

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Tropical AgriSciences



**The Effects of Tree Species Diversity and Structure on
Forest Microclimate in Spain**

MASTER'S THESIS

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DIPLOMA THESIS ASSIGNMENT

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Forestry Engineering
Tropical Forestry and Agroforestry

Thesis title

The Effects of Tree Species Diversity and Structure on Forest Microclimate in Spain

Objectives of thesis

The challenging environmental conditions of Mediterranean forests is expected to become drier and warmer due to global climate change.

Trees can significantly reduce the negative impacts of warming on forest microclimate, diminishing impacts on forests biodiversity and stability. However, the positive effect of the forest on the microclimate in the understory may vary according to the species and functional composition of the tree canopy.

The aim of this work will be to investigate how the main tree species of the Mediterranean forests in central Spain and their mixtures affect air and soil temperatures and soil moisture in the understory.

Methodology

Data will be collected using TMS4 microclimatic sensors at FunDiveEUROPE research plots (1 sensor per plot) in Alto Tajo Natural Park, Spain. These plots include the main tree species of the area – the Scots pine (*Pinus sylvestris*), the black pine (*Pinus nigra*), the Portuguese oak (*Quercus faginea*) and the evergreen oak (*Quercus ilex*) in mixtures. As part of the thesis, the plots will be visited, checked and, if necessary, sensors installed and data downloaded. A hemispherical photograph will be taken over each sensor to determine tree canopy cover.

Data analysis will be performed in R software using a script developed for this purpose. In the first stage, averages, maxima, minima and variability within selected time periods (e.g. daily or monthly averages of temperatures and maxima during the growing season, soil moisture in summer, etc.) will be calculated. These variables will then be used as dependent variables for the models, which will include as independent variables: tree species representation, stand density and tree canopy cover.

The proposed extent of the thesis

30 stran

Keywords

microclimate, tree species composition, Mediterranean mixed forest, Alto Tajo Natural Park, FunDivEU-ROPE

Recommended information sources

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I hereby declare that I have compiled this thesis entitled *The Effects of Tree Species Diversity and Structure on Forest Microclimate in Spain* independently and have stated all sources used. I agree to my thesis being published in accordance with §47(b) of the Act No. 111/1998 Coll. On Higher Education Institutions, as amended, regardless of the outcome of its defence.

In Prague, 22nd April 2022

Moana Ungrová

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Abstract

Climate change is expected to have a profound effect on Mediterranean ecosystems, resulting in harsher conditions with more frequent temperature extremes and associated drought events. Therefore, it is now critical to focus on sustainable forest management plans that aim to develop resilient forests able to withstand these conditions. The important knowledge on functional significance of forest diversity has been contributed by the FunDivEUROPE project, as part of which this research was conducted, taking place in the Mediterranean forests in the Alto Tajo Natural Park, Spain. With the aim to closer understand to the effect of local oak and pine species (*Quercus faginea*, *Quercus ilex*, *Pinus nigra*, *Pinus sylvestris*) on forest microclimate, TMS data-loggers were set at 36 sample plots, measuring soil temperature (T1, T2), air temperature (T3) and soil moisture during four years (2018-2021). The highest soil and air temperature extremes in the summer months were repeatedly found in the broadleaved stands and in the stands with low level of species richness. The lowest mean soil temperatures in the summer months were recorded in single species coniferous stands of the Scots pine (*Pinus sylvestris*). Diverse forest stands (i.e. 4-species stands) were found to be the most thermally favourable, however they showed the lowest levels of the soil moisture. This is expected to be a result of high competition for water, since in monocultures the soil moisture level remained the highest. Thus, considering all the generally known benefits of forest diversity, highly diverse stands might be the right ones to cope with the future temperature extremes. As for the economically important timber species, especially *Pinus sylvestris*, it might be more suitable to be grown in the monocultures or in mixtures with *Q. faginea*.

Key words: Alto Tajo, FunDivEUROPE, microclimate, tree species diversity

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List of the abbreviations used in the thesis

BEF – Biodiversity and Ecosystem Functioning

LAI – Leaf Area Index

TMS - Temperature-Moisture-Sensors

1. Introduction

In the last several decades, it has been repeatedly shown that ongoing global climate change has a profound effect on the world ecosystems. Recently, there have been alarming reports warning on the widespread and dangerous disruption in nature and thus stability of the Earth system, with an emphasis on biochemical flows, land use change and biodiversity loss being the most crucial disrupted categories (IPCC, 2022; Steffen *et al.*, 2015).

Due to increasing severe drought events, forests of the Northern Hemisphere, especially Mediterranean forests, are facing increasing frequency and intensity of fire and regional die-off events, therefore contributing to the global reduction of the carbon sink efficiency of forests (Carnicer *et al.*, 2011; Valladares, 2017).

Considering the ecological importance of forests and their intricate relationship with climate, the interest in understanding their ecosystem functioning has been rising. Yet, most studies have been based on macroclimate data, i.e. free-air temperature data from weather stations in open areas outside forests. However, it is the microclimatic data that show the thermal heterogeneity available in the forests and additionally, it is the soil temperature rather than the air- temperature that defines many ecosystem functions in and close to the soil and thus affecting the ecosystem as a whole (Lembrechts *et al.*, 2020; Haesen *et al.*, 2021). Nowadays, the functional significance of tree species diversity is receiving much attention also thanks to modern technologies enabling large-scale experiments with more species richness levels. One of such, the FunDivEUROPE project, has been providing a closer insight into these matters (Baeten *et al.*, 2013).

In Iberian forests, it has already been shown, for instance, that tree species diversity increases productivity (Jucker *et al.*, 2014a), the species interactions play an important role in modulating the response of tree species to drought (Grossiord *et al.*, 2014, 2015) and this thesis is aiming at understanding their effect on local forest microclimate.

2. Aims of the Thesis

The aim of this thesis is to determine the effect of pines and oak species and their mixtures on local microclimate in Alto Tajo National Park in the north-eastern Spain. The species found/studied in the sample plots were the black pine (*Pinus nigra* Arn.), the Scots pine (*Pinus sylvestris* L.), the Portuguese oak (*Quercus faginea* Lam.) and the evergreen oak (*Quercus ilex* L.).

The influence of the tree species on the soil humidity, air temperature and soil temperature measured in the depth of 2 cm and 10 cm belowground were observed. Further, the hemispherical photographs were used to calculate the leaf area index (LAI) and subsequently determine the additional effect of the forest structure on local microclimate.

The research was conducted at 36 sample plots, established within the FunDivEUROPE project. The input data needed for the analysis were the data measured by the data loggers for four years (2018 – 2021). These data served as a basis for creating graphs schematically representing individual measured variables.

3. Literature Review

3.1. Biodiversity and Ecosystem Functioning (BEF)

According to the Convention on Biological Diversity (CBD, 1992) biodiversity as such is defined as “the variability among living organisms from all sources including inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species, and of their habitats”. As complex as its definition; biodiversity is not just a passive result of interactions between species and environmental conditions but it has been repeatedly shown that differences in biodiversity can largely affect ecosystem functioning (Naeem, 2002; Cardinale *et al.*, 2012).

Most of the biomes and ecosystems have been disrupted and have been facing substantial losses in species richness, as a consequence of human activities (IPCC, 2022). Supported by this alarming threat, the effect of biodiversity loss on ecosystem functioning has received increasing attention in ecological research during the last decades (e.g. Naeem, 2002; Hooper *et al.*, 2005, 2012).

According to (Baeten *et al.*, 2013), early experiments on BEF lacked biological and environmental complexity as they were primarily carried out in grasslands and little was known about BEF in forest ecosystems. Recent studies have shown that across variety of systems diverse communities generally outperform those that are species poor with forest ecosystems being no exception (Cardinale *et al.*, 2012; Jucker *et al.*, 2014a). Mixed species stands were found to be more productive in terms of above-ground woody biomass production (Jucker *et al.*, 2014a; Baeten *et al.*, 2019), which has also shown to be more stable through time (Jucker *et al.*, 2014b), than monocultures. Besides they therefore sequester more carbon in their above-ground biomass, diverse forests also store more carbon belowground, recycle nutrients more efficiently, show signs of higher resilience as they exhibit less pest outbreaks and generally shelter higher number of associated taxa (Cardinale *et al.*, 2012). However, considering how extremely rich and complex forest ecosystems are, it can be assumed that our current knowledge is only a small glimpse into their functioning.

3.2. Mediterranean biome

Compared with other type of climates, the regions under Mediterranean-type climates represent a relatively small proportion of the continental areas of the world and, in addition to that, they appear fragmented in different territories of the Northern and Southern Hemispheres (Gil-Pelegrín *et al.*, 2017).

The Mediterranean-type climates include sub-varieties with common characteristics: rainfall patterns characterized by a severe summer drought and presence of warm to hot summer and mild or cold winter (Lionello *et al.*, 2006). In addition to the typical dry summer, high atmospheric pressures associated with high frequency of meteorological droughts become frequent during spring and autumn (García-Ruiz *et al.*, 2011). Despite of the severe life conditions, the variations in temperature and precipitation produce complex mosaic of environments resulting in high biological diversity (Gil-Pelegrín *et al.*, 2017). In terms of its plant diversity, the Mediterranean Basin Hotspot is the third richest biodiversity hotspot in the world (Mittermeier *et al.*, 2004).

Mediterranean forests harbour less species than tropical forests, yet they comprise a considerable grade of functional diversity regarding e.g. photosynthetic capacity, hydraulic architecture, stomatal regulation, productivity, light demand or sensitivity to drought (Grossiord *et al.*, 2015).

Nevertheless, just as the traditional human land use has also contributed to enhance diversity of the vegetation in Mediterranean ecosystems (Gil-Pelegrín *et al.*, 2017), current land use is a driver of the biodiversity loss – especially due to conversion of natural vegetation into cultivated and urban areas, differences in management intensity within the same land-use, and the land abandonment as a result of socio-economic changes (Valladares *et al.*, 2013). Among other human activities currently threatening this biome belong infrastructural development triggered by the tourism industry (resulting in increasing habitat fragmentation and isolated populations) and pressure on scarce water resources (Mittermeier *et al.*, 2004; Cuttelod *et al.*, 2008; Valladares, 2004; Valladares *et al.*, 2013; Gil-Pelegrín *et al.*, 2017).

3.2.1. Climate change in the Mediterranean biome

Due to the ongoing global climate change, the impact of changing environmental conditions on Mediterranean ecosystems has recently been widely studied (e.g. by (Martínez-Vilalta and Piñol, 2002; Peñuelas and Boada, 2003; García-Ruiz *et al.*, 2011; Valladares, 2017). The climate of Mediterranean areas is expected to become warmer and drier, with increasing evapotranspiration and decreasing water availability for plants (Christensen *et al.*, 2007; Valladares *et al.*, 2013), and with higher frequency of extreme heatwaves contributing to general rise in fire risk (Valladares *et al.*, 2013).

In Mediterranean forests, trees compete for two primary resources – light and water (Poorter *et al.*, 2012; Carnicer *et al.*, 2014). The light use complementarity strategies has been found to support increases in stand-level productivity of mixed forests (De Cáceres *et al.*, 2021) but increased competition for water may reduce this effect (Jucker *et al.*, 2014a).

However, the prevailing tree species of pines and oaks have developed contrasting ecological strategies and therefore their adaptation to climate change is expected to be unequal (Poorter *et al.*, 2012). Valladares (2004) mentions that increasing shade accompanying the abandonment of ecosystems, together with potential global dimming, might result in decreased spatial heterogeneity of light and therefore gradual disappearance of light demanding shrub communities. This might affect plant recruitment and natural forest regeneration, as the photoinhibition and drought can be more severe in the shade.

Nevertheless, in Iberian forests, altitudinal shifts of forest types have already been recorded (Peñuelas and Boada, 2003; Jump *et al.*, 2006) and the increasing temperatures and drought correlating with forest decline and tree mortality has been shown (Carnicer *et al.*, 2011). However, the severity of the climate change seems to be particularly strong for the *Pinus* species. According to the recent studies conducted in the Spanish forests, the drought affects light and water demanding *Pinus* species more than shade and drought tolerant *Quercus* species (Galiano *et al.*, 2010; Poorter *et al.*, 2012). As described by Ruiz-Benito *et al.* (2013), the higher mortality rates at high temperatures of pines might be caused by stomatal closure, which prevents the hydraulic failure, and subsequent carbon starvation as the carbon stores are being depleted due to high respiration costs. Whereas oaks' drought tolerance mechanism consists of less severe stomatal closure and

continuing transpiration at relatively high rates, therefore likely they die because of hydraulic failure rather than carbon starvation.

The important drought-induced mortality of Iberian mountain populations of *Pinus nigra* and *Pinus sylvestris* has been observed (Galiano, Martínez-Vilalta and Lloret, 2010; Grossiord *et al.*, 2015), corresponding with previous results reported by Martínez-Vilalta and Piñol (2002). Nevertheless, even though according to García-Valdés *et al.* (2015) the expected increased droughts might favour rather coniferous species colonization, the species composition of Iberian forests will more likely change in the future in favour of broad-leaf species, as the *Quercus ilex* has already been shown to negatively limit the *Pinus* species recruitment (Carnicer *et al.*, 2014).

3.3. Microclimate

According to Geiger (1965) microclimate can be described as a suite of climatic conditions measured in localised area near the earth's surface. The climate defining variables such as precipitation, solar radiation, air and soil temperature, wind and air humidity are modified by vegetation cover, particularly by forests (Aussenac, 2000). Trees attenuate solar radiation, reduce the velocity of wind and thus reduce the heat convection, and lower air temperature and increase moisture content via evaporation and transpiration. Below forest canopies the temperature extremes are strongly buffered compared to open habitats, however the microclimate that forests create also depends on several features, making the microclimate notably variable factor (Wang *et al.*, 2015; Lembrechts *et al.*, 2020).

The drivers of microclimate variations can be either of horizontal or vertical character. Among the horizontal factors, landscape topography, slope orientation, soil, water balance and their interactions can be included (Lembrechts *et al.*, 2020). Topographically variable landscapes, providing diverse conditions, have shown to harbour abundant microclimatic variations (Zellweger *et al.*, 2019) that provide microrefugia to various plants and insects reducing their climate change-related extinction (Suggitt *et al.*, 2018). Topographic conditions, i.e. depressions where dense

cold air accumulates, might also raise the risk of frost, yet this risk is substantially reduced under canopy cover (Zellweger *et al.*, 2019).

The horizontal distribution in microclimate buffering can be observed at the stand, continental and global scale. At the stand level, there are often strong microclimatic gradients towards forest edges, due to increased solar radiation and wind, however these gradients also depend on the variables such as wind direction, cloudiness etc. At the continental scale, the further distance from the coast and mountains decreases lateral heat transfer and air mixing, and at the global scale the drivers of forest microclimates differ across latitudes, as the largest buffering of maximum temperatures can be found in tropical forests, whereas buffering of cold extremes is largest in boreal forests (De Frenne *et al.*, 2021).

The vertical temperature gradients in the forests are the result of the complexity of the forest structure and its composition, therefore it is controlled especially by the vegetation itself (the density of the canopy – leaf and plant area index) and by the intensity of turbulent air mixing (Lembrechts *et al.*, 2020; De Frenne *et al.*, 2021).

As mentioned, the tree canopy in forests serves as a thermal insulator; in European forest it has been repeatedly proven that sub-canopy temperatures are generally lower in summer and higher in winter compared to the free-air temperatures (Aussenac, 2000; Valladares, 2017; Zellweger *et al.*, 2019; Thom *et al.*, 2020; Haesen *et al.*, 2021). During the warm and clear summer days, the incoming shortwave solar radiation is being absorbed and reflected by the forest canopy – this process together with increased evapotranspirative cooling ensures the decreased understorey maximum temperatures. Therefore, during the day the air temperature peaks within the forest vertical structure are most often located within the top of the canopy, where the incoming energy is being absorbed. However, according to Davis *et al.* (2019), the evapotranspiration cooling effect is diminished under water-scarce conditions. On the other hand, in winter (or at night) the canopy shields the outgoing longwave radiation resulting in understorey heat retention and warmer temperatures compared to those under open-field conditions (De Frenne *et al.*, 2021).

Yet, the temperatures in the forest understorey can be altered by changes in canopy cover and composition – these changes might be either of natural (e.g. natural disturbance, death of one or several trees) or artificial character (forest management intervention, e.g.

thinning, strip felling, clear-felling etc.). Intense habitat modifications strongly decrease the ability of forest cover to mitigate the local impact of macroclimate warming, resulting in negative implications on forest biodiversity dynamics and functioning (Aussenac, 2000; Zellweger *et al.*, 2019; Thom *et al.*, 2020). Forests' effective ability to counteract the effects of macroclimate warming on the forest understory has been shown e.g. by De Frenne *et al.* (2013) or Zellweger *et al.* (2020) stating that thermophilization within plant communities had been found to be attenuated in forests with dense canopies.

The influence of trees on the microclimate of a given stand varies depending on the species composition. Within a species composition, it depends on the age of the stand (Porté *et al.*, 2004; Zellweger *et al.*, 2019) - younger and denser stands tend to have lower soil surface temperatures than older and thinner stands (Aussenac, 2000; De Frenne *et al.*, 2021). Nevertheless, the greatest buffer effect, i.e. changes in sub-canopy temperature against the free-air temperatures, are brought by adult stands with closed canopies and high leaf area indexes (Aussenac, 2000).

Leaf area index (LAI), defined as the one-half of the total surface leaf area per unit ground area, is a variable being frequently used to assess the amount of understorey light, influencing the understorey microclimatic conditions driving the forest regeneration and species performance. It is very dynamic variable, highly dependent on the season and biological factors, indicating the potential available water, nutrients in the soil and overall tree species health (von Arx *et al.*, 2013; Valladares, 2004). It can be quantified using either direct (litterfall collection) or, more commonly, indirect method (digital hemispherical photography, light transmittance measurements with optical sensors) (Olivas *et al.*, 2013). There are several other canopy structural parameters that are often used to give adequate representation of vegetated ecosystems, such as canopy openness (the area fraction of the sky hemisphere that is unobstructed by canopy elements when viewed from a single point) or total gap (which includes all gaps observed from a single point with some angular view range) (Gonsamo *et al.*, 2013).

The air temperature is not the only important microclimatic parameter. Another microclimatic parameter and a crucial driver of species' distribution is the soil moisture. Canopy density and soil moisture are partly coupled: forest stands with a dense canopy transpire more water and therefore deplete soil moisture faster than areas having a sparse or no canopy (Aussenac, 2000), however forests with dense canopies usually do not grow

in water-limited regions, therefore soils are mostly rewetted before soil moisture drops below a critical point (von Arx *et al.*, 2013). In terms of stand structure diversity, horizontal heterogeneity in soil moisture has been shown to be larger in mixed than in pure stands (Schume *et al.*, 2004).

The nature and density of the forest cover affects also the soil temperature. According to Lembrechts *et al.* (2020), it is the soil temperature that is crucial for defining many ecosystem functions in and close to the soil, such as evapotranspiration, soil respiration, root growth, biochemical cycling, decomposition etc., because, among other things, many organisms (fungi, soil microorganisms etc.) relate to the fine-scale soil/near-surface temperatures. In general, soils under forest cover are, as well as the air temperature, colder in summer and warmer in the winter compared to soil in the open ground or clear-felled areas (Aussenac, 2000).

In general, microclimates strongly affect biological and ecological processes such as nutrient cycling, tree regeneration and growth, primary productivity, plant communities and forest density that further influences carbon sequestration and groundwater through its influence on soil dynamics (Chen *et al.*, 1999; Porté *et al.*, 2004; De Frenne *et al.*, 2021). For example, forest edge-to-interior climatic gradients have been found to be the drivers of carbon storage, as in temperate forests carbon stocks were found to be on average higher at the edge than in forests interiors. In contrast, in the tropics forest fragmentation generally leads to decrease of above ground carbon stocks because of the warmer and drier conditions at the forest edges (De Frenne *et al.*, 2021; Meeussen *et al.*, 2021). It can be argued if it is the microclimate that dictates localized processes, or the microclimate is rather an effect of the processes to which species respond (De Frenne *et al.*, 2021). In any case, these issues show us how immensely complex, fascinating and delicate forest ecosystems are.

3.4. FunDivEUROPE Project

The set of forest stands, where this research was conducted, is a part of European permanent network of forest plots established through FunDivEUROPE - a project aiming to assess the functional significance of forest biodiversity across the continent (Baeten *et al.*, 2013; Jucker *et al.*, 2014a).

In total, the network encompasses 209 plots in six countries (Fig. 1) and thus extend over much of the European bioclimatic gradient. Chosen field sites represent major European forest types, from boreal forest (Finland) through hemi-boreal (Poland), beech forest (Germany), mountainous beech forest (Romania), to thermophilous deciduous forest (Italy) and Mediterranean mixed forests in Spain (Baeten *et al.*, 2013; Jucker *et al.*, 2014a).

All plots were set up in mature forest stands (i.e. at least in the mid-to-late stages of stem exclusion), had been continuously forested at least since the oldest available land-use maps (therefore considered as ancient forest) and had undergone only low frequency thinning or minimal management interventions in recent years (Baeten *et al.*, 2013; Jucker *et al.*, 2014a). The details on the Experimental Platform design and establishment are described by Baeten *et al.* (2013). Sixteen target species are comprised within the site network, several of which are represented at more than one site (Jucker *et al.*, 2014a).

The network of sites is part of the Experimental Platform of the project, and is studied in parallel with the Inventory Platform (consisting of national and regional forest inventories), as seen in Figure 1. This provides added value and source of valuable data enabling a development of complex research on forest ecosystem functioning (e.g. (Jucker *et al.*, 2014a; Jucker *et al.*, 2014b; Grossiord *et al.*, 2015; Baeten *et al.*, 2019).



Figure 1 Locations of the FunDivEUROPE study sites

(source: Baeten *et al.*, 2013)

4. Materials and Methods

The research was conducted in a continental Mediterranean mixed forest of the Alto Tajo Natural Park. The data were collected on permanent forest plots, with different combinations of pines and oaks, that are included in the exploratory platform of the FunDivEUROPE project (www.fundiveurope.eu).

The measurement was launched in 2018 when the TMS dataloggers were installed at 36 plots throughout the natural reserve and the data were collected for the next nearly 4 years. Right above each datalogger the hemispherical photo, capturing the canopy cover, was taken.

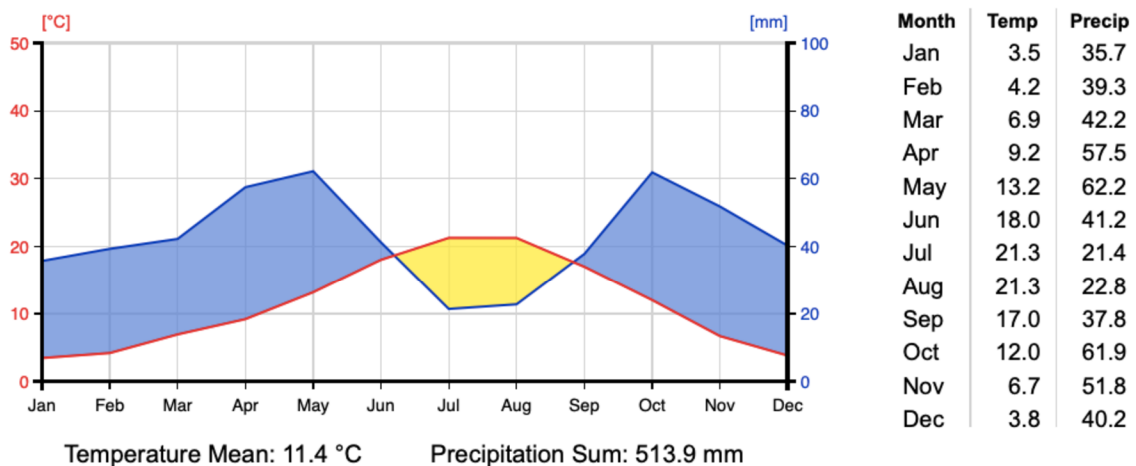
The detailed steps of data acquisition and processing are described in the following sections.

4.1. Field site

The sample plots, where the microclimate was measured, were located in the Alto Tajo Natural Park, located in Castile-La Mancha - an autonomous community of Spain – in the Guadalajara province of central Spain (40.9°N, 1.9°W).

The reserve extends along the Sistema Ibérico mountain range and is characteristic by rugged topography, at an elevation of 960 - 1400 m.a.s.l. The prevailing soil type in this area is cambic cambisol (FAO classification) on a cracked limestone bedrock. Under these conditions, soil depth is usually shallow (between 20 - 40cm) however, according to Peñuelas and Filella (2003) tree roots might penetrate to several metres deeper through the cracked bedrock.

Due to the higher altitude, its type of climate corresponds to category Cfb – temperate oceanic climate, typical for subtropical highlands (Köppen climate classification, 1923). It is characterized by warm mild summers and cool wet winters, with mean annual temperature 11,4 °C and mean annual rainfall precipitation of 513 mm. Typically, the precipitation is more evenly distributed through the year and therefore the drought period is not as severe as in other types of the Mediterranean climate.



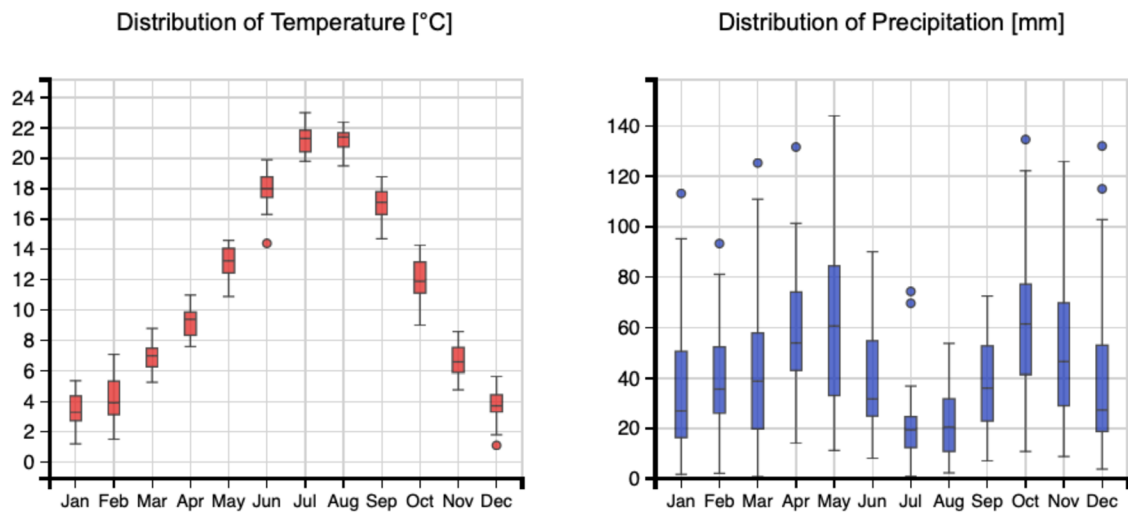


Figure 2 Climate charts of nearby municipality Molina de Aragón, Castilla-La Mancha, Spain using data from years 1990-2019 (source: Zepner *et al.*, 2020)

Understory vegetation is mainly represented by various shrub species (*Arctostaphylos uva-ursi*, *Buxus sempervirens* and *Genista scorpius*) and juveniles of the dominant tree species.

The study plots, in total 36 plots (30 x 30 m) with different combinations of the four target species, were established in 2011, making the total area 50 x 50 km in size (Baeten *et al.*, 2013). These plots range in species richness from monoculture to 2, 3 and 4-species mixtures. Each target species is represented in all diversity levels and each combination of species (i.e. species composition) was replicated at least twice. The plots are situated nearby towns Buena Fuente, Armallones, Villanueva de Alcorón, Casa Vicente and Taravilla (Fig. 3).

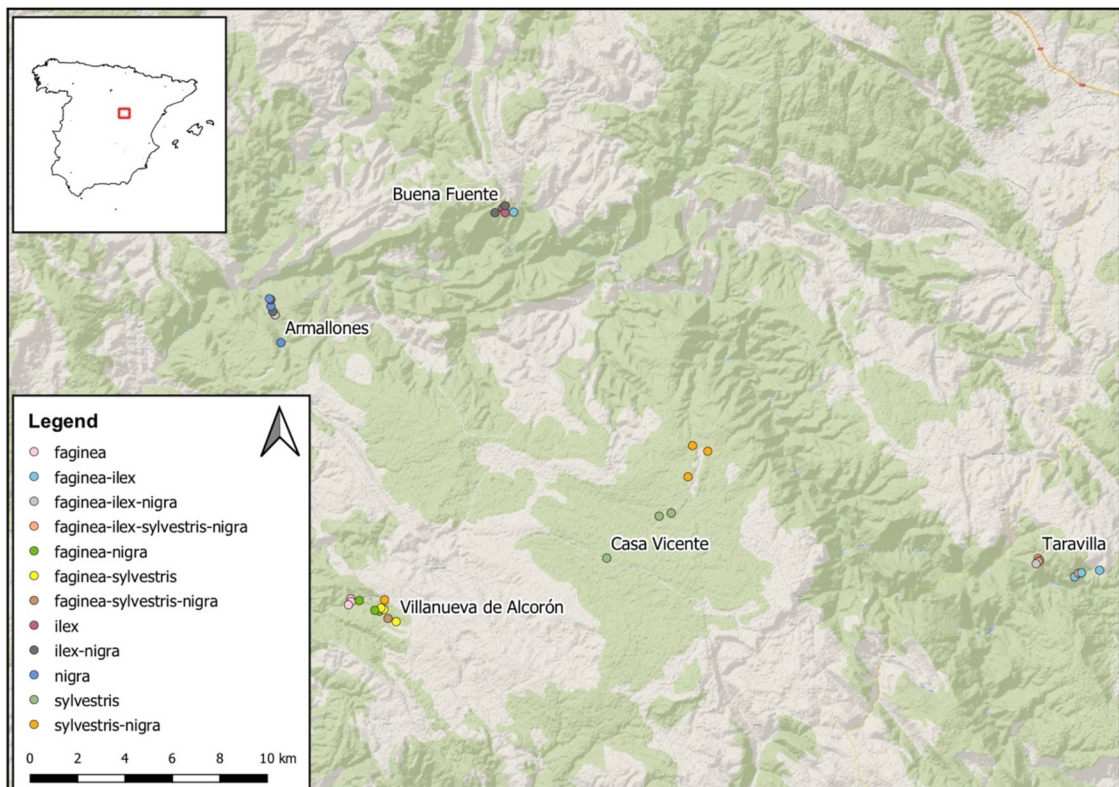


Figure 3 Research plots and their species combinations (source: author)

4.2. Data loggers

For the microclimate measurement in the sample plots and thus acquiring the necessary data, the Temperature-Moisture-Sensors (TMS) data loggers designed by the TOMST company were used.

These TMS loggers are devices designed to capture the climatic conditions at the ground level, those experienced by herbaceous plants. Thus, the logger itself resembles a plant 15 cm tall, rooted in the upper soil layer, as shown in the Figure 4 (Wild *et al.*, 2019).

Within this research, the model TMS-4 was applied. The device has three integrated independent sensors measuring air, surface and soil temperature as well as soil moisture. The sensor for the air temperature T3 measurement is located approximately 15 cm above ground level. The soil temperature sensors are located approximately in the depth of 2 cm (T2) and 10 cm (T1) below ground. The soil moisture sensor is adjacent to the sensor of T1. Interval of measurements is every 15 minutes (Wild *et al.*, 2019).

Each TMS data logger is equipped with a long-lasting battery and large memory capacity, making it a suitable device for taking long-term measurements in the field and applicable in vast range of research in the fields of forestry, agriculture, climatology etc. (Wild *et al.*, 2019). Thanks to this fact and its robust construction, the required maintenance is therefore minimal. However, according to Wild *et al.* (2019) a common limitation of the openly installed TMS loggers are wild animals and therefore protection (e.g. wire cage) is recommended.

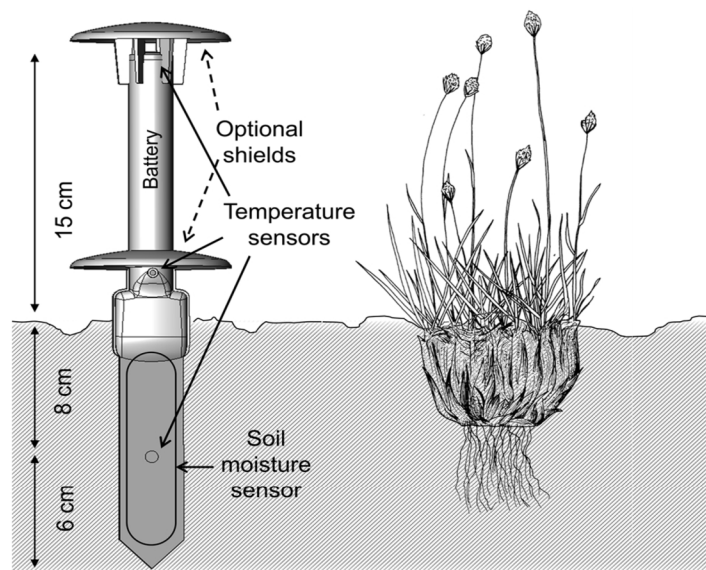


Figure 4 Scheme of the TMS data logger (source: Wild *et al.*, 2019)

4.3. Data processing

The first data extraction was done in 2018, the last in December 2021. Generally, the extraction process is easily manageable; it is done using the necessary TMD adapter that is connected via a USB connector with a laptop. The TMD adapter transfers the data wirelessly from the data logger, it just has to be attached to the highest point of the required TMS device. For gathering the measured data it is indispensable to use the specially designed Lolly Manager software developed by TOMST. Generally, the data downloading is quick, however the time depends on the amount of data stored in the logger. Lolly Manager also includes a simple data viewer Log View that allows to check the data in the field and view a graph of the measured temperature and humidity values.

To clean and analyse the data the software R was used. Within the primary step it was necessary to revise the downloaded data and clean them of obviously erroneous measurements. Those may have occurred as a result of sensor damage or other adverse external influences. For this purpose, the PLOTteR package was used enabling visualizing and erasing the erroneous data.

4.4. Leaf Area Index

Leaf area index (LAI) has been quantified by indirect method using the hemispherical photos of the canopy cover. For this technique, special hemispherical wide-angle lens or fish eye lens must be used, by photographs taken underneath the canopy looking upwards.

The hemispherical photos were taken above each data logger using the fish eye lens, and the obtained photographs were processed as follows:

1) photography preparation

This step is not necessary to do with photographs where the vegetation is sufficiently contrasting compared to the sky (typically the under-exposed ones). Photographs on which these two elements (vegetation and sky) are not contrasted enough should be edited in a graphic software, in order to obtain as much contrasting image as possible – with vegetation being black, sky white. For this purpose, the Adobe Photoshop was used.

2) conversion to a binary file

The main point of this step is thresholding, i.e. determination the brightness threshold, for which it is crucial to have the contrasting images prepared. After the threshold value setting, pixels are distributed into two groups (with lower or higher value) and thus classified as vegetation/sky. This process was done in the ImageJ software and as a result, .bmp files were obtained.

3) quantifying the proportion of vegetation and sky in the image

For the final step of hemispherical photography processing the CIMES program was used. It is a multi-purpose free package of programs for the determination of solar radiation regimes and canopy structure attributes (Gonsamo *et al.*, 2011), therefore allowing to calculate the desired LAI values. Other obtained values of canopy openness and total gap were calculated using special CIMES package *cimesr* in the R software.

5. Results

For the data evaluation, GAM models depicting the microclimatic variables and their distribution were created in the R Studio software.

The shallow soil temperature (T2) has been excluded from the evaluation since this variable had been found to be misrepresenting – it can be easily influenced by external factors such as accumulation of biological material (e.g. leaves) or by slight movement of the datalogger caused by natural forces or wild animals. The results of remaining variables are described in the following subchapters.

5.1. Soil temperature T1

The results of measured mean soil temperature in the depth of 10 cm below ground depending on forest type (Fig. 5) show that during summer seasons the highest mean soil temperature occurs in the broadleaved forest stands (where the maximum temperatures overcame 25 °C in the first two years as seen in the Figure 6), whereas the coniferous stands have the lowest soil temperature.

In winter, the difference between forest types stands is less obvious; in the mild winter of 2018/2019 coniferous stands also had the lowest mean soil temperature however, during the last two winter seasons they showed to have higher soil temperature than broadleaved and mixed stands.

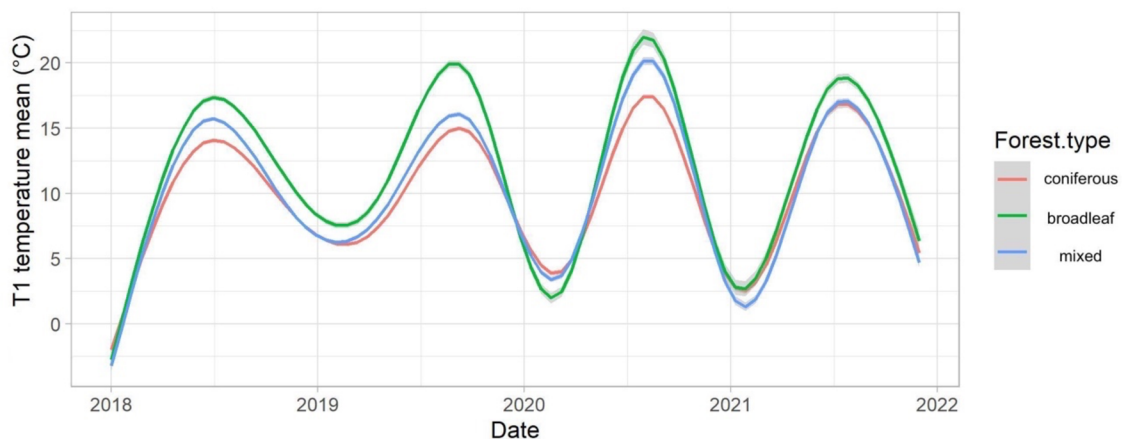


Figure 5 Mean soil temperatures T1 depending on the forest type

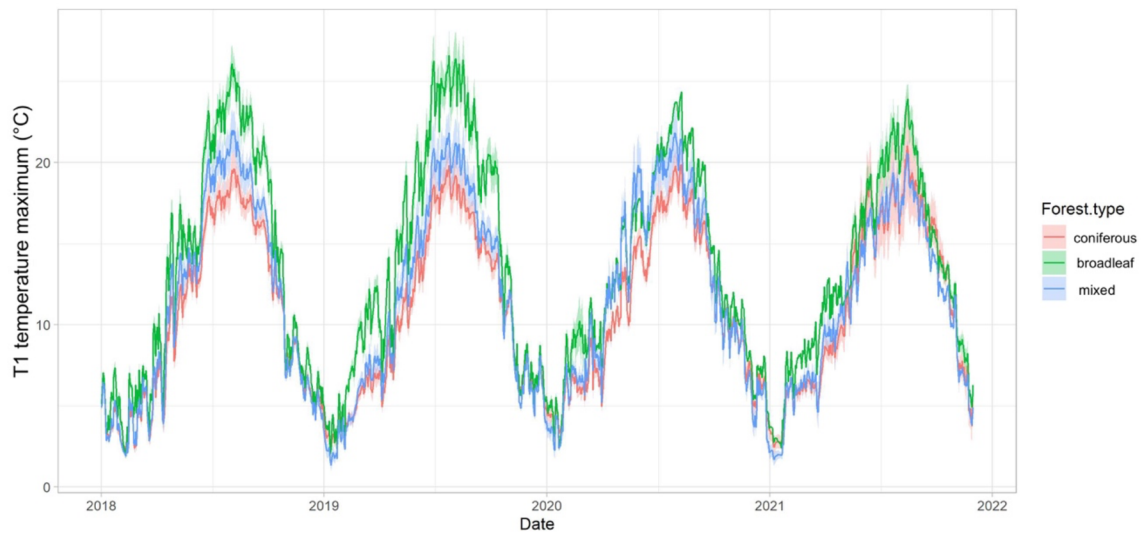


Figure 6 Maximum soil temperatures T1 depending on the forest type

The data of mean soil temperature depending on species richness (Fig. 7) demonstrate that in winter monocultures have significantly warmer soils than species rich stands (of approximately 1,2 °C) and these soils remained the warmest through the whole year of 2021. Winter soil temperatures in 2 and 4-species stands show similar values, however in summer seasons soils in 2-species stands are usually the warmest (except of summer 2021 with monocultures soil maximum temperatures reaching up to 23°C), and the more diverse stands soils are substantially cooler; that can be seen also in the Figure 8 showing that the maximum soil temperatures in 2-species stands regularly exceeds 20 °C, whereas soils in the 4-species stands usually do not overcome this value.

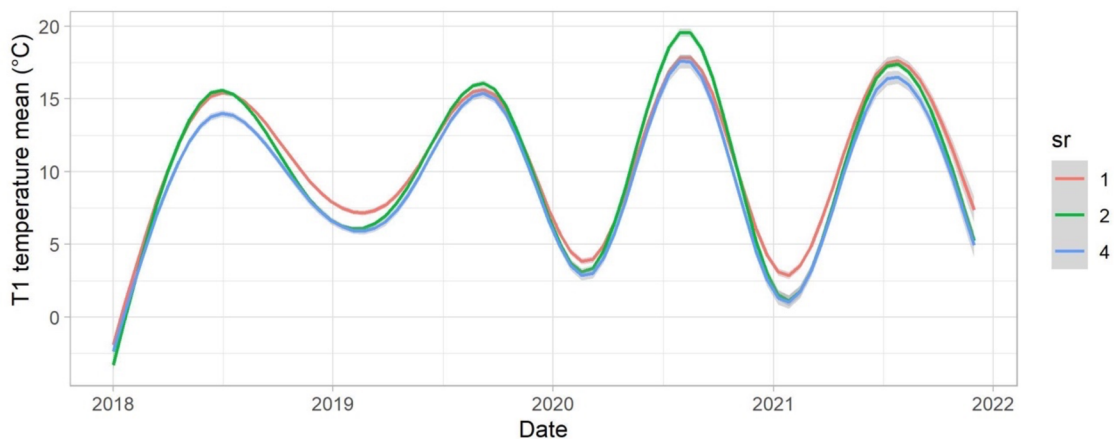


Figure 7 Mean soil temperatures T1 depending on the species richness

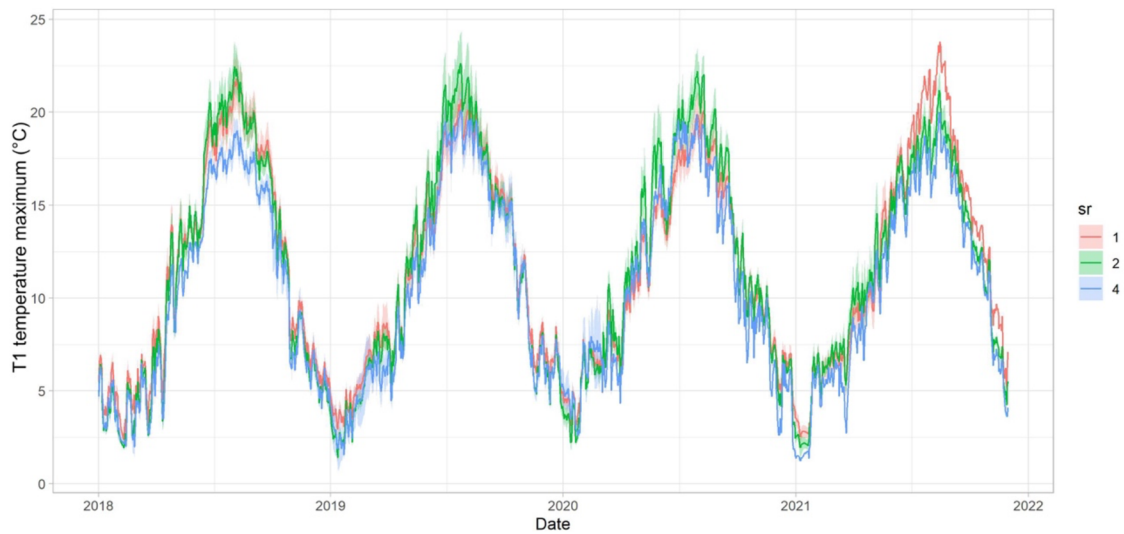


Figure 8 Maximum soil temperatures T1 depending on the species richness

The following graph of the mean soil temperature depending on the species mixtures (Fig. 9) clearly shows that in summer months, the soils were warmest in mixed stands of *Quercus faginea* – *Quercus ilex* – *Pinus nigra* species, where mean temperatures in July and August exceeded 25 °C. Soils in *Q. ilex* – *P. nigra* stands show wide range of temperatures in both summer and winter months. The results from the winter months show that the warmest soils were those found in the monoculture stands of *P. nigra* and again the *Q. faginea* – *Q. ilex* – *P. nigra* mixtures, while the coolest were those found in the *Q. faginea* – *P. sylvestris* mixtures. It can be noticed, that for most of the year the 4-species stands (i.e. *Q. faginea* – *Q. ilex* – *P. sylvestris* – *P. nigra*) belong to stands with the lowest temperature.

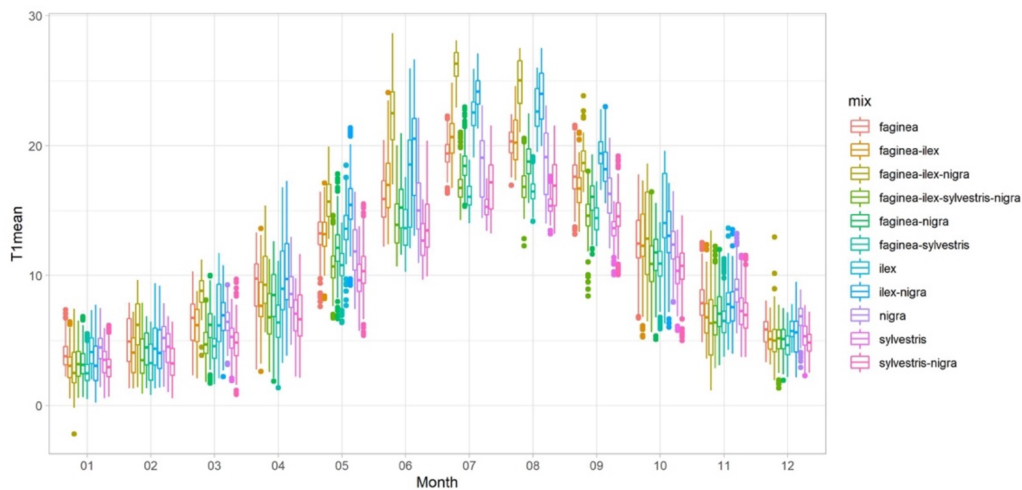


Figure 9 Mean soil temperatures T1 depending on the species mixtures

On the graph of daily soil temperature range (Fig. 10) it can be seen that broadleaved forest soils had the highest daily temperature range during almost entire observation period (with summer daily temperature range of 3 – 4,5 °C and winter 0,9 – 2,1 °C). On the other hand, the lowest temperature range was occurring in the coniferous soils through the whole period with exception of the last observed season of 2021 when the values were considerably higher compared to the previous years. Mixed stands, having an average values for the first two seasons, had the highest range in the third season and on the contrary the lowest temperature range during the last season.

In Figure 10 it can also be seen that the most species diverse stands were those with the lowest temperature range during summer seasons, with exception of summer 2020. During winter seasons, stands with 2 and 4 species showed to dispose with the highest temperature range whereas monoculture stands showed the lowest soil temperature range in all observed winter seasons.

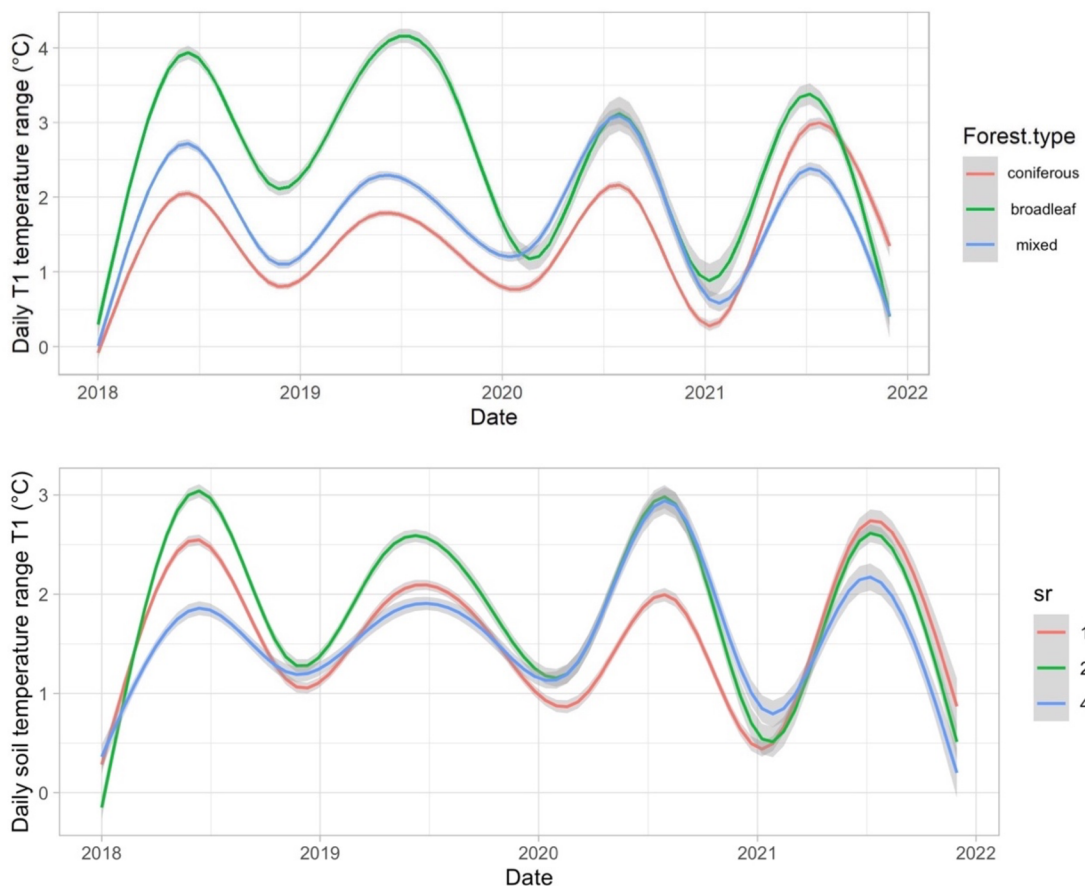


Figure 10 Daily soil temperatures T1 range depending on the forest type and species richness

5.2. Air temperature T3

In terms of air temperature depending on forest type, there is a relatively steady pattern – broadleaved stands show to be permanently the warmest type of forest, except of the winter 2019/2020 when the minimum temperatures of $-4\text{ }^{\circ}\text{C}$ were recorded there. In summer, local maximum temperatures commonly exceed $35\text{ }^{\circ}\text{C}$ (Fig. 12). During the summer months, coniferous stands appear to be the most thermally favourable ones; they also kept the lowest maximum temperatures of all forest types from the beginning of the measurement period until the spring 2021 when mixed stands, until that point permanently ranging between the broadleaved and coniferous stands temperatures, became the coolest.

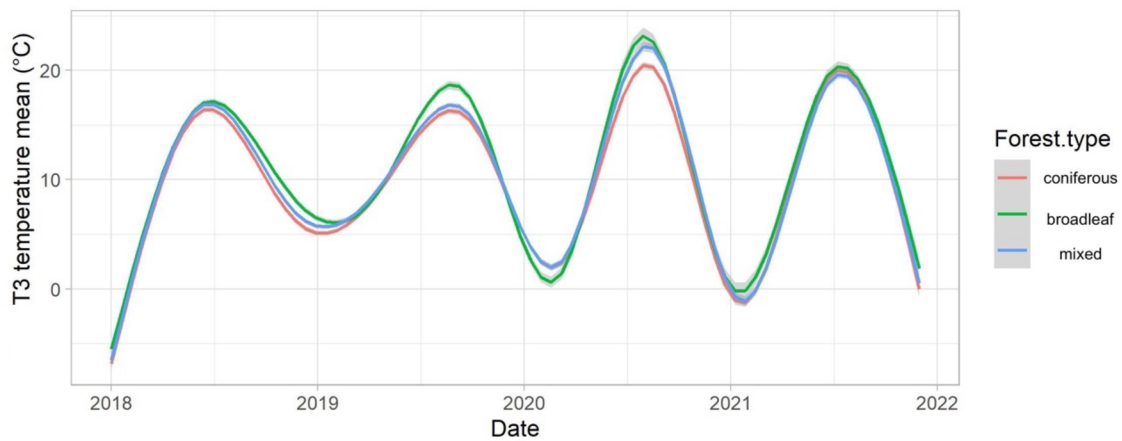


Figure 11 Mean air temperatures T3 depending on the forest type

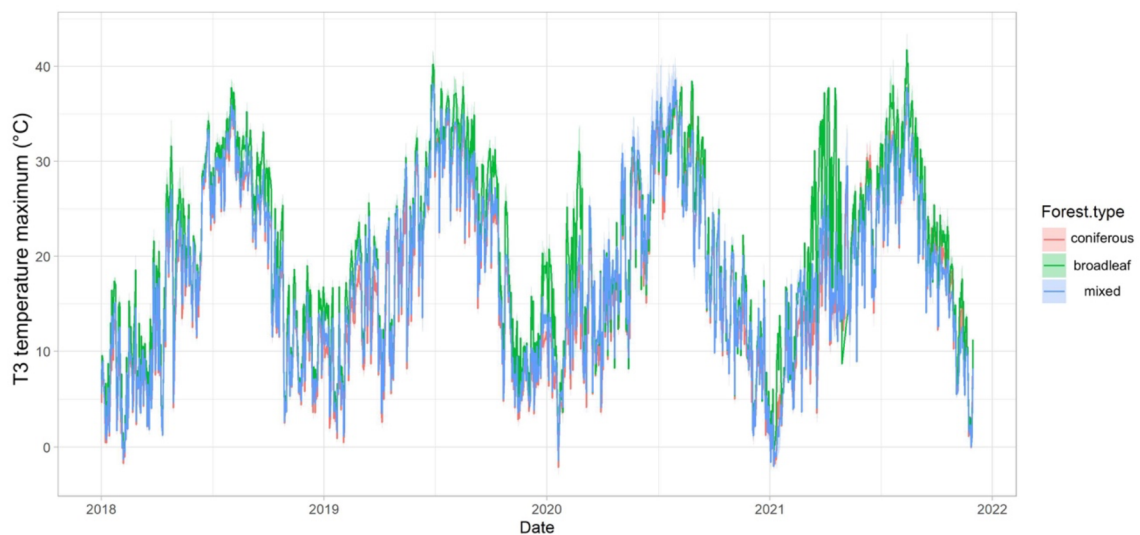


Figure 12 Maximum air temperatures T3 depending on the forest type

The following graph (Fig. 13) demonstrates that the differences in mean air temperatures between different species- richness levels are not very pronounced. However, summer months were found to be the warmest in monocultures and 2-species stands (reaching up to 40 °C, in monocultures even 42 °C in summer 2021), whereas the most species diverse stands (4-species) were thermally the mildest both in summers (when measured maxima were rarely exceeding 35 °C) and in winters when measured maxima were not as extreme as in species-poorer stands (Fig. 14).

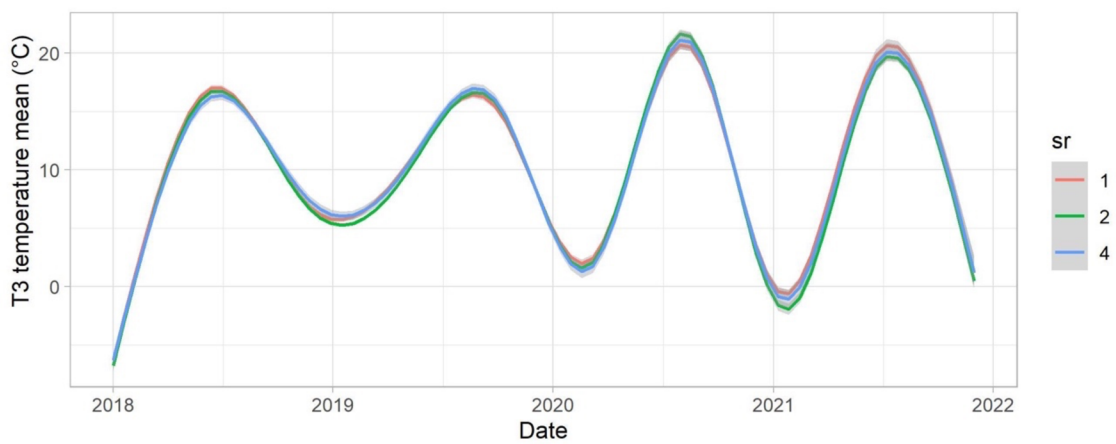


Figure 13 Mean air temperatures T3 depending on the species richness

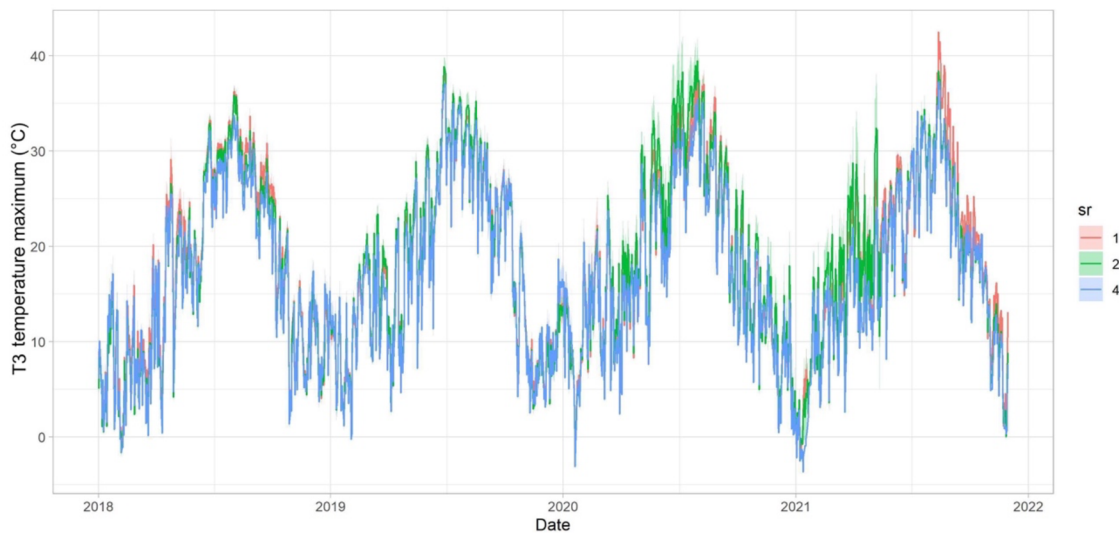


Figure 14 Maximum air temperatures T3 depending on the species richness

From the graph showing the comparison of the mean air temperature T3 in the individual years (Fig. 15) it can be noticed that 2020 was the warmest of the monitored years, and this was especially evident the late winter and spring (February, April, May), in the summer months and in November. Summer mean air temperatures were highest in July 2019 and 2020 (exceeding 20 °C) and in August were similar in all years with the mean of 20 °C. However, the it is visible that maximal temperatures in June 2019 outperformed other summer months. Winter months were also warm in the mentioned years, but in 2018 and 2021 the mean temperatures dropped below 0 °C.

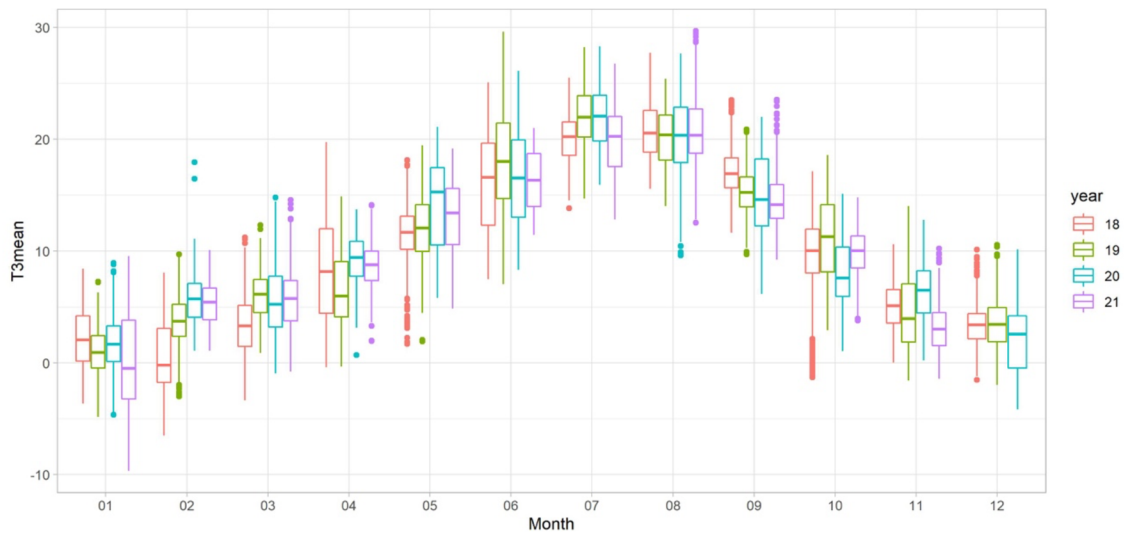


Figure 15 Mean air temperatures T3 in the individual years

The following graph (Fig. 16) shows how the mean air temperature varied in the individual months depending on the species mixtures. It can be seen that the summer months were similarly thermally favourable in the stands of *Quercus faginea* – *Pinus sylvestris* mixtures and also in monocultures of *P. sylvestris*. On the other hand, the highest mean temperatures were found in stands of *Quercus ilex* – *Pinus nigra*. High range of temperatures was measured in the broadleaved stands of *Q. faginea* – *Q. ilex*. In winter, the data showed the same results with exception of the highest temperatures that were measured in *Q. ilex* monocultures.

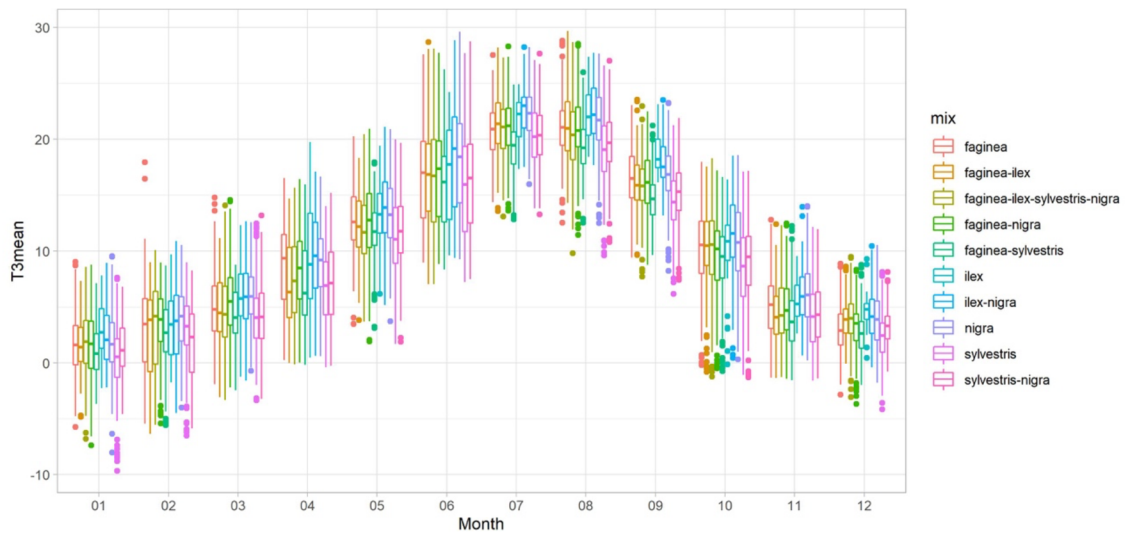


Figure 16 Mean air temperatures T3 depending on the species mixtures

The graph of daily air temperature range (Fig. 17) clearly demonstrates that the highest range occurred in the broadleaf stands – reaching values 17,5 – 20 °C during observed summer seasons and 12,5 – 14 °C in winters when the difference within other forest types is the most significant. The lowest daily temperature range in summer seasons vary over the years, however the lowest range in winter was always found in coniferous stands.

As for the daily T3 range, species diverse stands were found to be undeniably the most thermally stable compared to 2-species stands and monocultures; their daily temperature range was the lowest through the entire observation period ranging from 13 - 15,5 °C in summers and 7,5 – 11 °C in winters. Species-poor stands mutually showed similar values and during summer season alternated in having the highest values of daily T3 range.

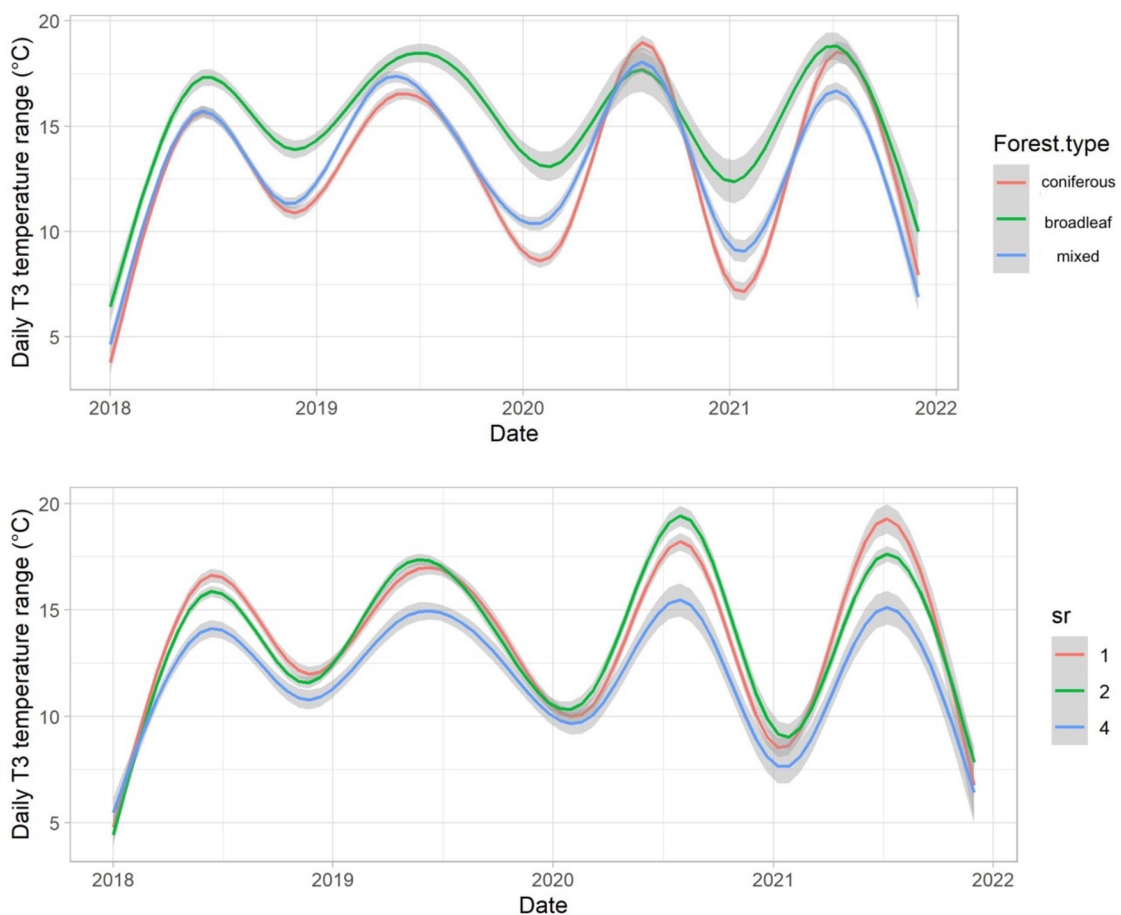


Figure 17 Daily air temperatures T3 range depending on the forest type and species richness

5.3. Soil moisture

The last measured value - the soil moisture showed, depending on individual forest types, quite variable results (Fig. 18). Broadleaved stands had the highest soil moisture in all observed winters/springs and it seems this trend might continue also after the measurement completion in December 2021. However, in the first two years in autumn they had the least moist soils of all forest types. On the contrary, in the following year 2020 with hot summer they disposed with the significantly highest soil moisture level of approximately 29 % (compared to 21 % in coniferous stands and 15 % in mixed stands). The mixed stands were predominantly drier than coniferous stands, but in summer 2021 they kept higher values than both coniferous and mixed stands (around 28 %). The spring 2019 was the driest from all observed ones with the moisture level not exceeding 35 % in any of the forest types.

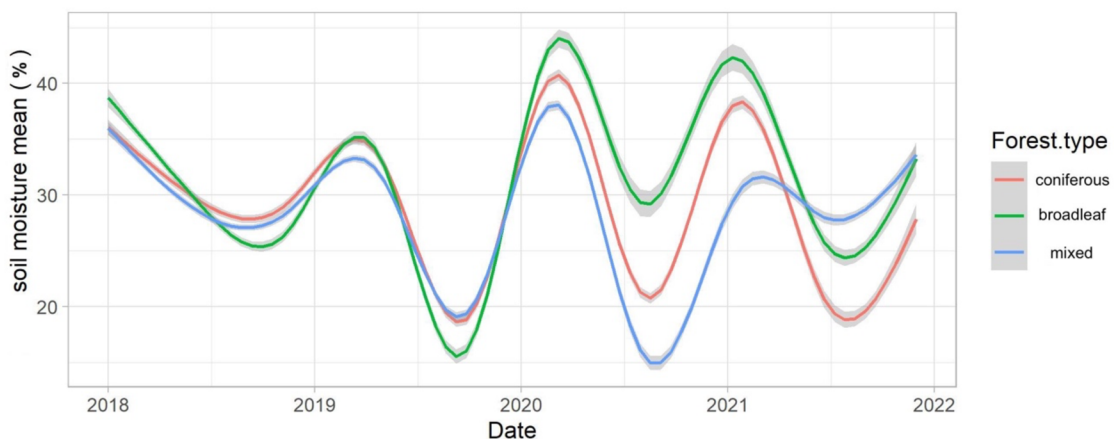


Figure 18 Mean soil moisture depending on the forest type

As seen on the following graph (Fig. 19), the soil moisture observed in different species-rich stands showed almost identical order during the whole observation period, i.e. monoculture stands kept having higher soil moisture level than species richer stands for most of the time, especially during the year 2020 when the summer/autumn difference was 7-8 % compared to the most diverse stands and approximately 12 % to stands with 2-species. Generally, the 2-species stands had lower soil moisture content, except of the

year 2018 when slightly exceeded monoculture stands. Only in summer 2020 their values dropped below the stands with 4-species, which constantly kept the lowest soil moisture values during all seasons.

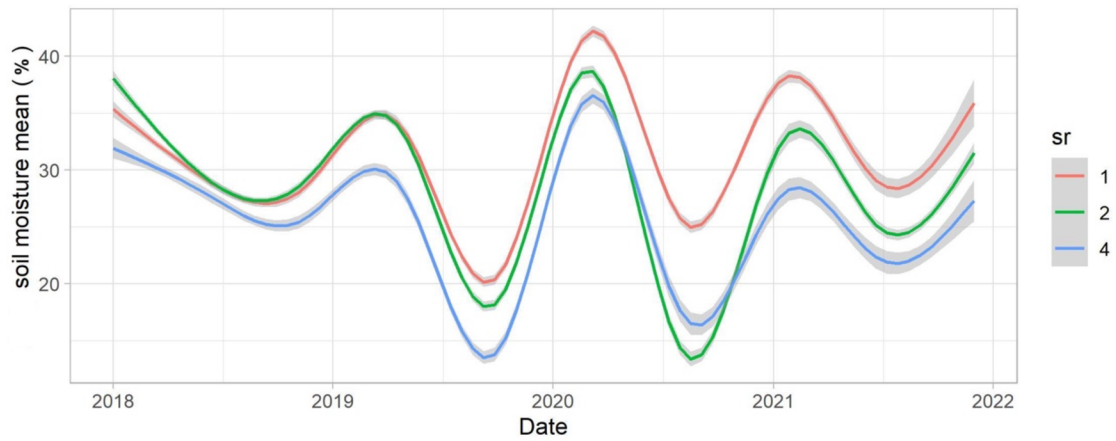


Figure 19 Mean soil moisture depending on the species richness

6. Discussion

6.1. Soil temperature T1

From the evaluated data it can be inferred that the greatest amplitude of soil temperatures is observed in broadleaved stands. In summer months, soil temperatures are warmest in these stands, both in mixtures with the black pine, i.e. *Quercus faginea* – *Quercus ilex* – *Pinus nigra* and *Q.ilex* – *P. nigra*), as well as in monoculture holm oak stands (*Quercus ilex*). The lowest mean soil temperatures in the summer months are recorded in single species coniferous stands of the Scots pine (*Pinus sylvestris*). These results correspond with the results of Porté et al. (2004) showing that soil temperatures were warmer in the mixed broadleaved-pine stands than in the pine plantations. An explanation in this case could be the higher LAI values of the coniferous species, which therefore do not transmit as much solar radiation as deciduous vegetation and thus the soil does not heat itself much. Von Arx *et al.* (2013) has shown that soil and air temperature in the forest understory varies depending on the amount of light penetrating through the vegetation.

However, during the winter season soil temperatures of the coniferous monoculture stands tend to be the highest, not following an inverse relationship with the soil moisture, that may be the result of the evergreen biomass acting as a temperature buffer.

Soils in the diverse forest stands (with 4-species included) are thermally favourable and stable throughout the year, being one of the coolest in the summer months and mild in winter.

6.2. Air temperature T3

The analysis of the measured data revealed that broadleaved stands have higher air temperatures than mixed or coniferous stands. Coniferous stands are the most thermally favourable in the summer months that is probably the result of their higher LAI values allowing them transmitting smaller amount of solar radiation (von Arx *et al.*, 2013). Additionally, no summer temperature peaks have been recorded there.

The resulting data did not show a significant effect of the species richness in the stand on the air temperature, since the values and overall trends have shown to be almost identical. However, the evaluation of the species mixtures revealed that the harsh summer temperatures were the lowest in the monocultures of *Pinus sylvestris*, in 2-species mixture of *Q.faginea* and *P.sylvestris* and diverse stands of all four observed species.

As in the case of soil temperatures, air temperatures in pine monocultures (especially *P.sylvestris*) are lower than in the mixed forest stand, which correlates with the results of Porté *et al.* (2004).

Similarly, it can be observed that monoculture broadleaved stands are consistently warmer than monoculture coniferous stands.

6.3. Soil moisture

From the soil moisture data obtained, it is clear that in the research area, species-poor stands are more moisture favourable than species-rich stands, which corresponds with the results of e.g. Jucker *et al.* (2014a), Grossiord *et al.* (2015) or De Cáceres *et al.*, (2021). A likely explanation is that in the diverse forest stands, competition for water occurs to a large extent whereas in monocultures the competition is not so significant.

Jucker *et al.* (2014a) points out the fact that mixed forests in Alto Tajo produce more aboveground woody biomass and thus sequester more carbon, however the increased competition for water in these stands threatens this potential.

From the point of view of soil moisture depending on the forest type, deciduous stands were found to keep high soil moisture content for most of the observation period, however they also show the biggest fluctuation in values. That could be explained by their inability to prevent large evaporation from the soil surface due to lower LAI (Aussenac, 2000). *Pinus* species are more water demanding and thus they may occur on naturally more humid sites than *Quercus* species. Since moisture is an essential but limited resource and its availability is expected to be more scarce in the future, it can be assumed that pine trees will lag behind in the competition for water, which will probably have a fatal impact on their distribution (Galiano *et al.*, 2010; Poorter *et al.*, 2012).

In diverse forest stands, i.e. stands with 4 species, the soil moisture is almost constantly the lowest; this might be due to high transpiration and thus self-cooling of these stands.

Comparison of soil moisture of individual stand mixtures would have been ideal for completeness of the results, however erroneous measurements have occurred and the resulting data were not representative enough and thus excluded from the evaluation.

7. Conclusions

Forest microclimate is essential for their overall biodiversity and maintaining the ecosystem functionality. This research, conducted within the FunDivEUROPE project, aimed at closer understanding of the influence of tree species diversity in Mediterranean forests of the Alto Tajo Natural Park, Spain.

Observed temperatures, both of soil and air, in the forests in Alto Tajo were found to be the mildest in the coniferous stands. On the other hand, pure broadleaved stands showed a high level of fluctuation of temperatures and were frequently reaching extreme air and soil temperatures in the summer seasons.

Mixed stands and stands high in tree species diversity, i.e. 4 species per stand, have shown to be thermally favourable, however they appeared to have the driest soils. Soils in the monoculture stands have shown to constantly keep the highest level of soil moisture, as a possible result of lower competition. Therefore, the economically important *Pinus* species whose decreasing recruitment had been recorded, may grow more suitably in monocultures rather than mixed species-rich stands. Mixture of *Pinus sylvestris* with *Quercus faginea* might be suitable as well, since this mixture kept low temperatures in a long term, however their water sharing capacity would require further observations.

Nevertheless, in view of the expected change in climate in the Mediterranean region, forests with high species diversity should deal well with the associated temperature extremes, regardless of other innumerable benefits that species-rich forests bring.

It is important to state that, the erroneous measures that have occurred have not allowed fully coherent results. The undeniable advantage of this type of research and the used technology is its possible longevity and further long-term observations, with potential to focus on the local soil conditions and precipitation. This should be conducted to further deepen our knowledge on this small fragment of the complex forest ecosystems. Understanding the microclimate changes in relation to the compositional variability of forests is essential for developing sustainable forest management strategies that are today, in the face of challenges imposed by global change, more important than ever before.

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- Appendix 1 *Pinus sylvestris* monoculture stand
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Appendix:



Appendix 1 *Pinus sylvestris* monoculture stand (source: doc. Ing. Radim Matula, Ph.D.)



Appendix 2 *Pinus nigra* monoculture stand (source: doc. Ing. Radim Matula, Ph.D.)



Appendix 3 Mixed species stand (source: doc. Ing. Radim Matula, Ph.D.)



Appendix 4 Mixed species stand (source: doc. Ing. Radim Matula, Ph.D.)



Appendix 5 Data collection (source: doc. Ing. Radim Matula, Ph.D.)