\rho_b = \frac{m_0}{V_g} and SG_b = \frac{\rho_b}{\rho_{water}}$$

where m_0 is the oven-dry mass, V_g is the green volume, and ρ_{water} is water density.

2. Air-dry wood density and specific gravity:

$$\rho_{ad} = \frac{m_0}{V_{ad}} and SG_{ad} = \frac{\rho_{ad}}{\rho_{water}}$$

where V_{ad} is the air-dry volume at a standard moisture content (typically ~ 12%).

3. Oven-dry wood density and specific gravity:

$$\rho_{od} = \frac{m_0}{V_0} and SG_{od} = \frac{\rho_{od}}{\rho_{water}}$$

where V_0 is the oven-dry volume.

It can be seen that in all three wood densities, the numerator is the same, i.e., kiln-dried wood. It is the denominator that changes in the three different types of wood density. The advantage of SG is that it standardizes units when comparing densities and provides information on other properties of wood, such as buoyancy.

SG impacts a tree's resistance to drought, pests, mechanical stress, longevity, and successional dynamics [100]. Wood stiffness (modulus of elasticity) and strength (modulus of rupture) are positively correlated with SG [65], which are essential for oak wood used in traditional boatbuilding, interior joinery, furniture, and paneling [10].While oak is no longer widely used in industrial shipbuilding, it remains relevant in traditional boatbuilding and heritage restoration (e.g., Everso Marine Restorations, WoodenBoat School), where its high density and durability are still valued. Similarly, oak continues to be a premium material in high-end furniture markets due to its mechanical strength, aesthetic grain, and longevity [90]. SG is also a critical factor in converting forest volume data to biomass, and it is strongly related to carbon density per unit volume [29, 101]. Hence, it helps estimate ecosystem carbon storage and fluxes [53].

Variations in the SG of wood are influenced by multiple factors, including climatic conditions, geographical location, and management practices [47]. Key determinants include the geographical distribution of the species and site conditions [46]. Studies have shown that slope and altitude increase the specific gravity in Persian oak [63]. Additionally, water availability influences the stiffness, strength, and density of wood in pedunculate oak (*Quercus robur*) and other angiosperms [2, 35]. Exposure to wind also has an influence, as it affects the morphology and stability of the leaves of the white oak [94] and induces the formation of reaction wood, which is usually denser than normal wood [115].

Several studies have linked annual ring width to wood density, though this relationship varies by species and growing conditions [72, 111]. In ring-porous hardwoods like English oak (*Quercus robur*) and Sessile oak (*Quercus petraea*), wider rings often correspond to higher wood density [93, 109]. This pattern contrasts with many softwoods, where wider rings usually mean lower density [85, 112]. However, in oaks, the strength and even direction of this relationship can differ widely across species and individual trees due to genetic and environmental factors [87, 111].

Specific gravity tends to be higher under environmental stress, and the degree of stress depends on the species [41, 67]. Older trees tend to have denser wood than younger trees of the same species because they have a greater accumulation of mature wood [20, 73, 96]. Among trees of the same species and age, those that grow faster may have a lower specific gravity than those that grow more slowly due to variations in cell structure and lignin content [44, 83].

Despite its ecological importance, there is a lack of comprehensive documentation addressing the influence of natural physical variables on the specific gravity of *Quercus* genus [3, 50, 51, 68, 86]. Most existing studies are limited to case studies focusing on specific species rather than examining a broad range of *Quercus* genus [39, 45, 52, 66, 95, 97]. Moreover, there is limited documentation on the general effects of natural physical variables on the specific gravity of oaks in the USA. However, this information could provide insights into the conditions that optimize growth and specific gravity in the *Quercus* genus and may also help infer how these trees might respond to environmental changes.

The objective of this study is to investigate how natural physical variables, specifically topography, water availability, and wind exposure, affect specific gravity in the *Quercus* genus across a wide geographic range in the southeastern region of the United States. Specifically, we hypothesize that H1: Specific gravity in the genus *Quercus* is influenced by natural physical variables such as topography complexity, water availability, and wind exposure. H2: As the natural physical environment becomes more hostile (e.g., complex topography, limited water, and stronger winds), the specific gravity of the *Quercus* genus will tend to increase. Understanding these influences is essential for assessing oak trees' resistance to environmental stresses and their role in forest ecosystem dynamics, succession, and longevity.

2 Materials and methods

Oak specific gravity data between 1962 and 2013 were obtained from the open repository LegacyTreeData, with 1981 being the most common year. The spatial boundaries selected are the eastern United States, where oaks have been widely distributed. (Fig. 1A). The repository is maintained by Virginia Tech and the Forest Inventory and Analysis (FIA) program. It contains a comprehensive collection of individual tree measurements, including volume, mass, and physical properties. As of May 1, 2016, the collection held records from over 250,000 trees, with detailed stem measurements carried out by private companies, government agencies, and university researchers over more than 100 years. These records include data from felled trees, documenting stem taper, volume, and mass (including wood, bark, branches, and foliage) for over 20,000 trees. The repository also compiles study plans and field notes whenever available. There is no evidence in the database of the type of management each plot presented.

Due to the varied temporal range, we chose to take explanatory variables (Fig. 1 B-E) that did not vary significantly over time. The database contained records for 33 oak species. Initially, it included 5,485 records but was reduced to 227 records containing specific gravity values (Fig. 1A, supplemental material).

According to the glossary of the database [75], SG was calculated from discs of specific sections of the studied tree, in our case the stem, as the oven-dry (105 °C) mass per unit of green volume of wood and/or bark, expressed as a proportion of the density of water. Mathematically, it is defined as:

$$\mathrm{SG} = \frac{\text{Oven - dry mass}}{\text{Green volume} \cdot \text{Density of water}}$$

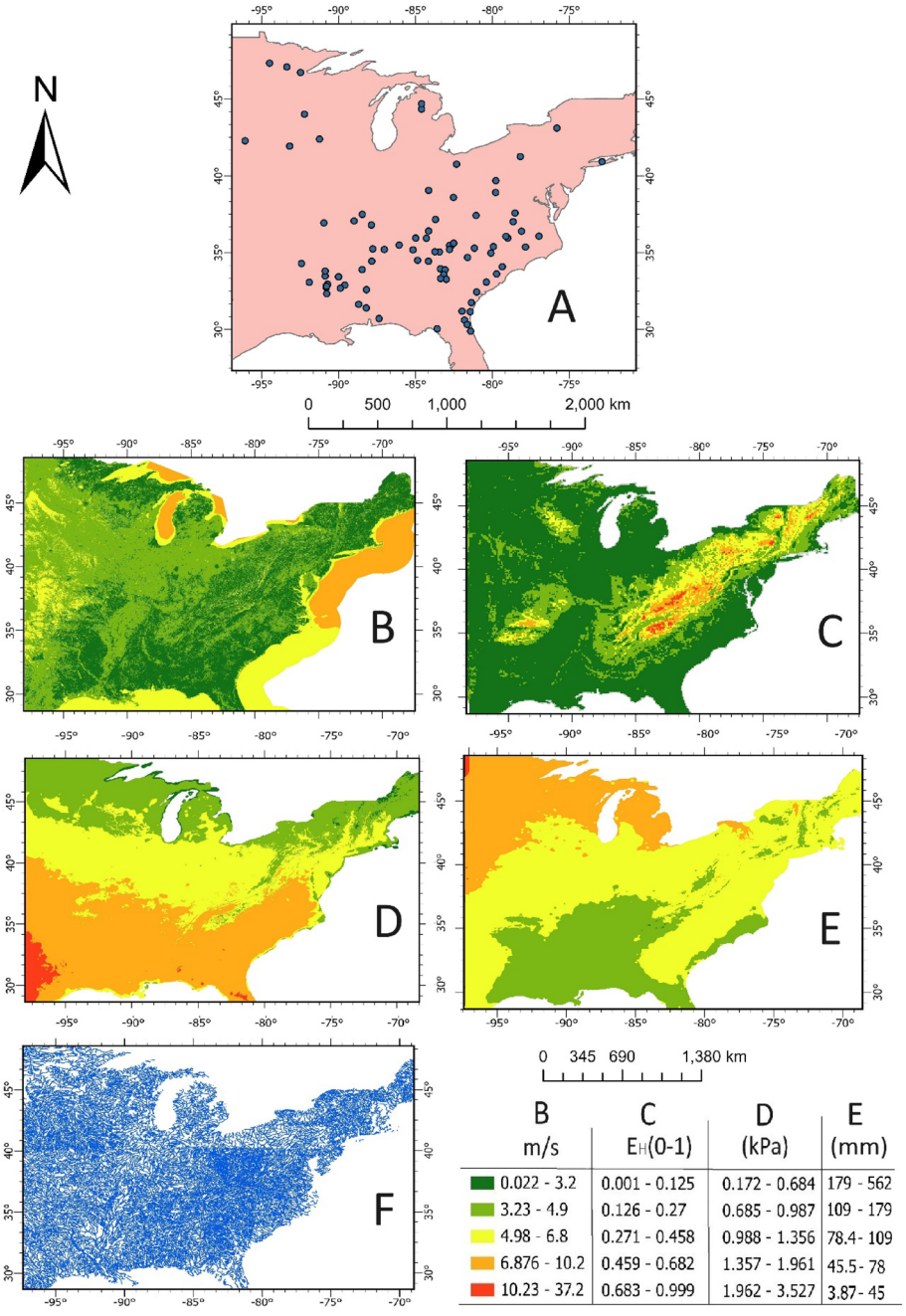

Fig. 1 **A**: Distribution of wood specific gravity points and B to F independent variables. **B** Wind speed at 10 m [23], **C** Topography diversity [91], **D** Mean vapor pressure deficit [22], **E** Mean precipitation [22], **F** Hydrographic network [61]

These records were linked to their respective coordinates by combining the variables AUTHOR, LOC, and SPCD, which connected the LEGACY TREE table to the LEGACY LOCATION table.

We employed the aggregation method of averages to address the issue of multiple records within the same location. This approach was necessary because the coordinates provided by the database represent a working polygon rather than individual tree points. Consequently, this grouping process does not significantly impact the analysis, as even disaggregated data at the individual tree level would be represented as a point

due to cartographic selection and generalization principles, leaving a total of 227 records (Fig. 1A) with an average of 10 records per aggregate, with a minimum of 1 and a maximum of 71. With the filtered records and their corresponding coordinates, we extracted the values of various natural physical variables (Fig. 1B-E, Table 1) for subsequent analysis. Mean vapor pressure deficit, precipitation, and proximity to rivers were included in the study due to the influence of climate documented in wood density worldwide [17]. Topography was included because of its demonstrated role in explaining tree-specific gravity at a global scale [104]. Wind speed was considered due to its influence on tree mechanics, as the specific gravity of wood is linked to its mechanical properties. This connection affects the tree's ability to withstand external forces, such as wind flow and gravity, as well as internal factors like biomass distribution and crown structure [32]

2.1 Data analysis

The "st_distance" function of the R "sf" package was used to calculate the closest Cartesian distance between each point and the nearest river [69]. To assess the influence of each variable on the response variable, a Bayesian linear model (Eq. 1) was used to avoid relying on p-values to determine the significance of effects. This approach tests the hypothesis of whether the impact of each variable is genuine. This approach is especially relevant given the known effects of the natural physical variables on plant physiology. In addition, the Bayesian model mitigates the risk of false positives by avoiding value hacking that can arise when handling large volumes of data.

Weakly informative priors were used to provide light regularization and improve model stability while still allowing the data to dominate posterior inference. A Normal prior with mean 0 and standard deviation 10 was assigned to all regression coefficients (Eq. 2), which offers a broad but finite parameter space and prevents extreme estimates when predictors span heterogeneous environmental gradients. The residual standard deviation σ was assigned a Half Normal prior with scale 100 (Eq. 3) to accommodate potentially large unexplained variability across the wide geographic and ecological range represented in the dataset. These choices avoid improper or overly diffuse priors, which can lead to unstable posteriors in sparse or noisy ecological data, while remaining sufficiently weak to avoid imposing strong prior structure. The model was implemented using the PyMC3 library in Python [80], with a Markov Chain Monte Carlo (MCMC) sampling method, 1000 samples, and 10 parallel chains.

$$y_i \sim N\left(X_i\beta, \sigma^2\right) \tag{1}$$

Table 1 Summary statistics of the input variables

	Mean	Std	Min	25%	50%	75%	Max
Wood specific gravity	0.60	0.03	0.51	0.57	0.61	0.63	0.70
Mean water vapor pressure (hPa)	14.26	2.70	7.84	12.29	15.31	16.31	18.27
Mean precipitation (mm)	110.75	17.45	55.65	100.56	110.99	120.71	176.65
Topographic diversity (0–1)	0.17	0.18	0.00	0.06	0.11	0.20	0.77
Average wind speed at 10 m ($m{\cdot}s^{-1}$)	2.98	0.91	1.11	2.35	2.78	3.44	5.74
Distances from the river (km)	2813	2785	92	964	2111	4007	16,921

where:

- y_i is the observed target SG value for data point i.
- X_i is the predictor variable for data point i.
- β is the vector of regression coefficients.
- σ^2 is the variance of the error term.

We modeled each observed target value y_i as being generated from a normal (Gaussian Eqs. 2 and 3) distribution with mean $X_i\beta$ (the predicted value based on the predictors) and variance σ^2. Introducing the prior distributions for β and σ^2 we have:

$$\beta \sim N\left(\mu_0, \Sigma_0\right) \tag{2}$$

$$\sigma \sim Half_N\left(\tau\right) \tag{3}$$

where:

- μ_0 and Σ_0 are the mean vector and covariance matrix of the prior distribution for β.
- τ is the scale parameter of the HalfNormal prior for the standard deviation σ.

3 Result and discussion

We fitted the Bayesian regression model as described above, and it did not present any convergence problems with the data provided. Our results demonstrated that the natural physical variables we considered in this study explained 0.36% of the variation in the specific gravity of the oak genus (Table 2). Previous studies have shown that, for a given tree, internal stand characteristics, such as the natural conditions in which the tree is located, can explain between 4 and 36% of the variation. In comparison, tree age can explain between 17 and 24% [28]. Additionally, 15% of the variation in SG can be explained by the tree's diameter at breast height [52], and ~ 90% can be explained by the compressive strength parallel to the grain [4]. This indicator is closely related ($R^2 = 0.72$) to the angle of the microfibers, which varies from tree to tree [110].

Our results suggest that natural physical variables have a similar influence on specific gravity as population (stand), age, and shape (DBH, height) variables, except for physiological variables with much greater explanatory power. Furthermore, it is observed that as environmental conditions become more adverse, the specific gravity of oaks increases. This trend aligns with findings from other studies in both tropical and temperate regions, where specific gravity or its proxy indicators exhibit similar patterns [18, 31, 60, 71, 102]. It is important to note that our data has a more tremendous sampling effort in the southeastern region, so our results are more reliable (Fig. 2).

Table 2 Point Estimates and Uncertainty Indicators for Bayesian Regression Model Parameters

Variables and good-fit indicators	Point estimates (mean)	Standard deviation	Credible interval	
Sigma	**0.03191**	**0.00153**	**Min**	**Max**
Distances from the near river (km)	0.00164	0.00080	0.0001*	0.003*
Average wind speed at 10 m ($m \cdot s^{-1}$)	0.005	0.00245	0.0002*	0.010*
Topographic diversity (0–1)	0.06295	0.01546	0.033*	0.09*
Mean precipitation (mm)	−0.0003	−0.00015	−0.0005#	−0.00005#
Mean water vapor pressure (hPa)	0.00295	0.00106	0.0009*	0.005*
Intercept	0.56756	0.02152	0.525381*	0.609739*
Bayesian R^2	0.36 +			

* Alpha 95%, # 90%, +good of fitness test in supplemental material

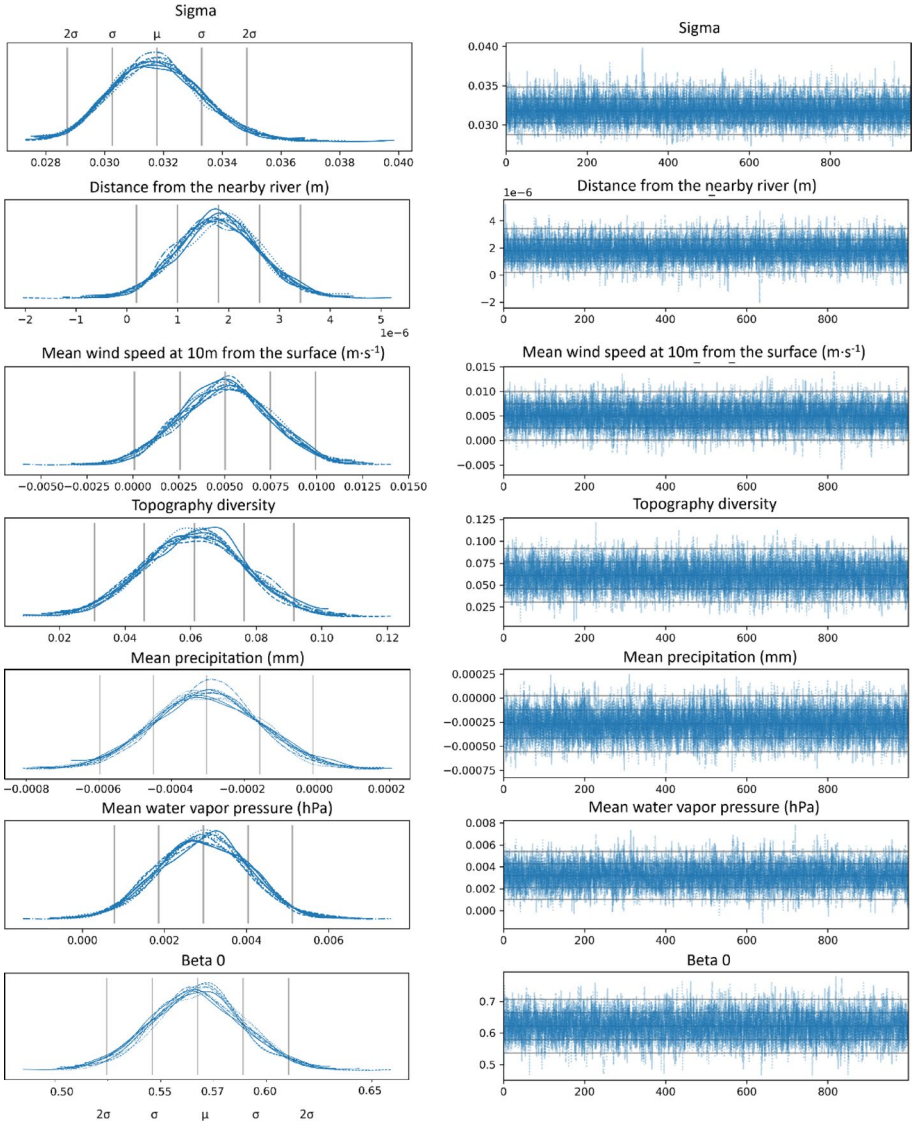

Fig. 2 Posterior distribution of regression coefficients

3.1 Topography

With a 95% credible interval (0.033–0.09), we can state that an increase in topographic diversity (indicating greater complexity) results in a corresponding increase in specific gravity of approximately 0.06 units. As the terrain gets steeper, life development conditions become more complex. According to de Castilho et al. [24], this effect is more pronounced in dominant than in understory trees. Two factors explain this: first, smaller trees have lower resource needs in hillside environments, but as they grow, their resource demands increase, intensifying environmental pressure. Second, mature plants require greater stability, particularly in rugged terrain, as steeper slopes tend to have thinner soils due to the geomorphic potential of the relief to generate runoff.

According to our results, young oaks growing on slopes may initially exhibit a wood density like that of those on flat ground, assuming all other environmental factors remain constant except for the slope. However, as they grow, they begin to experience the mechanical stress imposed by the incline, which leads to an increase in wood density

due to the need for additional structural support. Given that red oaks have a higher growth rate (moderate: 30–60 cm per year) compared to white oaks (less than 30 cm per year) [58, 79, 82], it is expected that the difference in SG between the two species will be smaller in hillside environments than on flat terrain at the same age. As the complexity of the terrain increases, environmental demands become more pronounced, leading to a corresponding rise in SG [63, 105].

3.2 Water

We observe that for every millimeter of rain, there is an average decrease of approximately 0.0003 units in the specific gravity of the wood, with a credible interval of 90% between -0.0001 and -0.00055 units (Table 2 and Fig. 1). Rainfall influences wood density by affecting tree growth rates and xylem structure [2, 7, 78]. An increase in rainfall reduces water stress and promotes greater cambial activity [8], translating into wider growth rings and a higher proportion of earlywood [31]. This early wood is composed of larger vessels and thinner cell walls, which facilitate water transport but decrease the overall density of the wood [35].

The 90% confidence in this relationship can be attributed to the efficiency of the *Quercus* genus in stomatal closure under mild water stress [6, 48, 49]. This mechanism increases resistance to the diffusion of CO_2 towards the leaf's interior and reduces transpiration, limiting water loss in comparison with other tree species.

On the other hand, an increase of 1 hPa in vapor pressure deficit is associated with an increase of 0.003 units in the specific gravity of wood (95% credibility interval: 0.0009—0.005). Vapor pressure deficit is a key indicator of the atmosphere's evaporative demand and has been linked to restrictions in photosynthesis due to the reduction of stomatal conductance [56, 59, 81].

The decrease in stomatal conductance reduces transpiration and restricts the flow of water in the xylem [88], which favors the formation of porous or smaller fibers with thicker cell walls [55, 113]. This contributes to increased SG, as it increases the proportion of material in the cell wall concerning the luminal area of the vessels [105]. In *Quercus*, this process is related to the efficiency of water transport and the balance between leaf area and sapwood allocation in wood formation [78].

Finally, a high and sustained mean vapor pressure deficit can reduce CO_2 absorption, which limits the photosynthetic rate [56, 59, 81]. With less carbon available, trees adjust their growth, prioritizing the formation of cellular structures over rapid expansion [70, 108]. Consequently, a slower growth rate, conditioned by carbon limitation, can sometimes generate an increase in the SG [21].

3.3 Distances

With a 95% credible interval, it can be stated that the specific gravity of wood increases by $0.18{\cdot}10^{-2}$ units (0.0001- 0.003) for every meter we move away from the river. This may be due to two reasons; firstly, how well adapted the stomata of oak trees are to tolerate periods of drought [25, 107]. Secondly, in undisturbed forests, thermo-aquatic conditions are stable, which means that changes are not as abrupt as in disturbed areas [74].

Rivers not only provide moisture but also act as a vital source of nutrients for the soil. This occurs through direct flooding [36] and the indirect transportation of nutrients from higher areas via runoff, which tends to accumulate in lower-lying regions [30].

Living close to a water body has its benefits, such as receiving fertilization, irrigation, and a water source during drought. According to Howard et al. [38] and Schreffler and Sharpe [84], fertilization and irrigation positively and significantly affect biomass and growth rates in oak trees. However, Svensson et al., [89] did not find such an effect in *Quercus robur* and *Quercus petraea*, probably due to the high background nutrient levels from past agricultural use, which leads to nutrient saturation. In addition, the deep-rooting habit of the trees allowed access to deep soil moisture, which reduced the effect of the irrigation provided compared to the control.

3.4 Wind

The response of trees to wind generally consists of developing a stronger wood that allows structural adaptations to withstand mechanical forces [92]. Our research is consistent with this approach because it was found that specific gravity in oaks increased by 0.005 (0.0002—0.010) units for each increase ($m{\cdot}s^{-1}$) in wind speed. While regional wind speed data at 10 m may not apply uniformly to individual trees on the surface due to local variations, it still provides valuable information. These variations in local conditions can influence how wind interacts with individual trees. On average, areas with higher wind speeds measured at 10 m tend also to experience higher wind speeds at the surface. This pattern is especially noticeable compared to regions with lower wind speeds at this height [114]. Even if local conditions, such as the location of trees in a grove or the presence of barriers, affect the distribution of surface wind speed, the general trend holds.

The way trees respond to wind loads varies with age and structural development. Young trees primarily avoid excessive mechanical stress through flexibility, often relying on a more pliable composition. In contrast, mature trees endure wind loads through structural reinforcement, developing wood with higher bending stiffness [27]. This aligns with our findings, as increased wood density in response to wind may reflect a strengthening mechanism in older trees rather than mere flexibility.

Wind exposure can also induce the formation of reaction wood, which is typically denser than normal wood [115]. Additionally, environmental stressors can influence biomass allocation, leading to structural modifications that enhance wood density under specific conditions [98, 99].

However, not all studies support a direct correlation between mechanical stress and increased wood density. Ashby et al. [5] found that in sweetgum (*Liquidambar*), wood density decreased under greater mechanical stress. While this contrasts with our results in oaks, species-specific differences in growth strategies could explain these discrepancies. Similarly, Woodcock and Shier [101] investigated whether treetops exhibited higher radial growth rates but found no significant effect. However, they did observe that canopy species consistently had higher specific gravity than non-canopy species. Their study included one oak species, but none of the sampled oaks were from the canopy, making it difficult to directly compare their results with ours. This suggests that while wood density may increase in response to wind, the relationship is not uniform and may depend on additional anatomical and ecological factors.

3.5 Ecological context

The ecology of the *Quercus* genus is well documented, especially regarding its adaptability to diverse environmental conditions and its functional role in temperate forest dynamics. Oaks are often classified as disturbance-adapted, light-demanding species that thrive in environments shaped by fire, drought, or wind exposure [1, 33]. Their deep rooting systems, efficient stomatal regulation, and capacity to produce dense, structurally resilient wood allow them to persist in xeric sites and on complex terrain [48, 64]. The positive associations observed in this study between specific gravity and topographic complexity, distance from water sources, and wind exposure are consistent with these ecological traits, reflecting a functional shift toward increased mechanical and hydraulic resistance under stressful conditions. These patterns also suggest that *Quercus* species may respond to environmental gradients not only through morphological plasticity but also through structural wood properties, which can serve as long-term records of environmental filtering and adaptation [98, 99]. Incorporating this understanding strengthens the ecological interpretation of our results and aligns with prior findings that position oaks as keystone species in landscapes undergoing environmental change.

3.6 Sample size limitation

The small sample size, limited to the southeastern United States, affects the reliability of the results because it reduces the representativeness and generalizability of the findings. With only 227 records of specific gravity values from this specific region, there is a limited ability to capture the full variability of genus *Quercus* across the eastern United States or other regions where oaks are also present. This geographical constraint may result in findings that reflect local environmental conditions, species characteristics, or forest management practices rather than broader patterns [11]. Additionally, while the explanatory variables were chosen to minimize temporal variation, the restricted spatial extent still limits the ability to account for regional differences, potentially leading to biased conclusions when applied beyond the study area.

3.7 Management implication

The results of this study have significant implications for forest management, particularly for improving forest health, optimizing carbon sequestration, and increasing timber production. Although natural physical variables account for only 0.36% of the variation in oak specific gravity, the positive correlation between specific gravity and challenging environmental conditions suggests that stress influences wood formation in complex ways. For example, water stress can lead to irregular heartwood shapes, such as notched cores at certain heights in oak trees [34]. High specific gravity wood, particularly from small-diameter trees in harsh environments, is more prone to brittleness, splitting, and warping due to internal stresses [16, 43]. The use of tension pre-harvesting techniques could help reduce imbalances and improve timber quality [106]. On the other hand, Divos and Tanaka [26] found in pines that the increase in tensile strength decreases the number of knots. Given that topography significantly influences factors such as light exposure, runoff, wind, and soil deposition, incorporating topographic data into planting and harvesting strategies can optimize timber quality. Additionally, bottomland hardwoods play a crucial role in watershed management by stabilizing floodwaters,

filtering nutrients, and reducing sediment loads. This creates a self-sustaining system that enhances soil quality and long-term forest productivity [12].

Topography, the most influential variable, affects light exposure, runoff, wind, and soil deposition. Thus, incorporating topographic data can optimize planting and harvesting strategies, especially in areas of complex relief that produce higher specific gravity timber. Bottomland hardwoods play a vital role in watershed management by storing floodwater and reducing flood risks. They also improve water quality through nutrient filtering, sediment reduction, and organic waste processing [76]. These wetlands create a self-sustaining system where vegetation stabilizes water flow, preventing rapid mineralization of organic matter by maintaining a reducing regime [12]. This process allows organic matter to accumulate gradually, enriching the soil and detritus layer [42]. As a result, this organic buildup enhances soil quality and traps sediment from upper slopes. This process increases soil thickness and promotes long-term forest productivity and stability.

4 Conclusions

This study confirms that natural physical variables, such as topography, water availability, and exposure to wind, significantly influence the specific gravity of *Quercus* species. Our Bayesian regression model demonstrates that these environmental factors explain a considerable proportion of specific gravity variability ($R^2 = 0.36$). This effect is comparable to the influence of stand characteristics, tree age, and morphology.

In accordance with H1, our findings indicate that topography, water availability, and wind exposure play a key role in the formation of specific gravity in *Quercus*. Furthermore, in support of H2, the results support the hypothesis that an increase in environmental adversity leads to higher specific gravity values. Specifically, more complex terrain is associated with higher specific gravity, due to the need for structural reinforcement in trees growing on steep slopes with limited resources. Higher precipitation correlates with lower specific gravity values, as increased water availability encourages wider growth rings with lower wood density. In contrast, a higher vapor pressure deficit is associated with increased specific gravity. This may be due to lower stomatal conductance, which favors the formation of denser wood. As the distance from rivers increases, so does specific gravity, due to lower soil moisture and nutrient availability. Specific gravity increases with wind speed, suggesting that trees develop stronger wood to resist mechanical stress.

These findings are consistent with previous research on the response of specific gravity and wood density to environmental conditions in different forest types. However, the spatial distribution of our dataset suggests that the conclusions are more robust for the southeastern regions, where sampling was more intensive. Looking ahead, it is recommended that the geographical coverage be expanded. Additionally, incorporating physiological and genetic factors will help refine the understanding of the variability of specific gravity in *Quercus*. These results have valuable implications for forest management and timber production. The selection of optimal locations, considering topography, water availability, and wind exposure, can inform forest management strategies to optimize specific gravity values.

In terms of practical applications for timber production: (1)Planting species on moderately sloping land can favor higher specific gravity values than flat areas or areas with

extreme slopes. (2) Areas with high rainfall and desirable water availability may be more suitable for species with lower specific gravity. And (3) Regions with strong winds, especially with frequent gusts, can benefit from selecting species with naturally more resistant wood structures. By integrating these environmental factors into forestry planning, timber managers and producers can improve the quality and value of their products.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Author contributions

Author Contributions: Conceptualization: José Miguel Febles Díaz, Emma Schopen, Zhaofei Fan Methodology: José Miguel Febles Díaz, Zhaofei Fan Writing - Original Draft Preparation: Favour Onyido, José Miguel Febles Díaz, Emma Schopen Writing - Review & Editing: Emma Schopen, Zhaofei Fan, Haomin Huang, Favour Onyido, José Miguel Febles Díaz Data Curation: Haomin Huang, Emma Schopen Discussion: Emma Schopen, Martin A. Spetich.

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Data availability

All data can be found in LegacyTreeData [https://charcoal2.cnre.vt.edu/TreeData/biomass_tools/biomass-tools/web/] .

Declarations

Ethics approval and consent to participate

The authors declare no conflict of interest. All ideas expressed in this document do not necessarily represent the views of the organizations/institutions to which the authors are affiliated. As this study does not involve human or animal subjects or biological material, the relevant ethical declarations (e.g., Consent to Participate, Consent to Publish) do not apply.

Competing interests

The authors declare no competing interests.

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