Universität
Zürich UZH

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Determination of Urban Trees Resilience, Resistance and Recovery to Drought Under Variable Nutrient Availability in the City of Zurich

GEO 511 Master's Thesis

Author: Micaela Dassié, 17-218-512

Supervised by: Prof. Dr. Paolo Cherubini (paolo.cherubini@wsl.ch)

Faculty representative: Prof. Dr. Markus Egli

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Department of Geography, University of Zürich

Micaela Dassié

17-512-218

Supervised by

Prof. Dr. Paolo Cherubini, WSL

Faculty member

Prof. Dr. Markus Egli, GIUZ, University of Zurich

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Abstract

Climate change is becoming increasingly evident, and as it progresses, cities are facing environmental challenges that directly affect the growth of urban trees, essential elements from which people derive numerous benefits. Urban trees are exposed to high temperatures, reduced precipitation, and spatial limitations, all of which impact their growth and health, thereby compromising the environmental services they can provide. The analysis of urban tree growth serves as an important tool for understanding their response to drought events. Tree response to drought is determined by their growth during a drought event, the speed at which they resume pre-drought growth, and their ability to maintain stable growth once favorable conditions return. Factors such as available soil volume and nutrient levels in the soil can significantly influence how well trees cope with water scarcity. This study assessed the drought response of three tree species in the urban context of Zurich, Acer platanoides, Betula pendula, and Robinia pseudoacacia. Specifically, it aimed to understand how differences in nutrient availability and location conditions affect tree recovery following drought events. To evaluate tree response, annual ring widths were measured. The values were detrended to eliminate age-related biases and were cross-dated to minimize error. These values were then compared with two drought indices representing seasonal and annual drought severity, SPEI-3 and SPEI-12. In addition, chemical and isotopic analyses were carried out on wood samples, as well as on soil and leaf samples from the same trees. For each species, individuals located near roads, subject to the presence of dogs and therefore likely to receive additional nutrient input, were compared to trees growing in open areas, such as schools or playgrounds, where such external inputs were absent. The results highlight that the species exhibit different responses, both in how drought events are reflected in their ring growth and in their nutrient uptake under varying urban conditions. Acer platanoides showed greater sensitivity to drought in its growth patterns, yet demonstrated high recovery capacity in environments with greater nutrient availability. Betula pendula exhibited a less pronounced response to drought in its ring width and showed greater resistance in areas with increased soil volume. Robinia pseudoacacia, on the other hand, displayed a generally more stable response across conditions. Among the nutrients examined, potassium was most strongly associated with drought tolerance indices, particularly in A. platanoides and B. pendula. These findings suggest that drought response in urban trees is highly species-specific and influenced by local urban factors. This work introduces new elements for understanding how urban trees adapt to climate-related stressors and draws attention to the importance of urban management strategies that aim to create better integration between urban development and the environment. In the context of a changing and increasingly challenging climate, such insights may serve as valuable guidance for planning more resilient urban spaces.

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1. Introduction

Context and current state of knowledge

Since the 19th century, global population has grown steadily, with an increasing number of people opting to move to cities. In the 1930s, only 30% of the total population lived in cities, with the remaining 70% residing in more rural areas. This trend continued for about two more decades, until the mid-1900s, when more and more people started to relocate to urban areas. In 1930, only 30% of the global population lived in urban areas, while projections indicate that by 2050, this figure will rise to approximately 68% (Perry and Cox, 2024).

The increasing number of people in urban areas requires adapting cities to support high population densities, ensuring not only functionality and infrastructure, also sustainability and the psychophysical well-being of the inhabitants. There is countless evidence that people's quality of life is highly dependent on surroundings (Dzhambov et al., 2021). Therefore, it is crucial, even in cities, to maintain and enhance green spaces. Urban trees play a fundamental role in improving life quality by providing shade, reducing temperatures through evapotranspiration, filtering air pollutants, reducing noise pollution, and supporting urban biodiversity. Moreover, they offer important social and psychological benefits, contributing to the overall well-being of city inhabitants (Tyrväinen et al., 2005). For example, it has recently been shown that people living in densely populated and polluted areas benefit from higher levels of tree cover (Chi et al., 2025).

Unfortunately, the growth of urban populations has coincided with increasing industrialisation and energy consumption, leading to progressively higher greenhouse gas emissions. It is estimated that energy use and industrial activities account for approximately 86% of total emissions (Le Quéré et al., 2018). These emissions are a key driver of climate change, which increasingly affects the health and vitality of urban trees, and in turn causes other kinds of problems. Factors such as air pollution, reduced precipitation, heatwaves, and the intensification of drought events increasingly challenge the survival and growth of urban trees (IPCC, 2022; Lelieveld et al., 2019). This situation is also visible in Switzerland, where climate change has led to a significant rise in average temperatures, exceeding 2°C since pre-industrial times, twice the global average (MeteoSwiss, 2023). Summer temperatures have increased even more sharply, namely +2.5°C since 1864, contributing to a fivefold increase in the frequency of heatwaves over the past thirty years. In addition, prolonged summer droughts have also intensified, with an average extension of four days per decade since 1961, and a soil moisture reduction of 15–20% in lowland regions. This has resulted in some severe drought events, which underline the growing vulnerability of Swiss ecosystems and water resources. Some Switzerland's cities already face specific challenges due to urban heat islands and impermeable surfaces, which limit water infiltration and exacerbate drought stress. For example, some studies show that in Zurich, urban trees play a crucial role by removing around 100 tons of air pollutants annually and providing essential services like temperature regulation and stormwater management (WSL, 2023). Projections for the coming decades are equally concerning. According to CH2018 scenarios, Switzerland is expected to experience an additional 2.5–4.5°C increase in summer temperatures and a 10–30% decrease in summer precipitation by 2050 (BAFU, 2021). These changes are likely to further impact both forested and urban areas, reducing tree growth and survival, and diminishing their ability to mitigate climate-related challenges (Brunner et al., 2019; WSL, 2023).

Independently from, and in addition to the effects of climate change, urban environments expose trees to unique and intensified drought conditions due to limited soil volume and impermeable surfaces. In fact, trees are frequently confined to small, compacted soil volumes that limit root development and access to essential nutrients. Studies suggest that a minimum of 20 m³ of soil is necessary for optimal tree growth (Kopinga, 1991). Physical limitations of the urban environment also represented by high levels of impermeable surfaces complicate the good wealth of the trees (Gill et al., 2007). Several recent studies have highlighted how drought stress critically influences the health and ecosystem services of urban trees. For instance, Rosenberger et al. (2025) demonstrated that standard weekly irrigation is insufficient to prevent drought stress in urban trees, especially when root space is limited to 12 m³. Their simulations showed that daily irrigation, particularly when supported by rainwater harvesting systems, significantly reduces drought duration but requires careful planning under future climate scenarios. Similarly, another study confirmed that water availability directly impacts the cooling potential and carbon sequestration capacity of urban green areas (UGAs); the findings revealed a substantial reduction in air temperature cooling during dry seasons, highlighting the need for irrigation to compensate for precipitation deficits (Guidolotti et al., 2025). Some research further emphasized that drought events, combined with urban heat island effects, have led to significant growth reductions in several common urban tree species since the year 2000, with species-specific differences in drought tolerance (Franceschi et al., 2023). Other studies used sap flow measurements and model simulations to demonstrate that passive irrigation systems, although beneficial, are often insufficient to fully eliminate drought stress in young urban trees, particularly during increasingly dry years (Tams et al., 2023). These studies provide a good overview of the conditions faced by urban trees under the actual changing climatic conditions.

However, we don't know how climate change will impact the vitality of different tree species. The effect of climate change depends strongly on the presence of nutrients in the soil in which trees grow. In fact, as discussed by Gessler et al. (2017), nutrient availability strongly influences how trees respond to drought. Nutrients play a key role in several physiological processes, including water uptake, photosynthesis, and stress tolerance mechanisms, and can have a huge impact on the resistance, resilience and recovery of trees. Therefore, understanding nutrient dynamics is fundamental when studying tree responses to climate change factors, particularly in the complex and constrained conditions typical of urban environments. Some of the essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), play fundamental roles in the physiological processes of trees, especially in water absorption and transport. Nitrogen is crucial for synthesizing proteins and chlorophyll, directly influencing photosynthesis and overall growth. Phosphorus contributes significantly to energy transfer and root development, enhancing the tree's ability to absorb water and nutrients from the soil. Potassium regulates osmotic balance and controls the opening and closing of stomata, thereby facilitating transpiration and efficient water movement within the plant. A balanced availability of these nutrients optimizes water uptake, photosynthetic efficiency, and resilience to environmental stresses (Ma et al., 2022; Liu et al, 2024; Shah et al., 2025).

Another distinctive and often overlooked factor in urban ecosystems is the presence of dogs and the nutrient load they introduce through their urine. In fact, dog's urine contains significant amounts of nitrogen and phosphorus, as well as others important nutrients, which can alter the nutrient composition of urban soils and, consequently, affect tree health and growth dynamics, positively or negatively (Allen, et al., 2020). While these nutrients are essential for tree development, an excess can create imbalances or even environmental harm. Research by De Frenne et al. (2021) examined the role of fertilisation caused by dogs in peri-urban areas, demonstrating how such inputs can negatively influence plant communities. Similarly, Paradeis et al. (2013) and Marschner et al. (1996) highlight the crucial role of phosphorus in plant physiology, though noting the risks associated with excessive accumulation.

Safeguarding the vitality of urban trees, therefore, requires a multilayered approach that considers both the environmental factors typical of urban areas and the complex interactions affecting nutrient availability and water supply.

Aim of the study, research questions and hypotheses

The primary objective of this thesis is to investigate how different urban tree species respond to drought conditions in relation to the availability of nutrients in the soil. This will be accomplished by calculating specific drought tolerance indices: "resistance", "resilience", and "recovery." These indices quantitatively describe the trees capacity to withstand, adapt from, and recover to drought stress.

A central methodological tool employed in this study is dendrochronology. The analysis of tree rings provides valuable insights into past growth patterns and enables the reconstruction of historical drought events and tree responses over time (Ballikaya et al., 2022). Furthermore, the chemical analysis of tree rings offers an additional perspective by allowing the assessment of the nutritional status of trees throughout their lifespan (Binda et al., 2020).

Dendrochronological approaches have been extensively applied in forest ecosystems to study species responses to climate variability. Zhang et al. (2023), for example, conducted a study in subtropical forests of China, highlighting how tree growth in these ecosystems is strongly influenced by climate factors such as temperature and moisture. Their findings emphasize that climate warming, particularly through increased drought stress, significantly affects the radial growth of trees, with important implications for forest health and carbon sequestration capacity. Tognetti et al. (2019) examined tree growth dynamics in Mediterranean mountain forests, emphasizing how increasing temperatures and drought conditions contribute to growth decline and forest vulnerability. Their study highlights the strong link between water availability and tree productivity, suggesting that drought-induced reductions in growth can perform as early indicators of forest ecosystem stress. The consistent evidence across various forest ecosystems highlights the essential role of dendrochronological and isotopic research in evaluating the impact of climate-induced drought factors on tree growth and overall ecosystem stability. The research proposed by Cherubini et al. (2021) proved the strong potential of tree rings isotopic analysis for investigating trees response to drought factors and provide a vision on forest health dynamics. Recent study proposed by Zhang et al. (2024) further support that tree rings analysis reveals important growth reduction primarily resulted from drought in forests environments for various species. Numerous studies have also focused on urban trees as biological indicators of air pollution. For example, Battipaglia et al. (2010) highlighted a reduction in tree-ring growth in Pinus pinea growing in areas with high vehicular traffic, which was associated with isotopic variations and physiological alterations due to atmospheric contamination. Similarly, Ballikaya et al. (2022) revealed that tree rings in urban environments can contain nanoparticles originating from anthropogenic sources and suggest their potential as historical indicators of urban pollution.

This thesis seeks to strengthen this knowledge by integrating dendrochronological and chemical analyses to explore the relationship between nutrient availability, drought tolerance, and species-specific physiological responses in urban trees, with focus on Acer platanoides (L.), Betula pendula (Roth) and Robinia pseudoacacia (L.). This will be done by determining the resistance, resilience and recovery of each tree species.

The research questions are thereafter defined:

Question 1: Are drought events visible in tree rings?

Question 2: Do the plant species react differently to treatments, namely the presence of dogs or not, which can provide or not a higher amount of nutrients to trees? Does Robinia pseudoacacia, a nitrogen fixing species, reacts differently in comparison with other species?

Question 3: Which nutrient has the highest correlation with species tolerance indices?

Question 4: Do the presence of dogs in Zurich affects trees drought response in a positive or negative way? Which tree species has the highest resistance, resilience and recovery? Which has the lowest?

For the described four research questions, the following hypotheses have been formulated:

Hypothesis 1: It is supposed that drought events are visible in tree rings, but not every time. This variability is attributed to the more complex environmental conditions experienced by urban trees, compared to those growing in forests, where the effects of extreme climatic events are generally more clearly reflected in growth patterns.

Hypothesis 2: A different response is expected between trees exposed to dogs and those that are not, further a different response for the singular species, based on the assumption that the input of nutrients, particularly nitrogen, originating from dog urine, influences tree growth in a specific manner depending on the species. It is expected that Robinia pseudoacacia will contain a higher value of nitrogen in the samples subject or not to dogs and show higher values of resistance, resilience, and recovery in areas without dogs, where the soil nutrient balance is potentially more suitable for its physiological needs.

Hypothesis 3: The answers to this research question will be explored during the analysis of the data.

Hypothesis 4: It is supposed that Acer platanoides and Betula pendula would benefit from this nutrient input, showing improved growth and drought tolerance, while in the case of Robinia pseudoacacia, a nitrogen-fixing species, an excess of nitrogen may hinder its ability to respond to drought stress. The highest, respectively lowest, values of resistance, resistance and recovery will be detected during the development.

2. Methods

General description

To address the complex interactions between drought tolerance, nutrient availability, and urban environmental stressors, this Master's thesis adopts an integrative and multidisciplinary methodological approach. The research focuses on the analysis of different tree species growing in the urban area of Zurich, aiming to evaluate their physiological responses to drought events through dendrochronological and chemical analyses. A central component of the methodology is the use of tree-ring measurements to reconstruct growth patterns and quantify drought response indices: Resistance, Resilience, and Recovery (Lloret et al., 2011). These indices are then compared with drought conditions defined by the Standardized Precipitation-Evapotranspiration Index (SPEI), which was calculated based on temperature and precipitation data from Zurich (Vicente-Serrano, 2010).

The tree samples analyzed in this study differ not only by species but also by treatment condition: some individuals are regularly exposed to nutrient inputs from dog urine, while others grow in areas without such influence. This distinction allows for an additional layer of comparison to assess whether nutrient inputs from canine sources influence tree growth and physiological responses. In addition, chemical and isotopic analyses of wood, soil, and related environmental samples (e.g., leaves, dog urine, and pet food) are used to assess nutrient availability and investigate potential correlations with drought response. A variety of laboratory techniques, including ICP-OES, EA-IRMS, and XRF, are applied for precise elemental and isotopic determination (Hoenig, 1997; Werner and Brand, 2001).

The combination of ecological field data, tree-ring chronologies, and detailed chemical profiling enables a comprehensive evaluation of species-specific adaptations and sensitivities, providing insights into the role of nutrients and environmental stress in shaping the performance of urban trees (Ferrini et al., 2014).

This chapter is structured as follows: first, the study area and the role of dendrosciences in tree-ring research are introduced, followed by a description of the selected tree species and the rationale behind their selection. Subsequent sections detail the collection and preparation of wood, soil, leaf, urine, and pet food samples, the analytical techniques employed, and the statistical procedures used to address the research questions.

Study site

The analysed samples come from the city of Zurich, capital of the Swiss canton of the same name and the largest city the country, with an area of almost 92 km² (Xu et al., 2019). The city of Zurich is located in north-east Switzerland, at an altitude of 409 m above sea level (Swisstopo, 2025).

Its urban agglomeration has a population of 430'000 inhabitants, while the metropolitan region has 1.9 million inhabitants (Casali et al., 2019; Stadt Zürich, 2020). The metropolitan area of Zurich is divided into 12 districts of varying scale (Mueller et al., 2015). For several times Zurich was awarded as the city with the highest quality of life in the world (Kaklauskas et al., 2018). To the north, the city limits extend beyond the two hills Käferberg and Zurichberg. Beyond these two hills, the municipality spreads towards the Glattal. The eastern boundary of the city is represented by the Adlisberg mountain (701 msm), while to the west it extends up to the Uetliberg, which is the highest point of Zurich, with a height of 870 msm. Zurich is represented in large part by a lake named for it, the Zurichsee, situated at the south area of the city. The city is transversed by two rivers: the Limmat, which is an outflow of the lake, and the Sihl. The Limmat river represents the lowest point of the city, that near Oberengstringen reach the height of 392 msm, and flows along the north-eastern edge of the valley. The Limmat is part of the Rhine catchment area, emerging from the canton of Glarus (where it is still called Linth), before exiting Lake Zurich to its north-west under the name Limmat. On the other hand, The Sihl springs from Canton Schwyz, flows through the Sihlsee (the largest artificial lake in Switzerland), and concludes its journey as a tributary of the Limmat (Swisstopo, 2025).

Zurich lies within the temperate climatic zone of Central Europe, with four distinct seasons. Designed by the climate that results from its location and from the orographic configuration of Switzerland. Specific to the Alps, they have a particularly strong influence on local and regional climate, where they act as a climatic divide and cause strong spatial differences (MeteoSwiss, 2025a). Precipitation in Switzerland is highly heterogeneous and mostly driven by topographic variation. Moderate precipitation is recorded throughout the year in the northern regions, in particular Zurich, with maxima in the summer months, mostly caused by convectively active thunderstorms. Some studies have shown increases in the frequency and intensity of heavy precipitation events in recent decades, and this trend is likely to continue under future climate change scenarios (MeteoSwiss, 2025a).

Wind regimes are similarly modulated by the country's complex terrain. One of the most significant meteorological phenomenons is that of the Foehn, specifically a warm, dry downslope wind that falls over the Alpine ranges, affecting both northern and southern flanks. The Foehn is characterized by rapid increases in air temperature and pronounced decreases in relative humidity. A third wind type to potentially affect the region is the Bise, a cold and dry north-easterly flow dominating over the Swiss Plateau (and thus including the Zurich area).

Most commonly occurring in winter, the Bise is typically accompanied by clear skies and a marked drop in temperature (MeteoSwiss, 2022).

At the Zurich-Affoltern measuring station, located at 444 meters above sea level, the annual average temperature in 2024 was 11.4°C, with the lowest average monthly temperature recorded in December (1.9°C) and the highest in August (21.1°C). The total precipitation for the year 2024 was 1,190.5 mm, sunshine duration amounted to 1,405 hours, and the average humidity was 11.1 hPa. The station collects comprehensive meteorological data, including air temperature, air humidity, dew point, precipitation, atmospheric pressure, wind, global radiation, sunshine duration, snow, air temperature at 5 cm above ground, and soil temperature (MeteoSwiss, 2025b).

The samples were situated in an area between the Albisrieden and Sihlcity areas. On Figure 1 below are presented the locations of the trees analysed in this work.

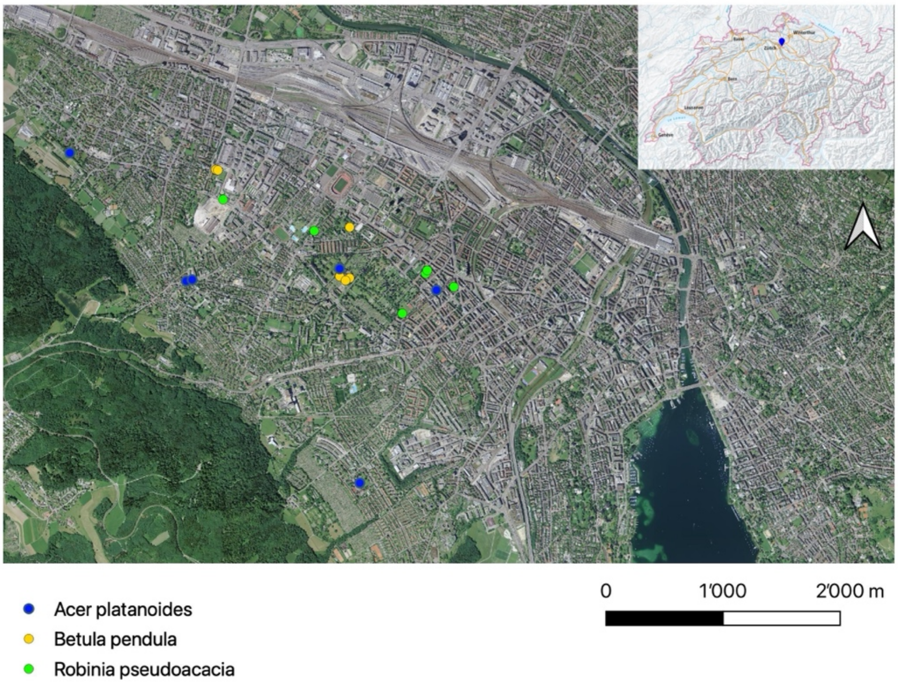


Figure 1: Satellite image of Zurich representing the location of the trees analyzed in this work (Maps from Swisstopo (2024) and GeoVite (2024), modified using QGIS).

Dendrosciences

Dendrosciences are a group of scientific disciplines that, through the analysis of tree rings, enable the study of variations in climate and environmental conditions over time. This field is divided into several specialized subdisciplines, among which Dendroecology and Dendrochronology are particularly prominent. Dendrochronology refers to the study of annual growth rings in trees, which allows for both the chronological dating of tree specimens and the identification of specific characteristics that reflect past climatic and environmental events (Schweingruber, 1996).

There are some key principles underlying this discipline. During the vegetative period, there is one new growth ring formed per year in trees. The size of a ring in a tree indicates the growing conditions for that specific tree in a specific year. A bigger width ratio indicates better growing conditions and smaller vice versa. When we look at a tree's cross-section, we can see several concentric rings, from the pith to the outside, with the current year's ring lying beyond the most recent one in the exterior layer. The enumeration of these rings permits the determination of the tree's age (Schweingruber, 1996).

Each ring is composed of two distinct components: earlywood, produced during the spring and characterized by larger cells with thinner walls, and latewood, formed in summer and typically denser and darker due to smaller cells with thicker walls (Schweingruber, 1988). Another principle asserts that climatic conditions influence the width of the annual rings. Trees of the same species growing within the same geographic area tend to form rings of comparable width in the same years, reflecting shared environmental influences (Fritts, 1976). The last principle involves the comparison of ring sequences among different trees of the same species through a process known as cross-dating, which allows for precise chronological alignment and verification of ring patterns (Stokes, 1996).

However, the visible rings in a cross-section do not always correspond precisely to the actual number of years the tree has grown. This discrepancy may arise due to the presence of false rings or missing rings. False rings are bands of latewood that form within a single growing season, typically in response to specific environmental stressors (Schweingruber, 1988). These features were observed in wood samples through radial microsections under high magnification, and their formation has been associated with periods of below-average rainfall in late summer, as well as with a combination of low precipitation and elevated temperatures in spring and summer (Copenheaver et al., 2010). While these structures can indicate how trees respond to drought, their formation isn't unique to water stress. False rings, however, do not entirely indicate drought conditions and can, depending on location, be useful proxies in paleodrought reconstructions (Wimmer et al., 2000; Vogel et al., 2001).

Missing rings refer to the absence of a growth ring for a known year, often due to extreme environmental stress, such as prolonged drought, pest infestations, or disease. In such cases, the tree may not produce sufficient wood tissue to form a visible ring. Accurate identification of false and missing rings during sample analysis is crucial, as they may otherwise lead to misinterpretations in chronological reconstructions.

Such a ring can also be an important signal of a tree's physiological reaction to certain meteorological events (Schweingruber, 1996; Coulthard & Smith, 2013).

Dendroecology is a subset of dendrochronology, which uses tree-ring patterns to study ecological process within forests. It more closely reflected natural conditions, as well as those with human management, as it provided insight into dynamics of forests. Dendroecological techniques allow scientists to date ecological events and disturbances, reconstruct historical climate and hydrology, and investigate relationships between environmental variability and biotic responses. Dendroecology is a powerful tool for interpreting long-term interactions between trees and their environment, as evidenced by these applications (Fritts and Swetnam, 1986; Rojas-Garcia et al., 2020).

Selection of tree samples

The samples used for the present analyses were provided by Grün Stadt Zürich (GSZ), which made a substantial number of specimens available for research purposes. Grün Stadt Zürich is a department of the municipal administration of Zurich, responsible for the planning, development, and maintenance of public green spaces. Its jurisdiction encompasses a wide range of areas, including parks, urban forests, sports and recreational facilities, cemeteries, public swimming pools, and playgrounds (Stadt Zürich, 2025).

The samples were supplied in the form of circular cross-sections of tree trunks, representing over thirty different species. A complete list of the samples provided is specified in the *Annexes* section. To save storage space and ease handling, the samples were later processed at the laboratories of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) in Birmensdorf, northeast of Zurich. The sections were sliced along the diameter into wooden strips (ca. 8 cm wide), thus ensuring all growth rings necessary to dendrochronological analysis were preserved in the respective sample.

Despite the considerable variety of available species, to perform statistical tests that would allow for meaningful comparisons between samples, it was decided to exclude species represented by fewer than three samples for each category, described as follows. Therefore, the analysis focused on samples from three main species: *Acer platanoides* (L.), *Betula pendula* (Roth), and *Robinia pseudoacacia* (L.).

The samples differ from one another in terms of species and the type of environmental conditions to which the trees were exposed. In this context, two distinct categories were defined based on the environmental conditions:

- Dog refers to trees growing along roadsides, typically confined within a small volume of open soil.
- No Dog refers to trees located in areas where access to dogs is restricted, such as schoolyards or playgrounds.

The following table summarizes the species and treatment types of the wood samples prepared in laboratory for the comparison (*Table 1*).

Table 1: Tree species and wood samples used for the analysis.

Tree species	**Dog**	**No Dog**	**Total number of samples**
Acer platanoides	3	3	6
Betula pendula	3	3	6
Robinia pseudoacacia	3	3	6

Two types of analyses were carried out on these samples. Initially, the width of the annual growth rings was measured for each specimen, after which the series were crossdated to enhance the reliability and precision of the measurements. The second analytical procedure involved the examination of isotopic composition and nutrient content within the wood samples.

Samples collection

As mentioned above, as far as wood samples are concerned, they were made available by Grün Stadt Zürich. The cross-sections were retrieved from one of the department's storage facilities, located in the Wiedikon district of Zurich, and subsequently transported to the main headquarters of the WSL in Birmensdorf.

Soil and leaf samples were collected within the city of Zurich. Since the trees from which the wood samples were obtained had already been felled, it was not possible to collect leaf samples directly from them. For this reason, the soil and leaf samples were collected from trees located near the original of wood samples, to maintain the highest possible consistency across samples. For the collection of these samples, it was necessary to request permission from Grün Stadt Zürich and once this was obtained and sample collection could then proceed. For each species, a total of six trees were selected: three classified as Dog trees and three as No Dog trees (Table 2).

Table 2: Tree species and number of trees from which the samples were collected.

Tree species	Dog	No Dog	Total number of samples
Acer platanoides	3	3	6
Betula pendula	3	3	6
Robinia pseudoacacia	3	3	6

The remaining sample set includes dog urine and petfood, that were collected from three dogs in the Canton of Ticino. Table 3 presented below, provides relevant information regarding the dogs whose samples were analyzed in the course of the present study.

Table 3: The dogs from which the samples of urine and petfood were analyzed.

Name	Age [years]	Gender
Newton	<1	Male
Grinta	12	Female
Coco	8	Male

Description of the species

Acer platanoides

Acer platanoides (L.) (Norway maple) is a tree species native to Europe and eastern Asia. In Switzerland, it is generally sparsely represented. The highest concentrations occur in the eastern Jura region and along the northern edge of the Alps, particularly in areas with warm summers and moderately continental climates. The species prefers colline and submontane broadleaf mixed forests, and on base-rich, well-supplied soils such as those found in hollows, ravines, and moist hillside areas. In quantitative terms, Acer platanoides accounts for only 0.2% of the total tree stems in Swiss forests, making it a relatively rare species. It does not form pure stands and is typically found in mixture with other broadleaf species. The wood of this species is elastic and resistant to compression. The species exhibits moderate natural regeneration and is comparatively less affected by browsing pressure from wild ungulates than other broadleaf trees (Brändli, 1998; LFI, 2024).

Betula pendula

Betula pendula (Roth) (silver birch) is a tree species present in the continents of Europe and Asia. In Switzerland, it is most found on the southern side of the Alps, particularly north of Canton Ticino, and in alpine regions such as Valais and the upper Rhine valley. It prefers acidic soils and steep slopes, and it often colonises disturbed sites such as clearings, landslides, and former fire areas. This species shows a broad ecological tolerance and typically occurs between 800 and 1200 m a.s.l., sometimes reached up to 1900 m. It requires light for regeneration and is therefore mostly found in open-canopy environments. In Swiss forests, accounts for 1.3% of stems, making it more common than several other native broadleaved species, for example the above-mentioned Acer platanoides. Betula pendula is distinctive because it can facilitate forest regeneration on recently disturbed sites. This species forms long-lasting pioneer forest stages, often after fires (Brändli, 1998; LFI, 2024).

Robinia pseudoacacia

Robinia pseudoacacia (L.) (black locust) is a tree species native to southeastern North America, introduced to Europe in the early 17th century. In Switzerland, it is most found on the southern side of the Alps, mostly on the south-east part, and in lowland regions of the Plateau and eastern Jura, often associated with river systems such as the Rhône, Reuss, and Aare. It thrives on dry, nutrient-poor sandy soils and is especially competitive in warm slopes. Although it prefers calcareous soils, it is frequently found on moderately acidic substrates. Robinia accounts for 0.2% of tree stems in Swiss forests, making it the most common non-native tree species. It is often found in broadleaf mixed stands or in pure formations, and it regenerates effectively through both seed and root suckers. Due to its rapid growth and nitrogen-fixing ability, it is used for stabilising slopes, post-fire regeneration, and afforestation of degraded soils. While it produces hard, durable wood suitable for construction and energy use, concerns have been raised regarding its invasive behaviour, particularly in ecologically sensitive areas of southern Switzerland. Its future spread remains uncertain, given its low proportion of young individuals in current forest inventories (Leibundgut, 1991; Brändli, 1998; LFI, 2024).

Preparation and analyses of the samples

Tree-ring width measurement and cross-dating

The wood samples remained in the WSL warehouse for several weeks, stacked with small wooden spacers placed between them to allow air circulation. This procedure ensures proper drying of the samples, which is essential for obtaining high-quality analytical results (Stokes, 1996; Speer, 2009). Since many of the wooden cylinders were large, they were initially cutted into smaller pieces to improve handling and optimize storage space during the analysis period. The cutting process was performed using a table saw. Subsequently, the samples were sanded using a sanding machine. The first dimension of sandpaper used was the grit 60 μm, followed progressively by grits 80 μm, 120 μm, 160 μm, 180 μm, 200 μm, and finally 240 μm. A stepwise approach between sanding grits is essential to preserve the integrity of the surface and to achieve the smoothest possible finish, which facilitates subsequent microscopic analysis (Asherin and Mata, 2001).

Once the sanding was completed, the samples were digitized using a specialized system developed at the WSL by Holger Gärtner and Loïc Schneider, known as Skippy. This dendrochronological imaging system consists of four main components: a movable platform on which the sample is placed, a high-resolution camera, a light-shielding structure with adjustable curtains, and a computer. The scanning process proceeds as follows: the sample is positioned on the sliding platform, with care taken to align it horizontally to facilitate focusing. This is achieved using small plastic supports placed under the sample. As the platform moves, the camera captures a sequence of high-resolution images. The total number of images per sample depends on its size: the larger the sample, the more images are required. These individual images are then stitched together using the software PTGui to create a single panoramic image of the sample (New House Internet Services BV, 2025).

Once the panoramic image was available, the measurement of the annual ring widths was carried out using the Coorecorder software. This program is widely used in dendroclimatology, climate change research, ecological modeling, and other studies involving the analysis of tree-ring data (Cybis Elektronik and Data AB, 2021). The first step in this process was the calibration of the scale using a millimeter grid that was previously placed on the sample and is visible in the panoramic image. Once calibrated, the latest ring was marked by clicking on its outer boundary and assigning the corresponding calendar year. The rings were measured progressing toward the center of the sample, the boundaries between them was marked. The software automatically assigns the appropriate year based on the previously defined outermost ring, assumed to be the most recent. For precise measurements, it is crucial that the distances are recorded as perpendicular as possible to the ring boundaries. Following this process in Coorecorder, the measurement files are converted into .fh format using the companion software CDendro. This program facilitates the organization of sample collections and integrates with Coorecorder for advanced dendrochronological analyses (Maxwell and Larsson, 2021). The data in .fh format were then used to crossdate the samples.

Cross-dating was conducted using the TSAPWin software and was performed among samples of the same species (Rinntech, 2024). This procedure enhances the reliability of the collected data and enables the identification of growth patterns over time for a given species. Based on the previously obtained ring-width measurements, graphical plots were generated for each sample. These plots were compared across multiple specimens to assess whether their growth trends aligned or if deviations were observed (Fritts, 1971; Stokes and Smiley, 1996; Phipps, 1985). Typically, trees of the same species growing in climatically similar environments are expected to exhibit comparable annual growth patterns, with favourable climatic years resulting in wider rings, and unfavourable years yielding narrower rings (Wilmking et al., 2019).

Nutrient and isotope analyses

This chapter outlines the collection and analysis of the various types of samples used in the study. The first sections provide a detailed description of the preparation procedures for each sample, with specific protocols depending on the material of origin. As many of the samples were subjected to the same analytical techniques, these methods are described separately in the second part of the chapter. This structure enhances the clarity of the experimental workflow and facilitates the understanding of the analyses performed and the data subsequently presented.

Preparation of wood samples

The wood samples previously analyzed during the cross-dating process were subjected to two types of laboratory analyses: Elemental Analysis–Isotope Ratio Mass Spectrometry (EA-IRMS) and Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) (Wilschefski and Baxter, 2019).

Initially, the samples were subdivided into smaller wood fragments to allow for precise sectioning. From each species, two groups of four annual growth rings were cut: one corresponds to the period of years 2016–2019 and the other to 2020–2023. This operation was performed under a microscope using a scalpel to ensure high precision. The reason of these two separate groups was that it was aimed to compare the nutrient values between two wood blocks, given that, following the COVID-19 pandemic, the number of dogs in Zurich increased (FSO, 2024). However, after analyzing the results, it was decided not to proceed with the comparison, as the increase in the number of dogs during the second period, although present, was not sufficient to detect reliable variations. Proceeding with the comparison could have led to misinterpretations of the data. Once the four-year wood sections were obtained, they were ground into a fine powder using a ball mill. An initial attempt to use a centrifugal mill resulted in combustion of the samples during the grinding process. Consequently, the ball mill was selected as it allowed for the preservation of the samples' elemental composition. Ball milling is a well-established mechanical method that employs high-energy grinding to reduce the particle size of materials. It is particularly effective for producing fine powders or nanoscale particles. The method involves placing bulk material into a container with heavy grinding balls, which exert mechanical forces through continuous impact and friction, gradually reducing the material to finer particles (Kumar et al., 2020; Bor et al., 2021).

For the EA-IRMS analysis, each powdered sample was weighed and placed into tin capsules. Each sample required duplicate preparation: one set for carbon (C) analysis and another for nitrogen (N) analysis. Tin capsules measuring 3 × 3 mm were used for the quantification and isotopic analysis of carbon, while capsules measuring 5 × 8 mm were used for nitrogen analyses. The procedure necessitates separate measurements of the two elements, as the quantification of each requires different analytical conditions (Brodie et al., 2011; Schollaen et al., 2017). The prepared capsules were stored in a designated plastic container and subsequently delivered to the Central Laboratory at the WSL.

The remaining powdered material from each sample was placed in Eppendorf tubes and submitted to the WSL Central Laboratory for further analysis via ICP-OES.

Preparation of soil samples

To perform the soil analyses, approximately 200 grams of soil were collected for each sample. Initially, the samples were dried in an oven at 70°C for 48 hours. After drying, the samples were sieved. A ceramic mortar was used to crush the soil into smaller particles, which were subsequently passed through a 2 mm mesh sieve. Soil fractions greater than 2 mm and those smaller than 2 mm were separated and placed into properly labelled plastic bags (Rowell, 1994; ISO, 2006).

The soil fraction smaller than 2 mm was then ground using a ball mill. The grinding process was carried out as follows: the soil samples were placed inside a metal capsule made of an alloy, which also contained two grinding balls. Approximately 10 grams of soil were weighed and inserted into the capsule. Once sealed, the capsule was placed into one of the machine's holders, while another sample was prepared in the same way and positioned in the opposite holder. It is essential that the two capsules are aligned symmetrically: either both with the lid facing inward or both facing outward. Moreover, the machine must only be operated when both holders are loaded. If only one sample is to be ground, the second holder must contain an empty capsule without grinding balls (Suryanarayanana, 2001). This is necessary to maintain mechanical balance; otherwise, the unbalanced motion could cause one of the capsules to detach, potentially damaging the equipment. If an empty capsule containing grinding balls were used, the balls, lacking resistance, would strike the inner walls with excessive force, posing a risk of structural damage (Suryanarayanana, 2001).

After grinding, the soil samples were weighed into tin capsules. For each sample, between 4 and 6 grams of material were measured, and the exact weight was recorded. The capsules were then sealed using two tweezers, aiming to form a rounded shape to ensure optimal conditions for subsequent EA-IRMS analysis (Werner and Brand, 2001).

A part of the ground samples was then prepared for XRF analysis. The first step involved preparing the sample holders in which the soil would be placed. Each holder consists of two plastic cylinders, one slightly smaller than the other. A thin plastic film is positioned between them, and the smaller cylinder is gently pressed into the larger one so that the film becomes taut and forms the base of the sample cup. It is crucial that this film remains smooth and even, as it allows X-rays to penetrate the sample and reflect correctly. Any surface irregularities may scatter the radiation and result in distorted measurements. For this reason, proper preparation of the container is just as important as the sample analysis itself, as improper handling can lead to inaccurate results. Each container is sealed with a plastic lid before measurements are taken. Inside the capsule, raised reference lines indicate the minimum amount of sample material required to proceed with the analysis (Jenkins, 2000).

Preparation of leaves samples

For each tree, between 5 and 10 leaves were sampled using a 2-meter extendable pruning shear. To minimize potential damage to the trees, soil sampling was carried out approximately 20 cm away from the trunk to avoid unintentional disturbance of the root system (Cornelissen et al., 2003).

The collected samples were then placed in a drying oven at 60°C for 24 hours to remove residual moisture prior to the grinding process (Wolkers and Oldenhof, 2021; Juckers et al., 2024). Grinding was performed using a Retsch ZM 1000 centrifugal mill equipped with a 12-tooth rotor, reducing the samples to a particle size of 0.25 mm. Following grinding, the samples were weighed: 2 mg of leaf material per sample. Samples were weighed using a precision balance and placed into 3x3 mm tin capsules. These capsules were then sealed as spherically as possible after expelling as much air as possible, to ensure optimal conditions for subsequent elemental analysis (Dunn and Carter, 2018).

The sealed capsules were organized in a plastic sample tray, with each slot clearly numbered. The tray was then delivered to the WSL laboratory responsible for conducting elemental and isotope analyses. In addition to the physical samples, a detailed Excel spreadsheet was completed, including relevant metadata such as sample name, weight, capsule material, and position into tray. At the Central Laboratory, EA-IRMS analysis were conducted, and it enables the determination of total carbon and nitrogen content, as well as their stable isotope ratios (δ13C and δ15N) (Langel and Dyckmans, 2014; Dunn and Carter, 2018). The analytical procedure is described in detail in the chapter dedicated to the IRMS methodology.

The amount of carbon within plant tissues reflects the atmospheric composition absorbed by the tree, while the δ13C ratio indicates the degree to which environmental conditions were favourable to growth. Nitrogen content is an indicator of nutrient availability, as nitrogen is essential for plant development. Isotopic signals help determine whether such environmental signals are effectively recorded in leaf and wood tissues (Dawson et al., 2002; Craine et al., 2009).

Preparation of dog urine and pet food samples

To analyze the nutrient content of dog urine and petfood, samples were collected and processed following specific preparation protocols to ensure accuracy and consistency in the results. These steps were necessary to prepare the materials for analysis using EA-IRMS. One of the primary objectives of this analysis was to examine the correlation between the C and N content in the petfood and the metabolic outputs observed in the urine (Dunn and Carter, 2018; Wolkers and Oldenhof, 2021).

Urine samples were collected from 3 dogs, and a small quantity of their respective pet food (8 g approx. for each dog) was obtained for analysis. The collection was conducted with careful consideration to avoid contamination, ensuring that the samples remained representative and suitable for subsequent testing. The collected urine samples were frozen in a standard freezer for two hours until they reached a solid state. This initial freezing step was essential for preserving the samples and preventing any degradation of the components (Wolkers and Oldenhof, 2021; Lu et al., 2024). Once solidified, the urine samples were transferred to a lyophilizer (freeze dryer) and subjected to freeze-drying for 24 hours. This process removed all water content from the samples while preserving the chemical integrity of the nutrients, leaving a dry, stable sample ready for further analysis (Juckers et al., 2024; Lu et al., 2024).

The petfood samples were processed separately (Kuhnle et al., 2013; O'Brien, 2018). Each sample was first dried in a laboratory oven set at 60 °C for 24 hours. The drying step was crucial to remove moisture and standardize the samples for subsequent grinding (Dunn and Carter, 2018). After drying, the food samples were finely grounded using a laboratory centrifuge to obtain a homogenous powder. This homogenization ensured consistency in the analysis, minimizing variability due to particle size (Carabel et al., 2006; Zhao et al., 2020). Finally, a quantity of 1 mg of the ground food sample was weighed and placed into a tin container, which served as the sample vessel for the analysis.

Once prepared, all samples were labelled and sent to the Central Laboratory of WSL, that provided EA-IRMS analysis. The goal was to determine the nutrient composition of the samples, focusing on key elements such as nitrogen, carbon, and their isotopic ratios. This data provided insights into the nutritional profiles of the samples, enabling comparisons between the dietary intake and metabolic outputs of the dogs (Werner and Brand, 2001).

Elemental Analysis Isotope Radio Mass Spectrometry (EA-IRMS)

EA-IRMS (Elemental Analysis Isotope Ratio Mass Spectrometry) analysis was performed on samples of wood, soil, leaves, petfood, and urine. This analytical technique allows for the assessment of the relative isotopic abundance in both natural and synthetic samples. It is particularly effective in detecting small variations in the isotopic ratios of specific elements, namely: $^{1}H/^{2}H$, $^{12}C/^{13}C$, $^{14}N/^{15}N$, and $^{16}O/^{18}O$ (Werner and Brand, 2001; Dunn and Carter, 2018).

The analytical instrument is composed of three main components: the Elemental Analyzer, the Continuous Flow Interface, and the Isotope Ratio Mass Spectrometer (Rodrigues et al., 2013). Figure 2 illustrates the structural layout of this system.

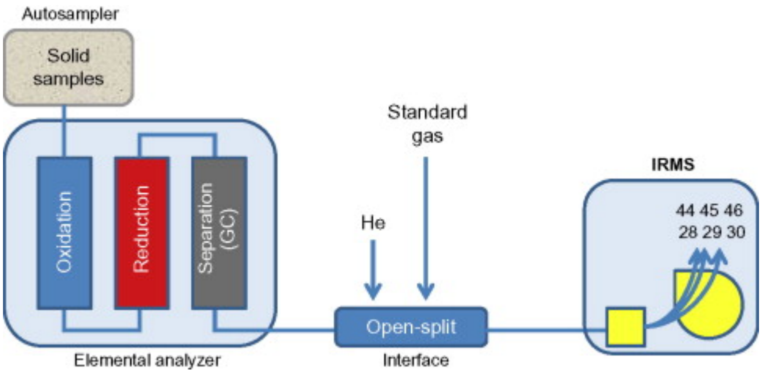


Figure 2: Schematic representation of a EA-IRMS system (Rodrigues et al., 2013).

In the initial phase, the samples are introduced into the Elemental Analyzer, where they undergo combustion, followed by a series of oxidation and reduction reactions. Water (H_2O) is then removed from the system. Subsequently, a gas chromatography column separates the N_2 and CO_2 gases. In the Continuous Flow Interface, the sample gas flow is split and reduced to prepare it for the final stage of the process. Within the Isotope Ratio Mass Spectrometer, gas molecules are ionized, then separated and collected based on their mass-to-charge ratio (Dunn and Carter, 2018). Upon completion of this sequence, the isotopic data for $\delta^{13}C$ and $\delta^{15}N$ are obtained (Rodrigues et al., 2013).

In addition to EA-IRMS (Elemental Analyzer–IRMS), other types of IRMS systems exist, that comprehends such as GC-IRMS (Gas Chromatography–IRMS) and C-IRMS (Combustion–IRMS), which are used depending on the nature and state of the sample material (Sharp, 2007).

X-Ray Fluorescence (XRF) Analysis

X-ray fluorescence (XRF) is an analytical atomic technique used to perform chemical analyses of environmental material samples by detecting X-ray fluorescence emission (Jenkins, 2000). It is a method that enables rapid acquisition of elemental data from the material under investigation. Several types of XRF techniques exist, including Wavelength Dispersive XRF (WDXRF), Energy Dispersive XRF (EDXRF), Polarized EDXRF (P-EDXRF), 3D-EDXRF, micro-EDXRF (μ-EDXRF), and Total Reflection XRF (TXRF) (Jenkins, 2000; Van Grieken and Markowicz, 2002).

Sample preparation protocols vary depending on several factors, most notably the physical state of the material, whether solid or liquid. For solid samples, various preparation techniques are available, such as pressed pellets, loose powder, fused beads, solid suspensions, acid digestion, and direct analysis. For this study, the loose powder method was selected, as it is particularly well-suited for this type of analysis and is characterized by a shorter preparation time compared to other techniques. In general, sample grinding to a particle size of approximately 60 μm is recommended to achieve reliable analytical results. For certain more complex samples, additional pre-treatment may be required; however, this was not necessary in the present study, where the samples were processed directly for XRF analysis (Jenkins et al., 1995; Queralt et al., 2016).

For this Master's Thesis, XRF analysis was done at the laboratories at the University of Zurich. The samples were placed inside the capsules and their corresponding masses were recorded, then the capsules were inserted into the device. The instrument has eight available positions, allowing eight samples to be analyzed per cycle. Each sample requires approximately 35 minutes to be analysed, resulting in a total cycle duration of 4 hours and 40 minutes (Jenkins, 2000).

The underlying principle of X-ray fluorescence (XRF) is based on the interaction between high-energy incident photons and atoms within the sample. Upon exposure to X-rays, inner-shell electrons are ejected, creating an unstable electron configuration. This instability is resolved when electrons from outer shells transition to fill the vacancies, releasing energy in the form of characteristic X-ray photons (Jenkins, 2000). The energy emitted is specific to each element and is described quantitatively by Moseley's Law (1914):

$$\sqrt{\nu} = k_1 \cdot (Z - k_2)$$

Where:

- ν represents the frequency of the X-ray emission line.
- Z is the atomic number.
- k_1 and k_2 are the constant of the specific radiation and the shielding constant, respectively.

Because of the electronic transitions described by Moseley's Law, each chemical element emits X-ray fluorescence at discrete and characteristic energy levels (Jenkins et al., 1995; Thompson et al., 2009). This results in a unique emission spectrum that facilitates both the qualitative identification and quantitative determination of elements present in the sample.

The detector within the XRF instrument captures the emitted photons and converts them into electrical signals, which are recorded as intensities over corresponding energy ranges. These intensities form an XRF spectrum specific to the analyzed material, from which the relative abundances of detectable elements can be assessed. From this spectrum, it is possible to determine the relative abundance of each detectable element (Jenkins et al., 1995; Thompson et al., 2009).

X-ray fluorescence analysis enables the quantification of elements with atomic numbers equal to or greater than that of sodium (Na). However, it is inherently limited in its capacity to detect light organic elements such as hydrogen (H), carbon (C), and nitrogen (N), which do not emit detectable characteristic X-ray lines under typical excitation conditions. Consequently, the elemental concentrations obtained via XRF represent relative percentages based solely on the detectable inorganic fraction of the sample. These values should therefore be interpreted with caution, especially in matrices containing significant organic matter. The accuracy of XRF quantification tends to be higher in mineral-rich or inorganic-dominated samples (Jenkins et al., 1995; Van Grieken and Markowicz, 2002).

To improve the interpretability of results in samples with organic content, a complementary technique known as Loss on Ignition (LOI) is commonly employed. LOI provides an estimate of the organic and volatile components by measuring mass loss upon combustion and is further discussed in the following chapter (Jenkins et al., 1995; Van Grieken and Markowicz, 2002).

Loss on ignition (LOI)

Loss on Ignition (LOI) is an analytical chemistry technique aimed at investigating the inorganic components of a sample. This procedure is particularly used in the study of minerals and soil constituents, and its primary objective is to quantify the proportion of organic matter within a sample by thermally removing it (Heiri el al., 2001).

Soil consists of a wide range of components, including living organisms, water, carbonates, organic material, decaying matter, and others and to quantify the relative proportion of a specific component within the total soil mass, the LOI technique is commonly employed (Santisteban et al., 2004). The procedure begins with the weighing of the soil sample prior to ignition. The sample is then placed in a heating device, such as a muffle furnace, where it is subjected to a specific temperature, selected according to the target component to be measured. The soil is held at this temperature for a defined period, after which it is cooled and weighed again. The difference in mass before and after heating corresponds to the amount of the targeted component that has been volatilized. The fundamental equipment required for conducting LOI includes a high-precision analytical balance, a drying oven, a temperature-controlled furnace, preheated crucibles, and a representative soil sample collected from the area of interest. The LOI method has a broad range of applications in scientific research. Its specific application depends on the nature of the material being analyzed, and the interpretation of results must be tailored accordingly (Heiri et al., 2001; Schumacher, 2002).

During the analyses, only the soil samples were subjected to Loss on Ignition (LOI), while this procedure could not be performed on the wood samples. In order to obtain more comparable values, the soil concentrations presented in the Results chapter are expressed as relative values and have not been subjected to LOI normalization. However, the results from the LOI analysis performed on the soil samples are provided in the Appendix chapter.

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) is an analytical technique used to detect and quantify chemical elements based on the emission of light from excited atoms and ions (Thompson et al., 2009). The technique employs a high-temperature plasma source that reaches temperatures between 6000 and 10,000 K. The source, typically argon gas, is ionized and sustained by inductive coupling at megahertz frequencies. This plasma excites atoms and ions in the sample, causing them to emit light at element-specific wavelengths, with the intensity of the emitted light being directly proportional to the concentration of each element (Tyler and Yvon, 1995).

For the analyses conducted at WSL, wood samples were submitted to the Central Laboratory, which carried out the procedure. The previously prepared samples were first subjected to digestion. This process involves the addition of nitric and hydrofluoric acid and is performed under pressure using microwave-assisted digestion in the Ultraclave IV system (MLS GmbH). All samples are digested in duplicate, together with certified reference materials and blanks, to ensure the accuracy of the procedure. The resulting digestion solutions are then diluted and analyzed using the ICP-OES 5800 instrument (Agilent). Each run includes internal controls and externally certified standards to validate the measurements. For accurate results, the samples must be dry and finely ground, with a minimum of 650 mg of material (WSL, 2023).

Meteorological data

Monthly Mean Precipitation and Mean Temperature

Many studies have shown a progressive decline in water availability, particularly in urban areas, where local conditions can intensify drought effects (MeteoSwiss, 2023; WSL, 2023). Although total annual precipitation has remained relatively stable, its irregular distribution has led to longer and more intense drought periods. Future projections indicate a further increase in water stress across Switzerland (NCCS, 2018).

To investigate the impact of drought on urban tree growth, this study integrates climatic data with dendrochronological analysis using standardized drought indices. Monthly mean temperature and precipitation data were obtained from the Zurich Affoltern meteorological station, managed by MeteoSwiss (Meteoswiss, 2024). All the tree samples were collected in Zurich, particularly in areas near this station, for this reason the meteorological data from Zurich Affoltern were considered representative of the entire urban area. Minimum, maximum, and average monthly values for both precipitation and temperature were used to construct the climatic indices applied in this study (Vicente-Serrano et al., 2010). The information concerning the station are visible in the Table 4.

Table 4: Geographical informations about the meteorological station of Zurich Affoltern.

Stations name	Abbreviation	Latitude	Longitude	Altitude [m a.s.l.]
Zurich Affoltern	REH	47.4276	8.5179	444

Assessment of SPEI values

The Standardized Precipitation-Evapotranspiration Index (SPEI), a widely used indicator of drought severity, was calculated following the method proposed by Vicente-Serrano et al. (2010), Beguerìa et al. (2014) and Stagge et al. (2014). This index quantifies water balance anomalies by incorporating both precipitation and potential evapotranspiration (PET). Its applicability across multiple time scales makes it particularly suitable for assessing both short- and long-term drought events (McKee et al., 2003; Vicente-Serrano et al., 2010).

In this study, the Hargreaves-Samani method was employed to estimate PET, due to its suitability for datasets with limited meteorological variables (Hargreaves and Samani, 1985). The input climatic variables considered include: Precipitation (*P*) [mm], Mean Temperature (*Tmean*), Maximum Temperature (*Tmax*), and Minimum Temperature (*Tmin*) [°C].

The Hargreaves-Samani equation used for monthly PET estimation is as follows:

$$\mathrm{PET} = 0.0023 \times (T_{mean} + 17.8) \times \sqrt{T_{max} - T_{min}} \times \; Ra \; \cdot N$$

Where:

- T_{mean} is the monthly mean air temperature [°C].
- T_{max} is the monthly maximum air temperature [°C].
- T_{min} is the monthly minimum air temperature [°C].
- Ra is the etraterrestrial radiation [MJ/m^2/day].
- N is the number of days within a month.

Ra was previously determined using the following formula (Allan et al., 1998):

$$R_a = \frac{24 \times 60}{\pi} \cdot G_{sc} \cdot d_r \cdot [\omega_s \cdot \sin(\phi) \cdot \sin(\delta) + \cos(\phi) \cdot \cos(\delta) \cdot \sin(\omega_s)]$$

Where:

- G_{sc} = 0.0820: the solar constant [M/m^2/min]
- $d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi J}{365}\right)$: relative Earth-Sun distance factor
- $\omega_s = \arccos(-\tan(\phi) \cdot \tan(\delta))$: sunset hour angle
- ϕ = latitude
- $\delta = 0.409 \cdot \sin\left(\frac{2\pi J}{365} - 1.39\right)$: solar declination
- J = Julian day of the year

The water balance (BAL) is calculated by subtracting PET from precipitation (P):

$$\mathrm{BAL} = P - \mathrm{PET}$$

This value represents the monthly water surplus or deficit, which serves as the basis for drought quantification (Vicente-Serrano, 2010; Beguerìa et al., 2014).

The SPEI was computed using the statistical software R and the spei() function provided by the SPEI package (Beguerìa & Vicente-Serrano, 2023). This index standardizes the water balance series by fitting the data to a Generalized Extreme Value (GEV) distribution and calculating standardized scores based on the deviation from the mean. The following formula is a simplified version of the calculation, based on Stagge et al. (2014):

$$\mathrm{SPEI} = \frac{\mathrm{BAL} - \mu}{\sigma}$$

Where:

- μ is the mean of the normalized water balance.
- σ is the standard deviation of the normalized water balance.

The computation of SPEI produces a monthly index value. To evaluate the impact of drought on tree growth, SPEI was additionally calculated to reflect conditions during the plants growing season. Specifically, a vegetative SPEI was derived as the average of monthly SPEI values over the growing period, defined as extending from March to August (Beguería et al., 2014; Rossi et al., 2014; Huang et al., 2019; Beguería & Vicente-Serrano, 2023).
The following generic formula allows for the calculation of vegetative SPEI across multiple timescales.

$$SPEI_{\mathrm{veg}}^{k} = \frac{1}{n}\sum_{i=1}^{n} SPEI_{i}^{k}$$

Where:

- $\mathrm{SPEI}_{\mathrm{veg}}^{\mathrm{k}}$ is the seasonal average SPEI for temporal scale k
- n is the number of months in the growing season (in this case, n =6, from March to August)
- $\mathrm{SPEI}_{\mathrm{i}}^{\mathrm{k}}$ represents the monthly SPEI value for month i at temporal scale k

Therefore, the growing season, defined as the period from March to August, is as follows (Rossi et al., 2014; Huang et al., 2019):

$$SPEI_{\text{veg}}^{k} = \frac{1}{6}\sum_{i=3}^{8} SPEI_{i}^{k}$$

The obtained SPEI values represent the drought intensity during the growing season of a specific year. The lower the value, the more severe the drought conditions, and vice versa. Table 5 represents the classification of drought events, based on the criteria provided by Vicente-Serrano et al. (2010).

The SPEI was computed at two different time scales, namely SPEI-3 and SPEI-12, to investigate the temporal characteristics of drought and their potential impact on tree growth (Tognetti et al., 2019; Yang et al., 2020). This multiscale approach allows for the detection of both short-term and long-term drought events, enabling a more specific interpretation of their consequences. SPEI-3 enables the identification of droughts that affect vegetative growth over the course of a season, while SPEI-12 captures long-term trends, highlighting persistent drought conditions on an annual or multi-annual scale (Yang et al., 2020; Zhang et al., 2023). With multiple temporal scales, it becomes possible to differentiate between meteorological, agricultural, and hydrological droughts, thereby providing a comprehensive overview of water scarcity dynamics over time (Vicente-Serrano et al., 2010). The SPEI value for a given temporal scale *k* is obtained by computing a moving average over the preceding k months of monthly water balance data. For example, the SPEI-3 is calculated by summing the water balance values of the previous three months and standardizing the result to obtain a final index value. The same procedure is applied for SPEI-12, with the only difference being that the water balances of the twelve preceding months are used (Vicente-Serrano et al., 2010; Beguería & Vicente-Serrano, 2023).

Table 5: Drought classification based on the SPEI values (Vicente-Serrano et al., 2010; Koutsoyiannis and Montanari, 2022).

Drought classes	SPEI values
Extreme wet	≥ 2
Severe wet	1,5 to 1,99
Moderate wet	1,0 to 1,49
Slightly wet	0,5 to 0,99
Normal	-0,49 to 0,49
Mild dry	-0,99 to -0,5
Moderate dry	-1,49 to -1,0
Severe dry	-1,5 to – 1,99
Extreme dry	≤ -2

Subsequently, for each of the computed SPEI indices, the eight driest years were identified.

Assessment of drought years

A drought year is defined as a year in which significant drought conditions occur, characterized by a prolonged period of below the normal water availability (Beithou et al., 2022). This phenomenon may result from precipitation levels below the long-term average, elevated temperatures that increase evapotranspiration, or a combination of both factors (Vicente-Serrano et al., 2010). Drought can have detrimental effects on tree growth and water resources (Linares et al., 2010).

Based on these SPEI values described in the previous chapter, the eight driest years within the study period were identified for the two temporal scales. They were identified from the values obtained for each year and subsequently used for the calculation of drought tolerance indices (Hirsch et al., 2023). These selected years provided the basis for calculating three growth-related indicators from the tree-ring data: average ring width before, during, and after each drought year. From these measurements, three drought tolerance indices were derived: resistance, resilience, and recovery. These indices quantify a tree's ability to maintain growth during drought, regain pre-drought growth levels, and recover after stress. By comparing tree growth data with climatic conditions, this methodological framework enables a temporally explicit evaluation of species-specific responses to drought, contributing to a better understanding of urban tree adaptation under increasing climate stress (Lloret et al., 2011).

Assessment of Tolerance Indexes

To calculate the tolerance indices, it was necessary to apply certain corrections to the measurements of the annual growth rings. The width of these rings is, in fact, subject to temporal variation, which requires data correction (Fekedulegn et al., 2003, Martínez-Vilalta, 2012). Factors such as tree age tend to reduce the climate sensitivity of annual rings over time.

Through the process of detrending, the raw values are adjusted to eliminate these effects, resulting in a measure that is not influenced by such factors and can be reliably compared across different samples.This adjusted value is referred to as the Ring Width Index (RWI) (Fekedulegn et al., 2003, Martínez-Vilalta, 2012, Xu et al., 2017, Bose et al., 2019).

After identifying the eight years characterized by the most extreme drought conditions, based on the SPEI calculated for the growing season, three key indicators were calculated to quantify tree responses to such events: Ring Width Index Before Drought Event (RWI_{BDE}), Ring Width Index During Drought Event (RWI_{DDE}), and Ring Width Index After Drought Event (RWI_{ADE}).

The average value of RWI_{BDE} across all eight drought years provides information on tree growth prior to drought events. It is calculated as the mean of tree growth over the three years preceding each drought year. This indicator offers insight into the pre-drought growth condition of the trees, allowing for the detection of potential early signs of stress or reduced growth before the period of drought (Lloret et al., 2011):

$$\mathrm{RWI\_BDE}(\mathrm{Y_i}) = \frac{1}{3}\sum_{\mathrm{t=Y_i-3}}^{\mathrm{Y_i-1}} \mathrm{RWI(t)}$$

Where:

- Y_i represents a drought year
- $RWI(t)$ denotes the tree-ring width index in each of the three years preceding the drought event.

The indicator $\mathrm{RWI}_{\mathrm{DDE}}$ measures tree growth during the eight identified drought years, providing a direct indication of how drought conditions affected annual ring growth during the drought period itself (Lloret et al., 2011):

$$\mathrm{RWI\_DDE} = \sum_{i=1}^{8} \mathrm{RWI}(\mathrm{Y_i}) \cdot \mathrm{W_i}$$

Where:

- $RWI(t)$ is the Ring Width Index (RWI) in the drought year Y_i
- W_i is a weight assigned to each year, proportional to its ranking among the eight drought years (e.g., 1 for the least severe, 8 for the most severe).

The indicator $\mathrm{RWI}_{\mathrm{ADE}}$ calculates tree growth during the three years following each drought year. This indicator provides insight into how trees continued to grow after the drought event, offering a measure of post-drought recovery and short-term resilience (Lloret et al., 2011):

$$\mathrm{RWI\_ADE}(\mathrm{Y_i}) = \frac{1}{3} \sum_{t=\mathrm{Y_i}+1}^{\mathrm{Y_i}+3} \mathrm{RWI}(t)$$

Where:

- Y_i denotes a drought year.
- $RWI(t)$ represents the tree-ring width index during the three years following the drought.

Based on these indicators, three tolerance indices were subsequently calculated for each tree: Resistance (Rt), Resilience (Rs), and Recovery (Rc). These parameters are commonly used to assess the ability of trees to respond to drought events, particularly in terms of how well they maintain or restore their growth rates following a drought (Lloret et al., 2011).

The calculation of the tolerance indices is described below, following the guidelines provided by Kaufman (1982), Lloret et al. (2011), Bose et al. (2019) and Zang et al. (2021).

Resistance (Rt) quantifies the tree's capacity to maintain its growth rate during the drought year in comparison to pre-drought levels. It is calculated as the ratio between radial growth in the drought year and the average growth during the three preceding years (Lloret et al., 2011; Serra-Maluquer et al., 2018):

$$\mathrm{Rt} = \frac{\mathrm{RWI_{DDE}}}{\mathrm{RWI_{BDE}}}$$

Where:

- RWI_{DDE} is the Ring Width Index (RWI) during the drought year.
- RWI_{BDE} is the mean RWI over the three years prior to the drought.

When the value Rt = 1 indicates that growth was unaffected by the drought; a value of Rt < 1 suggests a decline in growth due to drought stress, whereas a value of Rt > 1 implies an increase in growth during the drought event.

Resilience (Rs) measures a tree's ability to recuperate its pre-drought growth levels. It is calculated as the ratio between the mean growth during the three years following the drought and the mean growth during the three years preceding the event (Lloret et al., 2011; Bose et al., 2019; Fang et al., 2019):

$$\mathrm{Rs} = \frac{\mathrm{RWI_{ADE}}}{\mathrm{RWI_{BDE}}}$$

Where:

- RWI_{ADE} is the average ring width index over the three years following the drought event.
- RWI_{BDE} is the average over the three years prior to the event.

When the value Rs = 1 indicates that growth returned to pre-drought levels; a value of Rs < 1 suggests that growth remained below pre-drought levels; whereas an Rs value > 1 implies that the tree exhibited greater growth than before the drought occurred.

Recovery (Rc) evaluates the rate at which a tree recovers by comparing post-drought growth with growth during the drought year (Lloret et al., 2011; Bose et al., 2021):

$$\mathrm{Rc} = \frac{\mathrm{RWI_{ADE}}}{\mathrm{RWI_{DDE}}}$$

Where:

- RWI_{ADE} represents the mean ring width index over the three years following the drought event.
- RWI_{DDE} corresponds to the ring width index during the drought year.

When the value Rc > 1 indicates that growth increased relative to the drought year, reflecting a strong recovery capacity; a value Rc = 1 suggests that growth remained unchanged compared to the drought year; and a value Rc < 1 implies that the tree did not fully recover to its pre-drought growth levels.

Statistical analyses

Statistical analyses were conducted using the R software environment, employing the “dplyr” and “corrplot” packages for dendrochronological and correlation analyses (R Core Team, 2025). To assess the effect of dog presence on the concentration of nutrients and isotopes, specifically K, Na, P, and N, in wood, soil, and leaves, linear models (LM) were developed using the lm() function, with a separate model for each element (Rencher and Schaalje, 2008). The models included tree species, *Acer platanoides*, *Betula pendula*, and *Robinia pseudoacacia*, and treatment, Dog or No Dog, as independent variables, with nutrient concentration as the dependent variable. Following model development, post-hoc comparisons were performed using the “emmeans” package to assess differences between Dog and No Dog samples within each species (Lenth, 2018).

The results generated p-values, which were interpreted according to standard significance thresholds, $p < 0.05$, $p < 0.01$, and $p < 0.005$, and these were visually reported in the graphs using the conventional symbols *, **, and ***, respectively (Bühl, 2012). The outcomes were visualized using boxplots, which grouped the species by treatment, and statistical significance was indicated above each species group to facilitate visual interpretation. Additional comparisons were performed between the three species, *A. platanoides*, *B. pendula*, and *R. pseudoacacia*, within each treatment, to explore potential differences in nutrient and isotope accumulation across tree types.

To explore the relationship between nutrient and isotope levels and the drought tolerance indices, resistance, resilience, and recovery, non-parametric correlation analyses were performed, creating a correlation matrix based on Kendall's tau (τ) coefficient (Kendall, 1938, Huang and Qin, 2023). These analyses were conducted using the “dplyr” and “corrplot” packages. The investigations were carried out separately for each species and treatment, and also for the two temporal series represented by SPEI-3 and SPEI-12. This division allowed for the differentiation between short-term droughts, calculated using SPEI-3, and long-term droughts, calculated using SPEI-12 (Vicente-Serrano et al., 2010, Beguería et al., 2014).

For each combination of species, treatment, and SPEI index, correlations were calculated between nutrient levels and the corresponding resistance, resilience, and recovery indices. The Kendall method was selected due to its suitability for analyzing non-normally distributed data, as well as its robustness when working with limited sample sizes (Hardin and Hilbe, 2018). The p-values were interpreted according to conventional significance thresholds. Results were visualized through heatmaps generated using the “corrplot” package, and significance symbols were overlaid on each relevant cell to simplify visual interpretation (R Core Team, 2025).

3. Results

This chapter presents the results obtained for the different sample groups. Initially, the findings related to SPEI values and drought tolerance indices are presented, followed by the results concerning nutrient and isotope concentrations.

Tolerance indexes: Resilience, Resistance and Recovery

Table 6, presented below, summarizes the SPEI values obtained for yearly vegetative period of each the time series analyzed, SPEI-3 and SPEI-12, which allows for the detection of short- and long-term drought events (Beguerìa et al., 2014).

Table 6: Resulting SPEI values for the temporal scales 3 and 12 months.

YEAR	SPEI-3	SPEI-12
1996	-0.1958	0.1403
1997	0.2126	0.5548
1998	-0.8259	-0.4539
1999	1.0615	0.9825
2000	0.0563	0.9398
2001	1.5396	1.7396
2002	-0.0406	0.9701
2003	-1.5838	-0.2366
2004	0.2215	-0.7664
2005	-0.8228	-0.7315
2006	0.6889	0.3813
2007	-0.0087	-0.1237
2008	0.188	0.3065
2009	0.0458	0.4379
2010	-0.1134	-0.3716
2011	-1.246	-0.8651
2012	-0.7557	-1.2536
2013	0.2031	0.9828
2014	-0.3728	-0.4116
2015	-0.1705	-0.2048
2016	0.6673	-0.9312
2017	-1.0421	-1.2198
2018	-1.0335	-1.1406
2019	-0.5224	-1.3786
2020	-0.7814	-1.1349
2021	0.5509	-0.2257
2022	-1.4868	-1.0389
2023	-0.4881	-1.329

The calculation of the SPEI indices allowed for the identification of the eight driest years for the two different time scales. For SPEI-3, these years are 2003, 2022, 2011, 2017, 2018, 1998, 2005, and 2020, and for SPEI-12 respectively 2019, 2023, 2012, 2017, 2018, 2020, 2022, and 2016, listed in order from the most negative to the least negative values. According to the SPEI-3 values, the year 2003 is classified as a severe drought (< -1.5), while 2022, 2011, 2017, and 2018 are classified as moderate drought (from -1.5 to -1). The remaining years belongs under the mild drought category (from -1 to -0.5).

The SPEI-12 values do not include any years classified as severe drought. However, the first seven fall within the moderate drought category, while only one is considered a mild drought event.

The relationships between SPEI values and the RWI of the different species are illustrated in Figures 3.

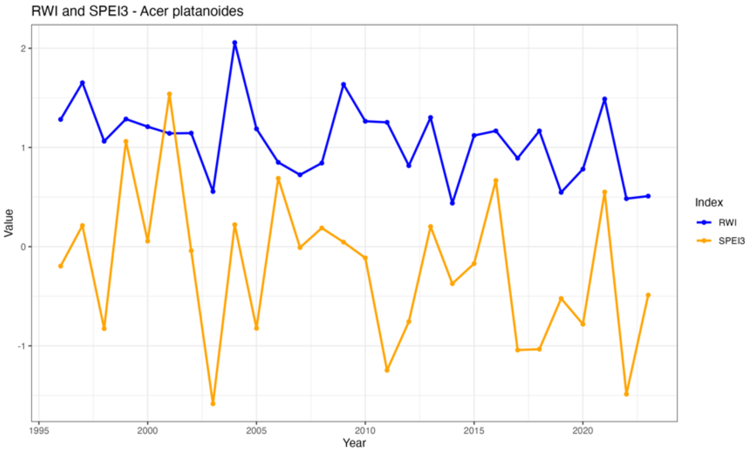


Figure 3-1: Mean RWI of Acer platanoides in relation to the SPEI-3 index.

Figure 3.1 shows the average RWI of the species *Acer platanoides* alongside the SPEI-3 index. In general, a correlation can be observed between years with lower SPEI-3 values and reduced tree-ring growth. This trend is evident in several of the driest years identified, particularly: 2003, 2017, 2020, and 2022. Additional years with reduced growth for *Acer platanoides* include 2007, 2012, 2014, and 2019. Based on the SPEI-3 index, these years are not classified as severe droughts. However, 2014 and 2019 fall within the mild drought category, with values between -1 and -0.5.

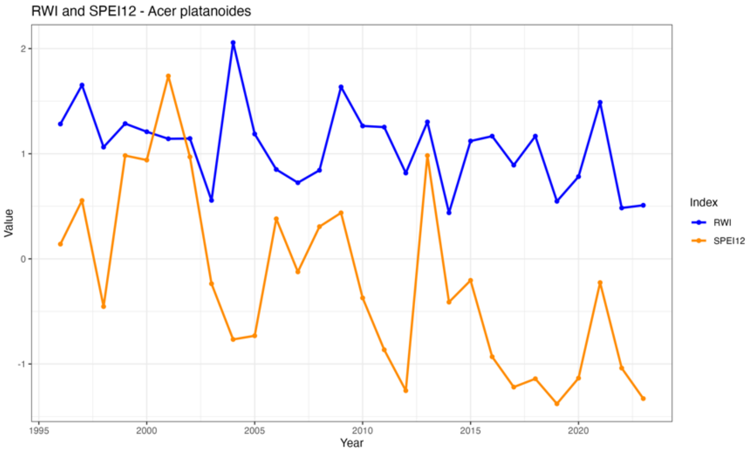


Figure 3-2: Mean RWI of Acer platanoides in relation to the SPEI-12 index.

Figure 3.2 shows the average RWI of the species *Acer platanoides* alongside the SPEI-12 index. A correspondence can be observed between the years identified as the most drought-affected according to the SPEI-12 index and the years with reduced ring growth for *Acer platanoides*. This trend is particularly evident in the years 2012, 2017, 2019, 2022, and 2023. Other years showing lower-than-average ring growth include 2003 and 2007. However, these two years are not among those identified as the most drought-affected according to the SPEI-12 index.

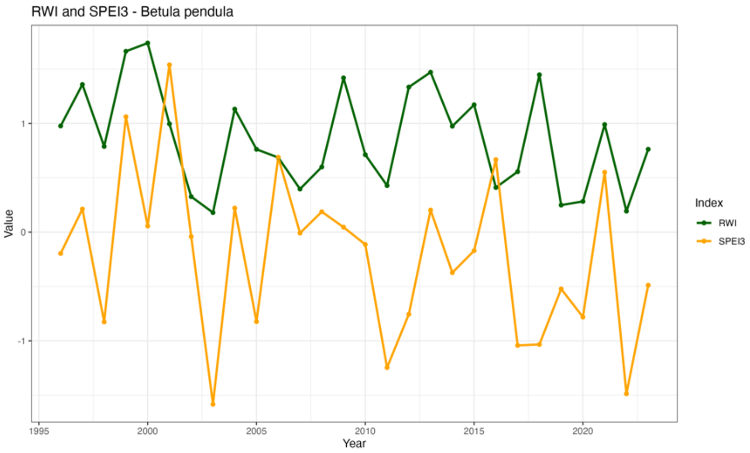


Figure 3-3: Mean RWI of Betula pendula in relation to the SPEI-3 index.

Figure 3.3 presents the average RWI of the species *Betula pendula* alongside the SPEI-3 index. The values reveal a correspondence between the driest periods, as calculated using the SPEI-3 index, and reduced ring growth for *B. pendula*. This relationship is particularly evident in the years 2003, 2011, 2017, 2020, and 2022. As for the years 2018, 1998, and 2005, the first two show a decrease in growth, although not particularly pronounced, while the latter exhibits an opposite trend, characterized by significantly increased growth.

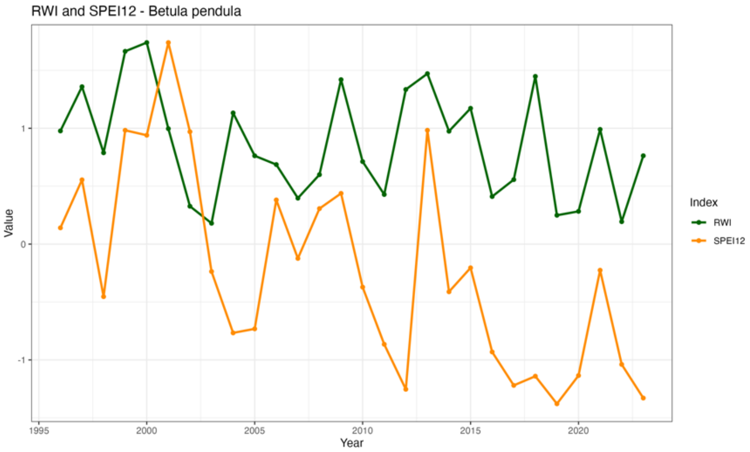


Figure 3-4: Mean RWI of Betula pendula in relation to the SPEI-12 index.

Figure 3.4 presents the average RWI of the species *Betula pendula* alongside the SPEI-12 index. In general, a correlation can be observed between the RWI values for *B. pendula* and the SPEI-12 index, particularly in the years 2016, 2017, 2019, 2020, and 2022. No clear correlation is observed for the years 2012, 2018, and 2023. Additionally, a correspondence is noticeable in years with higher SPEI-12 values, such as 2009 and 2013.

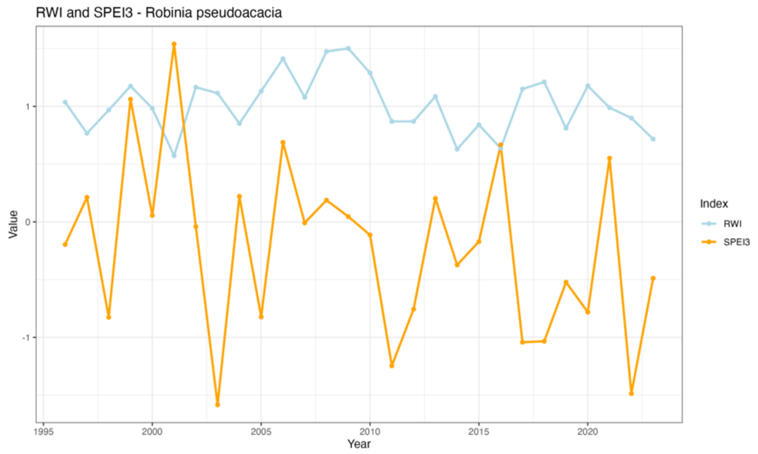


Figure 3-5: Mean RWI of Robinia pseudoacacia in relation to the SPEI-3 index.

Figure 3.5 presents the average RWI of the species *Robinia pseudoacacia* alongside the SPEI-3 index. The comparison between SPEI-3 values and the RWI of *R. pseudoacacia* does not reveal a significant correspondence. Among the years identified as the driest, only 2011 shows a corresponding decrease in ring growth.

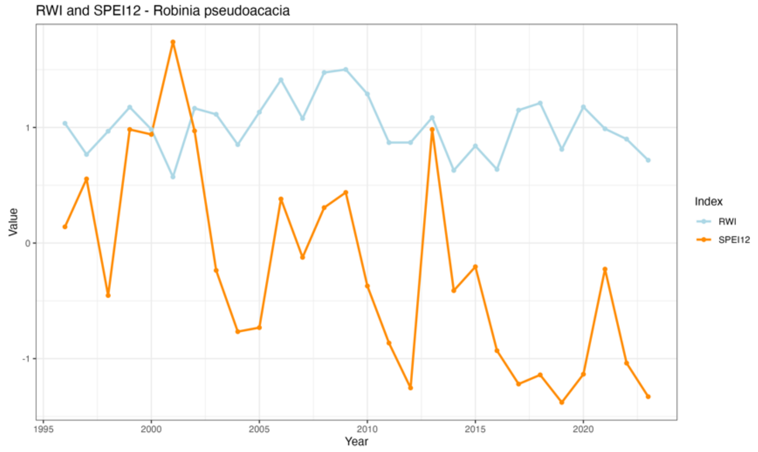


Figure 3-6: Mean RWI of Robinia pseudoacacia in relation to the SPEI-12 index.

Figure 3.6 presents the average RWI of the species *Robinia pseudoacacia* alongside the SPEI-12 index. A correlation between the SPEI-12 index and the RWI values for *R. pseudoacacia* is visible, though less pronounced, and corresponds to the years 2012, 2016, 2019, and 2023. In the remaining years, no clear relationship is observed between drought severity and annual ring growth.

For the selected time scales, drought tolerance index values were calculated for each species and treatment. Table 7 presents the resulted values for resistance, resilience, and recovery based on SPEI-3, while Table 8 provides the corresponding values for SPEI-12.

Table 7: Resistance, resilience and recovery mean values for each species and type based on the SPEI-3 results. The lowest and the highest value for each tolerance index is emphasized in yellow, respectively in blue.

Species	Type	Resistance	Resilience	Recovery
Acer platanoides	Dog	1.0721	0.8411	1.3001
	No dog	0.8646	0.9261	1.3705
Betula pendula	Dog	0.6723	1.0304	2.2078
	No dog	1.4366	1.2339	1.4812
Robinia pseudoacacia	Dog	1.0509	1.1564	1.1234
	No dog	0.9277	0.9034	1.032

Based on the values related to SPEI-3, the results indicate that the species with the highest resistance is *B. pendula* under the No Dog treatment, with a value of 1.44, while the lowest resistance is also observed in *B. pendula* under the Dog treatment, with a value of 0.67. Regarding resilience, the lowest value is recorded for *A. platanoides* under the Dog treatment, with a value of 0.84, whereas the highest resilience is observed in *B. pendula* under the No Dog treatment, with a value of 1.23. The species with the highest recovery is *B. pendula* under the Dog treatment, with a value of 2.2078, while the lowest recovery is found in *R. pseudoacacia* under the No Dog treatment, with a value of 1.03.

Overall, the highest tolerance index values are attributed to *Betula pendula*. The lowest values are distributed across different species and do not show a clear pattern.

For individual species, *A. platanoides* shows higher resistance under the Dog treatment, while resilience and recovery values are higher under the No Dog treatment. In general, the differences are relatively small. *B. pendula* exhibits higher resistance and resilience under the No Dog treatment, while recovery is greater under the Dog treatment. The differences between treatments are more pronounced, especially for recovery, where a variation of 0.7 is observed, and for resistance, which includes both the minimum and maximum values among all species.

Finally, *R. pseudoacacia* consistently shows higher values under the Dog treatment, with overall smaller differences between Dog and No Dog treatments compared to the variations observed in the other two species.

Table 8: Resistance, resilience and recovery mean values for each species and type based on the SPEI-12 results. The lowest and the highest value for each tolerance index is emphasized in yellow, respectively in blue.

Species	Type	Resistance	Resilience	Recovery
Acer platanoides	Dog	0.6998	0.6976	1.4749
	No dog	0.8354	0.9602	1.4195
Betula pendula	Dog	0.7707	1.1898	2.281
	No dog	1.35	0.9433	2.1206
Robinia pseudoacacia	Dog	1.0596	0.9724	1.0993
	No dog	0.9783	1.0382	1.224

The resulted values related to SPEI-12 indicate that the highest resistance is observed in *B. pendula* under the No Dog treatment, with a value of 1.35, while the lowest resistance is recorded for *A. platanoides* under the Dog treatment, with a value of 0.70. The highest resilience is found in *B. pendula* under the Dog treatment, with a value of 1.898, whereas the lowest resilience is again observed in *A. platanoides* under the Dog treatment, with a value of 0.6976. The highest recovery is also shown by *B. pendula* under the Dog treatment, with a value of 2.28, while the lowest recovery is recorded for *R. pseudoacacia* under the Dog treatment, with a value of 1.10. Also in this situation, the highest drought tolerance indices are consistently attributed to *Betula pendula*. The lowest values are distributed between A. platanoides and R. pseudoacacia.

For individual species, *A. platanoides* shows higher values for resistance and resilience under the No Dog treatment, whereas the Dog treatment displays lower values, which are also the lowest among all observed groups. However, recovery for *A. platanoides* is higher under the Dog treatment. The resistance values differ by less than 0.2, while the resilience and recovery indices differ by approximately 0.2 to 0.4 between treatments. In the case of *B. pendula*, resistance is higher under the No Dog treatment, with a difference greater than 0.5 compared to the Dog treatment. For resilience and recovery, the Dog treatment shows higher values, but the differences between treatments are smaller, not exceeding 0.2. *R. pseudoacacia* displays higher resistance and recovery values under the Dog treatment, whereas resilience is higher under the No Dog treatment. The differences between treatments for this species are minor compared to the differences observed in the other two species.

Isotopes results

C and δ13C

Table 9: Mean C content in wood, soil and leaves for each species and type of tree.

Species	**Wood (No Dog | Dog)**	**Soil (No Dog | Dog)**	**Leaves (No Dog | Dog)**
Acer platanoides	44.77 | 44.29	5.52 | 14.07	43.26 | 41.86
Betula pendula	45.19 | 44.89	3.64 | 4.38	42.33 | 44.04
Robinia pseudoacacia	45.77 | 45.31	5.99 | 6.69	41.93 | 40.12

Table 9 presents the average concentration of carbon (C) in wood, soil, and leaf samples for each species and treatment type. The results of the different materials are also illustrated in Figure 4.

The carbon content in wood is relatively similar across all species, with values generally around 44–45%. In general, the samples show little variability between the two treatments.

In soil, differences are observed between the Dog and No Dog areas. In particular, *Acer platanoides* shows a marked increase in carbon content in the Dog treatment. *Betula pendula* and *Robinia pseudoacacia* exhibit slightly higher values (<1%) in Dog samples compared to No Dog samples.

Carbon content in leaves is relatively homogeneous between Dog and No Dog treatments for all analyzed species. *A. platanoides* shows slightly lower average carbon values in the Dog treatment compared to the No Dog treatment. The same applies to *R. pseudoacacia*, which shows a slightly greater difference, although not particularly significant. *B. pendula* displays the opposite trend, with higher carbon values in Dog samples compared to No Dog. The lowest percentage is found in *R. pseudoacacia* under the Dog treatment, while the highest percentage is observed in *B. pendula* under the Dog treatment.

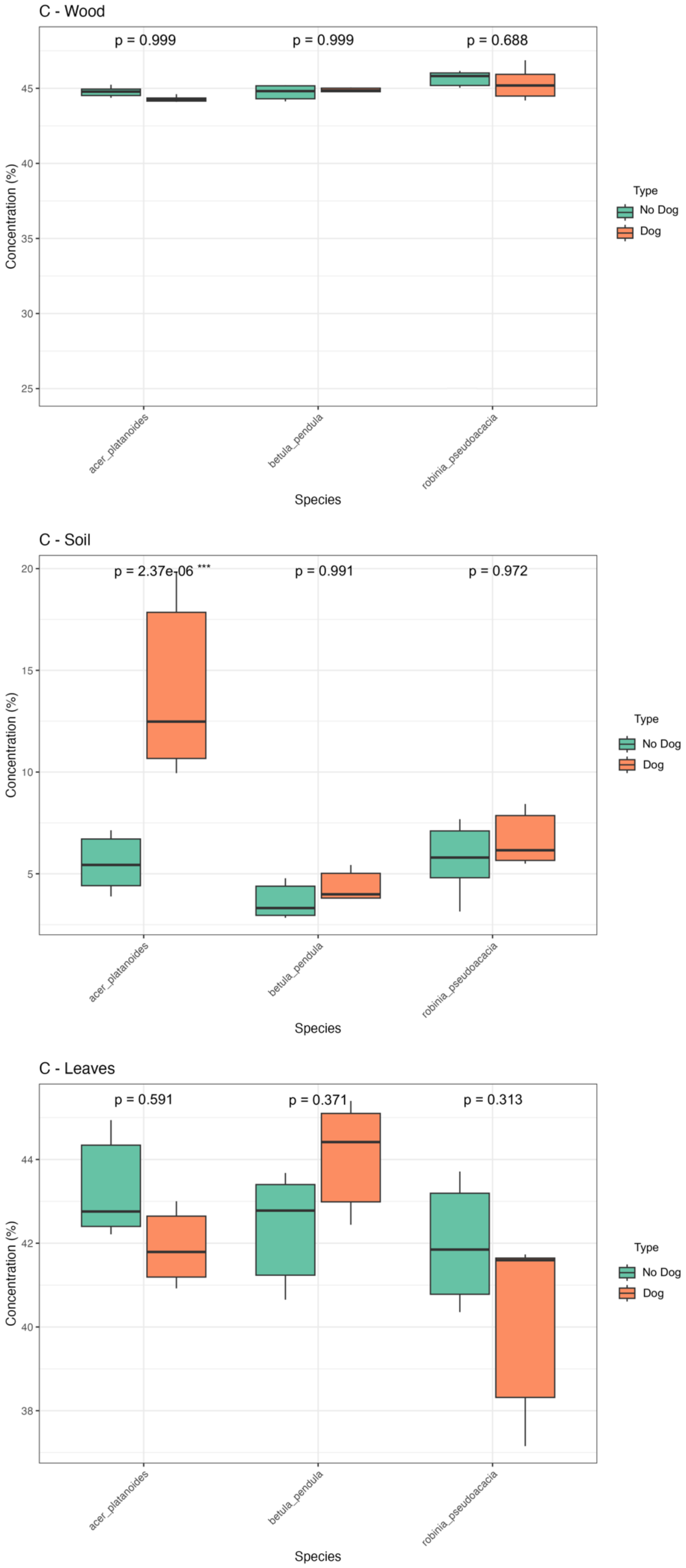


Figure 4: C content (%) in wood (upper), soil (middle) and leaves (bottom).

*Table 10: Results values from the Linear Model applied on C content data subdivided by material analysed, the values represent the comparisons between species and type. The symbols « * », « ** »and « *** » indicate the statistical significance of the comparison between two groups. The estimate and t ratio values indicate the difference between the first and the second group in the comparison. Positive, respectively negative, estimate and t ratio indicates that the first group has a higher, respectively lower, value compared to the second group.*

Material	contrast	estimate	t.ratio	p.value
Wood	A. platanoides No Dog - B. pendula No Dog	-0.42	-0.21	0.99
	A. platanoides No Dog - R. pseudoacacia No Dog	2.46	1.2	0.83
	A. platanoides No Dog - A. platanoides Dog	0.48	0.23	0.99
	B. pendula No Dog - R. pseudoacacia No Dog	2.89	1.41	0.72
	B. pendula No Dog - B. pendula Dog	0.3	0.15	0.99
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-3.01	-1.47	0.68
	A. platanoides Dog - B. pendula Dog	-0.6	-0.29	0.99
	A. platanoides Dog - R. pseudoacacia Dog	-1.02	-0.5	0.99
	B. pendula Dog - R. pseudoacacia Dog	-0.42	-0.21	0.99
Soil	A. platanoides No Dog - B. pendula No Dog	1.88	1.49	0.67
	A. platanoides No Dog - R. pseudoacacia No Dog	-0.22	-0.18	0.99
	A. platanoides No Dog - A. platanoides Dog	-8.55	-6.77	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	-2.1	-1.66	0.56
	B. pendula No Dog - B. pendula Dog	-0.75	-0.59	0.99
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.95	-0.75	0.97
	A. platanoides Dog - B. pendula Dog	9.69	7.66	**<0.001 (***)**
	A. platanoides Dog - R. pseudoacacia Dog	7.38	5.84	**<0.001 (***)**
	B. pendula Dog - R. pseudoacacia Dog	-2.31	-1.83	0.46
Leaves	A. platanoides No Dog - B. pendula No Dog	0.93	1.08	0.88
	A. platanoides No Dog - R. pseudoacacia No Dog	1.33	1.54	0.63
	A. platanoides No Dog - A. platanoides Dog	1.4	1.62	0.59
	B. pendula No Dog - R. pseudoacacia No Dog	0.4	0.46	0.99
	B. pendula No Dog - B. pendula Dog	-1.72	-1.99	0.37
	R. pseudoacacia No Dog - R. pseudoacacia Dog	1.81	2.1	0.31
	A. platanoides Dog - B. pendula Dog	-2.18	-2.53	0.14
	A. platanoides Dog - R. pseudoacacia Dog	1.74	2.02	0.35
	B. pendula Dog - R. pseudoacacia Dog	3.92	4.55	**<0.01 (**)**

In the wood samples, the comparison does not show any statistically significant differences in carbon content. P-values are consistently above the significance threshold (≥ 0.68). Some estimated values appear interesting, but they are not supported by the P-values, for example: *B. pendula* No Dog – *R. pseudoacacia* No Dog, estimate = 2.89, P-value = 0.72; *R. pseudoacacia* No Dog – *R. pseudoacacia* Dog, estimate = -3.01, P-value = 0.68.

In soil, statistically significant variations in carbon content are observed. *A. platanoides* No Dog vs *A. platanoides* Dog shows a very low estimate value of -8.55, supported by a P-value < 0.001, indicating a strong reduction in soil carbon in the presence of dogs. *A. platanoides* Dog vs *B. pendula* Dog shows an estimate value of 9.69, supported by a P-value < 0.001, indicating that the soil of *A. platanoides* contains much more carbon than that of *B. pendula* under the Dog treatment. *A. platanoides* Dog vs *R. pseudoacacia* Dog shows an estimate of 7.38 and a P-value < 0.001, suggesting that soil carbon content is significantly higher in *A. platanoides* under the Dog treatment compared to *R. pseudoacacia*. Overall, *A. platanoides* shows both intra-species and inter-species differences.

In leaf samples, the analysis reveals only one statistically significant difference, observed between *B. pendula* Dog and *R. pseudoacacia* Dog, with an estimate of 3.92 and a P-value < 0.01, indicating that *B. pendula* Dog has a significantly higher carbon concentration than *R. pseudoacacia* Dog. The remaining comparisons show high P-values, indicating no other statistically significant differences (Table 10).

Table 11: Mean δ13C ratio in wood, soil and leaves for each species and type of tree.

Species	Wood (No Dog | Dog)	Soil (No Dog | Dog)	Leaves (No Dog | Dog)
Acer platanoides	-27.14 | -25.60	-17.01 | -25.44	-25.66 | -30.75
Betula pendula	-27.43 | -26.82	-24.55 | -26.38	-30.55 | -28.96
Robinia pseudoacacia	-25.56 | -25.43	-16.50 | -24.23	-30.79 | -29.90

Table 11 presents the average concentration of the $\delta^{13}C$ ratio in wood, soil, and leaf samples for each species and treatment type. The results for the different materials are also illustrated in Figure 5.

The $\delta^{13}C$ isotopic ratio values in wood samples are generally homogeneous. For each species, the values range between -27‰ and -25‰, showing some variation between Dog and No Dog treatments. Additionally, internal variation within each treatment group is generally low.

The $\delta^{13}C$ values in soil are more negative under the Dog treatment compared to the No Dog treatment across all species. For *A. platanoides* and *R. pseudoacacia*, the difference between Dog and No Dog is more pronounced. For *B. pendula*, the variation is present but less marked. In general, greater variability is observed in the No Dog samples for each species. In particular, for *A. platanoides*, the values in the Dog group are around -24‰, while those in the No Dog group are closer to -19‰. In *B. pendula*, a greater difference is noted, with values near -25‰ for the Dog group and -22‰ for the No Dog group. For *R. pseudoacacia*, the values are more negative in the Dog group, around -24‰, compared to the No Dog group, which shows values around -14‰.

In the leaves, $\delta^{13}C$ values range from approximately -28‰ to -32‰. The only notable difference is observed in *A. platanoides* under the No Dog treatment, where the median value is less negative, around -26‰. The species *B. pendula* and *R. pseudoacacia* show slightly higher variability under the Dog treatment.

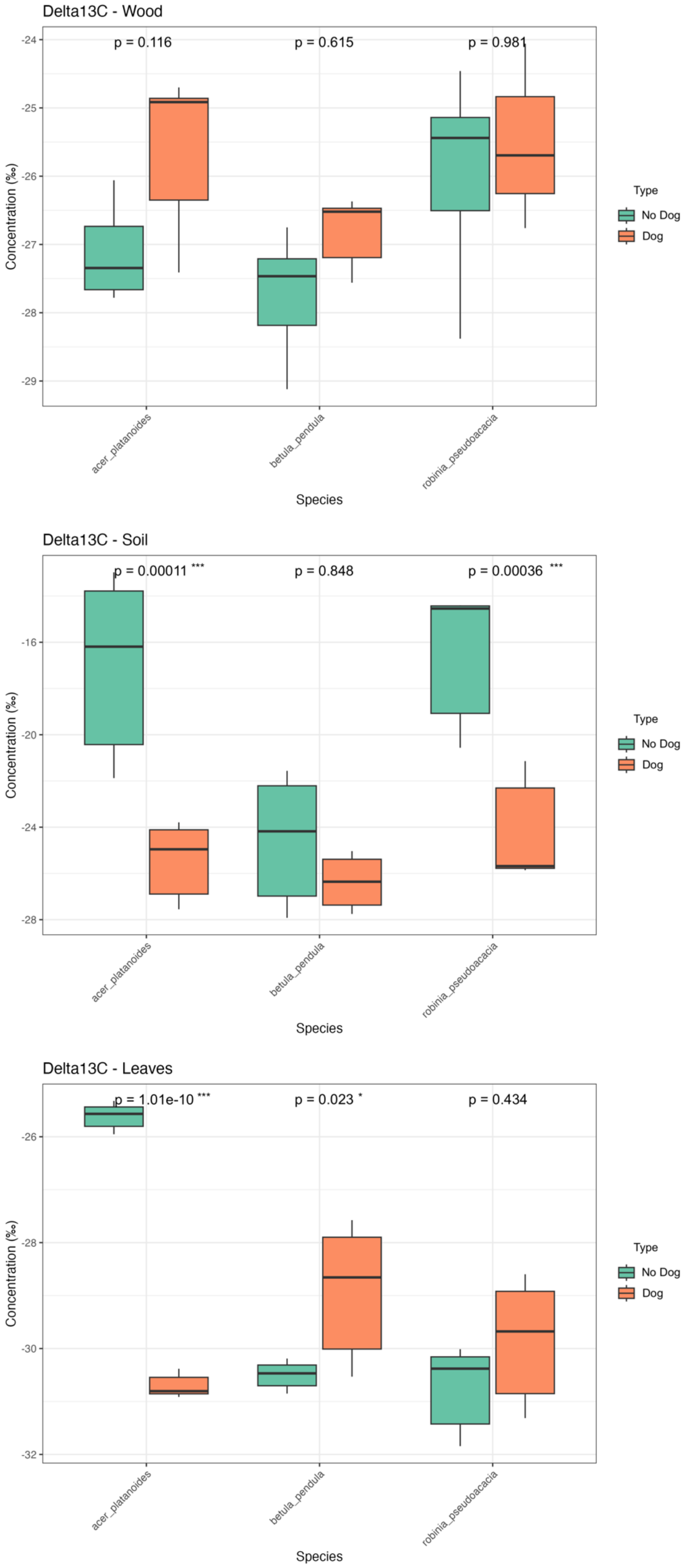


Figure 5: δ13C ratio (‰) in wood (upper), soil (middle) and leaves (bottom).

*Table 12: Results values from the Linear Model applied on δ13C ratio data subdivided by material analysed, the values represent the comparisons between species and type. The symbols « * », « ** »and « *** » indicate the statistical significance of the comparison between two groups. The estimate and t ratio values indicate the difference between the first and the second group in the comparison. Positive, respectively negative, estimate and t ratio indicates that the first group has a higher, respectively lower, value compared to the second group.*

Material	**contrast**	**estimate**	**t.ratio**	**p.value**
Wood	A. platanoides No Dog - B. pendula No Dog	0.59	1.01	0.91
	A. platanoides No Dog - R. pseudoacacia No Dog	-1.2	-2.07	0.32
	A. platanoides No Dog - A. platanoides Dog	-1.54	-2.65	0.11
	B. pendula No Dog - R. pseudoacacia No Dog	-1.79	-3.08	**0.04 (*)**
	B. pendula No Dog - B. pendula Dog	-0.92	-1.58	0.61
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.4	-0.7	0.98
	A. platanoides Dog - B. pendula Dog	1.21	2.08	0.32
	A. platanoides Dog - R. pseudoacacia Dog	-0.07	-0.12	0.99
	B. pendula Dog - R. pseudoacacia Dog	-1.27	-2.2	0.26
Soil	A. platanoides No Dog - B. pendula No Dog	7.54	4.82	**<0.001 (***)**
	A. platanoides No Dog - R. pseudoacacia No Dog	-0.5	-0.32	0.99
	A. platanoides No Dog - A. platanoides Dog	8.43	5.39	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	-8.05	-5.14	**<0.001 (***)**
	B. pendula No Dog - B. pendula Dog	1.83	1.17	0.84
	R. pseudoacacia No Dog - R. pseudoacacia Dog	7.72	4.93	**<0.001 (***)**
	A. platanoides Dog - B. pendula Dog	0.94	0.6	0.99
	A. platanoides Dog - R. pseudoacacia Dog	-1.21	-0.77	0.96
	B. pendula Dog - R. pseudoacacia Dog	-2.15	-1.38	0.74
Leaves	A. platanoides No Dog - B. pendula No Dog	4.89	10.4	**<0.001 (***)**
	A. platanoides No Dog - R. pseudoacacia No Dog	5.13	10.91	**<0.001 (***)**
	A. platanoides No Dog - A. platanoides Dog	5.09	10.83	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	0.24	0.52	0.99
	B. pendula No Dog - B. pendula Dog	-1.58	-3.37	**0.02 (*)**
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.88	-1.88	0.43
	A. platanoides Dog - B. pendula Dog	-1.79	-3.8	**<0.01 (**)**
	A. platanoides Dog - R. pseudoacacia Dog	-0.84	-1.79	0.48
	B. pendula Dog - R. pseudoacacia Dog	0.94	2	0.36

In wood, the comparisons between species and between Dog and No Dog treatments show slight variations in δ^{13}C values, with only one statistically significant result. For *B. pendula* No Dog vs *R. pseudoacacia* No Dog, the estimate = -1.79 and the P-value = 0.04, suggesting a significantly more negative δ^{13}C ratio for *B. pendula* under the No Dog treatment compared to *R. pseudoacacia*. A notable but not statistically significant intra-species variation is observed in *A. platanoides*, with an estimate = -1.54 and a P-value = 0.11. The remaining comparisons between species and treatment types show P-values > 0.26, indicating no statistically relevant differences, despite some high estimate values.

In soil, statistically significant differences in δ^{13}C values are observed between some species and treatment types. Strong positive differences are found for *A. platanoides* No Dog vs *B. pendula* No Dog, estimate = 7.54; *A. platanoides* No Dog vs *A. platanoides* Dog, estimate = 8.43; and *R. pseudoacacia* No Dog vs *R. pseudoacacia* Dog, estimate = 7.72.

One negative difference is observed between *B. pendula* No Dog vs *R. pseudoacacia* No Dog, with an estimate = -8.05. Each of these comparisons presents a P-value = 0.001, indicating strong statistical significance. Comparisons between species under the Dog treatment do not show statistically significant differences.

Comparisons of $\delta^{13}C$ values in leaves reveal some statistically significant differences, particularly for *A. platanoides* and *B. pendula*. *A. platanoides* No Dog shows significant intra-species contrasts, with an estimate = 5.09, as well as inter-species contrasts, especially with *B. pendula* No Dog (estimate = 4.89) and with *R. pseudoacacia* No Dog (estimate = 5.13), in all cases with P-values < 0.001. A statistically significant intra-species difference is also observed in *B. pendula*, with a lower estimate of approximately -1.58 and a P-value < 0.02. The remaining statistically significant difference is between *B. pendula* Dog vs *A. platanoides* Dog, with an estimate = -1.79 and a P-value < 0.01 (Table 12).

N and δ15N

Table 13: Mean N content in wood, soil and leaves for each species and type of tree.

Species	Wood (No Dog | Dog)	Soil (No Dog | Dog)	Leaves (No Dog | Dog)
Acer platanoides	0.24 | 0.235	0.22 | 0.84	1.70 | 1.58
Betula pendula	0.178 | 0.192	0.22 | 0.23	1.64 | 2.48
Robinia pseudoacacia	0.617 | 0.291	0.21 | 0.44	2.78 | 3.28

Table 13 presents the average concentration of nitrogen (N) in wood, soil, and leaf samples for each species and treatment type. The results for the different materials are also illustrated in Figure 6.

Total nitrogen concentration in wood varies between *A. platanoides* and *B. pendula* compared to *R. pseudoacacia*. In *A. platanoides* and *R. pseudoacacia*, values are slightly higher in the No Dog treatment. *R. pseudoacacia* generally shows values around 0.3%. *A. platanoides* and *B. pendula* exhibit similar concentrations between the two treatments, with only minimal differences, generally ranging from 0.2% to 0.3%, and a slight tendency toward higher values under the Dog treatment. No statistically significant differences are observed in any species. *R. pseudoacacia* shows the greatest variability, with the No Dog treatment differing by as much as 0.8% from the Dog treatment, which has a median around 0.2%. Variability is generally low across treatments, with high variability observed only in *R. pseudoacacia* under the No Dog treatment.

In soil, *A. platanoides* and *R. pseudoacacia* show statistically significant differences between Dog and No Dog treatments. In *A. platanoides*, nitrogen levels are notably higher under the Dog treatment, accompanied by substantial variability compared to the other species. *B. pendula* does not show any differences between Dog and No Dog treatments, with both groups presenting similar values around 0.2%.

In leaves, a moderate variation in nitrogen content is observed across species and treatment types. *A. platanoides* shows very similar nitrogen levels between Dog and No Dog treatments, with only a slight difference: the No Dog treatment has slightly higher values than the Dog treatment, approximately 1.7% vs 1.6%. In *B. pendula*, the difference is more pronounced, with the Dog treatment showing a mean value of around 2.5% compared to 1.6% in the No Dog treatment. *R. pseudoacacia* also displays slightly higher nitrogen values in the Dog treatment, around 3.3%, compared to approximately 2.78% in the No Dog treatment. It is also noted that for *R. pseudoacacia*, the Dog treatment shows greater variability than the other species and treatments.

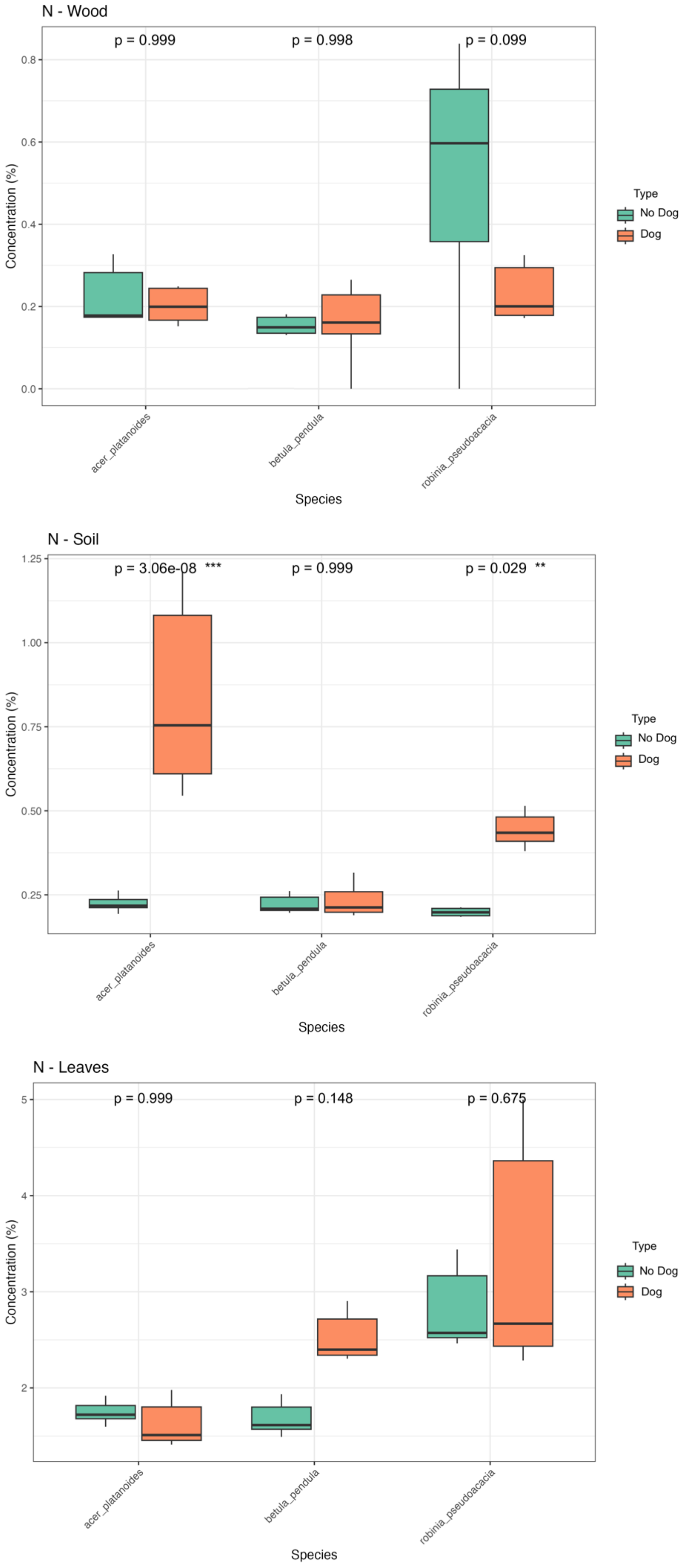


Figure 6: N content (%) in wood (upper), soil (middle) and leaves (bottom).

*Table 14: Results values from the Linear Model applied on N content data subdivided by material analysed, the values represent the comparisons between species and type. The symbols « * », « ** »and « *** » indicate the statistical significance of the comparison between two groups. The estimate and t ratio values indicate the difference between the first and the second group in the comparison. Positive, respectively negative, estimate and t ratio indicates that the first group has a higher, respectively lower, value compared to the second group.*

Material	contrast	estimate	t.ratio	p.value
Wood	A. platanoides No Dog - B. pendula No Dog	0.05	0.47	0.99
	A. platanoides No Dog - R. pseudoacacia No Dog	-0.32	-3.19	**0.03 (*)**
	A. platanoides No Dog - A. platanoides Dog	-0.04	-0.39	0.99
	B. pendula No Dog - R. pseudoacacia No Dog	-0.37	-3.66	**0.01 (*)**
	B. pendula No Dog - B. pendula Dog	-0.01	-0.12	0.99
	R. pseudoacacia No Dog - R. pseudoacacia Dog	0.27	2.73	0.09
	A. platanoides Dog - B. pendula Dog	0.07	0.75	0.97
	A. platanoides Dog - R. pseudoacacia Dog	-0.01	-0.07	0.99
	B. pendula Dog - R. pseudoacacia Dog	-0.08	-0.82	0.96
Soil	A. platanoides No Dog - B. pendula No Dog	0	0.03	0.99
	A. platanoides No Dog - R. pseudoacacia No Dog	0.02	0.25	0.99
	A. platanoides No Dog - A. platanoides Dog	-0.61	-8.42	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	0.02	0.23	0.99
	B. pendula No Dog - B. pendula Dog	-0.01	-0.15	0.99
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.24	-3.28	**0.02 (*)**
	A. platanoides Dog - B. pendula Dog	0.6	8.3	**<0.001 (***)**
	A. platanoides Dog - R. pseudoacacia Dog	0.39	5.4	**<0.001 (***)**
	B. pendula Dog - R. pseudoacacia Dog	-0.21	-2.9	0.06
Leaves	A. platanoides No Dog - B. pendula No Dog	0.07	0.2	0.99
	A. platanoides No Dog - R. pseudoacacia No Dog	-1.07	-3.21	**0.03 (*)**
	A. platanoides No Dog - A. platanoides Dog	0.12	0.36	0.99
	B. pendula No Dog - R. pseudoacacia No Dog	-1.14	-3.41	**0.02 (*)**
	B. pendula No Dog - B. pendula Dog	-0.85	-2.53	0.14
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.5	-1.49	0.67
	A. platanoides Dog - B. pendula Dog	-0.9	-2.69	0.1
	A. platanoides Dog - R. pseudoacacia Dog	-1.69	-5.06	**<0.001 (***)**
	B. pendula Dog - R. pseudoacacia Dog	-0.79	-2.37	0.19

The comparisons of nitrogen concentration in wood revealed two statistically significant differences (Table 14), both involving *R. pseudoacacia* No Dog. Compared to *A. platanoides* No Dog, the estimate = -0.32 and the P-value = 0.03, while for *B. pendula* No Dog, the estimate = -0.37 and the P-value = 0.01. The negative estimates in these significant comparisons suggest that *R. pseudoacacia* has significantly higher N concentrations compared to *A. platanoides* No Dog and *B. pendula* No Dog. The remaining intra-specific comparisons between No Dog and Dog treatments, as well as interspecific comparisons under the Dog treatment, do not show statistically significant differences.

In soil, several statistically significant differences are observed. Two of them are intra-specific. *A. platanoides* Dog vs No Dog shows an estimate = -0.61, supported by a P-value < 0.001, indicating that for *A. platanoides*, nitrogen content is significantly higher under the No Dog treatment. *R. pseudoacacia* Dog vs No Dog shows an estimate = -0.24 and a P-value = 0.02, suggesting that nitrogen is significantly higher in the Dog treatment for this species as well.

Two additional cases involve differences between species. *A. platanoides* Dog vs *B. pendula* Dog presents an estimate = 0.60 and a P-value < 0.001, while *A. platanoides* Dog vs *R. pseudoacacia* Dog results in an estimate = 0.39 and a P-value < 0.001. These findings indicate that *A. platanoides* under the Dog treatment has significantly higher nitrogen values in both cases. One comparison is close to statistical significance, *B. pendula* Dog vs *R. pseudoacacia* Dog, with an estimate = -0.21 and a P-value = 0.06, suggesting that the N value in *R. pseudoacacia* Dog is nearly significantly higher. Comparisons between species under the No Dog treatment do not show statistically significant differences.

Some statistically significant comparisons are visible in leaf samples, with most relevant results concerning *R. pseudoacacia* in contrast to the other species. *R. pseudoacacia* No Dog vs *A. platanoides* shows an estimate = -1.07 and a P-value = 0.03, while *R. pseudoacacia* No Dog vs *B. pendula* No Dog shows an estimate = -1.14 and a P-value = 0.02. In both cases, *R. pseudoacacia* No Dog has significantly higher nitrogen values. The comparison between *R. pseudoacacia* Dog vs *A. platanoides* Dog yields an estimate = -1.69 and a P-value < 0.001, suggesting that even under the Dog treatment, *R. pseudoacacia* has significantly higher nitrogen content. Intra-specific comparisons are not statistically significant, indicating that the presence of dogs does not significantly alter leaf nitrogen content within the same species.

Table 15: Mean δ15N ratio in wood, soil and leaves for each species and type of tree.

Species	Wood (No Dog | Dog)	Soil (No Dog | Dog)	Leaves (No Dog | Dog)
Acer platanoides	2.513 | 9.386	4.82 | 3.58	6.69 | 2.44
Betula pendula	1.172 | 2.944	3.70 | 4.29	0.55 | 3.70
Robinia pseudoacacia	0.941 | 2.126	2.65 | 3.37	0.18 | 3.73

Table 15 presents the average concentration of the $\delta^{15}N$ ratio in wood, soil, and leaf samples for each species and treatment type. The results for the different materials are also illustrated in Figure 7.

The isotopic nitrogen content in wood shows notable variations between species and treatment types. *A. platanoides* exhibits a statistically significant difference between the two treatments. Specifically, the Dog group shows a higher value, approximately 9.2‰, while the No Dog group has a lower average, around 2‰. *B. pendula* and *R. pseudoacacia* show higher values in the Dog treatment, approximately 2.8‰, compared to the No Dog treatment, which shows values around 1‰. The standard deviation generally indicates moderate variability within each species.

The $\delta^{15}N$ ratio reveals differences across species and treatments, although none of the intra-species comparisons are statistically significant. For *B. pendula* and *R. pseudoacacia*, Dog samples show higher values, around 2.8‰, while No Dog samples are below 2‰. *A. platanoides* shows the opposite trend, with No Dog values higher than Dog values, approximately 4.4‰ vs 3.8‰. Additionally, the No Dog samples of *A. platanoides* exhibit greater variability than the other groups analyzed.

$\delta^{15}N$ values in leaf samples vary across treatments and species, and for each species, the intra-species comparison is statistically significant. *A. platanoides* shows higher values in the No Dog group, approximately 6.7‰, compared to the Dog group, which shows values around 2.5‰. *B. pendula* shows the opposite trend, with higher values in the Dog group, around 3.7‰, compared to approximately 0.5‰ in the No Dog group. *R. pseudoacacia* also shows higher values in the Dog group compared to the No Dog group, approximately 3.7 × 100 vs 0.2‰. Greater variability is observed in both Dog and No Dog treatments of *A. platanoides* compared to the other two species.

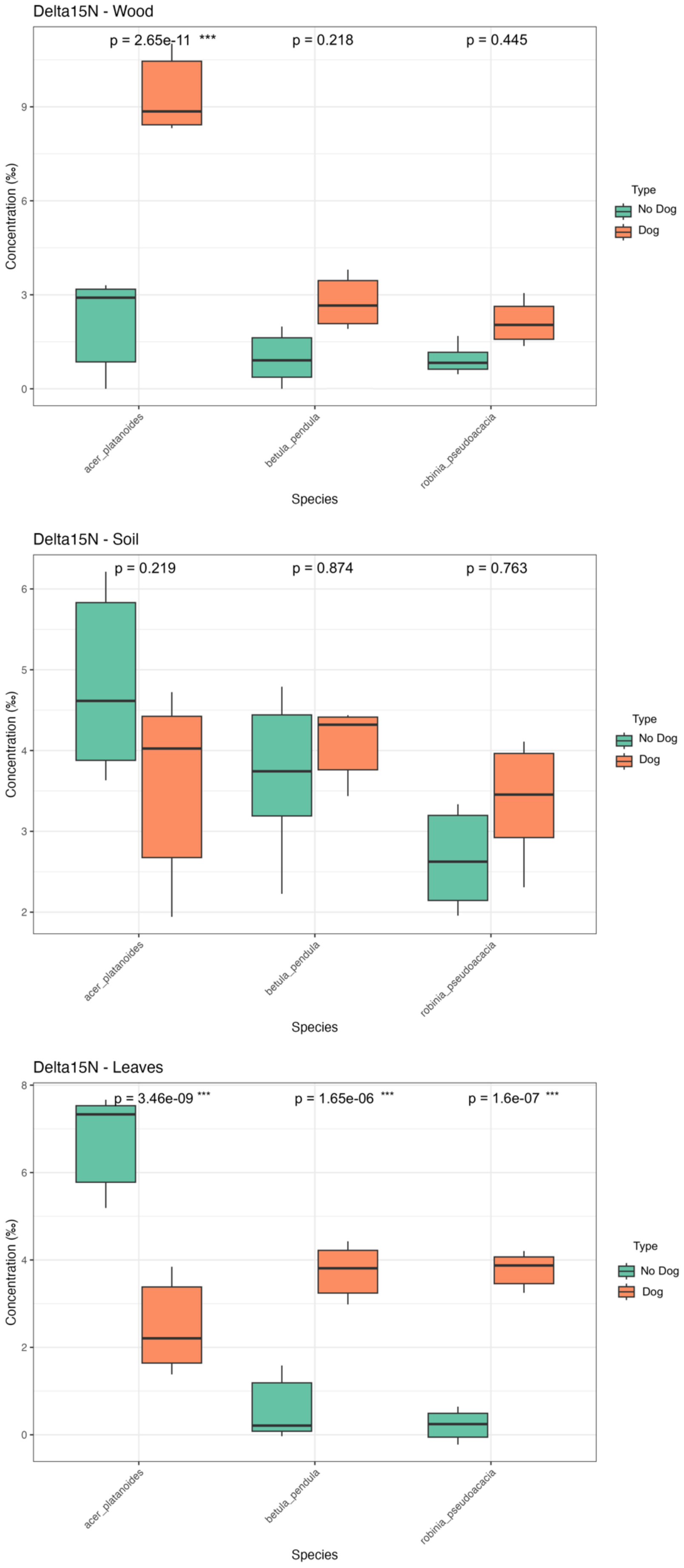


Figure 7: δ15N ratio (‰) in wood (upper), soil (middle) and leaves (bottom).

*Table 16: Results values from the Linear Model applied on δ15N ratio data subdivided by material analysed, the values represent the comparisons between species and type. The symbols « * », « ** »and « *** » indicate the statistical significance of the comparison between two groups. The estimate and t ratio values indicate the difference between the first and the second group in the comparison. Positive, respectively negative, estimate and t ratio indicates that the first group has a higher, respectively lower, value compared to the second group.*

Material	**contrast**	**estimate**	**t.ratio**	**p.value**
Wood	A. platanoides No Dog - B. pendula No Dog	1.12	1.75	0.5
	A. platanoides No Dog - R. pseudoacacia No Dog	1.15	1.81	0.47
	A. platanoides No Dog - A. platanoides Dog	-7.29	-11.44	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	0.04	0.06	0.99
	B. pendula No Dog - B. pendula Dog	-1.48	-2.32	0.21
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-1.19	-1.86	0.44
	A. platanoides Dog - B. pendula Dog	6.93	10.88	**<0.001 (***)**
	A. platanoides Dog - R. pseudoacacia Dog	7.26	11.39	**<0.001 (***)**
	B. pendula Dog - R. pseudoacacia Dog	0.33	0.51	0.99
Soil	A. platanoides No Dog - B. pendula No Dog	1.13	2.1	0.31
	A. platanoides No Dog - R. pseudoacacia No Dog	2.17	4.05	**<0.01 (**)**
	A. platanoides No Dog - A. platanoides Dog	1.24	2.32	0.21
	B. pendula No Dog - R. pseudoacacia No Dog	1.05	1.95	0.39
	B. pendula No Dog - B. pendula Dog	-0.59	-1.11	0.87
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-0.72	-1.34	0.76
	A. platanoides Dog - B. pendula Dog	-0.71	-1.32	0.77
	A. platanoides Dog - R. pseudoacacia Dog	0.21	0.4	0.99
	B. pendula Dog - R. pseudoacacia Dog	0.92	1.72	0.52
Leaves	A. platanoides No Dog - B. pendula No Dog	6.14	13.44	**<0.001 (***)**
	A. platanoides No Dog - R. pseudoacacia No Dog	6.51	14.24	**<0.001 (***)**
	A. platanoides No Dog - A. platanoides Dog	4.25	9.3	**<0.001 (***)**
	B. pendula No Dog - R. pseudoacacia No Dog	0.37	0.8	0.96
	B. pendula No Dog - B. pendula Dog	-3.15	-6.9	**<0.001 (***)**
	R. pseudoacacia No Dog - R. pseudoacacia Dog	-3.55	-7.78	**<0.001 (***)**
	A. platanoides Dog - B. pendula Dog	-1.26	-2.76	0.09
	A. platanoides Dog - R. pseudoacacia Dog	-1.3	-2.84	0.07
	B. pendula Dog - R. pseudoacacia Dog	-0.04	-0.08	0.99

The results concerning the $\delta^{15}N$ isotopic ratio in wood reveal statistically significant differences exclusively for the species *A. platanoides* (Table 16). In the intra-species comparison of *A. platanoides*, the estimate = -7.29, supported by a P-value < 0.001, indicating a substantial decrease in the nitrogen isotopic signal in the presence of dogs. In the comparison between *A. platanoides* Dog vs *B. pendula* Dog, a high estimate value = 6.93 is observed, supported by a P-value < 0.001. Similarly, the comparison between *A. platanoides* Dog vs *R. pseudoacacia* Dog yields an estimate = 7.26 and a P-value < 0.001, confirming statistical significance. Intra-species comparisons and all No Dog comparisons do not show statistically significant differences.

The results for the soil isotopic ratio show only one statistically significant difference between two species under the No Dog treatment. Specifically, *A. platanoides* No Dog vs *R. pseudoacacia* No Dog presents an estimate = 2.17 and a P-value < 0.01, suggesting that the soil under *A. platanoides* No Dog is isotopically more enriched in ^{15}N than that under *R. pseudoacacia* No Dog. Intra-species comparisons do not reach statistical significance.

The results for leaves reveal multiple statistically significant differences, both between species and between Dog and No Dog treatments. In the comparison between *A. platanoides* No Dog vs *B. pendula* No Dog, the estimate = 6.14, supported by a P-value < 0.001, and for *A. platanoides* No Dog vs *R. pseudoacacia* No Dog, the estimate = 6.51, also supported by a P-value < 0.001. In both cases, *A. platanoides* shows significantly higher δ^{15}N values compared to the other species. The intra-species comparison between *A. platanoides* Dog vs *A. platanoides* No Dog yields an estimate = 4.25 and a P-value < 0.001, indicating that the δ^{15}N ratio significantly decreases in the presence of dogs. For *B. pendula*, the intra-species comparison yields an estimate = -3.15, supported by a P-value < 0.001, suggesting an increase in δ^{15}N with dog presence. Similarly, the intra-species comparison of *R. pseudoacacia* shows an estimate = -3.55 and a P-value < 0.001, indicating that *R. pseudoacacia* also exhibits an increase in δ^{15}N under the Dog treatment.

Figure 8, shown below, presents the values related to the content of C, δ^{13}C, N, and δ^{15}N in dog urine and pet food samples.

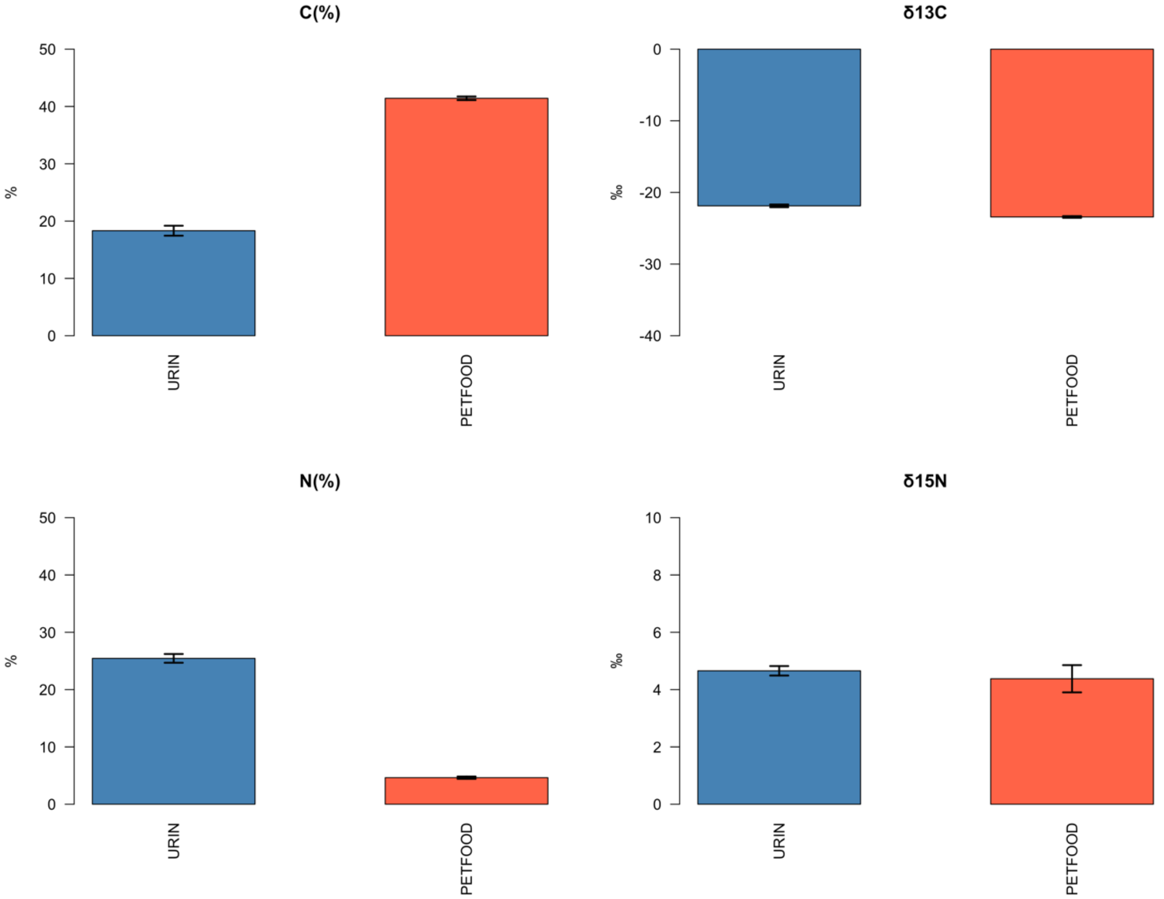


Figure 9: C, N, δ^{13}C and δ^{15}N content in dogs urine and petfood samples, C and N are represented in %, otherwhise δ^{13}C and δ^{15}N are represented in ‰.

The analysis of urine reveals values that differ from those previously discussed for wood, soil, and leaves (Figure 8). The carbon (C) concentration in urine is 18.32%, which is significantly lower than the values recorded in wood and leaves, which were approximately 40%. In pet food, the percentage is around 42%, reflecting the levels found in wood and leaves. The δ^{13}C value for both samples is approximately -20‰, showing continuity between the carbon ingested through pet food and that excreted in urine. The nitrogen (N) content is higher in urine than in pet food, with values of

25.45% and 6.43%, respectively. The value in pet food reflects the composition of the diet and is higher than that found in leaf samples. The $\delta^{15}N$ values are similar between urine and pet food, with values of 4.66‰ and 4.38‰, respectively.

Nutrients results

One of the main objectives of this study was to observe whether the presence of dogs influences the tree response to drought in a positive or negative way. This effect can be linked to the greater availability of nutrients for trees, as shown in a study by Gessler et al. (2017). Dogs can contribute significant amounts of certain nutrients, which are present in high concentrations in their urine. The main nutrients include N, P, K, and Na (Chang et al., 2018).

Below are the graphs showing the levels of these nutrients in the wood samples. The graphs display boxplots for the different species, divided by the two treatment types to which the samples refer. Above each species-specific boxplot, the p-value for the corresponding intra-species comparison is shown.

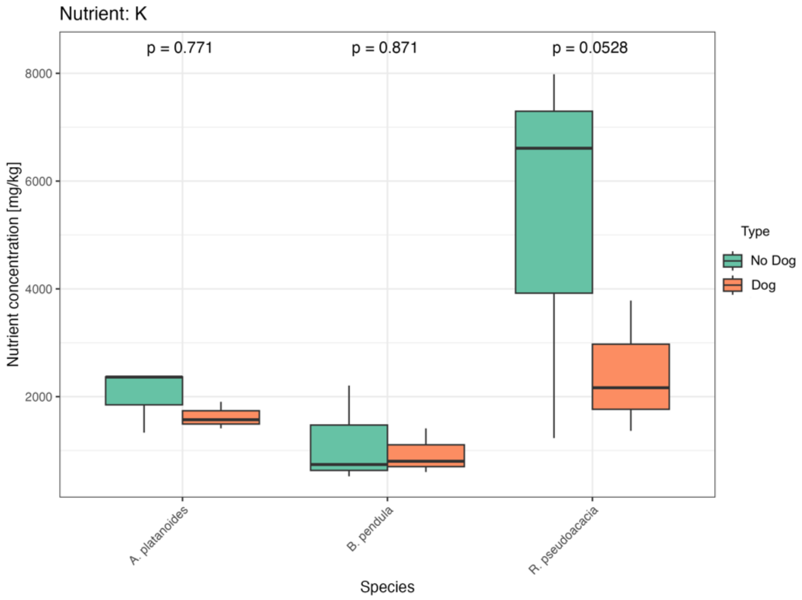


Figure 10: K concentration [mg/kg] in wood samples, subdivided by species and treatment.

Table 17: Results of the statistical comparison between each species and treatment for K values in wood samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	**estimate**	**t.ratio**	**p.value**
A. platanoides No Dog - A. platanoides Dog	392.76	0.3	0.77
B. pendula No Dog - B. pendula Dog	218.23	0.17	0.87
R. pseudoacacia No Dog - R. pseudoacacia Dog	2836.59	2.15	0.05
A. platanoides No Dog - B. pendula No Dog	866.07	0.66	0.8
A. platanoides No Dog - R. pseudoacacia No Dog	-3251.99	-2.47	0.08
B. pendula No Dog - R. pseudoacacia No Dog	-4118.06	-3.12	**<0.05 (*)**
A. platanoides Dog - B. pendula Dog	691.54	0.53	0.87
A. platanoides Dog - R. pseudoacacia Dog	-808.16	-0.62	0.82
B. pendula Dog - R. pseudoacacia Dog	-1499.7	-1.14	0.52

Potassium values in wood show variability across species and between Dog and No Dog treatments (Figure 10). Regarding intra-species comparisons, *A. platanoides* and *B. pendula* do not display statistically significant differences, with P-values > 0.05. For *R. pseudoacacia*, Dog treatment show lower potassium concentrations compared to the No Dog treatment, and the difference approaches significance, although it does not exceed the statistical threshold of P-value < 0.05. The median potassium value for the Dog group is approximately 2200 mg/kg, while for the No Dog group it is around 6600 mg/kg.

Only one statistically significant difference is observed, between *B. pendula* No Dog vs *R. pseudoacacia* No Dog, with an estimate = -4118.06. This highly negative value indicates significantly higher potassium concentrations in *R. pseudoacacia* compared to *B. pendula* in samples not exposed to dog presence. The highest potassium concentrations are found in *R. pseudoacacia*, with a median around 6600 mg/kg, while the other groups show median values around 2000 mg/kg. A high degree of variability is observed in *R. pseudoacacia* No Dog samples, in contrast to the other groups, which show more stable values (Table 17).

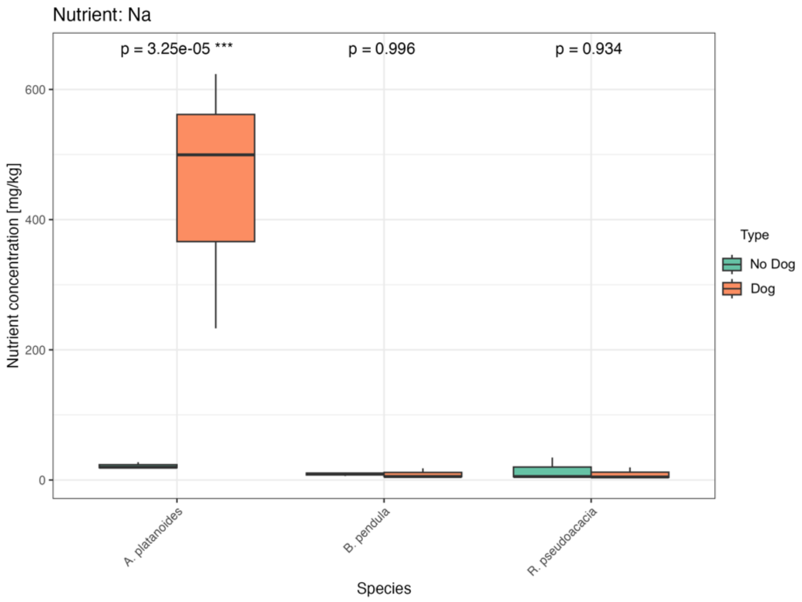


Figure 11: Na concentration [mg/kg] in wood samples, subdivided by species and treatment.

Table 18: Results of the statistical comparison between each species and treatment for Na values in wood samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	estimate	t.ratio	p.value
A. platanoides No Dog - A. platanoides Dog	-430.23	-6.44	**<0.001 (***)**
B. pendula No Dog - B. pendula Dog	-0.34	-0.01	0.99
R. pseudoacacia No Dog - R. pseudoacacia Dog	5.69	0.09	0.93
A. platanoides No Dog - B. pendula No Dog	12.66	0.19	0.99
A. platanoides No Dog - R. pseudoacacia No Dog	6.88	0.11	0.99
B. pendula No Dog - R. pseudoacacia No Dog	-5.78	-0.09	0.99
A. platanoides Dog - B. pendula Dog	442.56	6.62	**<0.001 (***)**
A. platanoides Dog - R. pseudoacacia Dog	442.8	6.62	**<0.001 (***)**
B. pendula Dog - R. pseudoacacia Dog	0.25	0.01	0.99

Sodium values are highly variable in *A. platanoides* and stable in the other species (Figure 11). For *A. platanoides* Dog, values are significantly higher compared to the No Dog treatment, with a P-value = 3.25×10^{-5}. The median sodium concentration in the No Dog samples is around 20 mg/kg, while in the Dog samples it is approximately 500 mg/kg. Moreover, the Dog samples show considerable variability.

A. platanoides Dog also shows statistically significant differences when compared to *B. pendula* Dog, supported by a P-value < 0.001, and to *R. pseudoacacia* Dog, also supported by a highly negative estimate and a P-value < 0.001. Therefore, *A. platanoides* under the Dog treatment is generally characterized by significantly higher sodium concentrations compared to all other groups included in the comparisons. For *B. pendula* and *R. pseudoacacia*, no statistically significant intra-species differences are observed in sodium levels between the two treatment types (Table 18).

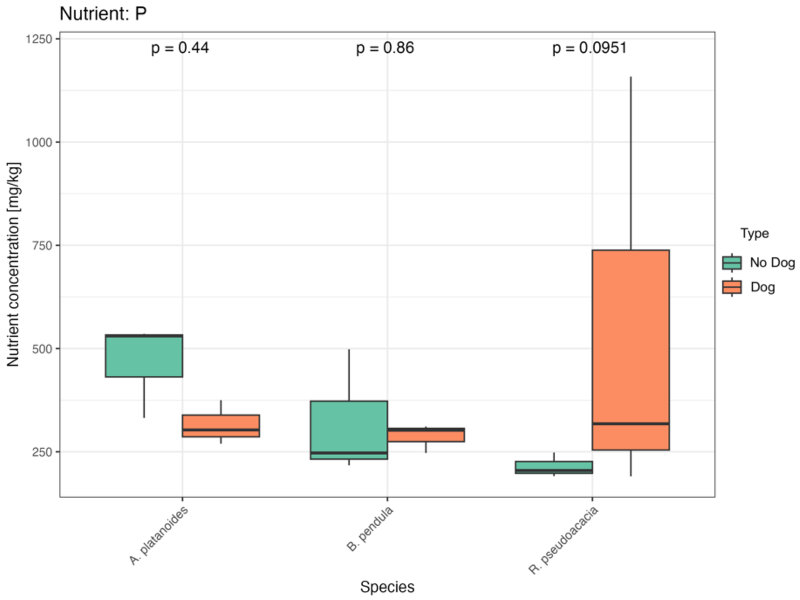


Figure 12: P concentration [mg/kg] in wood samples, subdivided by species and treatment.

Table 19: Results of the statistical comparison between each species and treatment for phosphorous (P) values in wood samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	estimate	t.ratio	p.value
A. platanoides No Dog - A. platanoides Dog	150.18	0.8	0.44
B. pendula No Dog - B. pendula Dog	34.01	0.19	0.86
R. pseudoacacia No Dog - R. pseudoacacia Dog	-340.96	-1.82	0.1
A. platanoides No Dog - B. pendula No Dog	145.16	0.78	0.73
A. platanoides No Dog - R. pseudoacacia No Dog	251.34	1.34	0.41
B. pendula No Dog - R. pseudoacacia No Dog	106.18	0.57	0.85
A. platanoides Dog - B. pendula Dog	28.99	0.16	0.99
A. platanoides Dog - R. pseudoacacia Dog	-239.8	-1.28	0.44
B. pendula Dog - R. pseudoacacia Dog	-268.79	-1.43	0.36

Phosphorus values in the wood samples do not show any statistically significant differences among the observed species. All P-values are > 0.1 (Table 19). For *R. pseudoacacia*, there is a trend toward higher P content in the Dog group, although the threshold for statistical significance is not reached. The Dog group of *R. pseudoacacia* also shows greater variability compared to the other groups, which appear generally more stable.

Nevertheless, the group with the highest phosphorus values is *A. platanoides* No Dog, with a median around 540 mg/kg. The remaining groups display values ranging between 200 and 300 mg/kg (Figure 12).

The concentration of nutrients in the soil and their corresponding graphs are presented below, then a summary table of comparisons for each is represented.

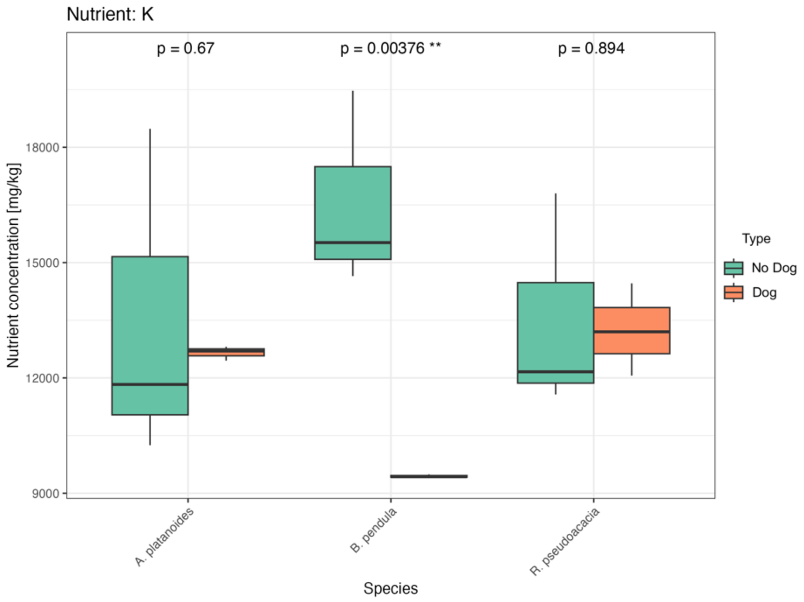


Figure 13: K concentration [mg/kg] in soil samples, subdivided by species and treatment.

Table 20: Results of the statistical comparison between each species and treatment for K values in the soil samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	**estimate**	**t.ratio**	**p.value**
A. platanoides No Dog - A. platanoides Dog	866.67	0.44	0.67
B. pendula No Dog - B. pendula Dog	7103.34	3.59	**<0.01 (**)**
R. pseudoacacia No Dog - R. pseudoacacia Dog	270.01	0.14	0.89
A. platanoides No Dog - B. pendula No Dog	-3026.67	-1.53	0.32
A. platanoides No Dog - R. pseudoacacia No Dog	10.01	0.01	0.99
B. pendula No Dog - R. pseudoacacia No Dog	3036.67	1.54	0.32
A. platanoides Dog - B. pendula Dog	3210	1.62	0.28
A. platanoides Dog - R. pseudoacacia Dog	-586.67	-0.3	0.96
B. pendula Dog - R. pseudoacacia Dog	-3796.67	-1.92	0.18

Potassium values in soil show a single statistically significant difference, observed in *B. pendula*, whose No Dog values are significantly higher compared to the Dog treatment (Figure 13). The No Dog values are generally higher than those of the other species, clustering around 1560 mg/kg, whereas the Dog values are lower than those of the other groups, around 960 mg/kg. The species *A. platanoides* and *R. pseudoacacia* display generally similar values, ranging between 12000–14000 mg/kg. Overall, it is observed that the No Dog types for each species exhibit greater variability compared to the Dog types, with the widest range seen in *A. platanoides* (Table 20).

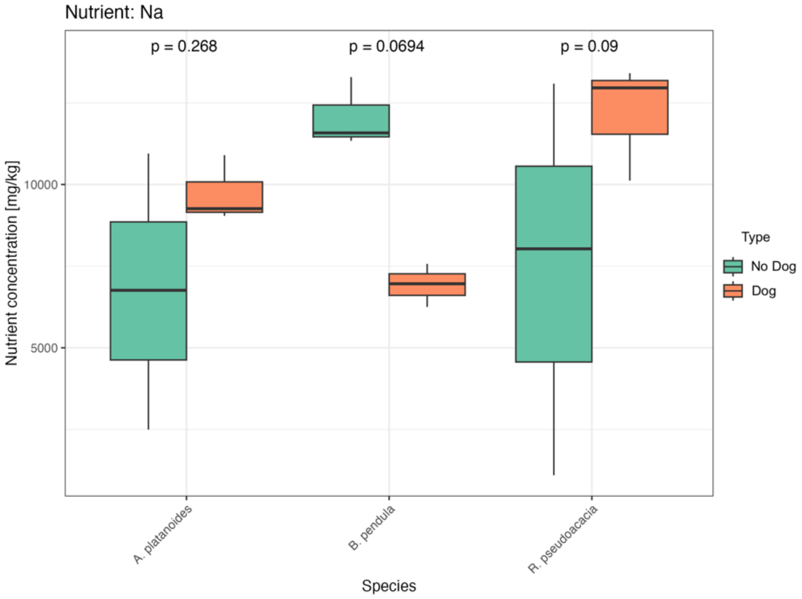


Figure 14: Na concentration [mg/kg] in soil samples, subdivided by species and treatment.

Table 21: Results of the statistical comparison between each species and treatment for Na values in the soil samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	estimate	t.ratio	p.value
A. platanoides No Dog - A. platanoides Dog	-2998.34	-1.17	0.27
B. pendula No Dog - B. pendula Dog	5143.34	2	0.07
R. pseudoacacia No Dog - R. pseudoacacia Dog	-4757.34	-1.85	0.09
A. platanoides No Dog - B. pendula No Dog	-5335	-2.07	0.14
A. platanoides No Dog - R. pseudoacacia No Dog	-671	-0.27	0.97
B. pendula No Dog - R. pseudoacacia No Dog	4664	1.81	0.21
A. platanoides Dog - B. pendula Dog	2806.67	1.09	0.54
A. platanoides Dog - R. pseudoacacia Dog	-2430	-0.95	0.63
B. pendula Dog - R. pseudoacacia Dog	-5236.67	-2.03	0.15

Sodium values in the soil samples do not show variations statistically significant (Table 21). However, the values are highly variable among species (Figure 14). The lowest content is found in *A. platanoides* No Dog, with a median around 7200 mg/kg, while the highest value is observed in *R. pseudoacacia*, around 13200 mg/kg. The p-values for *B. pendula* and *R. pseudoacacia* are close to the significance threshold but do not reach it. For *B. pendula* and *R. pseudoacacia*, greater variability is observed in the No Dog types, while the rest of the groups appear generally stable.

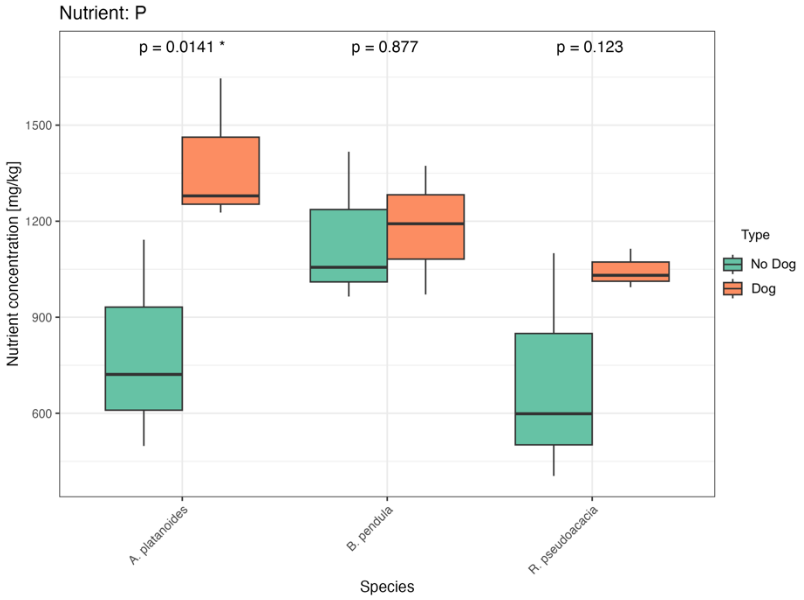


Figure 15: P concentration [mg/kg] in soil samples, subdivided by species and treatment.

Table 22: Results of the statistical comparison between each species and treatment for phosphorous (P) values in the soil samples. The p-values < 0.05, 0.01 and 0.005, and the respective symbols "", "**" and "***", indicate the significance of the contrast between the two groups.*

contrast	**estimate**	**t.ratio**	**p.value**
A. platanoides No Dog - A. platanoides Dog	-596.84	-2.87	**<0.05 (*)**
B. pendula No Dog - B. pendula Dog	-32.8	-0.16	0.88
R. pseudoacacia No Dog - R. pseudoacacia Dog	-345.27	-1.66	0.12
A. platanoides No Dog - B. pendula No Dog	-358.74	-1.73	0.24
A. platanoides No Dog - R. pseudoacacia No Dog	86.17	0.42	0.92
B. pendula No Dog - R. pseudoacacia No Dog	444.9	2.14	0.13
A. platanoides Dog - B. pendula Dog	205.31	0.99	0.6
A. platanoides Dog - R. pseudoacacia Dog	337.74	1.63	0.28
B. pendula Dog - R. pseudoacacia Dog	132.44	0.64	0.81

Phosphorus values in soil show a statistically significant difference, which occurs in the species *A. platanoides*. With a p-value = 0.0141, the Dog type shows significantly higher values, with a median around 1260 mg/kg, compared to the No Dog type, which is around 720 mg/kg (Figure 15). The other species do not show significant differences, although a variation in mean phosphorus content is observed, with the lowest values reaching 600 mg/kg. In general, a moderate variability is observed within each group, except for *R. pseudoacacia* Dog, which appears relatively stable (Table 22).

Nutrients and SPEI values correlation

The results of the correlations between nutrient values in wood and the tolerance indices resistance, resilience, and recovery are presented below. Results are shown for each species and sample type, with reference to the specific time series on which the SPEI indices were calculated.

In this Master Thesis, the number of data points used for the correlation analysis is limited. When data are scarce, statistical results often tend to mirror each other, a phenomenon observed in this study. For this reason, the results should be interpreted with caution (Zhou et al., 2019).

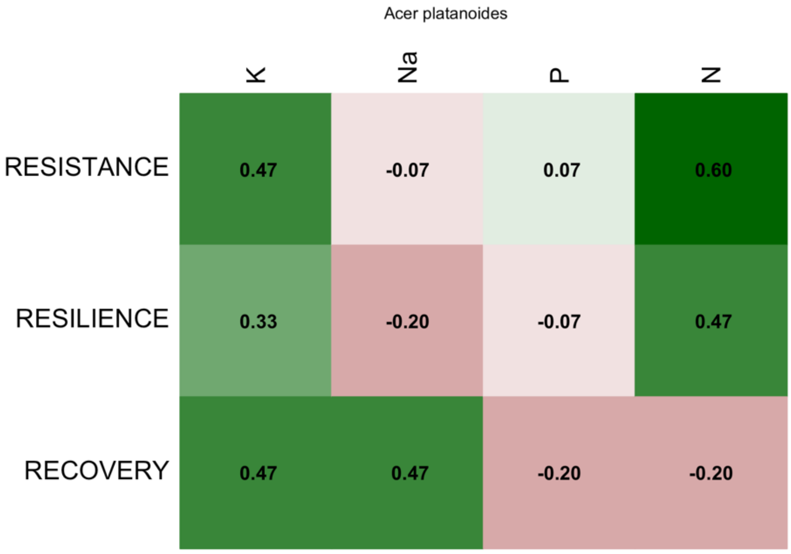
SPEI-3

The results presented below refer to the correlation between nutrient concentrations in wood samples and the values of resistance, resilience, and recovery, calculated based on the SPEI-3 index, for each species and treatment. They represent the correlations between nutrients and tree responses to seasonal drought events (Zhang et al., 2024).

Dog samples

The species *Acer platanoides* shows a moderate positive correlation between nitrogen (N) and resistance (τ = 0.6), suggesting that higher N content might be associated with a better ability to maintain growth during drought. However, the relationship is not statistically significant. A similar pattern is observed with resilience, where the tau value is 0.47, while the recovery index shows the strongest correlation with Na and K. Positive but non-significant correlations are also observed between K and all three indices (Table 23).

Table 23: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the Dog samples for A. platanoides.

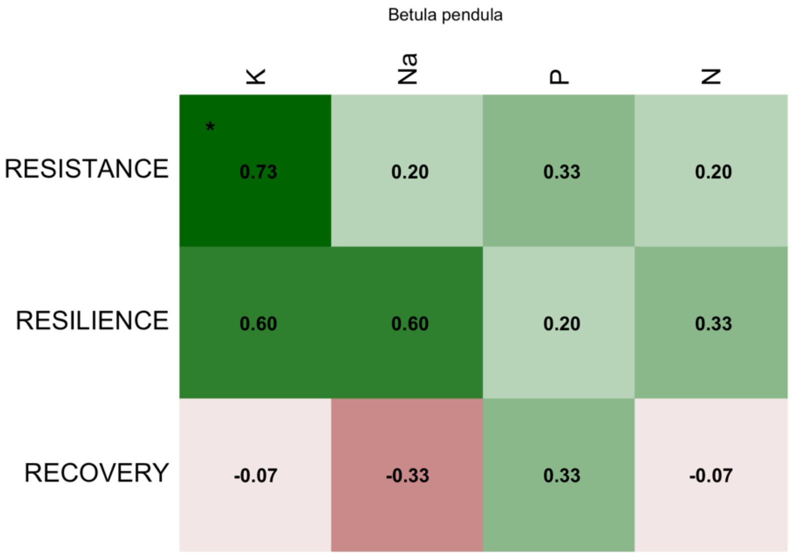


Acer platanoides

	K	Na	P	N
RESISTANCE	**0.47**	**-0.07**	**0.07**	**0.60**
RESILIENCE	**0.33**	**-0.20**	**-0.07**	**0.47**
RECOVERY	**0.47**	**0.47**	**-0.20**	**-0.20**

The species *Betula pendula* shows a significant positive correlation between K and resistance (τ = 0.733), indicating that higher potassium levels may contribute to greater drought stress tolerance. Moderate but non-significant correlations are also observed for K and Na with resilience (τ = 0.6). The recovery index shows the strongest correlation with P, although the overall value is not particularly high (Table 24).

Table 24: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the Dog samples for B. pendula.

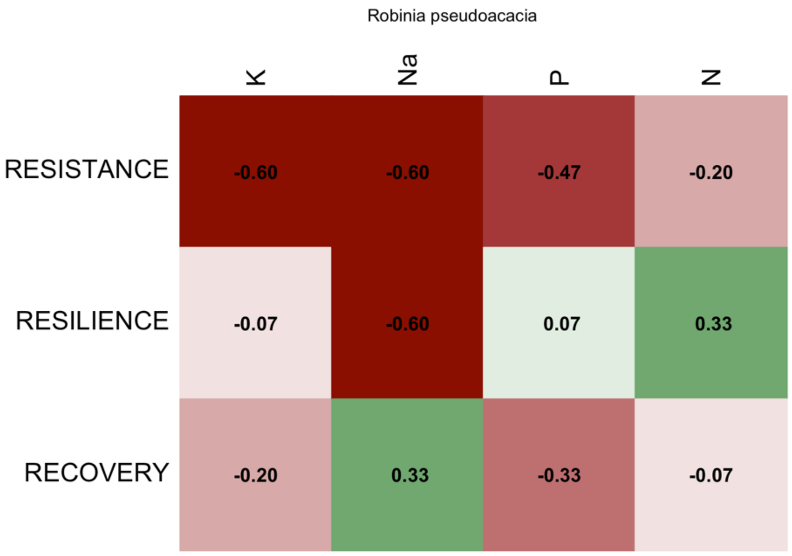


Betula pendula

	K	Na	P	N
RESISTANCE	* 0.73	0.20	0.33	0.20
RESILIENCE	0.60	0.60	0.20	0.33
RECOVERY	-0.07	-0.33	0.33	-0.07

The species *Robinia pseudoacacia* shows negative correlations between K and resistance (τ = –0.6), and between Na and the resistance and resilience indices, suggesting that excessive accumulation of these elements may not promote tolerance in this species. The remaining relationships are not strong and are often negative, indicating a reduced inverse influence of the nutrients to the indices resistance, resilience and recovery (Table 25).

Table 25: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the Dog samples forR. pseudoacacia.



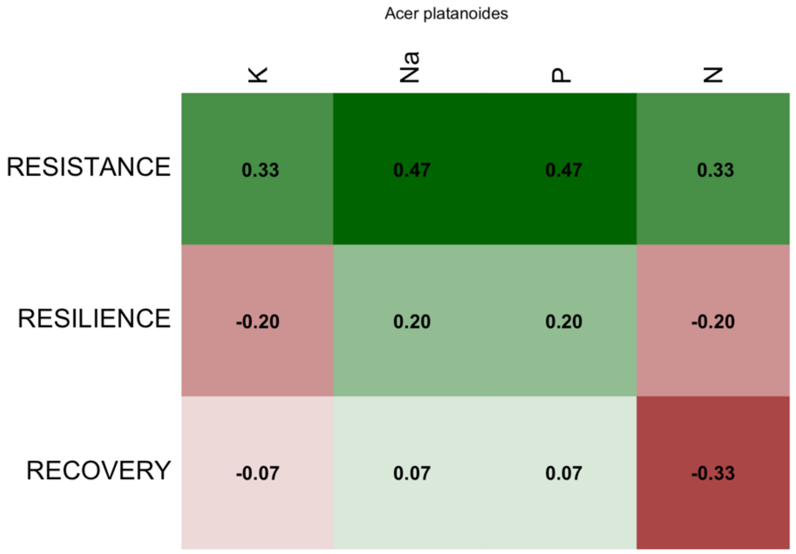
Robinia pseudoacacia

	K	Na	P	N
RESISTANCE	-0.60	-0.60	-0.47	-0.20
RESILIENCE	-0.07	-0.60	0.07	0.33
RECOVERY	-0.20	0.33	-0.33	-0.07

No Dog samples

The species *Acer platanoides* shows moderate positive correlations between resistance and the nutrients Na and P, with τ = 0.467, though none of them are statistically significant. Correlations between recovery and all nutrients are generally weak and mostly positive, indicating a slight positive influence of nutrients on the tolerance indices (Table 26).

Table 26: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the No Dog samples for A. platanoides.

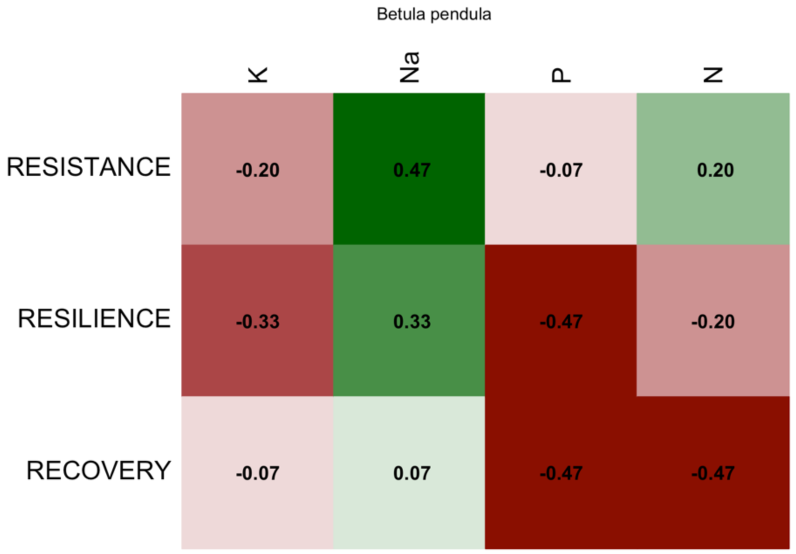


Acer platanoides

	K	Na	P	N
RESISTANCE	0.33	0.47	0.47	0.33
RESILIENCE	-0.20	0.20	0.20	-0.20
RECOVERY	-0.07	0.07	0.07	-0.33

Regarding *Betula pendula*, this species shows some moderate negative correlations with P and both resilience and recovery (τ = –0.467), as well as with N for recovery, though none are statistically significant. The highest positive correlation is observed between resistance and Na (τ = 0.467). The remaining data range from positive to negative (Table 27).

Table 27: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the No Dog samples for B. pendula.

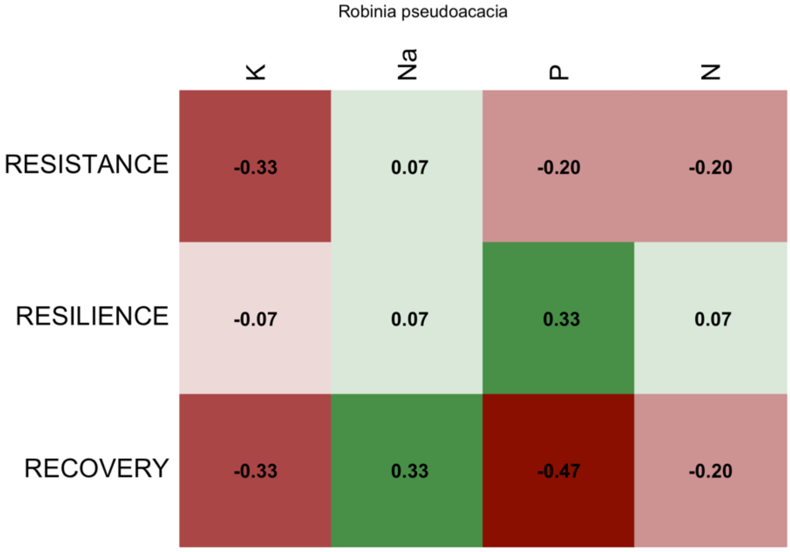


Betula pendula

	K	Na	P	N
RESISTANCE	-0.20	0.47	-0.07	0.20
RESILIENCE	-0.33	0.33	-0.47	-0.20
RECOVERY	-0.07	0.07	-0.47	-0.47

The species *Robinia pseudoacacia* shows generally weak or negative and non-significant correlations across all combinations. The most pronounced relationship is negative and not statistically significant, observed between the recovery index and P, with a tau value of –0.467 (Table 28).

Table 28: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-3 values, and the nutrients values in the No Dog samples for R. pseudoacacia.



Robinia pseudoacacia

	K	Na	P	N
RESISTANCE	-0.33	0.07	-0.20	-0.20
RESILIENCE	-0.07	0.07	0.33	0.07
RECOVERY	-0.33	0.33	-0.47	-0.20

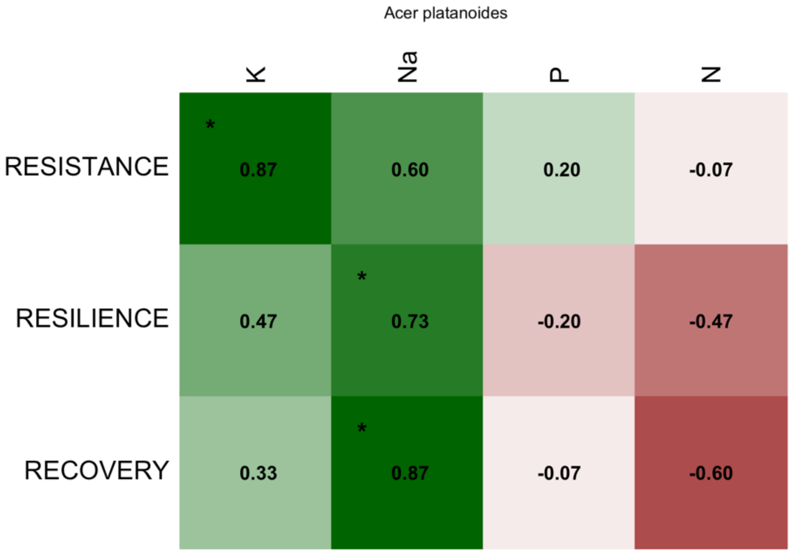
SPEI-12

The results presented below refer to the correlation between nutrient concentrations in wood samples and the values of resistance, resilience, and recovery, calculated based on the SPEI-12 index, for each species and treatment. They represent the correlations between nutrients and tree responses to annual drought events (Zhang et al., 2024).

Dog samples

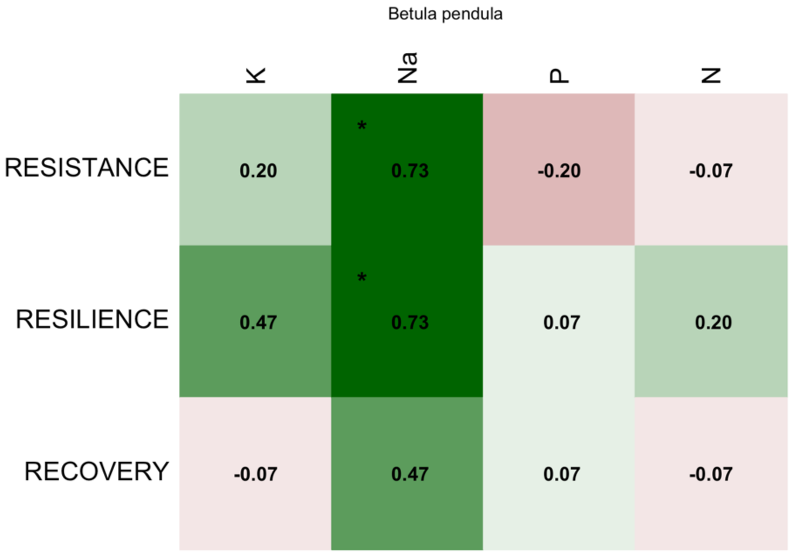
In comparison with the tolerance indices obtained using SPEI-12, *Acer platanoides* shows statistically significant correlations between K and resistance (τ = 0.867), Na and resilience (τ = 0.733), and Na and recovery (τ = 0.867). These results suggest a strong link between potassium and sodium availability and the species' ability to tolerate and recover from prolonged drought periods (Table 29).

Table 29: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the Dog samples for A. platanoides.



The species *Betula pendula* displays two significant correlations, observed between Na and resistance (τ = 0.733), and Na and resilience (τ = 0.733), indicating a potential positive role of sodium in drought response for this species. The remaining correlations are weak or non-significant and tend to be positive (Table 30).

Table 30: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the Dog samples for B. pendula.

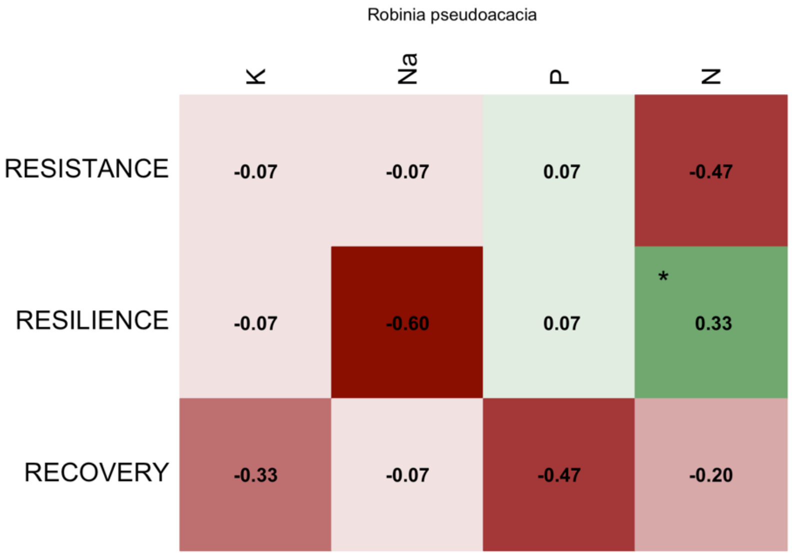


Betula pendula

	K	Na	P	N
RESISTANCE	0.20	* 0.73	-0.20	-0.07
RESILIENCE	0.47	* 0.73	0.07	0.20
RECOVERY	-0.07	0.47	0.07	-0.07

The species *Robinia pseudoacacia*, under the Dog treatment in prolonged drought conditions, shows a statistically significant correlation between N and recovery (τ = 0.334). The rest of the correlations are non-significant, and the strongest among them are negative, with the most pronounced being between Na and resilience (τ = –0.6). Overall, *R. pseudoacacia* tends to exhibit negative relationships (Table 31).

Table 31: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the Dog samples for R. pseudoacacia.



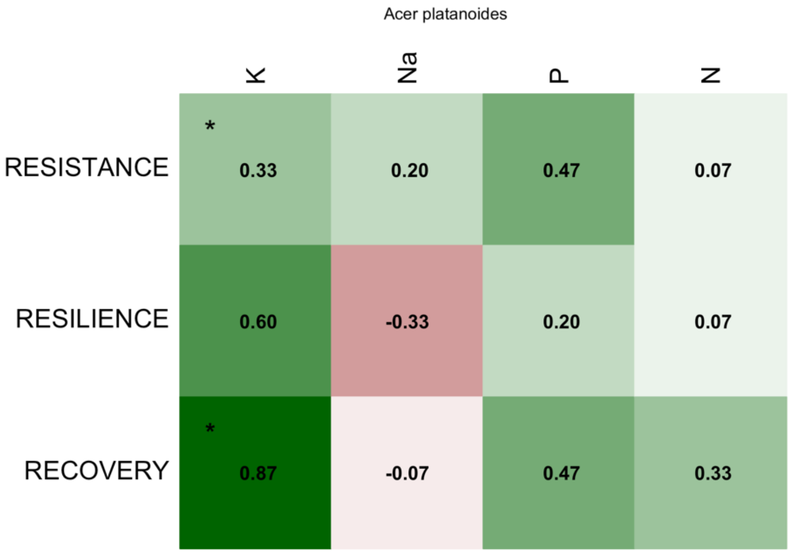
Robinia pseudoacacia

	K	Na	P	N
RESISTANCE	-0.07	-0.07	0.07	-0.47
RESILIENCE	-0.07	-0.60	0.07	* 0.33
RECOVERY	-0.33	-0.07	-0.47	-0.20

No Dog samples

The species *Acer platanoides* shows two positive and statistically significant correlations regarding K: specifically between K and recovery (τ = 0.867) and between K and resistance (τ = 0.334), suggesting that higher potassium content is associated with a better capacity for recovery and resistance during and after long-term drought events. Other positive but non-significant correlations are observed between K and resilience (τ = 0.6), and between P and both resistance and recovery (τ = 0.467), although they do not exceed the statistical significance threshold (Table 32).

Table 32: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the No Dog samples for A. platanoides.

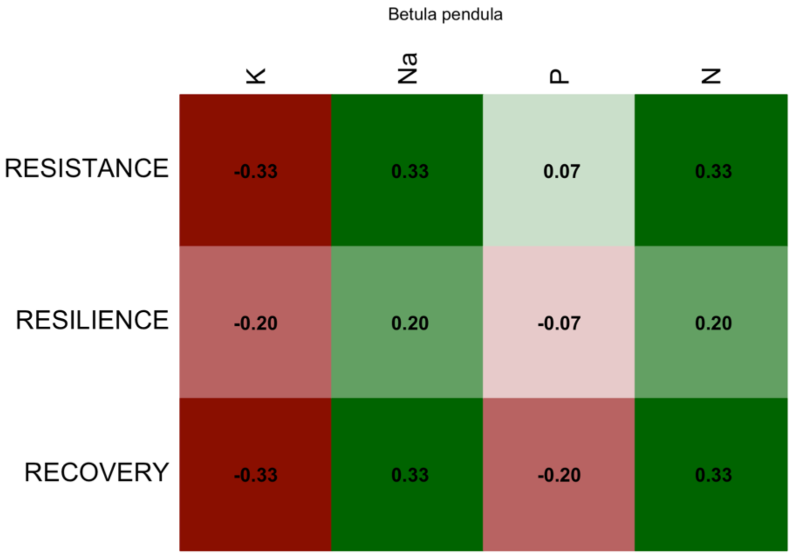


Acer platanoides

	K	Na	P	N
RESISTANCE	* 0.33	0.20	0.47	0.07
RESILIENCE	0.60	-0.33	0.20	0.07
RECOVERY	* 0.87	-0.07	0.47	0.33

In comparison with the tolerance index values measured using SPEI-12, *Betula pendula* does not show any statistically significant correlations. The observed relationships are all weak to moderate, with mixed signs and high p-values. The only consistent trend is a moderate positive correlation between Na and both resistance and recovery, though it is not statistically significant (Table 33).

Table 33: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the No Dog samples for B. pendula.

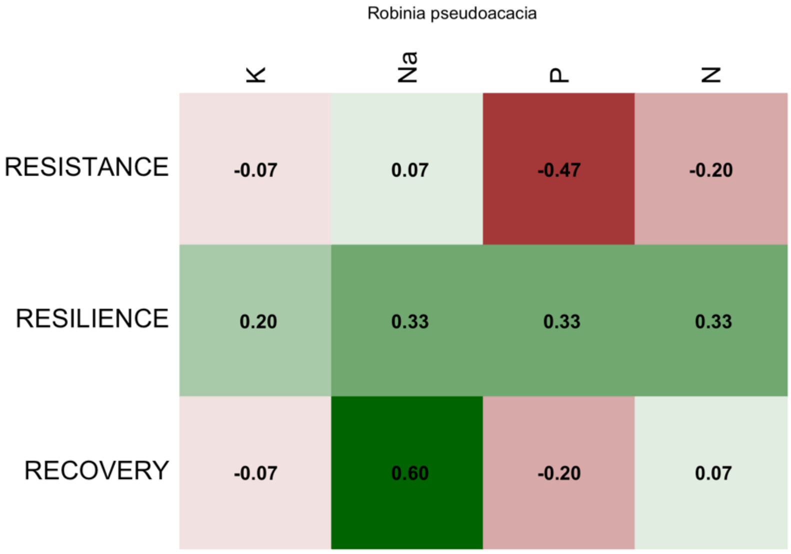


Betula pendula

	K	Na	P	N
RESISTANCE	-0.33	0.33	0.07	0.33
RESILIENCE	-0.20	0.20	-0.07	0.20
RECOVERY	-0.33	0.33	-0.20	0.33

The species *Robinia pseudoacacia* shows a moderate correlation between Na and recovery (τ = 0.6), which is not significant but may indicate a potential positive effect of sodium on recovery capacity after drought periods. All other correlations are weak and likewise not statistically significants (Table 34).

Table 34: Results of the correlation between resistance, resilience and recovery indexes, calculated from the SPEI-12 values, and the nutrients values in the No Dog samples for. pseudoacacia.



Robinia pseudoacacia

	K	Na	P	N
RESISTANCE	-0.07	0.07	-0.47	-0.20
RESILIENCE	0.20	0.33	0.33	0.33
RECOVERY	-0.07	0.60	-0.20	0.07

4. Discussion

This chapter discusses the results obtained from the sample analysis in light of the research questions and hypotheses proposed in the introductory chapter. The multidisciplinary approach, combining dendrochronological and chemical analyses, enabled an investigation into the responses of *A. platanoides*, *B. pendula*, and *R. pseudoacacia* to drought events, as well as the role of both soil space and dogs in the urban context of Zurich. The data revealed differences among species and treatments, offering valuable insights into the growth dynamics experienced by trees in urban environments. This discussion follows the order of the research questions and aims to interpret the findings in relation to existing literature, in order to confirm or refute the proposed hypotheses. Limitations of the study are also addressed, along with suggestions for future research on similar topics.

Visibility of drought events

Numerous studies have shown that drought events are reflected in tree rings, which under dry conditions exhibit reduced growth compared to more favorable periods (Deng et al., 2025; Zhang et al., 2023). This occurs primarily because during dry periods, radial growth is not prioritized over root growth, making it more susceptible to variation in ring width (Waring, 1987). The relationship between climate and annual tree-ring growth has also been observed in urban trees (Nitschke et al., 2017). Tree species exhibit specific and differentiated responses to climate stress, particularly rising temperatures. According to several studies, *Acer platanoides* shows increased sensitivity of radial growth to drought during the summer months, suggesting growing vulnerability in urban and semi-natural environments characterized by prolonged water stress (Gillner et al., 2014; Kunz et al., 2016). Compared to other *Acer* species, however, *A. platanoides* appears to be less prone to drought-induced variation (Haase et al., 2022). Other studies have shown that *Betula pendula* tends to be generally tolerant of weather variations, although some minor negative effects can occur under drought conditions (Matisons et al., 2022; Aldea et al., 2023). Regarding the species *Robinia pseudoacacia*, it stands out for its high recovery capacity after drought events: during stress periods, marked reductions in growth are recorded, but these are followed by rapid recovery phases, indicating strong resilience (Moser et al., 2016). The study by Franceschi et al. (2023) reported similar findings, identifying *R. pseudoacacia* as a highly drought-resistant species. In the context of the present work, *R. pseudoacacia* differs from the other species due to its symbiosis with *Rhizobium* bacteria, which support nitrogen assimilation and increase phosphorus availability in the soil. These factors support root development and enhance water uptake (Liu et al., 2013; Mansour et al., 2021). Symbiotic nitrogen fixation helps reduce the stress caused by limited water availability and promotes amino acid synthesis, leading to reduced drought sensitivity (Wan et al., 2021; Barquero et al., 2022).

In this Master Thesis, the relationship between climatic conditions and tree-ring growth was examined through the analysis of correlations between species-specific RWI values and SPEI values, calculated for both 3-month and 12-month time scales (Vicente-Serrano et al., 2010; Beguería et al., 2014; Bose et al., 2019; Fekedulegn et al., 2023).

The results analysis revealed that in several cases, a correspondence can be observed between drought periods, characterized by negative SPEI values (typically < 1), and a reduction in annual tree-ring growth rates. However, the observed relationship does not appear to be systematic. For *A. platanoides*, a strong coherence was observed between years with very low SPEI values and reduced RWI values. This is evident particularly for the years 2003, 2017, 2020, and 2022 for SPEI-3, and 2012, 2017, 2019, 2022, and 2023 for SPEI-12. In other drought years, no notable reductions in ring growth were observed for *A. platanoides*. For short-term drought events (SPEI-3), some years such as 2007 and 2012 show reduced growth without corresponding to officially defined drought years. In general, the results indicate that

A. platanoides tends to reflect years of drier climate, consistent with findings by Gillner et al. (2014) and Kunz et al. (2016), who report high sensitivity in response to drought years.

The species *B. pendula* also appears to be affected by drier years, especially 2003, 2011, 2017, 2020, and 2022 for the SPEI-3 index, and 2016, 2017, 2019, 2020, and 2022 for SPEI-12. In other years, no clear drought-induced reductions are evident. This confirms previous observations that *B. pendula* exhibits growth reductions in response to increasing drought, although this relationship is less pronounced than in *A. platanoides* (Matisons et al., 2022; Aldea et al., 2023).

In contrast, the species *R. pseudoacacia* shows a less evident relationship with the driest years. For SPEI-3 data, only in 2011 is there a marked variation in RWI corresponding to particularly negative drought conditions. For SPEI-12, slight correspondences are observed in four years. Overall, growth reductions in *R. pseudoacacia* appear to be less pronounced than in *A. platanoides* and *B. pendula*. This result diverges from other studies, which generally report significant growth reductions in *R. pseudoacacia* during drought periods (Moser et al., 2016).

Overall, the results show that although drought events are reflected in tree rings in several cases, the response is not always linear. This supports the initial hypothesis related to the first research question. Some species show stronger similarities, such as *A. platanoides* and *B. pendula*, while others, such as *R. pseudoacacia*, show less variation under changing water conditions. The varying sensitivity among species indicates that physiological factors play a clear role in tree responses to hydrological conditions. The observed variability confirms the hypothesis that in urban environments, tree responses to water conditions may be either reduced or amplified by local factors and are species-specific. The urban environment is highly heterogeneous, and its characteristics, such as shading, irrigation, soil compaction, and environmental management, play a significant role and vary considerably across different parts of the city, making it difficult to isolate the effects of hydrological conditions alone (Dale et al., 2022).

Species reactions to treatments

Soil in urban environments is subject to nutrient input from dogs. Their urine contains several elements—including nitrogen, phosphorus, potassium, and sodium—that can influence tree health and vitality (Chang et al., 2018; De Frenne et al., 2021). The variability in the content of these nutrients due to the presence of dogs has been highlighted in various studies, which have shown that such inputs can impact tree growth in urban settings (Allen, 2020; De Frenne, 2021). However, the actual availability of these elements in the soil does not automatically translate into their absorption by plants, as it is regulated by complex processes, including microbial transformations, volatilization, leaching, and interactions with organic matter (Malone et al., 2023; Shi et al., 2024). Moreover, nutrient assimilation varies according to the specific physiological strategies of different species, reflecting functional adaptations and heterogeneous environmental conditions (Barbehenn et al., 2015; Smith et al., 2018). As highlighted by Lima et al. (2024), nutrient uptake can vary significantly even within the same urban context. The amount of nutrients in urban landscapes is often highly variable, and this variability is also influenced by physical characteristics typical of urban environments, such as the prevalence of impermeable surfaces and limited soil availability, which can hinder root development and compromise the absorption of nutrients essential for tree growth (Kopinga, 1991; Allen et al., 2020; De Frenne et al., 2021).

In this study, Dog and No Dog samples differ not only in terms of dog presence but also in the spatial conditions in which the trees are located. Dog trees are situated along roadsides, in more constrained soils, whereas No Dog trees come from more open environments such as schools and cemeteries, where rooting space is generally greater. As a result, the findings are not always systematic across locations or species; nonetheless, this section of the discussion attempts to interpret the differences observed between soil and wood samples.

For this research, the levels of the main elements found in dog urine were compared in order to highlight differences between Dog and No Dog samples for each species. These elements include K, Na, P, and N. The studies by Chang et al. (2018) and De Frenne et al. (2021) measured the concentrations of these nutrients in urine samples from four dog breeds, reporting average concentrations of 97 mmol/L for K, 78 mmol/L for Na, approximately 484.6 mg/L for P, and 18 g/L for N. In the present study, the nitrogen concentration in dog urine was calculated and found to be approximately 24%, a value similar to and slightly higher than the 18% reported by Chang et al. (2018).

In addition to the nutrients mentioned above, total carbon (C) content and the isotopic ratios $\delta^{13}C$ and $\delta^{15}N$ were analyzed in soil, leaves, and wood, with the aim of gaining deeper insight into nutrient assimilation mechanisms and nutrient origin. However, the data related to carbon and $\delta^{13}C$ are less informative in assessing the direct influence of urine. Organic carbon introduced through urine deposition, although detectable in the soil, is not readily absorbed by plants. This is because it is rapidly utilized by soil microorganisms during mineralization processes, being converted into CO_2 and thus contributing more to microbial respiration than to root uptake (Malone et al., 2023; Shi et al., 2024). Therefore, the carbon contributed by dogs mainly serves as a resource for microbes rather than as a direct nutrient source for trees, which primarily rely on atmospheric CO_2 (Keenan et al., 2013). For this reason, carbon was not considered in the observations regarding correlations between nutrients and the resistance, resilience, and recovery indices.

The results show that for some elements, increases in the Dog soil samples compared to the No Dog samples were evident, highlighting that the presence of dogs—particularly in urban environments—can influence soil nutrient content and thus nutrient availability for trees (De Frenne, 2021). The data indicate that nitrogen (N) content in the soil is significantly higher in Dog areas for *Acer platanoides* and *Robinia pseudoacacia*, whereas no differences were found for *Betula pendula*. This partially confirms what has been reported in the literature, namely that dog urine is a rich source of nitrogen compounds, with an average concentration of about 18 g/L, and its deposition can contribute to increased soil N content (Chang et al., 2018; De Frenne et al., 2021). In wood, no substantial differences were observed between treatments, although *R. pseudoacacia* showed higher N levels, in line with its nitrogen-fixing ability (Mantovani et al., 2014; Li et al., 2023). In the leaves, no particularly marked differences between the two treatments were detected, which aligns with findings from other studies that reported no significant increases in wood nitrogen despite greater availability (Zhang et al., 2024).

The analysis of nitrogen isotopic composition ($\delta^{15}N$) in the different materials revealed species-specific responses to the presence of dogs, confirming that the impact of animal-derived nutrient input is not uniform. In particular, the wood of *Acer platanoides* shows a clear separation between groups, with a substantial increase in samples exposed to dogs, suggesting greater assimilation of organic nitrogen, reflected in the elevated $\delta^{15}N$ ratio. While N content in *A. platanoides* wood appears similar across Dog and No Dog samples, this confirms that the nitrogen source differs, as revealed by the isotopic signature. The study by Oulehle et al. (2022) showed that this species responds positively to increased nitrogen supply in its environment, with greater assimilation resulting in higher $\delta^{15}N$ values. Another possible explanation could be the use of fertilizer in areas where Dog trees are located. As noted in various studies, organic fertilization can result in elevated $\delta^{15}N$ values in tree rings (Percin et al., 2023). An additional contributing factor could be traffic-related influence: NO_x emissions from vehicles can lead to $\delta^{15}N$ enrichment in plant tissues. This was observed by Saurer et al. (2004), who reported increases up to +7.9‰ in tree ring $\delta^{15}N$ near a Swiss highway, showing how heavy isotopic NO_2 deposition from vehicular sources can significantly alter the isotopic signal in wood. Although their research focused on *Picea abies*, the findings represent an important source of insight into how nitrogen assimilation may influence tree rings, particularly in heavily trafficked cities such as Zurich.

The other two tree species, though showing less pronounced increases, appeared to respond in the same direction, albeit with weaker or statistically insignificant effects, suggesting a potential but less consistent response (Högberg, 1997; Craine et al., 2015). In the soil, by contrast, statistical significance was not observed. Trends varied by species: *A. platanoides* showed higher values in the undisturbed group, which may be due less to direct uptake by the species and more to differences in root activity that mediate the availability and form of accessible nitrogen—particularly interactions between roots and soil fungi or microorganisms involved in nitrogen uptake. These findings support the idea that ^{15}N assimilation by trees is not systematic (Hu et al., 2022; Guo et al., 2024; Li et al., 2025; Pronin et al., 2025).

Leaves provide the clearest picture, showing statistically significant differences between groups across all species. However, the direction of the effect is not consistent. *A. platanoides* exhibits a reduction in $\delta^{15}N$ in the presence of dogs, as also seen in the soil, in contrast to *B. pendula* and *R. pseudoacacia*, which show an increase. The differences observed in *A. platanoides* do not align with data from several studies, which emphasize that organic nitrogen sources such as dog urine tend to have higher isotopic signatures than inorganic sources and should therefore yield higher $\delta^{15}N$ values (Garten, 1993; Evans, 2001). This variation is likely attributable to other influencing factors.

Carbon content generally shows variation in the soil samples. In particular, soils from Dog samples—especially for *Acer platanoides*—exhibit a significant increase in carbon concentration compared to No Dog samples. This result is consistent with findings from several studies that have demonstrated how the input of organic matter from animal sources can increase soil organic carbon content (Malone et al., 2023; Shi et al., 2024). However, this increase is not systematically reflected in plant tissues. In wood, for instance, carbon values appear similar between the two treatments across all analyzed species, with no statistically significant differences. As for leaves, slight variations are observed between Dog and No Dog samples, but these too lack statistical significance. A particular case is represented by *R. pseudoacacia*, which shows a slight tendency toward lower values in the Dog group and high internal variability.

The discrepancy between variations in soil carbon and stability in plant tissues suggests that carbon introduced through organic animal sources, such as dog urine, is not readily assimilated by plants. As previously discussed, several studies have shown that carbon from animal-derived organic material can increase soil organic matter, but its direct uptake by plants is limited (Shi et al., 2024). In fact, the availability of organic carbon for root absorption is often low, as such carbon is primarily utilized by soil microorganisms to support mineralization and immobilization processes (Malone et al., 2023). Additionally, urea present in urine is rapidly hydrolyzed in the soil, producing NH_4^+ and CO_2. This process occurs within a few hours, and the resulting CO_2 is released into the atmosphere, without contributing to the formation of stable organic matter in the soil (Khan et al., 2018). Consequently, although urine represents a source of carbon for the soil, it does not act as an assimilable carbon resource for plants, but rather fuels microbial activity and local biogeochemical cycles (Zhou et al., 2020; Huang et al., 2024).

Phosphorus, like nitrogen, shows significant enrichment in the soil of Dog samples, particularly for *Acer platanoides*, consistent with the findings of De Frenne et al. (2021), who reported high P concentrations in dog urine (~484.6 mg/L). However, this increased availability does not translate into higher concentrations in woody tissues, where values remain comparable between Dog and No Dog samples across all species. This pattern may be attributed to the low solubility of P in acidic soils, a condition that can occur in Dog soils due to the presence of urine and dissolved salts (Johan et al., 2021; Marosz & Nowak, 2008). Although *A. platanoides* tolerates a wide pH range, under more acidic conditions it may reduce nutrient uptake, including phosphorus, thereby explaining the absence of accumulation in Dog wood despite its higher availability in Dog soil (Nowak and Rowan, 1990).

Although none of the species show statistically significant differences in sodium (Na) content in the soil between Dog and No Dog areas, there is a trend toward higher Na levels in Dog soils for *B. pendula* and *R. pseudoacacia*, suggesting a potential influence of dog urine, which contains Na levels around 1808 mg/kg (Chang et al., 2018). In wood, the variation becomes more pronounced for *A. platanoides* Dog, which shows significantly higher Na values compared to No Dog and the other species. This is consistent with findings by Marosz (2011) and Dmuchowski et al. (2021), who observed that *A. platanoides* tends to accumulate sodium to a notable degree, especially in urban environments exposed to de-icing salts and dog urine, both common sources of sodium (Löfgren, 2001; Walker, 2021). The proximity of Dog samples to roads—and thus to winter salt application—may have contributed to this difference. The absence of a corresponding difference in soil samples may be due to the fact that they were collected in spring, when sodium levels from de-icing salts are typically lower (Löfgren, 2001). Relevant findings on this topic were presented by Krutul et al. (2018), who compared nutrient levels in *A. platanoides* between areas with high and low nutrient input. Their study revealed that *A. platanoides* shows distinct behavior in sodium assimilation compared to other elements, such as potassium.

Regarding potassium (K), no significant differences were observed among the species in wood samples. In the soil, *B. pendula* is the only species showing a statistically significant difference, with Dog values lower than those of the other species. This unexpected effect may indicate a soil poor in clay minerals, which are generally less effective at retaining potassium. In *A. platanoides* and *R. pseudoacacia*, although not statistically significant, Dog values are slightly higher, supporting the hypothesis that dog-related input may contribute to potassium accumulation, albeit to a lesser extent than nitrogen and phosphorus (Gazol et al., 2018; De Frenne et al., 2021).

With regard to the differences that distinguish *R. pseudoacacia* from *A. platanoides* and *B. pendula*, variations were observed in the uptake of certain elements. *Robinia pseudoacacia* is a nitrogen-fixing species that, through symbiosis with *Rhizobium* bacteria, is able to fix atmospheric nitrogen (Mantovani et al., 2015; Liu et al., 2020). For this reason, it was expected in this study that *R. pseudoacacia* would generally exhibit higher nitrogen content compared to *A. platanoides* and *B. pendula*. According to the literature, *R. pseudoacacia* can significantly enrich the soil with nitrogen, benefiting not only the trees themselves but also improving overall soil quality (Vlachodimos et al., 2013; Shi et al., 2021). Furthermore, some studies indicate that nitrogen-fixing species such as *R. pseudoacacia* tend to have higher nitrogen content in their leaves compared to non-fixing species (Houlton et al., 2008; Sayad et al., 2015).

In the results of the present study, *R. pseudoacacia* shows higher soil nitrogen concentrations in the Dog samples compared to the other groups, except for *A. platanoides* under the Dog treatment. However, this greater availability is not reflected in a similarly marked increase in wood nitrogen, where values are comparable to those of the other two species. In fact, previous studies have also observed that *R. pseudoacacia*, despite being a nitrogen-fixing species, does not necessarily exhibit higher nitrogen levels in biomass, a distinction that is more clearly seen in the leaves (González-Muñoz et al., 2011).

Differences related to *R. pseudoacacia* also emerge when comparing δ^{15}N values. In wood, *R. pseudoacacia* shows lower δ^{15}N values than the other two species in both Dog and No Dog treatments, particularly compared to *A. platanoides*, which shows the highest values among the studied species. These lower values are consistent with the nitrogen-fixing nature of *R. pseudoacacia*, which tends to assimilate nitrogen of atmospheric origin, typically associated with an isotopic signal near zero ($\approx$ 0‰), thereby explaining the lower values (Craine et al., 2015). Conversely, non-nitrogen-fixing plants such as *A. platanoides* and *B. pendula* tend to show higher ^{15}N isotopic ratios (Amarger et al., 1979; Craine, 2015).

In addition to nitrogen levels, the most pronounced differences are observed in potassium concentrations in wood: in the No Dog samples, *R. pseudoacacia* exhibits significantly higher values compared to *B. pendula*, and generally higher than those of the other samples. However, this difference is not observed in the Dog types, suggesting that the elevated values for *R. pseudoacacia* No Dog are likely due to external factors related to the soil conditions in which these No Dog trees are located, rather than to a species-specific response in potassium uptake (Da Silva et al., 2016).

As for phosphorus (P), *R. pseudoacacia* does not show statistically significant differences compared to *A. platanoides* and *B. pendula*, although the Dog treatment values are characterized by high variability.

Regarding sodium (Na), *R. pseudoacacia* differs from *A. platanoides*, which shows a marked increase in Na levels in the Dog samples, but remains similar in value to *B. pendula* and the rest of the No Dog samples. The difference is attributed to *A. platanoides*, which has been observed in several studies to have a tendency for greater Na accumulation in urban environments, rather than to a functional trait of *R. pseudoacacia* as a nitrogen-fixing species (Dmuchowski et al., 2011; Marosz, 2011).

In the context of this study, *Robinia pseudoacacia* stands out for its differentiated nutritional strategy—specifically, its ability to fix atmospheric nitrogen through symbiosis with *Rhizobium* bacteria (Mantovani et al., 2015; Liu et al., 2020). Beyond this trait, the species exhibits general stability in potassium, sodium, and phosphorus levels in wood, even under conditions of potential accumulation from dog urine input, and no major differences are observed when compared to the other species.

Overall, the results indicate that the tree species analyzed respond differently to the presence of dogs and to the available soil volume. The observed variations occur both among species and across the materials analyzed. In general, the presence of dogs may influence soil composition, but the effect on element accumulation in plant tissues is variable and not always evident. In plant tissues, particularly in wood, most of the analyzed elements show relatively stable values, with no statistically significant differences between treatments in the majority of cases.

It should also be noted that, for logistical reasons, soil samples were not collected directly at the base of each tree analyzed, but rather from nearby areas with similar characteristics. Although efforts were made to replicate the original site conditions, it is possible that local microvariability in urban soils contributed to discrepancies between soil and tissue values, further confirming the complexity of urban systems and the eco-physiological responses of different species (Smith et al., 2018; Lima et al., 2024). This represents a potential limitation of the present study, and it is also the reason why nutrient values in soil and wood were not directly compared.

Trees resistance, resilience and recovery based on SPEI

Drought events are among the leading causes of tree mortality and are projected to become increasingly frequent (Adams et al., 2017). Urban trees are at greater risk of mortality compared to trees located in forests, as cities experience higher temperatures due to their built structure (Voogt and Oke, 2003). Prolonged drought leads to a loss of hydraulic conductivity in the xylem, ultimately causing tree death (Cherubini et al., 2021). Therefore, the duration of drought events is a critical factor in the survival of street trees (Bassuk et al., 1985). The management of urban environments is becoming increasingly important and requires careful planning, including the regular assessment of tree health (Cheng et al., 2021; Cheng et al., 2024).

The indices of resistance, resilience, and recovery are essential for understanding how trees respond to drought events. These indices are calculated based on tree ring width (Bose et al., 2019; De Soto, 2020; Chen et al., 2023; Deng et al., 2025). Resistance, resilience, and recovery vary depending on the duration of the drought (Huang et al., 2018). In addition to drought length, several factors influence tree-ring width during dry periods and, consequently, the values of resistance, resilience, and recovery to drought. These include species and tree size, as shown in numerous studies (Rozas, 2005; Kang et al., 2024; Deng, 2025).

According to the literature, *Acer platanoides* exhibits high drought resistance in both the short and long term (Kunz et al., 2016; Fuchs et al., 2021). Other studies have also observed strong resistance but noted significant variability among individuals of *A. platanoides* (Underwood and Hirons, 2025). The work of Contreras (2022) describes *A. platanoides* as a species characterized by good resilience, a finding supported by other studies as well (Hirsch et al., 2023).

The study by Bhuyan et al. (2017) reported that the *Betula* genus generally exhibits good resistance to drought. However, *B. pendula* shows varying levels of drought tolerance depending on its location (Hannus et al., 2021). Regarding *Robinia pseudoacacia*, numerous studies have demonstrated its drought resistance, including those by Moser et al. (2016) and Franceschi et al. (2023). Its resilience and recovery have also been found to be high in some studies (Moser et al., 2016; Chen et al., 2023), although others report a slower recovery rate (Yan et al., 2017).

Tree size is a key factor influencing growth, particularly during periods of limited water availability, as it determines the level of water demand (Diez et al., 2021; Kang et al., 2025). Another important factor affecting urban tree growth is nutrient availability, which is often highly variable in urban contexts due to diverse soil conditions and can be influenced by the input of dog urine (Lévesque et al., 2016; Singh et al., 2024).

Tree location is also fundamental during drought periods, as it determines the amount of soil available for root expansion and water access (Chen et al., 2011; Moser et al., 2015). These differences are reflected in variations in tree resistance, resilience, and recovery. Haase et al. (2022) explain that old and newly planted street trees have lower resistance compared to younger trees. Shoda et al. (2020) similarly observed that annual ring growth in street trees is lower than in trees growing in more spacious areas. Trees planted in urban environments can suffer from restricted soil volume, limiting root space, nutrient and moisture availability, and aeration due to built infrastructure and elevated temperatures (Zhang et al., 2020). Studies by Bassuk et al. (1985) also show that the optimal soil volume required for healthy tree growth is typically available only in parks or large medians, while street trees are often subject to exacerbated conditions due to limited rooting space and insufficient soil moisture to cope with dry periods.

In the present study, the combined assessment of resistance, resilience, and recovery indices—calculated for both short-term drought events (SPEI-3) and long-term drought events (SPEI-12)—was aimed at identifying how urban conditions influence tree growth and recovery following drought, across different species (Gill et al., 2007; Vicente-Serrano et al., 2010; Beguería et al., 2014; Gessler et al., 2016).

The results do not point to a single, consistent effect in terms of dog presence—and therefore potential nutrient input via urine—nor in terms of available soil volume on species responses. Instead, these effects vary by species and drought duration.

In the case of *Betula pendula*, the highest resistance values across all groups were found in the No Dog samples for both SPEI-3 (resistance = 1.44) and SPEI-12 (resistance = 1.35), suggesting that greater soil availability enhances this species' ability to maintain growth during both short- and long-term drought (Bassuk et al., 1985; Zhang et al., 2020). Conversely, in the Dog samples, *B. pendula* showed the lowest resistance values (resistance = 0.67), suggesting that short-term droughts may be particularly limiting under compacted soils and reduced rooting space, which impair water uptake (Gessler et al., 2005; Volkmann et al., 2016). Regarding recovery, *B. pendula* displayed the highest values among species for both short- and long-term drought, with recovery = 2.21 for SPEI-3 and recovery = 2.28 for SPEI-12 in the Dog group. These results suggest that the species may benefit from nutrient availability in the recovery phase, facilitating rapid regeneration of damaged tissues following both types of drought (Gessler et al., 2016; Samuelson et al., 2008).

Acer platanoides shows higher resistance under Dog conditions during short-term drought (SPEI-3 resistance = 1.07), indicating that the species may respond positively to increased nutrient availability even under unfavorable soil volume conditions (Gessler et al., 2016). However, under SPEI-12, both resistance and resilience are the lowest observed across all groups (resistance = 0.70; resilience = 0.6976) in the Dog samples, suggesting that this species does not benefit from nutrient availability alone during prolonged droughts and is instead limited by restricted rooting space (Ryan & Yoder, 1997; Cochard, 2008). Conversely, its recovery under long-term drought is higher in Dog samples (recovery = 1.47), indicating a positive effect of nutrient input in the post-drought growth phase (Unger et al., 2010; Singh et al., 2023).

Robinia pseudoacacia generally shows stable and homogeneous values across Dog and No Dog samples in all SPEI scenarios, with only slight variations. Its lowest recovery values are recorded under SPEI-3 in the No Dog group (recovery = 1.03) and under SPEI-12 in the Dog group (recovery = 1.10), which are the lowest recovery values overall for seasonal and annual droughts, respectively. However, differences between treatments remain limited. This behavior reflects the species' adaptability and conservative strategy, previously documented in the literature, linked to its ability to tolerate stress events through a deep root system (Moser et al., 2016; Franceschi et al., 2023).

The results obtained reflect the conditions under which urban trees grow; however, it is important to acknowledge a key limitation of this study: tree size was not considered. This may represent a constraint, as it likely influences species responses. The varying responses observed across species and environmental conditions highlight the importance of adopting species-specific approaches in the management of urban green infrastructure in cities such as Zurich.

Nutrients and tolerance indexes correlations for each treatment

This section discusses the relationship between nutrient content and the response of the three tree species to drought events of varying duration, as evaluated through the resistance, resilience, and recovery indices (Lloret et al., 2011; Gillner et al., 2014; Chen et al., 2023; Deng et al., 2025). These tolerance indices were calculated across two drought timescales: SPEI-3, which reflects responses to short-term water stress, and SPEI-12, which captures drought conditions over an annual timescale (Vicente-Serrano et al., 2010; Beguería et al., 2014; Yang et al., 2020; Wang et al., 2021). Correlations obtained using Kendall's tau (τ) test were analyzed separately for Dog and No Dog samples to identify any potential effects linked to nutrient inputs associated with dog urine. This approach allowed the identification of notable differences both among species and environmental factors, helping to define the potential role of nutrient availability in modulating tree responses to short- and long-term drought events (Allen et al., 2020; Wang et al., 2021).

According to the literature, several studies have attributed a substantial influence to nutrient availability in determining tree responses during and after drought (McDowell et al., 2011; Gessler et al., 2016). In particular, Gessler et al. (2016) outlined the role of nutrient levels in shaping both tree recovery and mortality. Nutrient availability prior to a drought event may have either beneficial or detrimental effects on tree survival. On the negative side, certain structural and functional changes can reduce hydraulic safety margins, increasing vulnerability to the formation of air embolisms within the vascular system during water stress (Cochard, 2008; Sperry et al., 2008). Some of these changes, driven by high nutrient availability, include increased stomatal conductance, accelerated height growth, a reduced root-to-leaf area ratio, and wider xylem vessel diameters (Fangmeier et al., 1994; Ryan and Yoder, 1997; Hodge, 2006; Plavcová and Hacke, 2012).

High nutrient availability before drought events may also improve drought response by reducing embolism vulnerability and increasing the production of nitrogen-based defense compounds (Samuelson et al., 2008; Godschalx et al., 2017). Nutrient supply also plays a key role during drought. Adequate nutrient availability—especially nitrogen—is essential for regenerating damaged tissues and has a positive effect on tree recovery (Gessler et al., 2016). Nevertheless, negative effects may arise from imbalances in the nutrient profile—such as phosphorus—that can adversely affect plant metabolism (Schulze, 1989).

In the post-drought period, nutrient levels become even more critical for recovery, as they affect the tree's ability to regenerate damaged tissues (Gessler et al., 2016). Furthermore, the post-drought phase requires adequate availability of both carbon and nitrogen, due to the need for increased mineralization in the soil (Unger et al., 2010; Singh et al., 2021; Singh et al., 2023). However, this availability is often short-lived and may be reduced by competition with soil microorganisms or by leaching losses (Malone et al., 2023; Shi et al., 2024). The success of root uptake thus depends on the roots' ability to rapidly regain functionality, which is determined by both the intensity and duration of the drought (Gessler et al., 2016; Volkmann et al., 2016). Under favorable conditions, this post-drought recovery can promote the growth of surviving individuals, but it may not be sufficient to fully compensate for the damage sustained during the drought (Gessler et al., 2005; Lloret et al., 2012). In soils with limited nutrient reserves, post-drought availability may be inadequate to support full recovery, leading to long-term reductions in growth (Suarez et al., 2004; Pichler and Oberhuber, 2007; Sergent et al., 2014; Gessler et al., 2016).

The correlation values obtained in this study identify potassium (K) as one of the most influential elements in modulating drought response, particularly for *Acer platanoides* and *Betula pendula*. In *A. platanoides*, statistically significant correlations were found between K and resistance in Dog samples, and between K and both resistance and recovery in No Dog samples—both referring to drought conditions calculated using SPEI-12, which reflects long-term drought events. In *B. pendula*, a significant influence of K was also observed, but in response to short-term drought (SPEI-3), with a positive correlation between K and resistance in Dog samples ($\tau = 0.733$). For *R. pseudoacacia*, no statistically significant correlations were found, but negative trends were observed between K and both resistance and resilience in Dog samples, suggesting that an excess of potassium might interfere with the species-specific drought response strategy. The results obtained for *A. platanoides* and *B. pendula* present both species as benefiting from the presence of this nutrient, supporting previous studies that identify potassium as a key element in regulating stomatal opening and reducing water loss—thus enhancing drought resistance and recovery under long- and short-term stress conditions, respectively (Hoekstra et al., 2001; Kim et al., 2015).

Sodium (Na) shows a generally more variable response. In *A. platanoides* Dog samples, significant positive correlations were observed with resilience ($\tau = 0.733$) and recovery ($\tau = 0.867$) for values based on SPEI-12, suggesting a potential role in supporting recovery after long-term drought periods. In *Betula pendula*, Na also shows positive correlations with resistance and resilience in Dog samples calculated using drought values from SPEI-12. These findings contrast with the literature, which often reports negative effects of sodium in urban or roadside environments, where Na accumulation can cause osmotic stress and reduce water-use efficiency in soils (Ramakrishna and Viraraghavan, 2005; Godwin et al., 2011; Chen et al., 2010). In contrast, *R. pseudoacacia* shows predominantly negative correlations between Na and both resistance and resilience, particularly in Dog samples and for indices calculated from seasonal drought periods (SPEI-3). This confirms that the species does not benefit from saline input in terms of drought resistance. These results are in line with literature reporting the typically negative effects of Na on water assimilation in trees (Godwin et al., 2011; Chen et al., 2010). Nitrogen shows only one statistically significant correlation—with long-term drought resilience in *R. pseudoacacia* under the Dog treatment. This result suggests that the species demonstrates resilience after prolonged drought in restricted soils through nitrogen assimilation and likely benefits from the formation of nitrogen-based defensive compounds (Godschalx et al., 2017; Yuan et al., 2022). In all other comparisons, nitrogen does not show statistically significant correlations with the drought tolerance indices in any of the species. In *A. platanoides*, correlations are generally weak, suggesting that the species may benefit from nitrogen input, but only to a limited extent. According to the literature, excessive nitrogen input may not lead to increased growth and can cause nutrient imbalances and physiological damage, including a higher shoot-to-root ratio that impairs water uptake in trees (Schulze, 1989; Hill and

Jones, 2018). Phosphorus does not show statistically significant correlations with any of the drought tolerance indices, regardless of species or drought duration.

Overall, the use of the SPEI-3 and SPEI-12 indices—representing seasonal and annual drought, respectively—allowed for differentiation of nutrient effects based on drought duration (Vicente-Serrano et al., 2010; Beguería et al., 2014). Stronger potassium-related responses were observed under long-term drought stress in *A. platanoides*, while more immediate responses were seen in *B. pendula*. Finally, *R. pseudoacacia* appears to be less dependent on nutrient content for its drought response.

The results of this study indicate that potassium is the principal element positively correlated with drought tolerance in two of the three species analyzed, while sodium shows species-specific effects that may be influenced by external factors. Nitrogen does not appear to be systematically associated with drought tolerance, despite numerous studies highlighting its potential as a key factor in tree drought response (Gessler et al., 2016).

The data obtained in this study should be considered primarily exploratory, as the number of available specimens for analysis was limited. As a result, the correlations identified often tend to mirror one another (Zhou et al., 2019). For future research, it is recommended to increase the number of samples in order to perform more robust analyses and to clarify the relationships between the resistance, resilience, and recovery indices and the levels of nutrients available to urban trees.

5. Conclusion

The aim of this Master's Thesis is to investigate how different tree species in urban environments respond to drought events, taking into account soil volume and nutrient availability. The species studied include *Acer platanoides* (L.), *Betula pendula* (Roth), and *Robinia pseudoacacia* (L.). The investigation is based on the calculation of drought tolerance indices: resistance, resilience, and recovery. These indices allow the assessment of trees' responses to drought, particularly by identifying their capacity to withstand, adapt to, and recover from such events over time.

A multidisciplinary methodological approach was adopted, combining dendrochronological analysis with chemical examination of annual growth rings. The detailed study of tree rings enables the reconstruction of long-term growth and the identification of drought-related signals, providing valuable insight into growth patterns over the years. In parallel, chemical analysis helps assess the nutritional status of trees and explore their dynamics in the urban context. Although these techniques are widely used in forest research, their application in urban settings—especially regarding chemical structure—is more limited. This thesis aims to expand research in this area by exploring how nutrient levels influence drought responses in various tree species, as reflected in tolerance indices measured in the urban setting of Zurich.

The first research question aimed to determine whether drought events are visible in tree-ring width in the studied species. The results showed that while some events are reflected in reduced annual ring width, the patterns are not systematic. *A. platanoides* exhibited a strong correspondence between both short- and long-term drought events (as calculated using SPEI-3 and SPEI-12) and reduced RWI values, particularly during 2003, 2017, and 2022. *B. pendula* followed a similar trend, although less pronounced. In contrast, *R. pseudoacacia* showed a weaker, less consistent response to drought indices. The initial hypothesis is therefore only partially confirmed: drought signals vary by species and by local site conditions. The heterogeneity of urban environments can amplify these variations.

Nutrient content analysis in wood revealed species-specific responses under different environmental conditions. *A. platanoides* showed elevated $\delta^{15}N$ levels in Dog samples, indicating a consistent response to different nitrogen sources, such as dog urine. A marked increase in Na was also observed in Dog samples, though this is likely attributable to proximity to roads rather than canine presence. No significant variation was found for P and K. *B. pendula* showed no notable differences between treatments, indicating a weaker or less detectable response to environmental and nutritional variation in long-term wood accumulation. *R. pseudoacacia* had lower $\delta^{15}N$ values compared to the other species, consistent with its nitrogen-fixing capacity, reflecting reduced dependence on organic nitrogen sources. No significant variations were observed for other nutrients, indicating greater physiological stability, especially in contrast to *A. platanoides*.

The effects of dog presence on seasonal and annual drought tolerance were assessed through resistance, resilience, and recovery indices by comparing different treatments. *A. platanoides* showed higher resistance under Dog conditions during short-term drought (SPEI-3), suggesting a positive effect of increased nutrients. However, during long-term drought, the species was disadvantaged by dog presence, displaying the lowest values of resistance and resilience. Nonetheless, it exhibited the highest recovery after long-term drought, suggesting a beneficial effect during the post-stress phase. *B. pendula* benefited from the absence of dogs in terms of resistance, but showed the highest recovery under Dog conditions for both short- and long-term drought. *R. pseudoacacia* maintained relatively stable and moderate values across treatments, likely reflecting an adaptive strategy less influenced by external factors. The initial hypothesis is partially confirmed: tree responses depend on species, soil volume, and drought duration. Dog presence may confer advantages during short-term drought, though not consistently.

The correlation analysis between nutrient levels and drought tolerance indices identified potassium as the most strongly associated element. In *A. platanoides*, significant positive correlations were found with resistance and recovery during long-term drought (SPEI-12). Similar correlations were seen in *B. pendula*, particularly for short-term drought. Sodium showed positive associations with resilience and recovery in *A. platanoides* Dog samples, but negative associations with tolerance indices in *R. pseudoacacia*. Nitrogen displayed one statistically significant positive correlation—with resilience in *R. pseudoacacia* during long-term drought. Phosphorus showed no significant correlations with any species.

This study provides useful insights into the well-being of urban trees in Zurich and contributes to a better understanding of tree health in urban environments. For effective urban planning, it is essential to identify species best suited to such conditions and able to cope with stressors such as elevated temperatures and limited nutrient availability. The main limitations of this research include the relatively small number of trees analyzed. Additional limitations relate to practical aspects of soil sampling, which is a highly variable factor that was not initially considered critical. The difficulty in accounting for certain determinants of tree response, such as tree size, also represents a limitation.

Future research should include a larger number of samples to enable more precise analyses. The results highlight the complexity of interactions between environmental and physiological factors that influence tree growth in urban environments. These findings support the need for multidisciplinary approaches in managing urban green spaces, particularly in the context of increasing future climate change challenges.

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Appendix

Table 35: Trees information based on Grün Stadt Zürich urban registry and measurement done at the WSL.

Name	**Species**	**Zone**	**Replanting planned**	**Birth**	**Death**
WD-1913	Acer platanoides "Globosum"	Street tree	Yes	1974	2024
AR-55	Acer platanoides	Street tree	Yes	1995	2024
AR-60	Acer platanoides	Street tree	Yes	1985	2024
AL-3111	Acer platanoides	Public park	Yes	1992	2024
WD-7825	Acer platanoides	Public park	Yes	1935	2024
WD-8772	Acer platanoides	Public park	Yes	1943	2024
AL-5341	Betula pendula	Street tree	Yes	1971	2024
AL-5342	Betula pendula	Street tree	Yes	1978	2024
WD-4189	Betula pendula	Street tree	Yes	1943	2024
WD-7842	Betula pendula	Public park	Yes	1992	2024
WD-7395	Betula pendula	Public park	Yes	1988	2024
WD-7431	Betula pendula	Public park	Yes	1923	2024
AR-222	Robinia pseudoacacia "Unifoliola"	Street tree	Yes	1995	2024
AR-538	Robinia pseudoacacia "Unifoliola"	Street tree	Yes	1994	2024
WD-1711	Robinia pseudoacacia "Bessoniana"	Street tree	Yes	1986	2024
WD-4609	Robinia pseudoacacia	Public park	Yes	1978	2024
WD-4611	Robinia pseudoacacia	Public park	Yes	1955	2024
WD-6046	Robinia pseudoacacia	Public park	Yes	1985	2024

Table 36: Resulting monthly values from SPEI-3 and SPEI-12 indices, from 1996 to 1999.

YEAR	MONTH	TMEA	TMAX	TMIN	Ra	NDAYS	PET	BAL	SPEI_3	SPEI_12
1996	1	-0.4	6.6	-8.2	10.48066302	31	50.02169381	-42.32169381	-0.04110612	1.212342814
1996	2	-1	11	-11.6	15.80310003	29	84.18440067	-36.38440067	0.096608482	1.10924881
1996	3	3.1	19.7	-9.6	23.62859349	31	190.5932417	-149.2932417	-0.962351388	0.759983334
1996	4	9.3	25.6	-2.8	32.44019912	30	323.2667692	-282.0667692	-0.825889086	0.239526479
1996	5	12.6	28.7	3.1	38.89575062	31	426.5650341	-292.2650341	-0.381905633	0.07031806
1996	6	17.4	31	7.3	41.80942906	30	494.3564036	-401.8564036	-0.386787037	-0.249013362
1996	7	17.4	28.7	6.9	40.43758593	31	473.8552111	-337.1552111	0.632054361	-0.001837465
1996	8	17	29.6	7.5	35.03170117	31	408.6261334	-293.9261334	0.750323575	0.022713495
1996	9	11	22.8	2.4	26.82176758	30	240.7376724	-197.6376724	1.069219485	-0.109830196
1996	10	9.4	21.6	-1.5	18.36302751	31	171.1625345	-89.36253448	0.564882756	0.279044443
1996	11	4.6	17.9	-5.6	11.76699671	30	88.16509345	27.63490655	0.56946336	0.424925066
1996	12	-0.6	10.7	-14.9	9.067181233	31	56.26136385	19.63863615	0.682966464	0.173664972
1997	1	-1.9	6.5	-10.6	10.48066302	31	49.13302089	-42.03302089	-0.170263226	0.22262837
1997	2	4	14.1	-5.5	15.80310003	28	98.22288494	-18.92288494	-0.49827837	0.329486256
1997	3	7.3	18.9	-2.7	23.62859349	31	196.5296124	-172.3296124	-1.040806782	0.190900261
1997	4	7.7	20.1	-3.8	32.44019912	30	279.0433858	-216.6433858	-0.084182472	0.592012192
1997	5	13.6	27.3	3.1	38.89575062	31	428.3798337	-385.9798337	-0.842732235	0.16834483
1997	6	16.2	29.5	7.4	41.80942906	30	461.1034605	-288.6034605	0.328071415	0.720053934
1997	7	17.4	27.3	9.6	40.43758593	31	426.9765732	-278.5765732	1.214492951	0.973994359
1997	8	19.7	30.9	10.1	35.03170117	31	427.1827357	-345.7827357	1.700634305	0.683601613
1997	9	15	28.1	4.5	26.82176758	30	294.8942679	-258.9942679	0.539689612	0.356553323
1997	10	9.1	24	-6.7	18.36302751	31	195.1440358	-125.7440358	-1.027686054	0.180599291
1997	11	4.5	14.2	-4.5	11.76699671	30	78.2961467	-48.4961467	-1.591563015	-0.276792446
1997	12	2.6	13.6	-5.4	9.067181233	31	57.48688734	66.11311266	-0.357999898	-0.034705477
1998	1	1.7	12.3	-7.8	10.48066302	31	65.32973967	21.17026033	0.415858386	0.343425977
1998	2	2.8	16.8	-9	15.80310003	28	106.489118	-69.08911797	0.720032086	0.072616612
1998	3	5.6	21	-5.2	23.62859349	31	201.7873345	-147.8873345	-0.467801965	0.201275278
1998	4	8.8	22	-1.8	32.44019912	30	290.470958	-205.870958	-0.267861174	0.291907632
1998	5	14.8	28.7	1.3	38.89575062	31	473.2434027	-443.4434027	-1.035363857	0.07915062
1998	6	17.5	31.9	6.5	41.80942906	30	513.2333763	-374.7333763	-0.763368899	-0.396076641
1998	7	18.8	33.9	8.4	40.43758593	31	532.8757125	-464.8757125	-1.305488432	-1.314263042
1998	8	18.6	34.6	5.7	35.03170117	31	488.7660843	-431.7660843	-1.115600013	-1.585264959
1998	9	13.9	25.8	5.3	26.82176758	30	265.627282	-115.327282	-0.653440816	-1.030636152
1998	10	10.3	20	0.1	18.36302751	31	164.1219517	-31.62195167	0.587791685	-0.622904658
1998	11	2.2	11.6	-10	11.76699671	30	75.46952107	61.43047893	1.936289623	-0.142798659
1998	12	0.7	11.8	-12.8	9.067181233	31	59.31999533	-28.61999533	1.168548058	-0.590198265
1999	1	1.2	12.7	-7.2	10.48066302	31	63.33713677	-8.73713677	0.162667064	-0.758428022
1999	2	-0.9	10.5	-18.3	15.80310003	28	92.30199864	43.69800136	0.496912223	-0.176489237
1999	3	5.9	18.6	-2.2	23.62859349	31	182.0989384	-133.8989384	0.965208097	-0.119751743
1999	4	9	21.8	-1.3	32.44019912	30	288.3190816	-193.8190816	1.212192703	-0.017112433
1999	5	15.1	29.2	5.9	38.89575062	31	440.4184918	-245.1184918	0.916205551	1.0439372
1999	6	15.3	29.1	4.6	41.80942906	30	472.6442335	-305.7442335	1.485012386	1.308214563
1999	7	18.8	31.9	8.7	40.43758593	31	508.2762634	-428.8762634	1.024135616	1.56332856
1999	8	18	29.5	9.4	35.03170117	31	400.8960828	-296.3960828	0.76646531	2.116566872
1999	9	16.4	28.3	8.9	26.82176758	30	278.781183	-165.581183	0.466121926	1.821068934
1999	10	9.1	19	1	18.36302751	31	149.4246844	-103.8246844	0.719690525	1.549580264
1999	11	1.9	15.9	-6.5	11.76699671	30	75.70158246	16.59841754	0.638862973	1.400045074
1999	12	1.9	12	-9	9.067181233	31	58.36301239	64.63698761	0.918422998	1.704870879

Table 37: Resulting monthly values from SPEI-3 and SPEI-12 indices, from 2000 to 2007.

YEAR	MONTH	TMEA	TMAX	TMIN	Ra	NDAYS	PET	BAL	SPEI_3	SPEI_12
2000	1	0.2	11.5	-14.5	10.48066302	31	68.58631451	-42.48631451	0.415214009	1.669196254
2000	2	3.8	16.4	-4.8	15.80310003	29	104.8310184	22.86898164	1.173844254	1.608215065
2000	3	6	17.5	-4	23.62859349	31	185.9189198	-114.7189198	0.479715173	1.776785185
2000	4	9.9	25.8	-2.4	32.44019912	30	329.2584468	-283.2584468	0.304076031	1.298445679
2000	5	15.1	27.9	4.2	38.89575062	31	444.1828208	-325.7828208	-0.383137362	0.878360456
2000	6	17.9	31.3	6.1	41.80942906	30	517.0015132	-461.2015132	-1.097050564	0.108865943
2000	7	16.1	29.8	6.7	40.43758593	31	469.7647647	-272.5647647	0.406386535	0.842628639
2000	8	18.8	32.5	10.2	35.03170117	31	431.7022124	-313.7022124	0.627632878	0.733542679
2000	9	14.6	26.1	4.7	26.82176758	30	277.3884556	-172.7884556	1.705980064	0.678564762
2000	10	10.3	17.8	1.9	18.36302751	31	146.7028992	-82.00289923	0.692475448	0.807159352
2000	11	5.6	13.2	-3.6	11.76699671	30	77.87269788	-4.472697882	0.570546988	0.666694283
2000	12	3.5	13	-7.8	9.067181233	31	62.80194543	-20.00194543	-0.327417762	0.198638816
2001	1	1.3	10	-7.8	10.48066302	31	60.21735228	44.18264772	0.086105692	0.720647744
2001	2	3	15.2	-7.5	15.80310003	28	100.8566224	-65.85662244	-0.506007094	0.24559715
2001	3	7	19.4	-4.1	23.62859349	31	202.5410292	30.5589708	2.079013803	1.076734321
2001	4	7.2	20.6	-2.3	32.44019912	30	267.7875315	-121.6875315	2.083593042	1.841796869
2001	5	15.6	28.4	4.4	38.89575062	31	453.778353	-357.678353	1.729041305	1.509931912
2001	6	15.3	29.5	4.2	41.80942906	30	480.298889	-287.498889	1.32490055	2.038998094
2001	7	18.9	30.5	10	40.43758593	31	479.0907055	-356.3907055	0.861563604	2.06445852
2001	8	19.2	32.4	8.6	35.03170117	31	450.8592248	-339.3592248	1.159458683	1.905902042
2001	9	11.8	22.7	2.7	26.82176758	30	244.9870874	-73.28708745	1.617940673	2.204955309
2001	10	12.8	24.4	4.3	18.36302751	31	179.6194118	-97.41941179	1.246613189	2.179903493
2001	11	3	11.3	-3.1	11.76699671	30	64.08543015	21.01456985	1.531046222	2.543282406
2001	12	0.2	10.6	-15.5	9.067181233	31	59.45037317	-18.15037317	-0.112786707	2.254856685
2002	1	0.4	14.1	-10.3	10.48066302	31	67.18070989	-33.58070989	-0.801002839	2.059975974
2002	2	5.5	15	-5.7	15.80310003	28	107.8870331	-24.18703314	-1.224828845	2.270650253
2002	3	6.8	19.1	-3.3	23.62859349	31	196.149189	-140.949189	-0.513392721	1.594320473
2002	4	8.9	20.1	-1.8	32.44019912	30	279.6829043	-217.6829043	0.215073875	1.078246753
2002	5	13.1	28.6	3	38.89575062	31	433.5809064	-239.8809064	0.715899781	1.475883447
2002	6	19.2	34.7	6.2	41.80942906	30	569.8328496	-478.6328496	-0.05408846	0.705294864
2002	7	18.4	31.1	7.4	40.43758593	31	508.1097099	-438.7097099	-0.388907654	0.197215813
2002	8	17.8	29.1	9.7	35.03170117	31	391.6531468	-230.5531468	-0.218339151	0.769873708
2002	9	13.1	24.9	1.2	26.82176758	30	278.3999405	-179.6999405	0.875142006	0.211077927
2002	10	9.8	21.8	-1.6	18.36302751	31	174.8037823	-51.40378231	1.646461714	0.460891759
2002	11	6.7	15.4	-0.9	11.76699671	30	80.31092153	101.1890785	1.665729057	0.849581066
2002	12	4.2	12.8	-3.7	9.067181233	31	57.77320743	11.72679257	1.66515241	0.945567388
2003	1	0.5	13.7	-11.9	10.48066302	31	69.19096057	-7.990960572	1.403527323	1.168897959
2003	2	-2	12.7	-14	15.80310003	28	83.08849148	-58.98849148	-0.796634337	1.016175289
2003	3	7.2	20.6	-3.6	23.62859349	31	207.1930064	-181.0930064	-1.255068829	0.824429868
2003	4	9.5	24.6	-3.9	32.44019912	30	326.2253299	-285.8253299	-1.521154862	0.450890862
2003	5	15.1	28.8	2.1	38.89575062	31	471.4582236	-396.7582236	-1.575119852	-0.316988113
2003	6	22.5	34.5	12	41.80942906	30	551.4671316	-508.2671316	-1.82742622	-0.47842997
2003	7	20.1	34.3	10.5	40.43758593	31	533.0923364	-430.5923364	-1.62966549	-0.524802944
2003	8	22.3	36.7	9.1	35.03170117	31	526.1985791	-435.6985791	-1.694643935	-1.374691525
2003	9	14.1	27.4	3.2	26.82176758	30	290.4255709	-235.1255709	-1.309655574	-1.556549735
2003	10	6.4	21.7	-5.6	18.36302751	31	165.5505028	-22.75050282	-0.651319188	-1.478196237
2003	11	4.9	13.6	-2.9	11.76699671	30	74.8656418	-19.5656418	0.369999496	-1.794498209
2003	12	1	12.5	-9.8	9.067181233	31	57.39474187	-23.19474187	0.358316461	-1.950917608
2004	1	1.3	12.8	-8.8	10.48066302	31	66.33435801	80.46564199	0.397549693	-1.806611198
2004	2	1.9	14.2	-10.1	15.80310003	29	102.3616991	-69.76169908	0.117450913	-1.862848804
2004	3	4.4	21.7	-6.7	23.62859349	31	199.3147985	-148.9147985	0.422964222	-1.777134416
2004	4	9.7	23	0.3	32.44019912	30	293.2771481	-265.6771481	-1.029443934	-1.717627293
2004	5	12.1	26.9	1.5	38.89575062	31	417.9070845	-290.5070845	-0.212840386	-1.284509319
2004	6	16.6	30.5	7.8	41.80942906	30	472.8187591	-336.2187591	0.318082638	-0.320567386
2004	7	18.1	30.3	8.9	40.43758593	31	478.8241937	-347.5241937	1.064142159	0.014692187
2004	8	18.8	30.9	10.4	35.03170117	31	413.9127203	-347.3127203	0.766137053	0.486489173
2004	9	15.3	27.4	6.4	26.82176758	30	280.7204988	-215.3204988	0.277183202	0.578069789
2004	10	11.6	24.9	4	18.36302751	31	175.9763429	-39.57634293	0.340132954	0.50893937
2004	11	4.6	14.1	-5.8	11.76699671	30	81.13145773	-64.93145773	-0.139282086	0.212367944
2004	12	1.2	9.8	-5	9.067181233	31	47.25483868	-8.654838679	-0.45260668	0.281481081
2005	1	0.6	11.3	-12.7	10.48066302	31	67.35994616	-43.55994616	-2.092520951	-0.338844941
2005	2	-0.6	10.4	-12.9	15.80310003	28	84.49569139	-47.99569139	-1.69695899	-0.222782179
2005	3	5.5	21.4	-17.4	23.62859349	31	244.5114406	-199.2114406	-1.828588699	-0.523087504
2005	4	9.6	25.8	-0.8	32.44019912	30	316.3180561	-196.7180561	-0.529978407	-0.107079843
2005	5	14	31	2.1	38.89575062	31	474.0975688	-362.9975688	-0.700872091	-0.391992235
2005	6	18.5	32.9	3.4	41.80942906	30	568.7756045	-477.5756045	-0.862204711	-1.148555702
2005	7	18.7	33.5	8.4	40.43758593	31	527.2352952	-392.4352952	-0.964251126	-1.3090815
2005	8	17	28.8	7.3	35.03170117	31	403.0410033	-257.5410033	-0.051104033	-0.909475259
2005	9	15.8	27.8	5.2	26.82176758	30	295.617393	-254.617393	0.331516502	-1.054874338
2005	10	11	20	2.8	18.36302751	31	156.3833549	-71.48335491	0.536625144	-1.200977315
2005	11	3.9	18.9	-11.4	11.76699671	30	96.98303499	-75.88303499	-1.198563273	-1.236476835
2005	12	0.3	8.2	-14.6	9.067181233	31	55.87375056	15.82624944	-0.812170714	-1.155769455
2006	1	-1.6	6.3	-9.7	10.48066302	31	48.42317853	-20.62317853	-1.591940962	-1.129832947
2006	2	0.4	9.8	-8.3	15.80310003	28	78.80228885	-14.50228885	-0.025607975	-0.992775127
2006	3	3.8	21	-9	23.62859349	31	199.3158238	-46.11582384	1.183925466	-0.238491214
2006	4	9.3	22.8	-2.1	32.44019912	30	302.6924345	-121.2924345	1.939836944	0.226045779
2006	5	13.9	24.6	2.7	38.89575062	31	411.4082596	-258.3082596	1.855512877	0.825561739
2006	6	18.2	30.8	4	41.80942906	30	537.6420464	-491.2420464	0.500341447	0.752726189
2006	7	22.8	34.4	11.5	40.43758593	31	560.1682962	-514.0682962	-1.176851939	0.039635603
2006	8	15.6	25.4	8.3	35.03170117	31	344.9810816	-136.5810816	-0.169397941	0.682072323
2006	9	17.5	27.9	7.4	26.82176758	30	295.7931563	-191.8931563	0.937049889	0.972356771
2006	10	13.1	21.8	4.7	18.36302751	31	167.297846	-103.797846	1.865463202	0.836654861
2006	11	6.9	15.5	-2.7	11.76699671	30	85.55538894	-40.15538894	-0.342961723	1.010917027
2006	12	3	14.2	-6.6	9.067181233	31	61.32772135	-15.72772135	-1.397154779	0.787654118
2007	1	4.9	14	-10.6	10.48066302	31	84.13403121	-27.73403121	-1.634523255	0.837530692
2007	2	4.8	14.2	-3.6	15.80310003	28	97.03906355	-23.53906355	-1.042744563	0.809457598
2007	3	5.6	16.9	-3.3	23.62859349	31	177.181732	-73.38173198	0.618604981	0.674678957
2007	4	13.5	26.2	0.5	32.44019912	30	355.1759095	-351.2759095	-0.583216143	-0.603113942
2007	5	15.2	29.5	2.5	38.89575062	31	475.5404986	-343.0404986	-0.77880463	-0.970277082
2007	6	18	30.3	9	41.80942906	30	476.6462231	-371.1462231	-1.063973264	-0.292127421
2007	7	18.2	34.4	7.3	40.43758593	31	540.3335036	-355.3335036	0.325549723	0.455003928
2007	8	17.6	31.7	8.3	35.03170117	31	427.7223538	-222.4223538	1.429799396	-0.006557652
2007	9	13.1	24.7	3.7	26.82176758	30	262.0623387	-205.4623387	1.49102067	-0.066778416
2007	10	9.3	23.9	-1.8	18.36302751	31	179.8745279	-167.5745279	0.41218013	-0.384921492
2007	11	2.9	11.9	-6.4	11.76699671	30	71.89697414	-27.29697414	-1.177487748	-0.382102661
2007	12	1	11.5	-7.7	9.067181233	31	53.25621409	39.54378591	-1.304323113	-0.098411941

Table 38: Resulting monthly values from SPEI-3 and SPEI-12 indices, from 2008 to 2011.

YEAR	MONTH	TMEA	TMAX	TMIN	Ra	NDAYS	PET	BAL	SPEI_3	SPEI_12
2008	1	2.7	13.2	-4.9	10.480663	31	65.1735588	-7.7735588	-0.1839158	0.03541761
2008	2	3.4	17.5	-8	15.8031	29	112.842857	-75.242857	-0.5447016	-0.2457984
2008	3	4.9	18	-6.2	23.6285935	31	188.13125	-103.93125	-0.3285571	-0.439439
2008	4	8.2	20.2	-3.5	32.4401991	30	283.321885	-99.121885	1.26022155	1.0067941
2008	5	15.5	29	4.9	38.8957506	31	453.361297	-402.4613	0.65934928	0.71832068
2008	6	17.6	31.6	5.9	41.8094291	30	517.717865	-434.01786	-0.0490542	0.40265552
2008	7	18.6	31.2	8.1	40.4375859	31	504.408184	-390.90818	-0.9238884	0.1110214
2008	8	17.7	28	9	35.0317012	31	386.505707	-236.40571	0.50982455	0.03945792
2008	9	12.5	27.5	1.7	26.8217676	30	284.832123	-187.03212	1.20478248	0.14061439
2008	10	9.9	21	-0.8	18.3630275	31	169.333089	-23.333089	1.75947036	0.88865653
2008	11	4	14.7	-6.7	11.7669967	30	81.8800507	-53.880051	0.5167852	0.72679778
2008	12	0.7	8.5	-8.4	9.06718123	31	49.1673619	10.9326381	0.3468207	0.54109385
2009	1	-1.9	8.4	-9.9	10.480663	31	50.8277584	-14.127758	-1.2339014	0.58009994
2009	2	0.3	12.3	-12.3	15.8031	28	91.3638275	-43.963827	-0.6239242	0.76725866
2009	3	4.5	13.7	-5.1	23.6285935	31	162.896288	-46.896288	0.88671748	1.10805816
2009	4	11.8	23.1	2.6	32.4401991	30	299.986177	-284.58618	0.3002099	0.06880683
2009	5	15.4	32.2	1.6	38.8957506	31	509.319711	-408.01971	-0.5261913	0.14880871
2009	6	16.9	29.4	6.6	41.8094291	30	477.991557	-363.99156	-1.0017372	0.49641826
2009	7	18.6	30	9.4	40.4375859	31	476.331985	-305.63198	0.25935561	0.86791029
2009	8	19.7	32.4	7.1	35.0317012	31	471.131656	-409.73166	0.35616044	-0.0628767
2009	9	15.3	30.8	5.2	26.8217676	30	309.944877	-238.74488	-0.1433379	-0.3110196
2009	10	9.4	25.7	-1.8	18.3630275	31	186.753636	-143.55364	-1.5914537	-0.8816542
2009	11	6.6	16.9	-1.8	11.7669967	30	85.6693264	36.5306736	-0.4708986	-0.5144578
2009	12	1.1	9	-14.4	9.06718123	31	59.1059986	59.5940014	0.61314584	-0.2692498
2010	1	-1.6	6.9	-9.6	10.480663	31	49.1739703	-18.67397	1.02669821	-0.2842272
2010	2	0.8	13.3	-12.4	15.8031	28	95.9638498	-42.66385	0.33739115	-0.2782528
2010	3	4.7	22.5	-9	23.6285935	31	212.747858	-160.14786	-0.8644373	-0.8947724
2010	4	10.1	25.7	-1.3	32.4401991	30	324.502978	-294.70298	-1.1881636	-0.9189162
2010	5	12	27.8	4.3	38.8957506	31	400.628538	-257.22854	-0.2765611	0.00447291
2010	6	17.2	30.6	6.3	41.8094291	30	497.730792	-367.03079	0.09209494	-0.0188645
2010	7	20.2	33.5	8.7	40.4375859	31	545.612345	-375.91234	0.87212403	-0.4950471
2010	8	17.4	30.3	7.5	35.0317012	31	419.817796	-297.8178	0.68439096	0.09355966
2010	9	13.1	23.6	4.4	26.8217676	30	250.579524	-184.07952	0.78937495	0.37831694
2010	10	8.7	22.8	-3.5	18.3630275	31	177.933435	-131.33343	0.22126702	0.45545994
2010	11	5.4	17.8	-10.2	11.7669967	30	99.6739624	-23.473962	-0.3820571	0.07854991
2010	12	-0.8	11.4	-13.8	9.06718123	31	55.1710206	44.6289794	-0.3963165	0.00347368
2011	1	1.3	13.8	-10.5	10.480663	31	70.3582116	-17.258212	-0.1941736	0.04465693
2011	2	2.4	13.5	-7.8	15.8031	28	94.8788316	-70.578832	-0.5390066	-0.1057187
2011	3	6.4	19.5	-4.2	23.6285935	31	198.480086	-178.88009	-1.5137167	-0.2328617
2011	4	12.3	24.9	-0.3	32.4401991	30	338.220064	-316.82006	-1.9717195	-0.3217573
2011	5	15.3	28.6	1.9	38.8957506	31	474.324231	-384.82423	-1.7031004	-0.9196856
2011	6	17.2	32.4	6.9	41.8094291	30	509.872351	-441.47235	-1.5609514	-1.2843036
2011	7	16.9	31.2	7.9	40.4375859	31	482.927777	-327.22778	-0.3593526	-1.0364418
2011	8	19.3	33.6	7.9	35.0317012	31	469.776436	-397.77644	-0.3672254	-1.3953978
2011	9	16.3	29	6.4	26.8217676	30	300.016461	-217.71646	-0.0363778	-1.5005104
2011	10	9.2	22.8	-1.2	18.3630275	31	173.182179	-109.38218	-0.9719009	-1.4437882
2011	11	4.6	16.8	-2.8	11.7669967	30	80.5175917	-80.417592	-1.2690085	-1.5890843
2011	12	3.9	14	-4.9	9.06718123	31	60.9891334	85.0108666	-0.2963262	-1.4936268

Table 39: Resulting monthly values from SPEI-3 and SPEI-12 indices, from 2012 to 2016.

YEAR	MONTH	TMEA	TMAX	TMIN	Ra	NDAYS	PET	BAL	SPEI_3	SPEI_12
2012	1	2.4	11.6	-7.6	10.480663	31	66.142449	22.757551	0.21977556	-1.443211
2012	2	-3.4	14.9	-18.2	15.8031	29	87.32621	-78.82621	0.91044417	-1.4925821
2012	3	7.5	21	-4.1	23.6285935	31	213.542726	-201.04273	-1.3820842	-1.6057714
2012	4	9.2	28.6	-2.4	32.4401991	30	336.493913	-290.69391	-2.01808	-1.5068649
2012	5	14.4	28.9	0.3	38.8957506	31	477.562894	-396.36289	-1.7595301	-1.6218752
2012	6	17.7	31.9	7.8	41.8094291	30	502.759403	-318.8594	-0.6241008	-0.9340537
2012	7	18.1	32.7	7.4	40.4375859	31	520.630324	-372.63032	0.17584865	-1.1485613
2012	8	19.6	33.3	9.3	35.0317012	31	457.644219	-302.34422	1.07394777	-0.7043567
2012	9	14.2	27.2	4.2	26.8217676	30	284.020954	-193.92095	0.68129465	-0.574027
2012	10	9.5	22	-2.8	18.3630275	31	178.000943	-73.800943	0.67650615	-0.4064006
2012	11	6	17	-1.6	11.7669967	30	83.3389745	14.1610255	0.63097129	0.00945032
2012	12	2	14.4	-12.8	9.06718123	31	66.759253	81.840747	1.36113913	-0.0030334
2013	1	0.8	13.5	-11.3	10.480663	31	69.2176853	-16.217685	1.06057255	-0.1824843
2013	2	-0.6	10	-13.9	15.8031	28	85.5767037	-32.876704	0.97507091	0.07378153
2013	3	2.8	14.3	-9.3	23.6285935	31	168.597303	-111.2973	0.08740442	0.58578153
2013	4	9.3	24.3	-1.4	32.4401991	30	307.516522	-215.51652	0.47690084	1.01194687
2013	5	11.6	22.7	3.3	38.8957506	31	359.12024	-167.42024	1.45930908	1.78425471
2013	6	16.5	34	5.2	41.8094291	30	531.02344	-458.72344	0.74258927	1.32926583
2013	7	21.1	35.7	10.6	40.4375859	31	561.902821	-493.40282	-0.0839798	0.80112967
2013	8	18.9	33.5	9.4	35.0317012	31	450.013293	-378.21329	-1.4636833	0.38432413
2013	9	14.9	29	6.7	26.8217676	30	285.783184	-205.48318	-1.1471724	0.3208499
2013	10	11.5	22.8	2.3	18.3630275	31	173.69142	-49.09142	0.00774875	0.46179721
2013	11	4.6	17.4	-5.8	11.7669967	30	87.60053	34.59947	0.96223132	0.52167312
2013	12	0.6	12.1	-5.8	9.06718123	31	50.3275935	-7.3275935	0.92712396	0.04130885
2014	1	3.1	12.9	-4.3	10.480663	31	64.7722222	-4.9722222	0.13162249	0.1398226
2014	2	4	12.6	-4.8	15.8031	28	92.5463456	-16.246346	-0.2230379	0.24038776
2014	3	6.9	21.2	-2.6	23.6285935	31	203.00785	-174.10785	-0.4602775	-0.1319908
2014	4	10.8	21.8	-0.7	32.4401991	30	303.661613	-222.46161	-0.1442978	-0.1372083
2014	5	12.9	27.8	1.7	38.8957506	31	434.960998	-335.461	-0.458413	-0.9616571
2014	6	18.4	34.5	6	41.8094291	30	557.512139	-465.71214	-0.7602468	-0.9730202
2014	7	18.1	32.9	7.8	40.4375859	31	518.568414	-362.86841	-0.4430979	-0.3691928
2014	8	16.7	27.3	6.5	35.0317012	31	393.008117	-289.30812	0.02957866	0.103621
2014	9	15.4	26.6	4.3	26.8217676	30	290.152957	-219.45296	0.6545599	0.03770406
2014	10	12.5	24.3	2.8	18.3630275	31	183.948255	-106.34826	0.20087756	-0.2489714
2014	11	6.5	16.4	0	11.7669967	30	79.89929	5.60070996	-0.1439626	-0.4527279
2014	12	3.2	12.8	-15.6	9.06718123	31	72.3502925	-14.750292	-0.4970944	-0.4759191
2015	1	1.9	16	-9.5	10.480663	31	74.3386387	11.5613613	-0.2205998	-0.3998498
2015	2	-0.5	11.1	-10.9	15.8031	28	82.5820387	-52.882039	-0.8139732	-0.5947129
2015	3	6.3	18	-4	23.6285935	31	190.438952	-118.83895	0.09099232	-0.3293983
2015	4	10	23.1	-3	32.4401991	30	317.905214	-192.60521	0.42569473	-0.1271054
2015	5	14.2	28.1	4.2	38.8957506	31	433.851013	-286.45101	0.720851	0.25549883
2015	6	18.3	31.4	6.9	41.8094291	30	515.482079	-395.48208	0.46925159	0.59530803
2015	7	22.3	36	9.1	40.4375859	31	599.646445	-557.54645	-1.0102131	-0.5161155
2015	8	20.3	35.5	9	35.0317012	31	489.890108	-426.59011	-1.7196141	-1.1071111
2015	9	13.5	26.6	4.2	26.8217676	30	274.160468	-237.66047	-1.9722965	-1.1608153
2015	10	9.6	20.9	0	18.3630275	31	164.005163	-124.80516	-1.5660227	-1.2516871
2015	11	7.5	19.8	-5.7	11.7669967	30	103.730228	-45.330228	-1.2725596	-1.4145654
2015	12	3.4	13.3	-3.5	9.06718123	31	56.1761961	-44.076196	-2.6677702	-1.5385957
2016	1	2.8	12.2	-10.5	10.480663	31	73.3429605	90.3570395	-0.2465982	-1.3423272
2016	2	4.3	16.5	-2.9	15.8031	29	102.603284	-26.203284	0.75422921	-1.2474514
2016	3	4.9	21.4	-3.9	23.6285935	31	192.359446	-164.15945	0.95149502	-1.4646172
2016	4	9.2	21.1	-2.8	32.4401991	30	295.457703	-211.0577	-0.0056665	-1.5365858
2016	5	13.1	27	1.6	38.8957506	31	431.88391	-263.68391	0.37921138	-1.4806685
2016	6	17.1	32.7	9.5	41.8094291	30	484.945292	-286.74529	1.36425793	-0.8644848
2016	7	19.8	32.5	7.6	40.4375859	31	540.956407	-414.95641	1.12799061	-0.2008635
2016	8	19.3	32.6	8.6	35.0317012	31	453.973276	-397.57328	0.18663766	-0.0401699
2016	9	16.7	29.3	6	26.8217676	30	308.200644	-266.70064	-1.1618645	-0.1769527
2016	10	8.6	21.4	0.2	18.3630275	31	159.149644	-98.149644	-1.330158	-0.0371896
2016	11	4.9	13	-6.3	11.7669967	30	80.9690855	16.8309145	-0.5000587	0.22508455
2016	12	0.4	9.2	-5.4	9.06718123	31	44.9582753	-44.558275	-0.6991755	0.21661082

Table 40: Resulting monthly values from SPEI-3 and SPEI-12 indices, from 2017 to 2023.

YEAR	MONTH	TMEA	TMAX	TMIN	Ra	NDAYS	PET	BAL	SPEI_3	SPEI_12
2017	1	-2.7	7.7	-15.1	10.48066302	31	53.87938853	16.82061147	-0.456893314	-0.136180561
2017	2	3.8	19.5	-4	15.80310003	28	106.5653066	-57.1653066	-1.403603024	-0.303893393
2017	3	8.3	21.3	-1.5	23.62859349	31	209.959404	-154.159404	-0.447374958	-0.274624393
2017	4	9	23.8	-3.8	32.44019912	30	315.1533566	-221.5533566	-0.392350645	-0.298494187
2017	5	15.1	31.1	1.4	38.89575062	31	497.2397157	-442.8397157	-1.214796723	-1.181980576
2017	6	20.2	33.2	5.7	41.80942906	30	574.8747996	-490.9747996	-1.631944404	-2.126446506
2017	7	19.7	32.9	10.4	40.43758593	31	512.858169	-395.358169	-1.591704154	-1.794042159
2017	8	19.6	32.6	10.3	35.03170117	31	441.1383263	-363.3383263	-0.974609223	-1.643235323
2017	9	13.3	25.7	3.8	26.82176758	30	269.3512108	-171.6512108	0.081629656	-1.293388272
2017	10	10.9	22.5	-0.8	18.36302751	31	181.3817852	-152.0817852	-0.58256528	-1.513826823
2017	11	4.9	16.3	-2	11.76699671	30	78.84354169	10.75645831	-0.053652423	-1.493044095
2017	12	1.7	13.3	-8.4	9.067181233	31	58.7254434	40.8745566	-0.217479351	-1.218788846
2018	1	5.1	12.8	-4.2	10.48066302	31	70.55669517	59.94330483	1.487753942	-1.113662971
2018	2	-0.8	7.4	-13.1	15.80310003	28	78.33466823	-39.73466823	1.412599182	-1.049333647
2018	3	4	14.5	-9	23.62859349	31	178.0400983	-114.8400983	1.019922904	-0.900441024
2018	4	12.9	27	-2.2	32.44019912	30	371.3320226	-361.9320226	-1.41240467	-1.505106326
2018	5	15.8	28.2	7.3	38.89575062	31	425.9946131	-346.5946131	-1.254474143	-1.039752814
2018	6	18.9	30.6	7.5	41.80942906	30	508.8565649	-444.8565649	-1.620570505	-0.763967281
2018	7	21.4	35.5	9.5	40.43758593	31	576.2985034	-521.4985034	-1.493992709	-1.342294204
2018	8	21	34.6	7.6	35.03170117	31	503.5752362	-359.5752362	-1.439317498	-1.292254704
2018	9	16.2	29.1	2.2	26.82176758	30	326.3559558	-243.7559558	-1.455891577	-1.537422223
2018	10	10.6	23	-0.9	18.36302751	31	181.7820954	-135.8820954	-1.112261336	-1.503270542
2018	11	5.4	15.7	-3.5	11.76699671	30	82.53788232	-65.73788232	-1.740953212	-1.692519321
2018	12	3.9	13.2	-4.7	9.067181233	31	59.35373804	112.246262	-0.023210634	-1.510126969
2019	1	0.5	7.3	-7.3	10.48066302	31	52.25234735	10.24765265	0.710937926	-1.787995473
2019	2	3.3	18.5	-5.8	15.80310003	28	105.8555782	-66.65557819	1.337193502	-1.898376341
2019	3	7.1	19	-3.1	23.62859349	31	197.2072534	-120.0072534	-0.162765515	-1.935754713
2019	4	9.4	24.9	-1.6	32.44019912	30	313.4183666	-257.9183666	-0.538155759	-1.580147115
2019	5	11.2	23.2	-0.8	38.89575062	31	393.9991688	-274.4991688	0.26138072	-1.275320331
2019	6	19.8	35.5	8.4	41.80942906	30	564.6714342	-485.3714342	-0.715800249	-1.438005016
2019	7	20.9	35.9	10.3	40.43758593	31	564.5542724	-464.7542724	-0.903904592	-1.130971217
2019	8	19.2	33.1	10	35.03170117	31	444.1794596	-314.8794596	-1.074968318	-0.911418593
2019	9	15.3	27.8	4.8	26.82176758	30	293.7841744	-218.7841744	-0.53965339	-0.781161152
2019	10	11.5	22.9	3.4	18.36302751	31	169.4020809	-46.30208086	0.574847183	-0.36316763
2019	11	5.5	16.6	-3.3	11.76699671	30	84.3912038	-34.8912038	0.105655537	-0.272326455
2019	12	3.4	13.9	-4.9	9.067181233	31	59.42601549	2.773984513	0.158351595	-0.77159143
2020	1	2.3	14.2	-5.1	10.48066302	31	65.98618183	-36.48618183	-1.412324964	-1.025981317
2020	2	6.2	17.5	-4.8	15.80310003	29	119.4625543	-5.362554272	-0.449927556	-0.747423527
2020	3	5.9	19.2	-5	23.62859349	31	196.4189701	-151.9189701	-0.435814812	-0.936774031
2020	4	12.3	24.4	-4.3	32.44019912	30	360.944182	-328.444182	-1.046107034	-1.241417428
2020	5	13.8	27.1	2.3	38.89575062	31	436.4199648	-357.8199648	-1.374736256	-1.669032957
2020	6	16.9	28.4	7.4	41.80942906	30	458.7356054	-336.5356054	-0.753927227	-0.842525808
2020	7	20	34.8	8.1	40.43758593	31	563.147527	-507.147527	-0.732922678	-1.064722513
2020	8	19.8	33	8.8	35.03170117	31	462.0045847	-320.0045847	-0.345143469	-1.054640803
2020	9	16	29.2	4.7	26.82176758	30	309.6251487	-278.8251487	-1.338901752	-1.273823153
2020	10	9.6	18.9	2.1	18.36302751	31	147.0411932	-45.14119324	-0.115007641	-1.288394524
2020	11	5.5	22.1	-4.1	11.76699671	30	96.83253231	-70.03253231	-1.096301415	-1.393622672
2020	12	2.3	13.6	-5.7	9.067181233	31	57.08691026	20.31308974	-0.118138775	-1.354148687
2021	1	0.8	10	-13.4	10.48066302	31	67.23558075	83.86441925	0.336925864	-0.931469506
2021	2	3.5	18.7	-12.2	15.80310003	28	120.4999869	-85.49998689	0.728840742	-1.297799037
2021	3	5.4	23.1	-3.4	23.62859349	31	201.2047932	-146.5047932	0.274791808	-1.308195881
2021	4	8	23.1	-2.8	32.44019912	30	293.9017621	-259.5017621	-1.116022494	-0.98241895
2021	5	11	26.4	0.3	38.89575062	31	408.0415873	-258.7415873	0.152239778	-0.356585361
2021	6	19	31.5	6.5	41.80942906	30	530.8125113	-356.6125113	0.466576656	-0.464526476
2021	7	18.3	29	10.5	40.43758593	31	447.6801279	-215.0801279	1.986958089	0.999907417
2021	8	17.4	31.2	8.2	35.03170117	31	421.6550819	-362.6550819	1.540956144	0.757435436
2021	9	15.9	27	5.2	26.82176758	30	291.2021877	-265.1021877	0.93421341	0.804887775
2021	10	8.9	22.3	-1.7	18.36302751	31	171.2579326	-154.3579326	-1.505981167	0.266167534
2021	11	3.8	11.5	-1.9	11.76699671	30	64.19790756	-35.09790756	-1.852771156	0.394485157
2021	12	3	14.1	-5.2	9.067181233	31	59.07501162	51.42498838	-0.943795643	0.537584244
2022	1	1.6	15.4	-5.6	10.48066302	31	66.43388721	-24.53388721	-0.409177509	0.015884117
2022	2	4.4	15.6	-5.5	15.80310003	28	103.7820771	-60.68207714	-0.335953204	0.159695872
2022	3	6.3	20.5	-6.3	23.62859349	31	210.1898983	-185.0898983	-1.562016537	-0.075339736
2022	4	9.3	23.3	-1.8	32.44019912	30	303.9056355	-216.0056355	-0.752073016	0.207171327
2022	5	16.2	31	4.1	38.89575062	31	489.0426588	-443.0426588	-1.422282722	-0.713948093
2022	6	19.7	34.3	7.8	41.80942906	30	556.9004033	-455.9004033	-1.390365968	-1.224567204
2022	7	21.3	35.3	9.7	40.43758593	31	570.3894587	-523.2894587	-2.097319665	-2.193481314
2022	8	20.3	35.4	10.2	35.03170117	31	477.7228378	-395.8228378	-1.696898948	-2.233100599
2022	9	14.4	27.5	3.4	26.82176758	30	292.5505229	-172.7505229	-1.247154326	-1.987143807
2022	10	13.3	22.9	4.5	18.36302751	31	174.6638847	-95.56388475	-0.335682007	-1.838514641
2022	11	7.2	17.6	-1.1	11.76699671	30	87.77594922	-7.175949216	0.392095552	-1.677986675
2022	12	2.8	15.1	-9.4	9.067181233	31	65.91922439	17.38077561	0.044577468	-1.826408143
2023	1	3.2	16.4	-7.8	10.48066302	31	77.19786068	-24.79786068	-0.521798121	-1.955515971
2023	2	3.3	15.6	-8	15.80310003	28	104.3197682	-89.91976818	-1.642954394	-2.068039604
2023	3	7.3	19.3	-2.9	23.62859349	31	199.2404937	-110.8404937	-0.925810151	-1.850342912
2023	4	8.5	20.5	-3	32.44019912	30	285.3791773	-181.5791773	0.220657172	-1.745365182
2023	5	14.4	26.4	4.8	38.89575062	31	415.0251681	-333.5251681	0.489874524	-1.307187032
2023	6	20.2	31	8.1	41.80942906	30	524.5956263	-486.4956263	-0.590305362	-1.417971809
2023	7	20.4	36.2	10	40.43758593	31	563.7528615	-428.0528615	-1.07041358	-0.949870174
2023	8	19.9	35	7.8	35.03170117	31	491.1074922	-347.0074922	-1.052709194	-0.703532226
2023	9	18	30.2	5.2	26.82176758	30	331.2756514	-291.8756514	-1.075867479	-1.190337597
2023	10	12.5	25.6	1.6	18.36302751	31	194.3488898	-125.7488898	-1.350286786	-1.326488688
2023	11	6	15.2	-3.5	11.76699671	30	83.56270365	110.9372963	0.023977708	-0.865178732
2023	12	3.7	11.2	-12.4	9.067181233	31	67.5237087	69.4762913	1.616698992	-0.630411105

Table 41: RWI mean values of Acer platanoides.

Year	RWI
1996	1.29
1997	1.66
1998	1.07
1999	1.29
2000	1.21
2001	1.15
2002	1.15
2003	0.56
2004	2.06
2005	1.19
2006	0.86
2007	0.73
2008	0.85
2009	1.64
2010	1.27
2011	1.26
2012	0.82
2013	1.31
2014	0.44
2015	1.13
2016	1.17
2017	0.9
2018	1.17
2019	0.55
2020	0.79
2021	1.49
2022	0.49
2023	0.51

Table 42: RWI mean values of Betula pendula.

Year	**RWI**
1996	0.98
1997	1.36
1998	0.79
1999	1.67
2000	1.74
2001	1
2002	0.33
2003	0.18
2004	1.14
2005	0.77
2006	0.69
2007	0.4
2008	0.6
2009	1.42
2010	0.72
2011	0.43
2012	1.34
2013	1.48
2014	0.98
2015	1.18
2016	0.42
2017	0.56
2018	1.45
2019	0.25
2020	0.29
2021	1
2022	0.2
2023	0.77

Table 43: RWI mean values of Robinia pseudoacacia.

Year	RWI
1996	1.04
1997	0.77
1998	0.97
1999	1.18
2000	0.99
2001	0.58
2002	1.17
2003	1.12
2004	0.86
2005	1.14
2006	1.42
2007	1.08
2008	1.48
2009	1.51
2010	1.29
2011	0.87
2012	0.87
2013	1.09
2014	0.63
2015	0.85
2016	0.64
2017	1.15
2018	1.22
2019	0.82
2020	1.18
2021	0.99
2022	0.9
2023	0.72

Table 44: Total concentration of P, K and Na in soil samples.

Species	Treatment	Nutrient	Concentration [mg/kg]
A. platanoides	Dog	P	1279
A. platanoides	Dog	P	1646
A. platanoides	Dog	P	1227
A. platanoides	No Dog	P	721.4
A. platanoides	No Dog	P	498.1
A. platanoides	No Dog	P	1142
B. pendula	Dog	P	971.1
B. pendula	Dog	P	1192
B. pendula	Dog	P	1373
B. pendula	No Dog	P	964.7
B. pendula	No Dog	P	1417
B. pendula	No Dog	P	1056
R. pseudoacacia	Dog	P	993.8
R. pseudoacacia	Dog	P	1114
R. pseudoacacia	Dog	P	1031
R. pseudoacacia	No Dog	P	598.6
R. pseudoacacia	No Dog	P	404.4
R. pseudoacacia	No Dog	P	1100
A. platanoides	Dog	K	12450
A. platanoides	Dog	K	12810
A. platanoides	Dog	K	12700
A. platanoides	No Dog	K	11830
A. platanoides	No Dog	K	10250
A. platanoides	No Dog	K	18480
B. pendula	Dog	K	9408
B. pendula	Dog	K	9430
B. pendula	Dog	K	9492
B. pendula	No Dog	K	15520
B. pendula	No Dog	K	14650
B. pendula	No Dog	K	19470
R. pseudoacacia	Dog	K	12060
R. pseudoacacia	Dog	K	14460
R. pseudoacacia	Dog	K	13200
R. pseudoacacia	No Dog	K	11570
R. pseudoacacia	No Dog	K	12160
R. pseudoacacia	No Dog	K	16800
A. platanoides	Dog	Na	10900
A. platanoides	Dog	Na	9040
A. platanoides	Dog	Na	9260
A. platanoides	No Dog	Na	6760
A. platanoides	No Dog	Na	2495
A. platanoides	No Dog	Na	10950
B. pendula	Dog	Na	7570
B. pendula	Dog	Na	6960
B. pendula	Dog	Na	6250
B. pendula	No Dog	Na	13290
B. pendula	No Dog	Na	11580
B. pendula	No Dog	Na	11340
R. pseudoacacia	Dog	Na	10120
R. pseudoacacia	Dog	Na	12960
R. pseudoacacia	Dog	Na	13410
R. pseudoacacia	No Dog	Na	1098
R. pseudoacacia	No Dog	Na	8030
R. pseudoacacia	No Dog	Na	13090

Table 45: Total concentration of P, K and Na in wood samples.

Species	Treatment	Nutrient	Concentration [mg/kg]
A. platanoides	Dog	P	269.64
A. platanoides	Dog	P	302.98
A. platanoides	Dog	P	374.97
A. platanoides	No Dog	P	530.47
A. platanoides	No Dog	P	332.09
A. platanoides	No Dog	P	535.55
B. pendula	Dog	P	302.23
B. pendula	Dog	P	311.24
B. pendula	Dog	P	247.15
B. pendula	No Dog	P	217.23
B. pendula	No Dog	P	247.18
B. pendula	No Dog	P	498.23
R. pseudoacacia	Dog	P	1158.33
R. pseudoacacia	Dog	P	190.74
R. pseudoacacia	Dog	P	317.91
R. pseudoacacia	No Dog	P	191.18
R. pseudoacacia	No Dog	P	248.25
R. pseudoacacia	No Dog	P	204.68
A. platanoides	Dog	K	1412.31
A. platanoides	Dog	K	1904.51
A. platanoides	Dog	K	1572.5
A. platanoides	No Dog	K	2363.8
A. platanoides	No Dog	K	1333.24
A. platanoides	No Dog	K	2370.56
B. pendula	Dog	K	601.71
B. pendula	Dog	K	1411.53
B. pendula	Dog	K	801.47
B. pendula	No Dog	K	522.55
B. pendula	No Dog	K	2205.79
B. pendula	No Dog	K	741.05
R. pseudoacacia	Dog	K	3782.86
R. pseudoacacia	Dog	K	2165.26
R. pseudoacacia	Dog	K	1365.67
R. pseudoacacia	No Dog	K	1231.3
R. pseudoacacia	No Dog	K	7982.6
R. pseudoacacia	No Dog	K	6609.66
A. platanoides	Dog	Na	499.52
A. platanoides	Dog	Na	623.55
A. platanoides	Dog	Na	233.01
A. platanoides	No Dog	Na	18.34
A. platanoides	No Dog	Na	27.42
A. platanoides	No Dog	Na	19.63
B. pendula	Dog	Na	5.35
B. pendula	Dog	Na	5.08
B. pendula	Dog	Na	17.99
B. pendula	No Dog	Na	9.42
B. pendula	No Dog	Na	6.16
B. pendula	No Dog	Na	11.84
R. pseudoacacia	Dog	Na	19.39
R. pseudoacacia	Dog	Na	3.6
R. pseudoacacia	Dog	Na	4.69
R. pseudoacacia	No Dog	Na	5.33
R. pseudoacacia	No Dog	Na	34.52
R. pseudoacacia	No Dog	Na	4.9

Table 46: LOI (%) results in soil samples.

SAMPLE	**LOI %**
Acer platanoides Dog N.1	17.34
Acer platanoides Dog N.2	37.3
Acer platanoides Dog N.3	22.32
Acer platanoides No Dog N.1	7.67
Acer platanoides No Dog N.2	7.78
Acer platanoides No Dog N.3	8.85
Betula pendula Dog N.1	7.24
Betula pendula Dog N.2	7.29
Betula pendula Dog N.3	9.72
Betula pendula No Dog N.1	7.49
Betula pendula No Dog N.2	9.04
Betula pendula No Dog N.3	7.98
Robinia pseudoacacia Dog N.1	12.9
Robinia pseudoacacia Dog N.2	13.05
Robinia pseudoacacia Dog N.3	11.69
Robinia pseudoacacia No Dog N.1	8.03
Robinia pseudoacacia No Dog N.2	7.39
Robinia pseudoacacia No Dog N.3	6

Personal declaration:
I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis

Date	Signature
25.04.2025	M. Dassie