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SPECIAL ISSUE

Evidence for tree-induced water stress and root system reorientation in grapevines

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ABSTRACT

Agroforestry in vineyards has been proposed as a strategy to buffer climatic stress, potentially moderating microclimate and enhancing water availability for the vines. However, the net effects of tree proximity on grapevine water status remain unclear due to potential competition for water and nutrients. This study aimed to investigate the effects of tree proximity on grapevine growth and physiology.

To do so, measurements were conducted on three vineyard sites in Geisenheim, Germany, where grapevines were grown in close proximity to tree rows. Predawn water potential and stomatal conductance, grape composition, and single berry weight were assessed on these sites as a function of distance to the tree row. In one site, where *Vitis vinifera* L. 'Riesling' was grown north of a row of field maples (*Acer campestre*), root systems of six vines were excavated and 3D-digitised in situ, soil was sampled for organic carbon and nitrogen, and fresh and dry biomass were determined.

Results showed that vines closer to the trees exhibited lower stomatal conductance and more negative pre-dawn leaf water potentials, and lower berry weight. Root architecture analysis revealed a pronounced tendency for roots to grow away from the trees, with limited root proliferation toward the tree row, indicating growth limitation due to competition for water.

These findings suggest that the nature of vine × tree interactions under the conditions of our study is competitive rather than facilitative, especially with regard to the acquisition of water. This study provides a foundation for further research on such interactions in vineyard agroforestry, offering insights into root spatial dynamics and water competition under varying environmental conditions.

KEYWORDS: Terclim 2026, agroforestry, vitiforestry, tree–vine interaction, water balance, root architecture

INTRODUCTION

Agroforestry is emerging as a promising adaptation strategy to buffer climatic challenges (Jose, 2009). Trees in or around vineyards could serve as a potential approach to modulate the microclimate. Their canopy provides partial shade that reduces heat and radiative stress, as well as wind, potentially helping prevent grape overheating and sunburn (Dupraz *et al.*, 2018; Norton, 1988).

Beyond temperature regulation, vineyard agroforestry is associated with hydrological benefits critical under climate change. Deep-rooting trees can improve the water status of vines by increasing soil water infiltration and drawing up deep soil moisture (via a potential hydraulic lift) that becomes available to shallower vine roots as occurs between trees and understory plants (Hawkins *et al.*, 2009; Ludwig *et al.*, 2003; Neumann & Cardon, 2012). This can offset drought stress on vines even when trees and vines ostensibly compete for water (Smart *et al.*, 2005)such water redistribution has been demonstrated in two fundamental ways, either lifting water from deep edaphic sources to dry surface soils or redistributing water downward (reverse flow. Of particular relevance to this study is hydraulic lift in maples. Emerman and Dawson (1996) demonstrated that, under certain circumstances, mature sugar maples (*Acer saccharum*) transport up to 102 L of water upward each night. This places sugar maple among the species exhibiting the highest rates of upward hydraulic lift reported to date (Neumann & Cardon, 2012).

At the same time, it remains unclear whether and under which conditions the advantages of vitiforestry outweigh the disadvantages. There is competition between trees and grapevines for water, nitrogen, and other nutrients (Lang *et al.*, 2019; Lehr *et al.*, 2025). Competition for water between grapevines and cover crops has been widely documented, with evidence indicating that it can induce water stress of varying intensity. The magnitude of this competition depends on factors such as cover crop spatial arrangement (inter-row *vs* under-vine), life cycle (annual *vs* perennial), and the grapevine's root plasticity. Temporal dynamics are also critical: early-season water uptake by cover crops may deplete soil moisture before grapevine budbreak, whereas winter cover can reduce competition by enhancing soil water replenishment and limiting runoff compared to bare soil (Celette *et al.*, 2008; Celette & Gary, 2013). Similarly, trees may impose water stress in neighbouring plants due to their high water demand (Demir *et al.*, 2024). Moreover, competition with other crops can reduce the availability of nitrogen and other nutrients, which in turn may limit both vegetative and reproductive growth of grapevines (Wheeler & Pickering, 2005). Ultimately, competition for light in tree-crop systems can be a major driver of altered growth patterns and may even lead to a reduction in yield (Friday & Fownes, 2002; Zamora *et al.*, 2009). In particular, the shading effect on grapevines can have manifold impacts. Shading reduces photosynthetic activity, which in turn leads to lower biomass accumulation, reduced yield, decreased total soluble solids, and increased titratable acidity in grapevines (Cartechini & Palliotti, 1995). To mitigate competition, trees may employ allelopathic mechanisms by releasing root exudates that can inhibit the root growth of other species. Allelopathic behaviour has also been documented in maple species (Tubbs, 1973; Zhang *et al.*, 2007).

The underlying mechanisms mediating vine × tree interactions remain poorly resolved under field conditions. In particular, an open question is how grapevine root systems develop in the presence of trees. Root systems govern when and where plants can access water and nutrients (Lynch, 2022; Wasson *et al.*, 2012). They influence the growth and development of the scion and become especially important under drought stress, where a well-balanced relationship between shoot vigour and root capacity is vital to ensure that water uptake adequately meets transpirational needs (Alsina *et al.*, 2011; Zhang *et al.*, 2016).

It remains unclear whether vine roots tend to grow toward tree roots (for instance, following moisture gradients or exploiting tree-root-created macropores in the soil), or conversely grow away from trees (perhaps avoiding competition zones for water and nutrients), or if their rooting pattern is largely unaffected by nearby trees. This lack of knowledge extends to the overall spatial partitioning of soil resources between vines and trees (Favor & Udawatta, 2021).

This study aimed to elucidate how grapevines respond to the presence of nearby trees. In particular, it examined whether tree-vine interactions lead to beneficial resource sharing (*e.g.*, via hydraulic lift) or to competitive stress from water and/or nutrient competition, potentially causing root system avoidance of tree root zones and thereby providing insights for the design and management of agroforestry systems. Specifically, the objectives were to (1) assess whether grapevines growing near trees exhibit altered aboveground and belowground growth compared to vines farther away, (2) disentangle the extent to which observed grapevine growth differences are attributable to altered radiation regimes, nutrient availability, or vine water relations, and (3) determine the extent to which vine responses to tree influence reflect competitive interactions or avoidance. To this end, the water relations and growth of grapevines growing were examined as a function of proximity to mature trees across three vineyards in Geisenheim, Germany. The vine root system was analysed through field excavations and *in situ* 3D digitisation in one of the three vineyards to assess root system adaptations to tree-induced water stress and growth differences.

MATERIALS AND METHODS

1. Experimental sites

Experiments were conducted in three vineyards in Geisenheim, Germany, in 2025 (Figure 1). All three vineyards were situated on comparable and homogeneous calcareous sandy loam soils, with a plant-available water capacity of 300–400 mm at sites 1 and 3 and 200–300 mm at

site 2 (HLNUG, 2026). Across all three sites, the vines were trained to vertical shoot positioning (VSP) and cane-pruned using a semi-arched cane in east-west-oriented rows, with a bud load of 10 per vine. A tree row was located on the south-southeastern side, at a distance of 4 m from the first vine row. The investigated vines were positioned in the middle of the row, at a minimum distance of 4 m from the western end post. Specifically, the vines were situated in the first, second, and eighth rows, corresponding to distances of 4 m, 6 m, and 18 m from the tree row, respectively. All selected vines were healthy, showed uniform vigour, and had a comparable spatial position relative to the tree row.

Site 1 (49°59'30.4" N, 7°58'13.1" E) was bordered on its south-southeastern side by a row of three field maples (*Acer campestre*, canopy height: 12 m, canopy depth: 7 m). The vineyard was planted in 1977 with *Vitis vinifera* L. 'Riesling' grafted onto Teleki 5C (*V. berlandieri* × *V. riparia)* rootstock (vine and row spacing of 0.85 m and 2 m, respectively).

At site 2 (49°59'19.8" N, 7°57'09.3" E), birch trees (*Betula pendula*, canopy height: 12 m, canopy depth: 6 m) were located on the south-southeastern side. The vineyard was planted in 1986 with *Vitis vinifera* L. 'Riesling' grafted on SO4 (*V. berlandieri* × *V. riparia*) (vine and row spacing of 1 m and 2 m, respectively).

At the third site (49°59'16.3" N, 7°57'17.8" E), London planes (*Platanus* × *hispanica*, canopy height: 9 m, canopy depth: 6 m) were planted on the south-southeastern side. The vineyard was planted in 2022 with *Vitis vinifera* L. 'Souvignier gris' grafted on SO4 (*V. berlandieri* × *V. riparia*) (vine and row spacing of 1 m and 2 m, respectively).

2. Physiological measurements

At the three sites, indicators of vine water status and drought stress were assessed, including leaf water potential, stomatal conductance, shoot growth, berry composition, and fresh and dry biomass.

The vine water status and physiological performance were assessed between June and August 2025. The different phenological stages were determined according to Coombe (1995). The data were used to identify differences between grapevines growing in close proximity to trees (4 m, 6 m) and those located in the centre of the vineyard (18 m).

2.1. Water status

Predawn water potential was measured on mature, undamaged leaves using a pressure chamber (Soilmoisture Corp., Santa Barbara, CA, USA) following the protocol of Turner (1988) on 7 July 2025 (modified E-L 33) after a period of low precipitation (< 13 mm during the last 23 days). For each vineyard (sites 1–3), three distance treatments (4 m, 6 m, and 18 m from the tree row) were considered. At each distance, three vines were selected as described in section 'Experimental sites'. From each vine, one leaf was sampled at a position 30–60 cm above the cane, resulting in a total of 27 leaves.

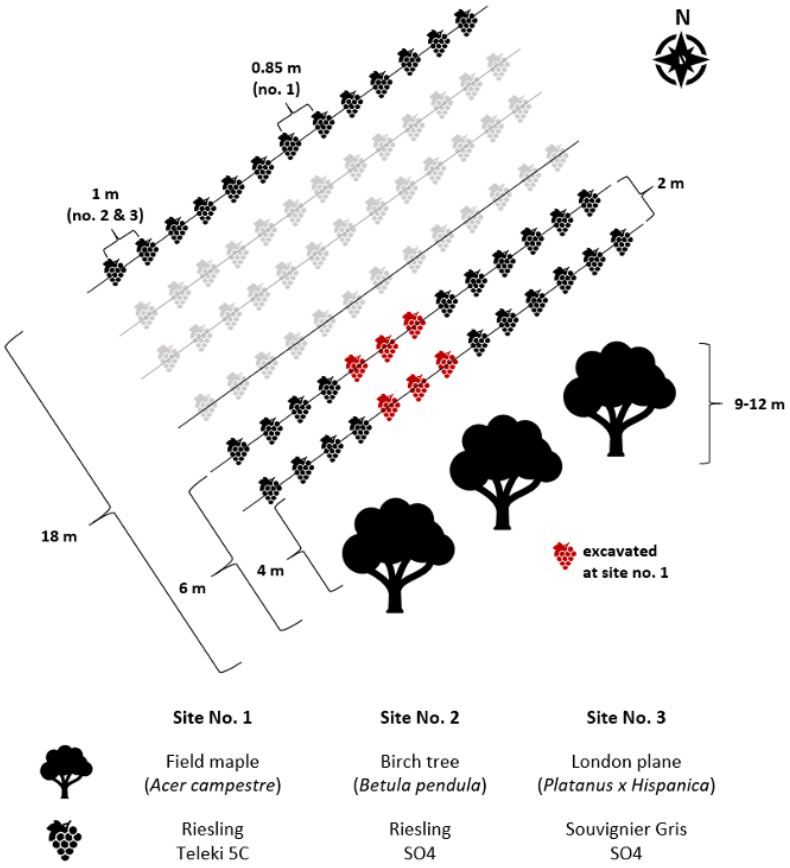


FIGURE 1. Schematic representation of the experimental site and sampling layout.

Stomatal conductance measurements (g_s) were carried out on mature fully expanded leaves using a porometer (Li-Cor LI-600, Li-Cor Biosciences, Lincoln, NE, USA) on 10 July 2025 (modified E-L 33), a high solar irradiation day, at six time points between 8:00 a.m. and 8:00 p.m. At each time point, nine sun-oriented leaves were measured at each distance in each vineyard (total n = 486 leaves); these leaves were located 30–60 cm above the cane. To represent the diurnal course, measurements were grouped into discrete time points by assigning all values to the respective measurement start time. Measurement times varied by up to approximately 40 minutes.

2.2. Soil analysis

Undisturbed soil samples were collected from the vertical walls of soil pits (2 m deep, 0.5 m wide) excavated for root system analysis on 15 December 2025. Monoliths of 10 × 10 cm surface were taken at distances of 3 and 7 m from the tree row at three depths (0–30 cm, 30–60 cm, 60–90 cm). Soil was dried, ground, and sieved to 2 mm to remove coarse soil particles and roots. Fine soil (< 2 mm) was analysed for carbon and nitrogen content (total n = 18 soil samples). The removed roots were ground with a ball mill and added back to the sieved soil sample, then the analysis was repeated to capture the effect of the root fraction on soil C and N content. Total soil carbon, total organic carbon and total nitrogen in the soil samples were determined as in Di Giacinto *et al.* (2020).

2.3. Vegetative growth and berry composition

The Nitrogen Balance Index (NBI) and the chlorophyll index of mature primary leaves were measured on the adaxial and abaxial side using a Dualex Scientific portable optical leaf clip meter (Force A, Orsay, France) on 4 August 2025 (Site 1) and 7 August 2025 (Site 2-3, modified E-L 35), as the sampling date was close to veraison. In each vineyard, nine sun-oriented leaves were selected at each distance (total n = 81 leaves); these leaves were located 30–60 cm above the cane.

Shoot growth was measured on 25 June 2025 (modified E-L 31) using a measuring tape, immediately prior to canopy trimming. In each vineyard for each distance, three grapevines were selected, and on each vine, the first, third, and sixth shoots counted from the trunk were chosen (total n = 81 shoots).

Representative berry samples (3 × 100 berries per distance at each of the three sites, total n = 27 berry samples) were collected and weighed on 29 August 2025 (modified E-L 37), as the sampling date was close to harvest and all berries were still intact and healthy. Juice extraction was performed using a sampling press at 1 bar (Longarone 85, QS System GmbH, Norderstedt, Germany). Berry composition was analysed by Fourier-transform Infrared spectroscopy (FTIR) using a FT2 Winescan (FOSS, Hillerød, Denmark), including measurements of total soluble solids (TSS), reducing sugars, total acidity, malic acid and tartaric acid. N-OPA was determined according to (Dukes & Butzke, 1998).

3. Root system excavation, 3D-digitisation, and quantification of fresh and dry biomass

At site 1, six grapevines were excavated within plots of 1.70 × 0.85 m (according to the inter-vine distance) to a depth of up to 1.20 m between August and October 2025. Three vines were located adjacent to the tree row (4 m from the trees), and three were situated in the next vine row further into the vineyard (6 m from the trees). The selection of vines followed the procedure described in the 'Experimental sites' section. The selected vines were arranged in a compact 2 × 3 layout within the field, with adjacent vines representing the two distance classes (4 and 6 m) from the tree row. This design allowed for the assessment of a potential gradient of tree influence on the vines while keeping excavation effort and site disturbance manageable.

Before excavation on 6 August 2025 (modified E-L 35), leaves, shoots, bunches, canes, and trunks were separated and their fresh weights were determined. The samples were then oven-dried at 60 °C for seven days, after which dry weights were recorded. The trunk included the portion of the scion as well as the grafting point, while the portion of the rootstock was counted as part of the roots. Leaves were weighed including the petiole; canes refer to the two-year-old fruiting shoots. Following digitisation described below, the fresh and dry weights of the roots were also recorded.

The excavation, subsequent data collection, and data processing were conducted following the protocol of Fichtl *et al.* (2024). In brief, to preserve the natural spatial configuration of each root system, a detailed and careful approach was applied. Before manual excavation, a trench was dug approximately 0.85 m away from the trunk using a mini-excavator, reaching a depth of 2 m. Manual excavation started by removing a hand-width layer of soil around the vine. Then, working carefully from within the trench, excavation continued toward the vine using a weeding trowel. To ensure the roots' natural locations and maintain a constant orientation relative to the soil surface during the measurement period, a framework of bamboo rods was affixed to both the trunk and the roots. This primary support was augmented by tethering the trunk to the existing trellis wire with a fastening band, thereby providing additional rigidity and mitigating any potential mechanical displacement.

Following excavation, the structural (lignified) root systems were digitised directly *in situ* in three-dimensional Euclidean space using a Fastrak 3D digitizer (Polhemus, Colchester, USA). A transmitter mounted on a specialised frame generated an electromagnetic field towards the vine. A handheld pointer was used to record points in the 3D electromagnetic field, allowing for the point-by-point recording of every root and branching point.

A laptop was connected to both the pointer and the transmitter to store the coordinate data. Root points were recorded using DigiTool software (Moualeu-Ngangu *et al.*, 2020), which utilises a tree structure to capture first, second, and subsequent orders of roots. After digitisation, the diameters of main and lateral roots were measured using a digital calliper to enable subsequent determination of total root volume.

To evaluate spatial root distribution, root volume data were aggregated into 5-cm intervals along the inter-row axis. Root orientation was assessed at the level of main roots (*i.e.*, roots originating directly from the trunk), based on the assumption that the directional growth of main roots determines the spatial exploration strategy of the grapevine root system. As primary structural axes, main roots define the initial direction of soil colonisation. For each main root, the terminal root tip position was identified as the digitised point with the maximum Euclidean distance from the root origin. Root growth direction was classified based on the horizontal coordinate, with negative values indicating growth toward the adjacent tree and positive values indicating growth toward the vineyard.

Due to the extreme labour intensity of the 3D root excavation and mapping process, which involves the detailed manual exposure and spatial recording of mature root systems, the number of excavated vines was restricted to the tree-affected zone at the 4 m and 6 m distance. To provide a structural baseline for the 5C rootstock under undisturbed conditions, an external reference dataset from a nearby vineyard (4 km distance) was used as a benchmark (Fichtl & Friedel, 2025). This comparison allowed us to derive root distributions that are independent of individual tree-specific biases. The dataset consists of six vines originating from a vineyard in Oestrich-Winkel, Germany, excavated and analysed according to the method used in our study. Variety (Riesling), rootstock (5C), and planting year (1977) were identical to our study, and the sites share highly similar edaphic conditions (calcareous sandy loam soils). The vertical distribution of root length across soil depth and the spatial distribution of main grapevine roots in the horizontal plane were compared to the dataset of our study. For the vertical analysis, root length from both datasets was binned into 5-cm intervals and expressed as a percentage of the total root length.

4. Statistical analysis

All statistical analyses were performed using R at a significance level of $\alpha = 0.05$.

For stomatal conductance, data were analysed using a linear mixed-effects model (LMM) with distance, site, and measurement time as fixed factors, including two-way interactions between distance and site. To account for repeated measurements on the same individuals, vine was included as a random effect. Similarly, for vertical root distribution, an LMM was applied to compare the experimental data (4 m and 6 m from the tree line) with the reference dataset (Fichtl & Friedel, 2025). The model included the fixed factors treatment group (4 m, 6 m, and reference) and soil depth (5-cm intervals), along with their interaction, and vine as a random effect.

Nitrogen balance index, shoot length, and leaf water potential were analysed using two-way ANOVAs, with distance and site as fixed factors and their interaction. Soil properties within the excavation at site 1 (distance: 3 and 7 m; soil depth) and juice quality parameters (distance: 4, 6, and 18 m; site: three sites) were also evaluated using two-way ANOVAs, including interaction terms for each model. Biomass components and total biomass were compared between distance classes using Welch's two-sample *t*-tests, assuming unequal variances.

When significant ANOVA effects were detected, post-hoc comparisons were performed using estimated marginal means with Tukey adjustment. In the presence of significant interactions, comparisons among distance classes were conducted within each site or soil depth. Standard deviations were calculated for each distance class to describe within-group variability. For directional root traits, mean root volume and root length were analysed using a two-way ANOVA (factors: distance and direction), followed by Tukey's post-hoc tests to identify asymmetries within each distance treatment. Paired *t*-tests were additionally used to evaluate directional asymmetries (vineyard side *vs*. tree side) within each distance treatment. To test for directional preferences of main roots, exact binomial tests were applied separately for vines at 4 m and 6 m distance, and for all roots pooled, assuming a null hypothesis of equal probability ($p = 0.5$) for growth in either direction.

Following the *in situ* digitisation of root systems, the spatial data were processed through a multi-step pipeline as described by Fichtl *et al.* (2024) to prepare them for further analysis and modelling. In brief, the sequentially ordered points were reassembled into linear root segments by connecting coordinates according to their branch hierarchy. Distances between two points in Euclidean space were computed to derive precise root lengths for each segment. This distance-based reconstruction formed the basis for subsequent quantitative analysis, *i.e.*, the assignment of root diameters and the determination of root volume. Descriptive statistics for root volume and root length include the mean, range, and coefficient of variation (CV).

All structural (lignified) roots were considered, unless a specific root type was explicitly indicated and analysed separately (*i.e.*, main roots).

All statistical analyses were conducted in R (version 4.4.3; R Core Team, 2025) in combination with the RStudio GUI (version 2024.12.1; RStudio Team, 2020). The packages tidyverse (version 2.0.0; Wickham, 2019), tidyr (version 1.3.1; Wickham *et al.*, 2026), dplyr (version 1.1.4; Wickham *et al.*, 2025), ggplot2 (version 4.0.0; Wickham, 2016), plotly (version 4.10.4, Sievert, 2020), stringr (version 1.5.1; Wickham, 2025), multcompView (version 0.1-10; Graves *et al.*, 2006), patchwork (version 1.3.2, Pedersen, 2019), lme4 (version 1.1-37, Bates *et al.*, 2003), lmerTest (version 3.1-3, Kuznetsova *et al.*, 2013), emmeans (version 1.11.0, Lenth & Piaskowski, 2017) and agricolae (version 1.3-7; Mendiburu, 2006) were used.

RESULTS

1. Physiological measurements

Stomatal conductance (g_s) differed statistically between vines at varying distances from the adjacent trees in all three sites (Figure 2). Vines located at a distance of 4 m exhibited the lowest g_s values, with mean stomatal conductance below 0.05 mol m^{-2} s^{-1}. Vines at 6 m distance showed slightly higher values, while the highest g_s was observed in vines located 18 m from the trees, with mean values around 0.13 mol m^{-2} s^{-1}. The variability of g_s also increased with distance from the trees, as reflected by the broader interquartile range in vines at 18 m.

The Nitrogen Balance Index (NBI) showed a comparable pattern, increasing from 4 m (mean 8.83) to 6 m (mean 10.38) and 18 m (mean 11.53), with no significant difference between the latter two distances. Variability within groups remained comparable across distances.

Shoot length was significantly influenced by the site ($p < 0.01$), but no significant effect of distance or interaction between distance and site was found. Mean shoot length was 96.9 cm at 4 m, 107.4 cm at 6 m, and 128.0 cm at 18 m.

Pre-dawn leaf water potential measurements supported these results, revealing a clear gradient in vine water status with increasing distance from the trees. Values were most negative in vines at 4 m (mean –0.37 MPa), intermediate at 6 m (mean –0.26 MPa), and least negative at 18 m (mean –0.14 MPa).

A significant interaction between distance and site was observed for stomatal conductance, NBI, and leaf water potential ($p < 0.001$).

Stomatal conductance was significantly affected by distance, site, and measurement time, with a significant interaction between distance and site ($p < 0.001$, Figure 3). Pairwise comparisons confirmed significant differences between distance classes within sites ($p < 0.05$; Tukey-adjusted). Across all sites, stomatal conductance was consistently lower at 4 m compared to 6 m and 18 m, while values at 18 m were generally highest, with the exception of site 3 during the final three measurement intervals. Diurnal patterns showed reduced stomatal conductance during the early morning and late afternoon, with higher values around late morning to midday. However, due to the significant interaction between distance and site, the magnitude of these differences varied among vineyard sites.

Total dry biomass differed between grapevines at 4 m and 6 m distance from the tree row (Figure 4). On average, total biomass was significantly higher at 6 m (1856 g) than at 4 m (1342 g), representing an increase of approximately 38 % ($p = 0.030$).

At the organ level, most biomass components showed higher mean values at 6 m compared to 4 m; however, these differences were not statistically significant. Trunk and root biomass contributed the largest proportion to total plant biomass and tended to be greater at 6 m ($p = 0.168$ and $p = 0.061$, respectively). Similarly, shoot and leaf biomass showed no significant differences between distances ($p = 0.245$ and $p = 0.297$). Bunch biomass was also higher at 6 m, although the difference was not statistically significant ($p = 0.081$).

The proximity to the tree row significantly affected all investigated juice parameters (Figure 5, $p < 0.001$ for distance in all cases). Single berry weight and N-OPA followed an overall increasing trend with greater distance from the trees (from 4 m to 18 m). However, the significant interaction between distance and site ($p = 0.050$) for single berry weight indicated that this spatial pattern was not uniform, particularly evident in the divergent values at 6 m distance. While single berry weight showed no standalone site effect ($p = 0.547$), N-OPA levels remained below 75 mg Ile eq/L at 4 m across all sites, while reaching their maximum at the 18 m control, particularly at site 3.

In contrast, TSS and pH presented a more heterogeneous pattern. Although distance had a significant main effect, the results were strongly influenced by the vineyard site and significant interaction effects ($p = 0.001$). For TSS, values at 4 m and 6 m were generally lower than at 18 m, but site 3 consistently maintained higher TSS levels than sites 1 and 2 regardless of distance. Similarly, pH values showed high variability between sites; for instance, at the 6 m distance, pH decreased at site 2 while remaining relatively stable or increasing at other locations. Across all four traits, site 3 (blue bars) consistently showed the highest absolute values at the 18 m control distance.

2. Root system architecture and soil chemical environment

Root system architecture of the vines was markedly influenced by the presence of the trees (Figure 6). Roots predominantly grew away from the trees, extending into the vineyard. The majority of roots, both in terms of number, length, and volume, were concentrated in the area opposite the trees, whereas only a few small roots extended toward the tree row.

The same applies to the mean root volume values of all excavated vines. Figure 7 shows the distribution of mean root volume along the inter-row direction for vines located 4 m and 6 m from the *Acer campestre* tree row. The zero point represents the vine position. Negative values indicate the direction toward the tree row, and positive values represent the direction toward the adjacent vineyard rows. At a distance of 4 m, root distribution exhibited an asymmetric pattern. Mean root volume on the tree side was significantly lower (76.4 ± 34.4 cm^3) compared to the vineyard side (427.1 ± 69.6 cm^3; $p = 0.041$). In this treatment, only 15.2 % of the total root volume was located toward the *Acer campestre* tree row, with no substantial accumulation of roots in the tree-side soil volume. In contrast, the root distribution at a distance of 6 m appeared more balanced. Although the mean root volume on the tree side (271.4 ± 121.3 cm^3) remained lower than on the vineyard side (403.7 ± 143.7 cm^3), this difference was not statistically significant ($p = 0.384$). At this

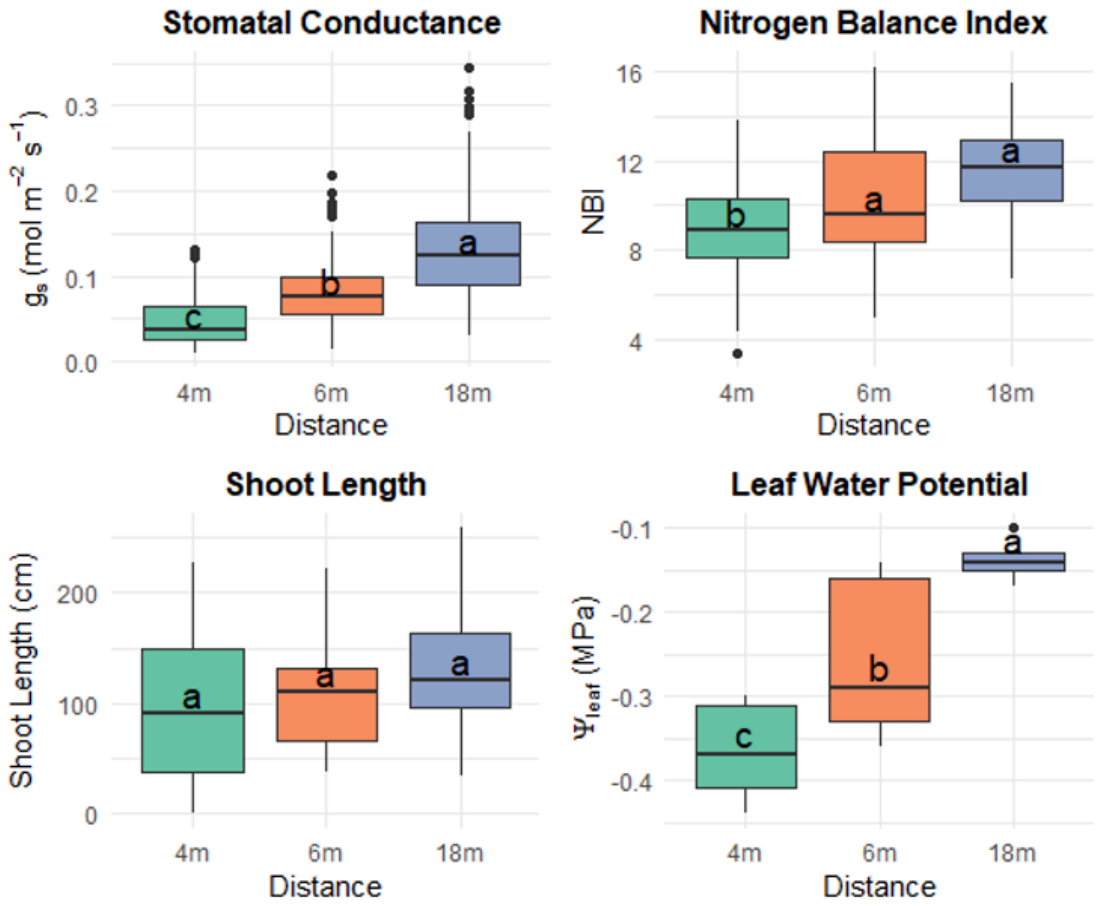


FIGURE 2. Boxplots of shoot growth, water, and nitrogen status for grapevines located at different distances from adjacent trees in Geisenheim, Germany.

Four traits are shown: Stomatal conductance (gs, mol m^{-2} s^{-1}), Nitrogen Balance Index (NBI, unitless), shoot length (cm), and pre-dawn leaf water potential (MPa) involving *Vitis vinifera* L. 'Riesling' and 'Souvignier gris' grafted on Teleki 5C and SO4 rootstocks. Boxes display the interquartile range (IQR) with the horizontal line indicating the median, whiskers extending to 1.5 × IQR, and circles denoting outliers. Different letters (a, b, c) indicate significant differences (Tukey's HSD, $p < 0.05$).

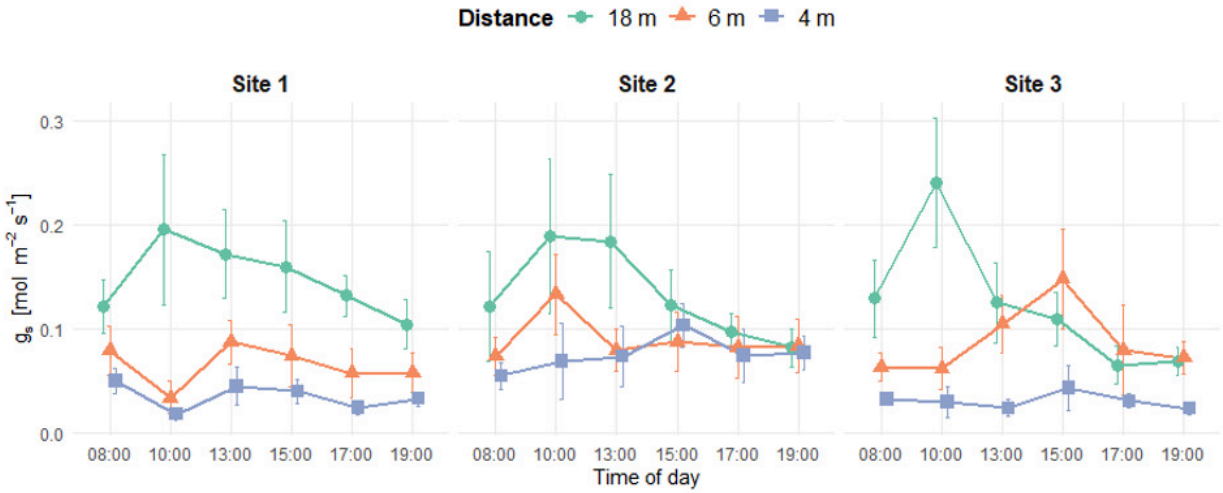


FIGURE 3. Diurnal course of stomatal conductance (gs) for grapevines at different distances from an adjacent tree row in Geisenheim, Germany.

The plot shows the mean values (points and lines) and standard deviation (error bars) for three distance classes (4 m, 6 m, and 18 m) involving *Vitis vinifera* L. 'Riesling' and 'Souvignier gris' grafted on Teleki 5C and SO4 rootstocks. Measurements were taken at six time points between 08:00 and 19:00. Panels represent individual vineyard sites (Site 1–3), illustrating site-specific diurnal responses to tree proximity.

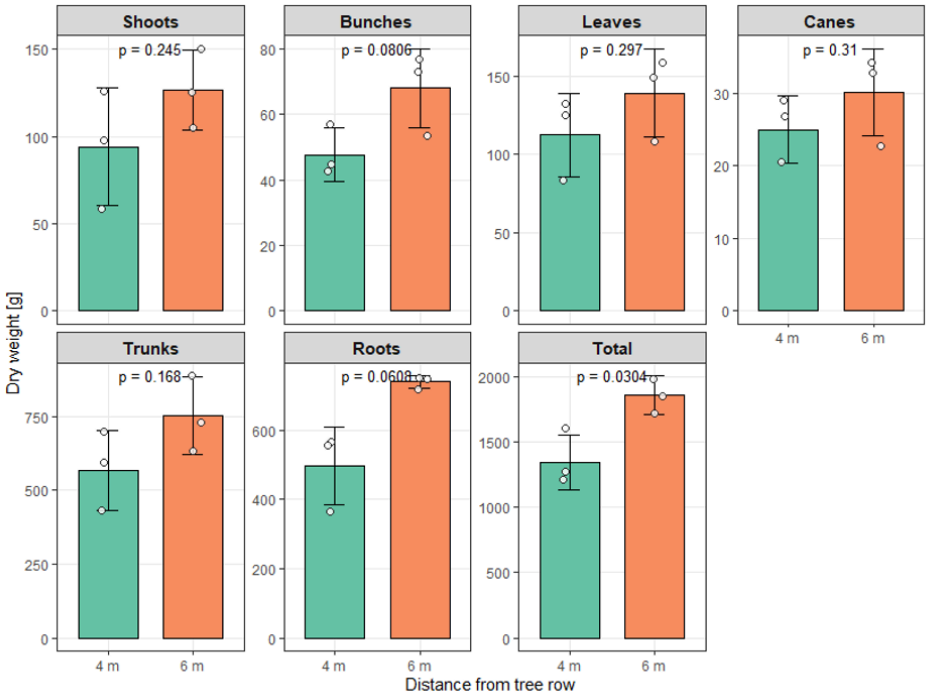


FIGURE 4. Dry biomass of excavated *Vitis vinifera* L. 'Riesling' grafted on Teleki 5C rootstocks in proximity to an *Acer campestre* tree row in Geisenheim, Germany.

Barplots represent the mean, and error bars indicate the standard deviation (± SD). Individual points are overlaid to show the distribution of the original measurements. Subtitles indicate *p*-values from Welch's t-tests assessing the effect of distance (4 m vs 6 m) within each biomass category.

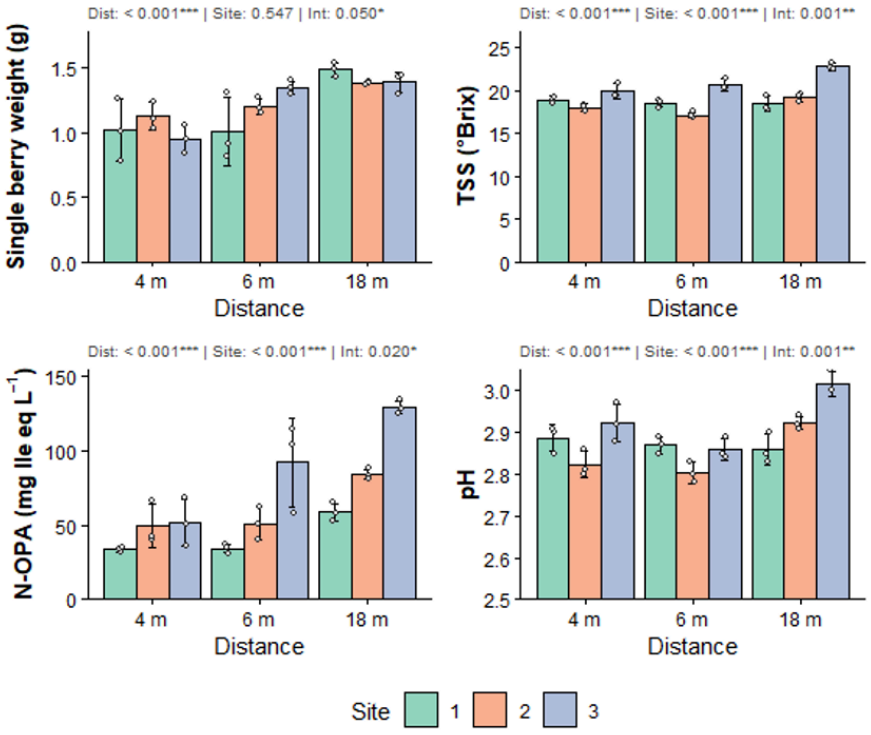


FIGURE 5. Berry weight and juice quality parameters for grapevines located at different distances from adjacent trees in Geisenheim, Germany.

Four traits are shown: single berry weight (g), total soluble solids (TSS, °Brix), yeast-available nitrogen (N-OPA, mg Ile eq L^{-1}), and juice pH, measured in *Vitis vinifera* L. 'Riesling' and 'Souvignier gris' grafted on Teleki 5C and SO4 rootstocks. Bars represent the mean, and error bars indicate the standard deviation (± SD). Individual measurements are overlaid as points. Data are coloured by vineyard site (Sites 1, 2, and 3). Subtitles indicate p-values from a two-way ANOVA assessing the effects of distance, site, and their interaction, with significance levels marked as * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

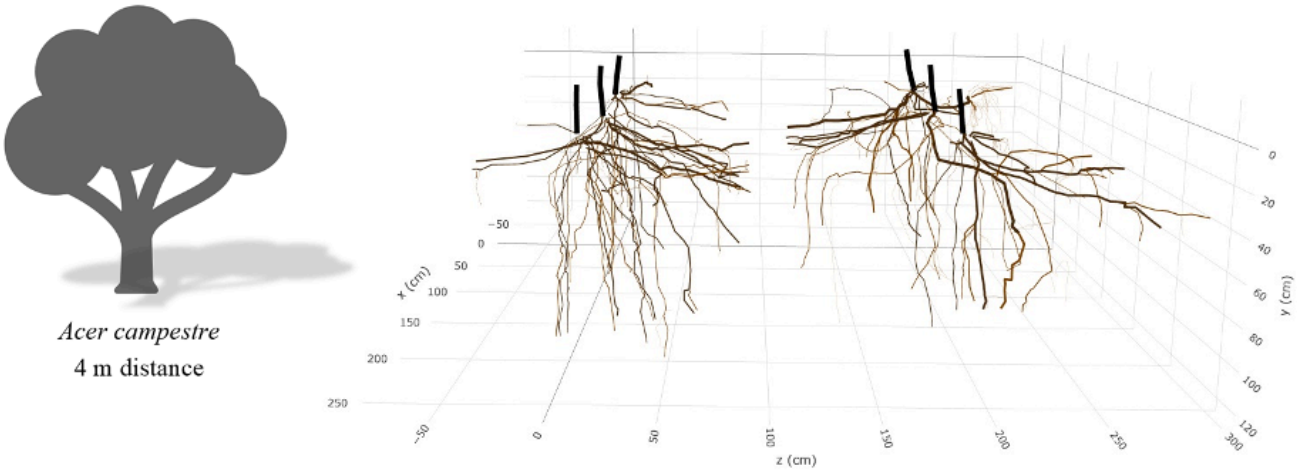


FIGURE 6. Excavated root system architectures of six vines (*Vitis vinifera* L. 'Riesling' grafted on Teleki 5C) close to an adjacent *Acer campestre* tree row in Geisenheim, Germany.

The excavation area spans 0.85 m in width and 1.2 m in depth. The tree pictogram indicates the position of the adjacent tree row (*Acer campestre*, 4 m distance), viewed along the vine row. The grapevines were individually digitised using a 3D electromagnetic tracking system and subsequently reconstructed in R at their original spatial positions, preserving actual root lengths and inter-vine distances (x-axis = planting row direction, y-axis = vertical direction, z-axis = inter-row direction).

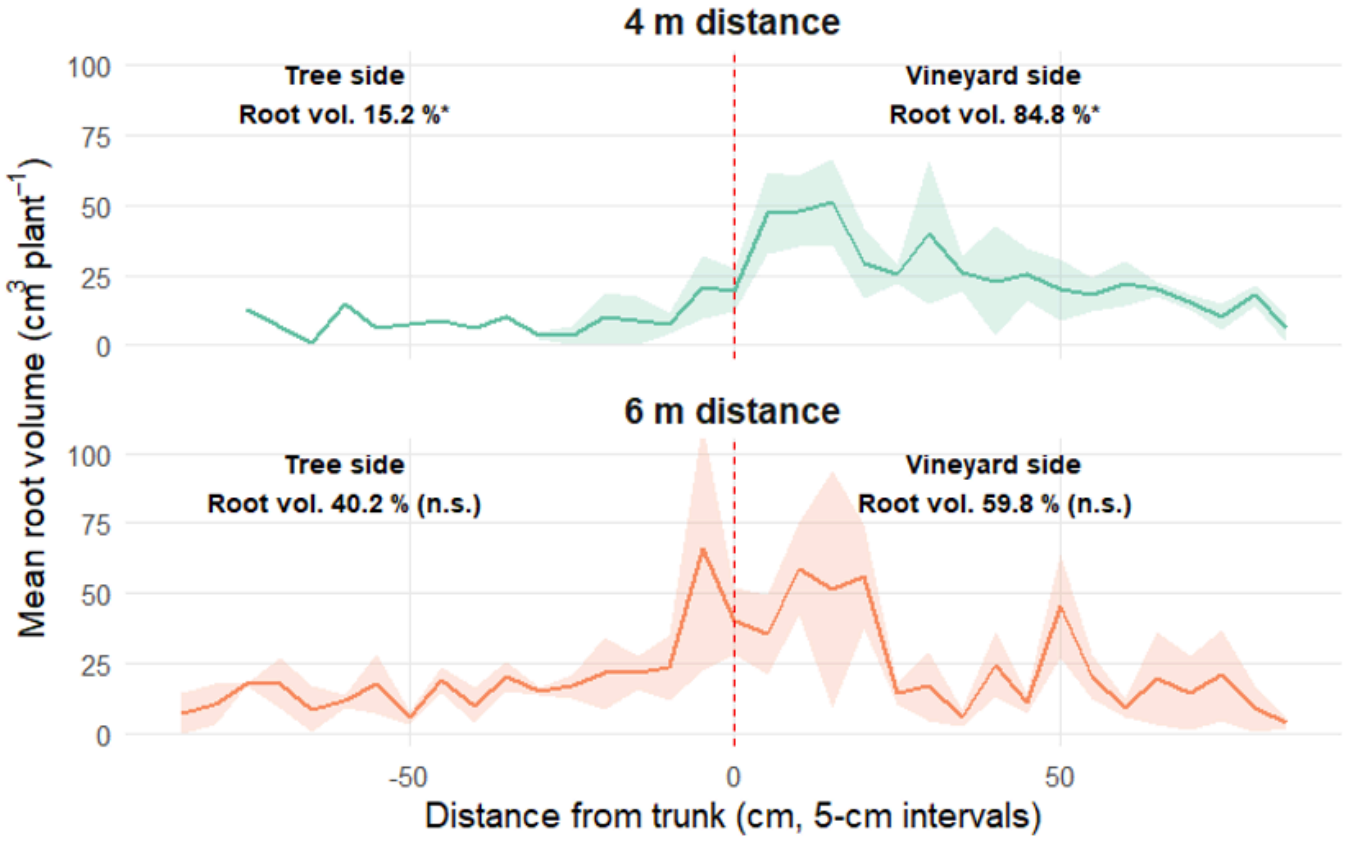


FIGURE 7. Distribution of total root volume along the inter-row axis of vines (*Vitis vinifera* L. 'Riesling' grafted on Teleki 5C) in proximity to an *Acer campestre* tree row in Geisenheim, Germany.

Root volumes were measured for vines located 4 m and 6 m from the tree row. The zero point represents the vine position, with negative values indicating the direction toward the tree row and positive values indicating the direction toward the adjacent vineyard rows. Solid lines represent the mean root volume (n = 3), while shaded areas indicate the standard error (± SE), summed in 5-cm intervals along the inter-row axis. Asterisks (*) indicate significant differences between tree and vineyard sides within a distance treatment (Tukey's post-hoc test, $p < 0.05$), while 'n.s.' denotes no significant difference.

distance, the tree side accounted for a much higher proportion of total root volume (40.2 %) compared to the 4 m treatment. A two-way ANOVA confirmed a significant overall effect of spatial direction (tree side vs vineyard side) on root volume ($p = 0.045$).

When pooling main roots across both vineyard rows (Figure 8), a pronounced directional bias was observed. Overall, 69.6 % of main roots were oriented away from the tree toward the vineyard, which differed significantly from an equal directional distribution (exact binomial test, $p = 0.0046$; 95 % CI: 0.56–0.81, n = 56). Analysed separately, the directional bias was significant at 4 m distance from the tree ($p = 0.043$) and showed a similar, though non-significant, tendency at 6 m distance ($p = 0.076$). The root system architecture of the same rootstock (5C) in Fichtl and Friedel (2025) shows a balanced distribution of main roots without directional bias, but with a larger sample size (n = 86).

Across the vines sampled at a distance of 4 m from the tree line, root system architecture showed a significant spatial bias away from the trees (Table 1). The mean total root volume was significantly higher on the vineyard side (427.1 cm^3) compared to the tree side (76.4 cm^3, $p = 0.037$). Individual total root volume ranged from 334.1 to 606.3 cm^3. Correspondingly, the ratio of root volume oriented toward the vineyard relative to that oriented toward the trees ranged from 3.0 to 11.1, indicating that between approximately threefold and more than elevenfold greater root volume developed away from the trees.

At a distance of 6 m, this directional pattern was no longer statistically significant ($p = 0.663$). While mean total root volume was higher overall (675.0 cm^3), the distribution varied markedly between vines (CV = 155.6 % for the volume ratio): one vine exhibited predominantly tree-side root growth (0.4 ratio), whereas another showed a strong shift toward the vineyard side (20.5 ratio).

Root length data showed a directional pattern similar to that observed for root volume, though with less pronounced magnitude. At a distance of 4 m from the tree line, the mean total root length was significantly greater on the vineyard side (1201.0 cm) than on the tree side (353.0 cm; $p = 0.043$). The resulting vineyard-to-tree length ratios (2.4–4.7) indicate a consistently higher proportion of root length developing away from the trees, though the disparity was smaller than for root volume. At a distance of 6 m, no significant directional preference in root length was observed ($p = 0.700$). Total root length ranged from 1343.9 to 2680.9 cm, with one vine exhibiting a strong tree-oriented distribution (0.2 ratio) and another a clear shift toward the vineyard side (6.3 ratio).

Compared with the volume data, the lower absolute ratios in root length suggest that not only the amount but also the thickness of roots is greater on the vineyard side, leading to the larger directional differences observed in root volume relative to root length.

Any expected avoidance response of grapevine roots into deeper soil layers, aimed at circumventing the increased competition from field maple in the upper 30 cm of the soil profile, was not observed. Figure 9 illustrates the vertical distribution of proportional root length at 4 m and 6 m distances from the tree row, alongside reference data from Fichtl & Friedel (2025). Across all datasets, the maximum relative root length occurred between 20 cm and 40 cm below the soil surface. While the highest values for vines at all distances were concentrated in this depth interval, none of the groups exhibited a single prominent maximum. Instead, the vertical distribution was relatively evenly distributed across the 20 to 40 cm depth range in all three cases. Likewise, the proportional distribution of root length decreased to negligible levels across the lower vertical soil layers regardless of the treatment.

A linear mixed-effects model treating soil depth as a categorical factor and vine as a random effect revealed no significant differences in the proportional vertical root distribution between the three groups (4 m, 6 m, and Fichtl & Friedel, 2025; group × depth interaction: $p = 0.158$). Accordingly, the vertical profiles in Figure 9 are shown as mean ± SE, and the curves for the three groups largely overlap across most soil layers.

The spatial distribution of organic carbon (C_{org}) and total nitrogen (N) was significantly influenced by both distance to the tree row and soil depth (Figure 10). In the bulk soil, C_{org} and N contents showed a strong vertical gradient, with the highest concentrations found in the topsoil (0–30 cm) and significantly decreasing values with increasing depth ($p < 0.001$). Proximity to the tree row (3 m) significantly altered nutrient levels compared to locations farther from the tree row (7 m). At the 3 m distance, topsoil C_{org} (mean 1.12 %) and N (mean 0.09 %) were significantly higher than at 7 m. A significant interaction between distance and depth was observed for C_{org} ($p = 0.001$). While the 3 m distance showed elevated carbon levels in the upper layers (0–30 and 30–60 cm), these differences vanished in the deepest layer (60–90 cm), where C_{org} remained stable around 0.64 % regardless of the distance to the tree.

The inclusion of roots in the analysis (Soil + Roots) amplified the observed trends, particularly at the 3 m distance. At 3 m, topsoil C_{org} reached its maximum (mean 1.45 %), which was significantly higher than the levels observed at 7 m (mean 0.9 %). Similar to the bulk soil, the distance-related differences were most pronounced in the upper 0–60 cm, while the 60–90 cm layer showed uniform, lower concentrations.

Total nitrogen content followed a similar pattern ($p < 0.001$ for distance and depth). In the topsoil (0–30 cm), N levels were markedly higher at the treeline (3 m) compared to the vineyard (7 m). For both C_{org} and N, the 7 m distance exhibited a more attenuated vertical gradient compared to the more pronounced fluctuations and higher enrichment levels recorded closer to the tree row.

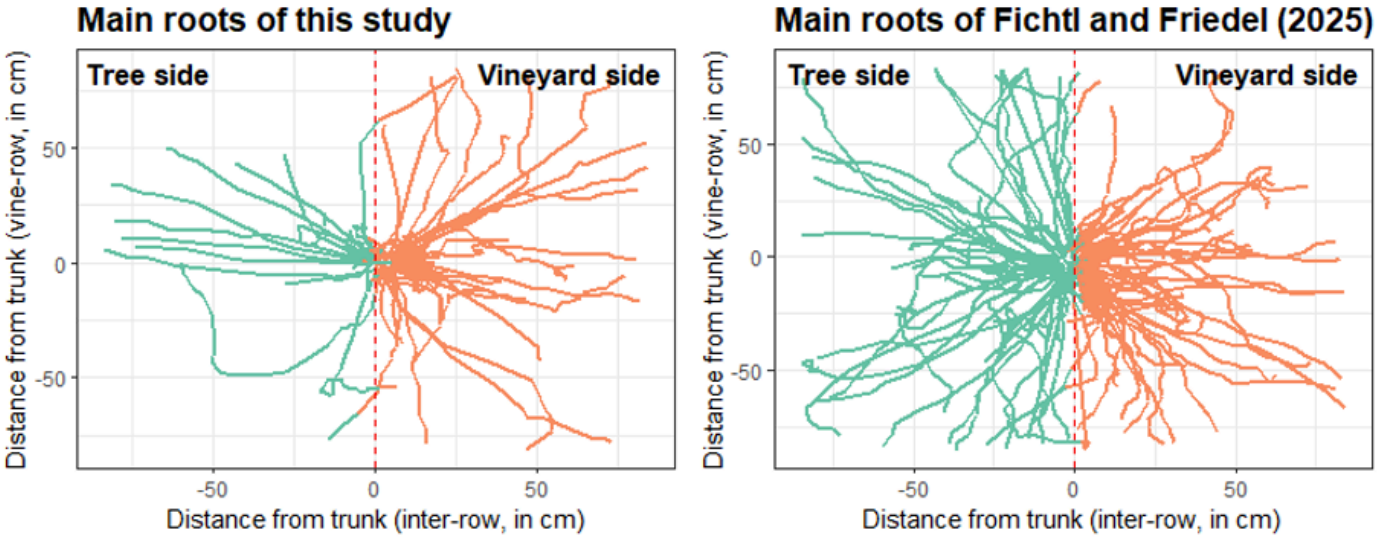


FIGURE 8. Spatial distribution of main grapevine roots (*Vitis vinifera* L. 'Riesling' grafted on Teleki 5C) in the horizontal plane near an *Acer campestre* tree row in Geisenheim, Germany.

The figure shows a top-down view of digitised main roots pooled from all six vines per plot. Negative values on the x-axis indicate growth toward the tree, whereas positive values indicate growth away from the tree. Root segments growing toward the tree are shown in green, while those growing away from the tree are shown in orange.

TABLE 1. Belowground root traits of grapevines (*Vitis vinifera* L. 'Riesling' grafted on Teleki 5C) located at two distances from an *Acer campestre* tree row in Geisenheim, Germany.

Parameter	Distance to tree: 4 m			Distance to tree: 6 m		
	Mean	Range	CV	Mean	Range	CV
Root volume (cm3)						
Vineyard direction	427.1*	306.5–547.4	28.2 %	404.0 (n.s.)	158.5–656.0	61.6 %
Tree direction	76.4	27.6–142.8	78.0 %	271.0	32.0–424.6	77.4 %
Total volume	504.0	334.1–606.3	29.4 %	675.0	583.1–754.1	12.8 %
Ratio (Vineyard/Tree)	7.8	3.0–11.1	54.5 %	7.3	0.4–20.5	155.6 %
Root length (cm)						
Vineyard side	1201.0*	826.9–1532.5	29.5 %	1115.0 (n.s.)	343.7–1841.8	67.3 %
Tree side	353.0	213.5–518.8	43.7 %	811.0	183.5–1410.1	75.7 %
Total length	1555.0	1040.4–1859.7	28.8 %	1926.0	1343.9–2680.9	35.6 %
Ratio (Vineyard/Tree)	3.7	2.4-4.7	31.8 %	2.9	0.2–6.3	107.2 %

Shown are mean values, ranges (minimum – maximum), and coefficients of variation (CV) for root volume (cm^3) and root length. The ratio represents the distribution of roots within individual vines, calculated as the value on the vineyard side divided by the value on the tree side. Asterisks (*) indicate significant differences between the vineyard-facing and tree-facing sides within a distance treatment (paired *t*-test, $p < 0.05$; n.s. = not significant). The dataset is based on 2137 digitised data points collected across 369 individual main and lateral roots across six vines ($n = 3$ per distance).

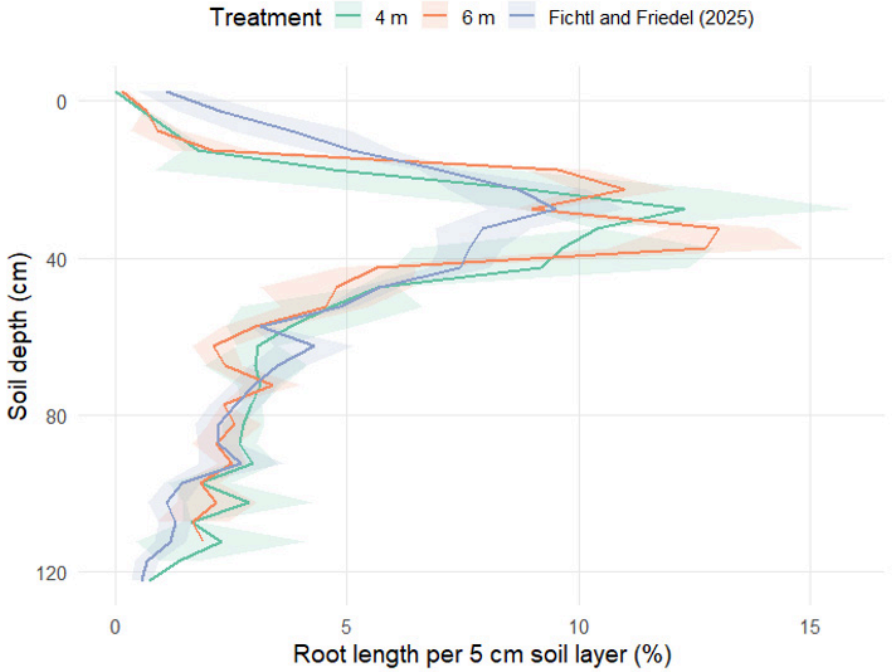


FIGURE 9. Vertical distribution of relative grapevine root length (*Vitis vinifera* L. 'Riesling' grafted on Teleki 5C) at two distances from an Acer campestre tree row in Geisenheim, Germany and from a reference dataset (Fichtl & Friedel, 2025).

The proportional root length per 5-cm soil layer (%) was quantified at soil depths from 0 to 120 cm for vines located 4 m (green) and 6 m (orange) from the tree row. The third line (blue) represents data from Fichtl and Friedel (2025). Lines represent mean percentage of total root length per 5-cm soil layer, with shaded areas showing standard error (mean ± SE). Soil depth is referenced from the surface (0 cm) downward.

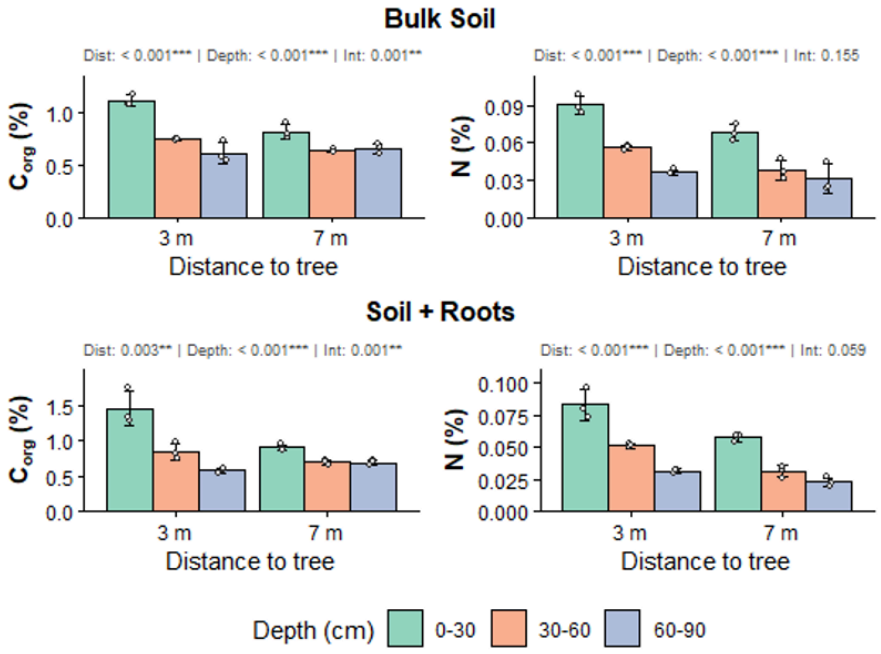


FIGURE 10. Organic carbon and total nitrogen content in bulk soil and soil including roots at two distances from an Acer campestre tree row in Geisenheim, Germany.

The upper panel displays results for bulk soil, while the lower panel shows results for soil including roots (soil + roots). Two key indicators are presented: organic carbon content (Corg, %) and total nitrogen content (N, %). Each bar represents measurements at two distances to an Acer campestre row: 3 m and 7 m, subdivided by soil depth (indicated by colour). Subtitles provide p-values for the effects of distance, depth, and their interaction based on a two-way ANOVA. Significance levels: * ($p < 0.05$), ** ($p < 0.01$),*** ($p < 0.001$). Barplots represent the mean, error bars indicate the standard deviation (± SD), and individual points show the original measurements ($n = 3$).

DISCUSSION

Agroforestry systems represent a promising strategy to address climate-change-induced increases in drought stress in vineyards. By reducing overall stand transpiration and potentially facilitating hydraulic redistribution from deeper tree root layers to the shallower root zones of the vine, it is hypothesised that specific spatial arrangements of trees and grapevines can generate beneficial interactions (Neumann & Cardon, 2012; Favor & Udawatta, 2021).

The results of this study indicate that, given the temperate climatic conditions in which the study was conducted, in the long run competition for water (Celette and Gary, 2013) has a substantially greater impact on grapevine water balance and root growth than the potential benefits associated with enhanced soil water infiltration and access to deep soil moisture (Smart *et al.*, 2005). The latter hypothesis, often suggested in the literature, cannot be confirmed based on the present findings. The preliminary investigations revealed the moderate stress experienced by grapevines growing in close proximity to tree rows, irrespective of the tree species or vine age. Stomatal conductance, leaf water potential, and growth parameters clearly indicated that these vines were subjected to increased water stress, suggesting a concomitant reduction in overall physiological performance.

The persistent differences in stomatal conductance across distances over the course of the day indicate a sustained stress response of the vines, suggesting that tree-related effects influence vine functioning at a broader spatial and temporal scale.

In this 50-year-old vineyard in Geisenheim, the agroforestry combination of field maple and grapevine demonstrates a pronounced growth tendency of grapevine roots away from the tree, indicating a distinct avoidance strategy rather than active competition. Subsequent analyses of root system architecture confirmed that grapevine roots consistently extended away from the tree-dominated soil zone, adjusting their position in the horizontal but not in the vertical plane. As grapevine roots show hydrotropism, this is a further indication that water resources close to the tree row may be limited, likely due to the presence of high-density tree root systems and the resulting competition. Although total nitrogen concentration was higher in the soil close to the tree row, N-OPA was higher in vines grown at 6 and 18 m distance to the tree row. Hence, it is also possible that competition for mineralised nitrogen is a promoting factor in root reorientation. In parallel, the elevated soil organic carbon concentrations observed close to the tree row indicate a long-term accumulation of organic matter, likely driven by litter inputs and tree root turnover. Increased soil organic carbon is widely recognised as a key mechanism for carbon sequestration in agricultural soils, contributing to climate change mitigation while simultaneously improving soil structure, water-holding capacity, and microbial activity that could support nutrient cycling and overall soil functioning (Cardinael *et al.*, 2015; Lal, 2004).

Vertical growth distribution of Riesling grafted to 5C rootstock in the present vineyard closely matches those observed in a vineyard located 4 km away (Fichtl & Friedel, 2025). Horizontal growth in this dataset, however, was equally distributed to both sides of the row, in sharp contrast to the vines excavated in this study, which showed a clear directional bias away from the tree row that was stronger in vines at 4 m than at 6 m distance. This comparison highlights a significant suppression of root development in the tree-affected zone. In that reference vineyard, however, no directional growth tendencies were observed, as no trees were situated in the immediate vicinity of the vines. Moreover, vines formed an average of 14 main roots, whereas in the present study, vines located in close proximity to the tree developed only about 8 main roots per vine on average (Figure 8, data not shown). While the present study demonstrates reduced physiological performance at closer distances to the tree, the comparison with Fichtl and Friedel (2025) further supports the interpretation that tree proximity is associated with diminished root growth. This pattern is consistent with the findings of Gómez-del-Campo *et al.* (2005), who reported that grapevine biomass is generally reduced under water stress compared to well-watered controls.

Interestingly, these findings contrast with recent observations by Ruiz *et al.* (2026), who demonstrated that interspecific competition does not necessarily lead to detrimental water stress. In a Mediterranean vineyard, they found that vines competing with cover crops maintained a stable water status by shifting their water uptake patterns, accessing both shallow (0–30 cm) and deeper (30–100 cm) soil layers. While Ruiz *et al.* (2026) used isotopic tracers to show high plasticity in water uptake depth as a strategy to mitigate topsoil competition, our results, specifically the lack of vertical root avoidance (see Figure 9), suggest that such a compensatory mechanism may be limited in agroforestry systems under temperate conditions. In our study, the absence of a downward shift in vine root distribution might be related to the greater presence of tree roots in deeper soil layers, in contrast to cover crops, which are largely restricted to the topsoil. This may have limited the vines' ability to access deeper moisture resources, leading to the observed reductions in stomatal conductance and growth rather than a successful compensatory response as reported for cover crop systems.

At the same time, the present study is subject to several limitations. The choice of vineyard sites is inherently limited when dedicated vitiforestry systems are to be investigated, as designated vitiforestry trial vineyards are often still young, requiring researchers to rely on existing vineyards where tree rows are present, even though their establishment decades ago did not account for vitiforestry considerations. The sample size of six excavated grapevines only allows for limited statistical analyses, which is largely attributable to the highly labour-intensive nature of the excavation method. Furthermore, conclusions for agroforestry systems are only partially transferable, as excavations were limited to one soil type, one tree species, and one climatic zone. In systems with smaller and/or younger trees, characterised by reduced

tree height, less developed root systems, and only moderate drought stress due to higher rainfall, grapevine root growth may diverge and potentially yield more desirable outcomes (Van Zyl, 1984; Esteban *et al.*, 2001). While our physiological measurements align closely with the observed gradients in vine water status, we cannot rule out other contributing factors such as allelopathic effects from tree root exudates; therefore, further research is required to disentangle these biochemical interactions from physical resource competition.

Despite significant site-specific interactions, the consistent trend in physiological measurements toward the tree row across all three locations validates our multi-site approach and suggests that the observed distance effects are robust, even within a single growing season. They hence highlight potential directions for future research.

Although the grapevine root system appears to exhibit a long-term orientation away from the adjacent tree, and vegetative vigour is significantly reduced compared to vineyard interiors, it is nevertheless noteworthy that the vines have persisted under these competitive conditions for approximately 50 years, even though individual vine losses occurred over the course of the years. Despite the presence of large field maples, the vines have remained functional. This suggests that adaptive root system development may represent a key mechanism enabling grapevines to secure their own survival under suboptimal environmental conditions. These findings are consistent with studies from Italy, which demonstrate that training systems directly associated with trees are an integral component of traditional cultural vineyard landscapes and have proven viable for decades to centuries, including in systems involving field maple (Torquati *et al.*, 2015). However, our results provide evidence that this coexistence is likely maintained through a clear avoidance strategy rather than a facilitative interaction like hydraulic lift. While hydraulic lift has been reported for other maple species (Emerman & Dawson, 1996), the observed hydrotropic root avoidance in this study points toward water competition in the tree-dominated zone being the primary driver of root architecture in this specific agroforestry setting.

For the design and management of viticultural agroforestry systems, our data indicate a gradient in resource availability and vine performance in relation to the distance from the tree row. This suggests that maintaining a minimum buffer zone may be beneficial for minimising direct competition for water and soil nutrients. Vines located closer to the tree row may require more intensive monitoring or supplemental nutrient supply to compensate for potential competition.

CONCLUSION

This preliminary study provides evidence that competition for water between grapevines and adjacent trees can have a pronounced effect on vine water status and root system architecture under temperate climatic conditions. In the specific agroforestry system studied, vines situated close to a mature tree row exhibited reduced stomatal conductance, more negative pre-dawn leaf water potentials, and lower N uptake. Root growth patterns in vines neighbouring field maples were predominantly oriented away from the trees, suggesting that water competition may outweigh any potential facilitative effects such as enhanced soil infiltration or access to deep soil moisture. These initial results highlight the importance of considering tree–vine interactions in vineyard agroforestry, particularly with regard to water availability and root spatial partitioning. Future research is required to validate these findings across alternative tree species, tree orientations, and soil conditions to optimise the design of agroforestry systems that balance microclimate benefits with minimal resource competition.

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REFERENCES

Alsina, M. M., Smart, D. R., Bauerle, T., De Herralde, F., Biel, C., Stockert, C., Negron, C., & Save, R. (2011). Seasonal changes of whole root system conductance by a drought-tolerant grape root system. *Journal of Experimental Botany*, *62*(1), 99–109. https://doi.org/10.1093/jxb/erq247

Bates, D., Maechler, M., Bolker, B., Walker, S., Jagan, M., & Ly, A. (2003). *lme4: Linear Mixed-Effects Models using 'Eigen' and S4* (p. 2.0-1) [Dataset]. https://doi.org/10.32614/CRAN.package.lme4

Cardinael, R., Chevallier, T., Barthès, B. G., Saby, N. P. A., Parent, T., Dupraz, C., Bernoux, M., & Chenu, C. (2015). Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon—A case study in a Mediterranean context. *Geoderma*, *259–260*, 288–299. https://doi.org/10.1016/j.geoderma.2015.06.015

Cartechini, A., & Palliotti, A. (1995). Effect of Shading on Vine Morphology and Productivity and Leaf Gas Exchange Characteristics in Grapevines in the Field. *American Journal of Enology and Viticulture*, *46*(2), 227–234. https://doi.org/10.5344/ajev.1995.46.2.227

Celette, F., & Gary, C. (2013). Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. *European Journal of Agronomy*, *45*, 142–152. https://doi.org/10.1016/j.eja.2012.10.001

Celette, F., Gaudin, R., & Gary, C. (2008). Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *European Journal of Agronomy*, *29*(4), 153–162. https://doi.org/10.1016/j.eja.2008.04.007

Coombe, B.G. (1995). Growth Stages of the Grapevine: Adoption of a system for identifying grapevine growth stages. *Australian Journal of Grape and Wine Research*, *1*(2), 104–110. https://doi.org/10.1111/j.1755-0238.1995.tb00086.x

Demir, G., Guswa, A. J., Filipzik, J., Metzger, J. C., Römermann, C., & Hildebrandt, A. (2024). Root water uptake patterns are controlled by tree species interactions and soil water variability. *Hydrology and Earth System Sciences*, *28*(6), 1441–1461. https://doi.org/10.5194/hess-28-1441-2024

Di Giacinto, S., Friedel, M., Poll, C., Döring, J., Kunz, R., & Kauer, R. (2020). Vineyard management system affects soil microbiological properties. *OENO One*, *54*(1). https://doi.org/10.20870/oeno-one.2020.54.1.2578

Dukes, B. C., & Butzke, C. E. (1998). Rapid Determination of Primary Amino Acids in Grape Juice Using an *o* -Phthaldialdehyde/N-Acetyl-L-Cysteine Spectrophotometric Assay. *American Journal of Enology and Viticulture*, *49*(2), 125–134. https://doi.org/10.5344/ajev.1998.49.2.125

Dupraz, C., Blitz-Frayret, C., Lecomte, I., Molto, Q., Reyes, F., & Gosme, M. (2018). Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system. *Agroforestry Systems*, *92*(4), 1019–1033. https://doi.org/10.1007/s10457-018-0214-x

Emerman, S. H., & Dawson, T. E. (1996). Hydraulic lift and its influence on the water content of the rhizosphere: An example from sugar maple, Acer saccharum. *Oecologia*, *108*(2), 273–278. https://doi.org/10.1007/BF00334651

Esteban, M. A., Villanueva, M. J., & Lissarrague, J. R. (2001). Effect of irrigation on changes in the anthocyanin composition of the skin of cv Tempranillo (Vitis vinifera L) grape berries during ripening. *Journal of the Science of Food and Agriculture*, *81*(4), 409–420. https://doi.org/10.1002/1097-0010(200103)81:4<409::AID-JSFA830>3.0.CO;2-H

Favor, K., & Udawatta, R. P. (2021). Belowground Services in Vineyard Agroforestry Systems. In R. P. Udawatta & S. Jose (Eds.), *Agroforestry and Ecosystem Services* (pp. 65–94). Springer International Publishing. https://doi.org/10.1007/978-3-030-80060-4_4

Fichtl, L., & Friedel, M. (2025). *Grapevine3D: A Root System Architecture Dataset of 48-Year-Old Field-Grown Grapevines* (Version 1.0) [Dataset]. Zenodo. https://doi.org/10.5281/ZENODO.17637194

Fichtl, L., Leitner, D., Schnepf, A., Schmidt, D., Kahlen, K., & Friedel, M. (2024). A Field-to-Parameter Pipeline for Analyzing and Simulating Root System Architecture of Woody Perennials: Application to Grapevine Rootstocks. *Plant Phenomics*, *6*, 0280. https://doi.org/10.34133/plantphenomics.0280

Friday, J. B., & Fownes, J. H. (2002). Competition for light between hedgerows and maize in an alley cropping system in Hawaii, USA. *Agroforestry Systems*, *55*(2), 125–137. https://doi.org/10.1023/A:1020598110484

Gómez-del-Campo, M., Baeza, P., Ruiz, C., & Lissarrague, J. R. (2005). Effects of water stress on dry matter content and partitioning in four grapevine cultivars (Vitis vinifera L.). *OENO One*, *39*(1), 1. https://doi.org/10.20870/oeno-one.2005.39.1.905

Graves, S., Piepho, H.-P., & Selzer, L. (2006). *multcompView: Visualizations of Paired Comparisons* (p. 0.1-10) [Dataset]. https://doi.org/10.32614/CRAN.package.multcompView

Hawkins, H.-J., Hettasch, H., West, A. G., & Cramer, M. D. (2009). Hydraulic redistribution by Protea 'Sylvia' (Proteaceae) facilitates soil water replenishment and water acquisition by an understorey grass and shrub. *Functional Plant Biology*, *36*(8), 752–760. https://doi.org/10.1071/FP09046

HLNUG. (2026). *Weinbaustandort-viewer-hessen by the Hessian Agency for Nature Conservation Environment and Geology. Https://weinbaustandort.hessen.de/* [Dataset]. https://weinbaustandort.hessen.de/

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, *76*(1), 1–10. https://doi.org/10.1007/s10457-009-9229-7

Kuznetsova, A., Bruun Brockhoff, P., & Haubo Bojesen Christensen, R. (2013). *lmerTest: Tests in Linear Mixed Effects Models* (p. 3.2-1) [Dataset]. https://doi.org/10.32614/CRAN.package.lmerTest

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lang, C. P., Merkt, N., Geilfus, C.-M., Graeff–Hönninger, S., Simon, J., Rennenberg, H., & Zörb, C. (2019). Interaction between grapevines and trees: Effects on water relations, nitrogen nutrition, and wine. *Archives of Agronomy and Soil Science*, *65*(2), 224–239. https://doi.org/10.1080/03650340.2018.1493197

Lehr, P. P., Gschwendtner, S., Du, B., Rennenberg, H., Schloter, M., & Zörb, C. (2025). Grapevines and trees: A biodiversity study of microbiomes in an established temperate agroforestry system. *Journal of Environmental Management*, *379*, 124882. https://doi.org/10.1016/j.jenvman.2025.124882

Lenth, R. V., & Piaskowski, J. (2017). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (p. 2.0.3) [Dataset]. https://doi.org/10.32614/CRAN.package.emmeans

Ludwig, F., Dawson, T. E., De Kroon, H., Berendse, F., & Prins, H. H. T. (2003). Hydraulic lift in Acacia tortilis trees on an East African savanna. *Oecologia*, *134*(3), 293–300. https://doi.org/10.1007/s00442-002-1119-x

Lynch, J. P. (2022). Harnessing root architecture to address global challenges. *The Plant Journal*, *109*(2), 415–431. https://doi.org/10.1111/tpj.15560

Mendiburu, F. (2006). *agricolae: Statistical Procedures for Agricultural Research* (p. 1.3-7) [Dataset]. https://doi.org/10.32614/CRAN.package.agricolae

Moualeu-Ngangu, D., Adler, M., Pao, Y.-C., Myint, S. S., Fricke, A., Chen, T.-W., & Stützel, H. (2020). *Digitool: A tool for analyzing 3D plant architecture* (Version 101) [Computer software].

Neumann, R. B., & Cardon, Z. G. (2012). The magnitude of hydraulic redistribution by plant roots: A review and synthesis of empirical and modeling studies. *New Phytologist*, *194*(2), 337–352. https://doi.org/10.1111/j.1469-8137.2012.04088.x

Norton, R. L. (1988). 11. Windbreaks: Benefits to orchard and vineyard crops. *Agriculture, Ecosystems & Environment*, *22–23*, 205–213. https://doi.org/10.1016/0167-8809(88)90019-9

Pedersen, T. L. (2019). *patchwork: The Composer of Plots* (p. 1.3.2) [Dataset]. https://doi.org/10.32614/CRAN.package.patchwork

R Core Team. (2025). *R: A Language and Environment for Statistical Computing*. https://www.R-project.org

RStudio Team. (2020). *RStudio: Integrated development environment for r*. RStudio, PBC. http://www.rstudio.com/

Ruiz, I., Schwendenmann, L., Barbeta, A., Lehmann, M. M., Parmo, R., & Aizpurua, A. (2026). Soil Management Effects on Grapevine Water Uptake Depth in a Mediterranean Vineyard. *European Journal of Soil Science*, *77*(2), e70301. https://doi.org/10.1111/ejss.70301

Sievert, C. (2020). *Interactive web-based data visualization with R, plotly, and shiny*. CRC Press, Taylor and Francis Group. https://doi.org/10.1201/9780429447273

Smart, D. R., Carlisle, E., Goebel, M., & Núñez, B. A. (2005). Transverse hydraulic redistribution by a grapevine. *Plant, Cell & Environment*, *28*(2), 157–166. https://doi.org/10.1111/j.1365-3040.2004.01254.x

Torquati, B., Giacchè, G., & Venanzi, S. (2015). Economic analysis of the traditional cultural vineyard landscapes in Italy. *Journal of Rural Studies*, *39*, 122–132. https://doi.org/10.1016/j.jrurstud.2015.03.013

Tubbs, C. H. (1973). Allelopathic Relationship between Yellow Birch and Sugar Maple Seedlings. *Forest Science*, *19*(2), 139–145. https://doi.org/10.1093/forestscience/19.2.139

Turner, N. C. (1988). Measurement of plant water status by the pressure chamber technique. *Irrigation Science*, *9*(4), 289–308. https://doi.org/10.1007/BF00296704

Van Zyl, J. L. (1984). Response of Colombar Grapevines to Irrigation as Regards Quality Aspects and Growth. *South African Journal of Enology & Viticulture*, *5*(1). https://doi.org/10.21548/5-1-2365

Wasson, A. P., Richards, R. A., Chatrath, R., Misra, S. C., Prasad, S. V. S., Rebetzke, G. J., Kirkegaard, J. A., Christopher, J., & Watt, M. (2012). Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *Journal of Experimental Botany*, *63*(9), 3485–3498. https://doi.org/10.1093/jxb/ers111

Wheeler, S. J., & Pickering, G. J. (2005). Effects of Soil Management Techniques on Grape and Wine Quality. *In: Dris R (Author) Fruits: Growth, Nutrition, and Quality. WFL Publisher, Helsinki, Finland*, 195–205.

Wickham, H. (2019). *Welcome to the Tidyverse*. https://doi.org/10.21105/joss.01686

Wickham, H. (2025). *stringr: Simple, Consistent Wrappers for Common String Operations*. https://stringr.tidyverse.org. https://stringr.tidyverse.org

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis* (Second edition). Springer international publishing.

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2025). *dplyr: A Grammar of Data Manipulation*. https://dplyr.tidyverse.org/

Wickham, H., Vaughan, D., & Girlich, M. (2026). *tidyr: Tidy Messy Data*. https://tidyr.tidyverse.org/

Zamora, D. S., Jose, S., Jones, J. W., & Cropper, W. P. (2009). Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO. *Agroforestry Systems*, *76*(2), 423–435. https://doi.org/10.1007/s10457-008-9166-x

Zhang, J., Mao, Z., Wang, L., & Shu, H. (2007). Bioassay and Identification of Root Exudates of Three Fruit Tree Species. *Journal of Integrative Plant Biology*, *49*(3), 257–261. https://doi.org/10.1111/j.1744-7909.2007.00307.x

Zhang, L., Marguerit, E., Rossdeutsch, L., Ollat, N., & Gambetta, G. A. (2016). The influence of grapevine rootstocks on scion growth and drought resistance. *Theoretical and Experimental Plant Physiology*, *28*(2), 143–157. https://doi.org/10.1007/s40626-016-0070-x