Czech University of Life Sciences Prague

Faculty of Forestry and Wood Sciences

Department of Silviculture

"VULNERABILITY ASSESSMENT OF EUROPEAN FORESTS TO CLIMATE CHANGES BY A MULTITEMPORAL AND MULTISCALE APPROACH"

"Stanovení citlivosti evropských lesů na klimatickou změnu v čase a na různé úrovni posouzení"

Ph.D. Thesis

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Ph.D. THESIS ASSIGNMENT

Dr. Giuseppe D’Andrea, MSc.

Forestry Engineering
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Thesis title

Vulnerability assessment of European forests to climate changes by multitemporal and multiscale approach

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Objectives of thesis

- Evaluate dynamics of radial growth for Norway spruce (endangered by drought) in the Czech Republic).
- Evaluate dynamics of radial growth for European beech in the Central Europe (Czech Republic) and Southern Europe (southern Italy).
- Investigate and evaluate the effect of temperature and precipitation on radial growth of the studied tree species.
- Evaluate the relationship between NDVI (Normalized Difference Vegetation Index) and tree-ring widths for studied tree species.

Methodology

The growth development for Norway spruce and European beech will be assessed through dendrochronological analyses, examining their relationship with meteorological factors (temperature, precipitation) and NDVI. The statistical characteristics of the research plots will be determined based on the measured dendrochronological analyses (Fritts, 1976; Bunn, 2008; Speer, 2010).

Basic dendrometrical and descriptive characteristics necessary for the evaluation of the locality will be collected on the investigated research plots, where the main data will be the average height, average diameter in the breast height, and volume.

Climate data for all study sites will be obtained from the nearest meteorological stations.

To obtain NDVI MODIS (MOD13Q1 collection 6 product) time series collections (from 2000 to 2018 in the spruce study and from 2000 to 2017 in the beech study) to discuss the possible imbalance in NDVI models across different sites, will be used Climate Engine, an open source tool (Huntington et al., 2017). The NDVI data will be adjusted from atmospherically corrected bi-directional surface reflectance masked for disrupting factors such as water, clouds, heavy aerosols, and cloud shadows.

The obtained NDVI, temperature, and precipitation values will be used for comparison with annual tree-ring growth. The results will be compiled to describe the growth of spruce and beech trees in relation to climate change. In assessing NDVI, the main objective is to determine whether it can be considered an explanatory factor for the tree-ring growth of trees and health status indicator.

The proposed extent of the thesis

min. 70 p. text

Keywords

Global climate change (GCC), NDVI, air temperature, precipitation, forest health, Norway spruce, European beech, dendrochronology

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I hereby confirm that this Ph.D. research thesis “Vulnerability assessment of European forests to climate changes by a multitemporal and multiscale approach” was conducted and elaborated independently with the keen interest and consultation of my supervisor. The quoted literature review was used in this study to produced quality research in the field of silviculture based on actual data with a future recommendation.

I agree with publishing this Ph.D. research thesis according to Czech law n. 111/1998 Sb. about the universities in its current valid wording. This agreement is independent of the result of the defense.

January 2024, Prague

Signature of the author:

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ABSTRACT

The recent phenomenon of forest dieback has occurred in many forest types (biomes). Among these are the Mediterranean zone and Central European region in the zone of deciduous broadleaved forests which have different climate types. The focus of this thesis was to compare the global climate change (GCC) impact of forest stands/ecosystems using the specific approach—the evaluation of Normalized Difference Vegetation Index (NDVI) and dendrochronological reactions of selected stands on temperature and precipitation dynamics. For this purpose, we focused on the most important coniferous and deciduous tree species, i.e., Norway spruce and European beech. For the research, we selected: six Norway spruce plots in the Czech Republic, one European beech plot in Poland, two beech plots in the Czech Republic, and three beech plots in Italy, reflecting the areal range of this species. The spruce plots were chosen in three regions of the central part of the Czech Republic: Karlštejn (1–2), Cukrák (3–4), and Kostelec (5–6) with an altitude ranging between 319 and 422 m a.s.l., representing the hilly flat area. For beech, three sites in Central Europe (Chojnik 1, Rýchory 2, Rýchory 27) with an altitude between 510 and 1030 m a.s.l. and three sites in Southern Europe (Sellata 3, La Lama 4, Monte Volturino 5) were selected having an altitude between 1275 and 1740 m a.s.l.

We used an open-source tool, Climate Engine, to obtain NDVI MODIS (MOD13Q1 collection 6 product) time-series collections from 2000 to 2018 in the spruce study and from 2000 to 2017 in the beech study to discuss the possible imbalance in NDVI patterns between several sites.

For dendrochronological analysis, the core samples from 180 spruce and 180 beech individuals were provided by Pressler borer, i.e., 30 samples per research plot. Tree-ring samples were collected at breast height (1.3 m), perpendicular to the slope, following the standard dendrochronological procedures. The cross-dating procedure was performed by

Cdendro software (Cybis Electronik & Data), while tree-ring widths were measured by LINTAB (Rinntech) with an Olympus binocular magnifier, from bark to the pith (on a scale of 0.01 mm) and sets of tree-ring data were processed with TSAP-Win software.

From this study, it was revealed that the Norway spruce despite the low altitudes, if grows on soils with a good water availability, reports good growth rate; while European beech had major radial growth at low altitude in both Central and Southern Europe; moreover, the latter sites showed greater radial growth than the sites in Central Europe. The limiting factor in these forest sites is precipitation, which is positively correlated with the radial growth of trees, while air temperatures are negatively correlated with radial growth. As far as NDVI is concerned, drier beech locations at low altitudes (Italian forests) have NDVI (max seasonal) values more correlated with RWI.

However, further studies are needed to verify whether the NDVI index can be considered reliable only in deciduous forests or also in evergreen coniferous forests.

Keywords: Global climate change (GCC), NDVI, air temperature, precipitation, forest health, Norway spruce, European beech, dendrochronology

ANOTACE

Současný fenomén odumírání lesů se projevuje v mnoha lesních typech (biomech). Patří mezi ně rovněž oblast Středomoří a středoevropský region v zóně listnatých opadavých lesů různých klimatických typů. Těžištěm této práce bylo porovnat vliv globální změny klimatu (GCC) lesních porostů/ekosystémů pomocí specifického přístupu – hodnocení Normalized Difference Vegetation Index (NDVI) a dendrochronologických reakcí vybraných porostů na dynamiku teplot a srážek. Za tímto účelem byl výzkum zaměřen na nejvýznamnější jehličnaté a listnaté dřeviny, tedy smrk ztepilý a buk lesní. Pro výzkum bylo vybráno šest ploch smrku ztepilého v ČR a jedna buku lesního v Polsku, dvě bukové plochy v ČR a tři bukové plochy v Itálii, odrážející plošné rozšíření tohoto druhu. Smrkové plochy byly vybrány ve třech regionech střední části České republiky: Karlštejn (1–2), Cukrák (3–4) a Kostelec (5–6) s nadmořskou výškou 319 až 422 m n. m., tj. nižší oblast. U buku jsou tři lokality ve střední Evropě (Chojnik 1, Rýchory 2, Rýchory 27) s nadmořskou výškou mezi 510 a 1030 m n.m. a tři lokality v jižní Evropě (Sellata 3, La Lama 4, Monte Volturino 5) byly vybrány s nadmořskou výškou mezi 1275 a 1740 m n. m.

Byl využit nástroj s otevřeným zdrojovým kódem, Climate Engine, aby byla získána kolekce časových řad NDVI MODIS (produkt MOD13Q1 kolekce 6) od roku 2000 do roku 2018 ve studii týkající se smrku a od roku 2000 do roku 2017 ve studii s tématikou buku, abychom diskutovali o možné nerovnováze ve vzorcích NDVI mezi několika místy.

Pro dendrochronologický rozbor byly pomocí Presslerových nebozezů získány jádrové vzorky ze 180 kusů smrku a 180 jedinců buku, tj. 30 vzorků na výzkumnou plochu. Vzorky letokruhů byly odebrány ve výčetní výšce (1,3 m), kolmo ke svahu, podle standardních dendrochronologických postupů. Postup křížového datování byl proveden softwarem Cdendro (Cybis Electronik & Data), zatímco šířky letokruhů byly měřeny pomocí LINTAB (Rinntech) s binokulární lupou Olympus, od kůry po dřeň (na stupnici 0,01 mm) a sady dat stromového souboru byly zpracovány pomocí softwaru TSAP-Win.

Z této studie vyplynulo, že smrk ztepilý i přes nízké nadmořské výšky, pokud roste na půdách s dobrou dostupností vody, vykazuje dobrou rychlost růstu; zatímco buk měl velký radiální růst v nízké nadmořské výšce ve střední i jižní Evropě; posledně jmenované lokality navíc vykazovaly větší radiální růst než lokality ve střední Evropě. Limitujícím faktorem v těchto lesních lokalitách jsou srážky, které pozitivně korelují s radiálním růstem stromů, zatímco teploty vzduchu s radiálním růstem korelují negativně. Pokud jde o NDVI, sušší bukové polohy v nízkých nadmořských výškách (italské lesy) mají hodnoty NDVI (max sezónní) více korelované s RWI.

K ověření, zda lze index NDVI považovat za spolehlivý pouze v listnatých lesích nebo také ve stálezelených jehličnatých lesích, jsou však zapotřebí další studie.

Klíčová slova: Globální klimatické změny (GCC), NDVI, teplota vzduchu, srážky, zdravotní stav lesa, smrk ztepilý, buk lesní, dendrochronologie

LIST OF ABBREVIATIONS

AVHRR: Advanced Very High Resolution Radiometer

CHMU: Czech Hydrometeorological Institute

DBH: Diameter at breast height

ENVISAT: Environmental Satellite

EOS: Earth Observing System

EPS: Expressed population signal

ERS: European Remote-Sensing satellite

ESA: European Space Agency

ESSA: Environmental Survey Satellite Administration

EVI: Enhanced vegetation index

FAPAR: Fraction of Absorbed Photosynthetically Active Radiation

GCC: Global climate change

GIMMS: Global Inventory Modeling and Mapping Studies

GOES: Geostationary Operational Environmental Satellite

GOME: Global Ozone Monitoring Experiment

GPP: Gross primary production

LANDSAT: Land-Use Satellite

LiDAR: Laser Imaging Detection and Ranging

LSTD: Daytime temperature surface

LSTN: Nighttime temperature surface

METEOR: Meteorological Satellite

MIR: Mid-infrared

MODIS: Moderate Resolution Imaging Spectroradiometer

NASA: National Aeronautics and Space Administration

NASDA: National Space Development Agency

NDVI: Normalized Difference Vegetation Index

NIMBUS: Satellite Series to Meet the Needs of Atmospheric and Earth Scientists

NIR: Near-infrared

NNR: National Nature Reserve

NOAA: National Oceanic and Atmospheric Administration

NSC: Non-structural carbohydrates

PLA: Protected Landscape Area

RW: Tree-ring width

RWI: Tree-Ring Width Index

SAR: Synthetic Aperture Radar

SMS: Satellite Management System

SNR: Signal-to-noise ratio

SPOT: Satellite Pour l'Observation de la Terre

SWIR: Short-wave infrared

TIR: Thermal infrared

TIROS: Television Infrared Observation Satellite

TRWIS: Shaft Ring Width Indices

USGS: United States Geological Survey

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MAPS AND FIGURES

1. Introduction

Forests cover 31% of the Earth's land area (FAO, 2020), thus contributing significantly to sequestering large quantities of carbon by terrestrial ecosystems (forests fix 29% of annual CO_2 emission (Friedlingstein et al. 2019). Furthermore, forests provide habitats for over 80% of terrestrial species of animals, insects, and plants (FAO and UNEP 2020), thus containing the majority of the biodiversity in terrestrial ecosystems, further performing a critical role in climate formation and provide economic and social environmental benefits.

In recent decades, due to GCC, some of these features could be endangered: increasingly scarce precipitation and higher temperatures are leading to increasingly frequent and intense periods of drought (Anderegg et al. 2020), with consequent impacts on the entire structure and functioning of forest ecosystems (McDowell et al. 2020).

Forest species and their dependent communities can be affected by climate stressors; it is a dynamic that can take place in the short-term range, influencing, for example, the growth and reproductive cycle of trees (Babst et al. 2019), or in the long-term, by inducing changes in their distribution range (Batllori et al. 2020). Therefore, as a response to the increase in frequency and intensity of such phenomena, the resilience of many ecosystems will probably be exceeded (Field et al., 2014; IPCC, 2014), while some forest populations are more adapted to tolerate both drought periods and irregular precipitation regimes (Gazol et al. 2018b).

Central Europe boasts a unique natural heritage (CENTRAL EUROPE 2014). Recently, European forests have been affected by a multitude of factors, the most important being the increase in temperature, prolonged periods of drought, wildfires, bark beetle infestations, and several other pest and disease outbreaks related to GCC, which occur more frequently than in the past (Seidl et al. 2017) and are considered the main factors for decline and mortality due to damage of plant hydraulics, and reductions in carbon uptake (Gaylord et al. 2013; Hartmann et al. 2015).

Evaluation of the health and vitality state of forest ecosystems by monitoring their decline and mortality aspects is essential for developing and implementing climate-oriented measures for mitigation of impacts, as well as recovery and adaptation strategies. The vegetative state and conditions of the forests can be assessed both from ground-based surveys and remote sensing techniques, using images captured by drones, planes, and satellites. Many authors have demonstrated the effectiveness of satellite imagery used to study vegetation vigor and phenology of vegetation (Goward et al. 1985; Tucker et al. 1985; Peters et al. 2002) and satellite images are defined by ecologists as a potential “gold mine” (Kerr and Ostrovsky 2003; Turner et al. 2003).

Annual tree-ring analyses provide us with crucial information on the amount of wood that forms the stem, which can be directly related to biomass gain and carbon uptake (Van Breugel et al. 2011; Babst et al. 2014). For example, as reported by Xu et al. (2017), TRWIS (Shaft Ring Width Indices) are widely used as long-term determinants of past forest productivity, as well as gross primary production (GPP). The growth of trees is highly influenced by climatic factors, and many studies have examined tree growth response not only to climate models but also to directly measured values (e.g., Steckel et al., 2020) to climate models and their interannual variability in several forest species (Babst et al., 2012; Gao et al., 2018).

The main advantage of the growth data is the use of high temporal resolution, providing us with accurate dating and long-term series potential. Due to their limited spatial resolution (tree level), the principal disadvantage is that these data can only provide us insight into forest response to the climate on a local scale. In addition, although reliable estimates regarding tree growth and productivity can be easily obtained, tree rings require intense effort concerning the collection of wood samples, as well as laboratory work which is needed to cross and date-measure woody material.

All of these previously mentioned problems limit the potential use of this approach regarding real-time monitoring of forest growth and health condition in a large geographic area. On the contrary, satellite data generally are available and may allow us “near-real-time” evaluations about changes of forest health on a large scale (McDowell et al. 2015).

This study project and dissertation is primarily focused on low-altitude forests located in the colline belt, which, due to GCC, should be under morestress than those located in other vegetation altitudinal zones.

1.1. Aims of the research

The dissertation project is focused on the study of the economically and ecologically most important coniferous and deciduous tree species of the Czech Republic, the Norway spruce (*Picea abies* [L.] Karst.) and the European beech (*Fagus sylvatica* L.) which respectively constitute 48.1% and 9.3% (Ministerstvo zemědělství 2021) of the entire forest area of the Czech Republic (34.1% of forest cover, 2.67 million ha, **Figure 1** Ministerstvo zemědělství, 2021); under the current GCC scenario.

In particular, the thesis project aims to study:

(1) Dynamics of radial growth of Norway spruce in the Central European (Czech Republic) colline belt (strongly endangered by drought) and European beech in Central Europe (Czech Republic) and Southern Europe (southern Italy) in different vegetation altitudinal zones;

(2) Effect of climate factors (temperature and precipitation) on radial growth of the species covered by our research;

(3) Relationship between NDVI (Normalized Difference Vegetation Index) and tree-ring widths.

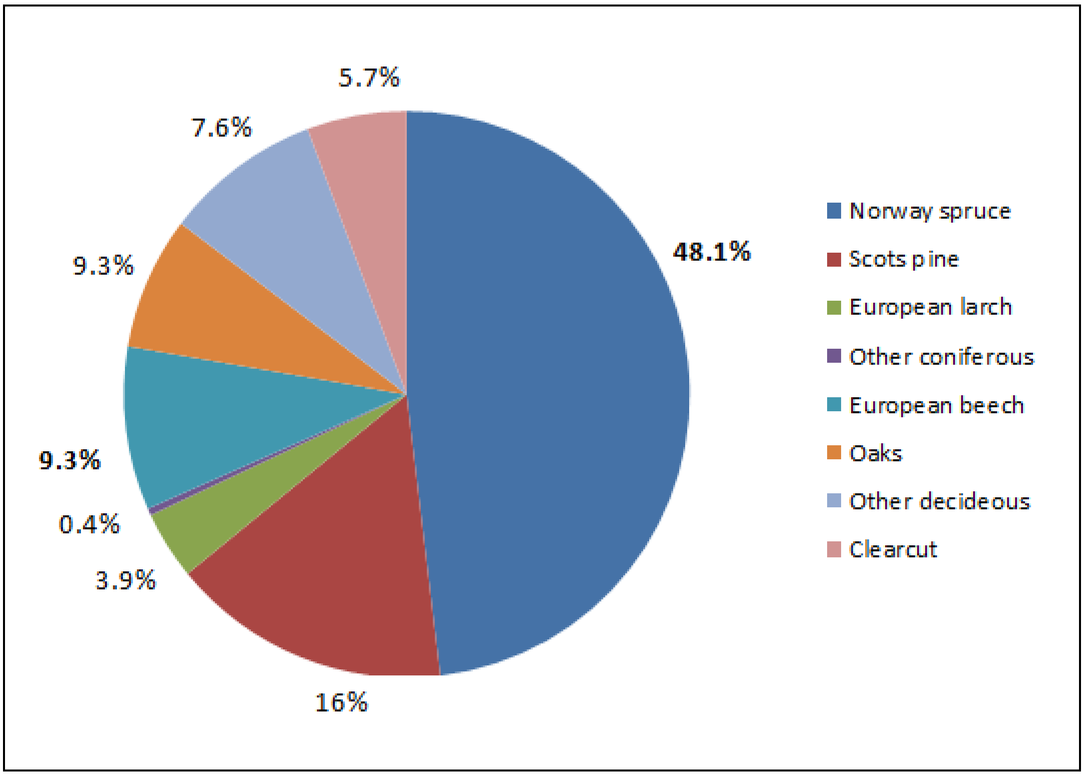

Figure 1. Current status (2021) of tree species composition in the Czech Republic (data from Ministerstvo zemědělství, 2021).

1.2. Hypotheses of the research

In this thesis, we hypothesized:

(1) Radial growth dynamics of spruce at the driest sites will show the lowest radial growth rates compared to the less arid sites, while as far as beech growth is concerned, the sites located at the lowest altitudes will report the lowest radial growth values compared to those at higher altitudes both in Southern Europe and in Central Europe; furthermore, we hypothesized that plots in Central Europe will show the higher radial growth values, being less arid than those in Southern Europe.

(2) Regarding the effects of temperatures and precipitation, we expect that temperatures negatively influence radial growth, while the precipitation positively.

(3) Regarding the relationship between NDVI and radial growth, we assume that the NDVI values will be more correlated with the radial growth values of the hardwood under study, i.e., beech.

2. REVIEW OF LITERATURE

2.1. Forest dieback and mortality

Forest mortality is a process that occurs naturally within the dynamics of forest populations (Franklin et al. 1987), but in recent years, due to GCC, mortality rates have increased (Allen et al. 2010; McDowell et al. 2018), and predictions report a further increase in future scenarios (Steinkamp and Hickler 2015). Many studies have highlighted an increased vulnerability of forests to climate change (Anderegg et al., 2012; Choat et al., 2012; Williams et al., 2013; Hartmann et al., 2018), which is becoming an emerging global phenomenon (Allen et al. 2015). In fact, several cases of forest mortality have been documented around the world, both at regional and local scales (Hartmann et al. 2018; Anderegg et al. 2020; Senf et al. 2020), leading to significant consequences for the functioning of these key ecosystems (Anderegg et al. 2013).

Recently, several local surveys across Europe reported an increase in the mortality rate of trees in response to drought (Peñuelas et al., 2001; Buras et al., 2018, among others). In this regard, Caudullo and Barredo (2019) reported 293 serious forest mortality events in Europe from 1970–2019.

A particular variability of the symptoms has been observed: most commonly in the wilting of the foliage, drying of branches, delayed spring bud burst, emission of epicormic branches along the stem, and longitudinal cracks of the bark. At the root level, some of the most common symptoms are the reduction of biomass, necrotic lesions, and necroses of absorbing roots.

GCC-caused forest decline is a phenomenon that principally affects drought-prone areas such as the Mediterranean region. Recently, since the 2000s, episodes of decline and mortality have also affected native species relatively resistant to drought, such as the oaks in southern Italy (Colangelo et al. 2018), and due to drought, many species of higher elevations than oaks, e.g., beech. They are more vulnerable, often stressed due to more frequent droughts, and will suffer a reduction in growth over time (Piovesan et al. 2008).

Episodes of forest decline and vulnerability have recently been reported in Central Europe, where an increase of temperature and drought stress events related to GCC are occurring more frequently than in the past, considered the main driving factors of forest tree decline. For example, growth decrease and mortality of oak floodplain forests as a response to changes in the water regime and climate have been reported in Serbia (Stojanović et al. 2015). In addition, recent results suggest that spruce will undergo significant radial growth reduction under the predicted GCC in the Czech Republic (Altman et al. 2017).

The emergence and diffusion of the aforementioned phenomena appear alarming, and such episodes could potentially alter the shape and dynamics of forest ecosystems very quickly with important feedback on the Earth’s system. As a rule, solar irradiation in combination with connected high temperatures can heavily damage the photosynthetic apparatus (Powles 1984; Correia et al. 1990). The negative consequences of prolonged heat/drought events range from the loss of carbohydrate reserves to hydraulic failure, as well as the increased risk of pest/pathogen attacks (particularly bark beetles), which contribute to reducing productivity and increasing forest mortality (Allen et al. 2015; Anderegg et al. 2015).

2.2. GCC impact on Norway spruce

Norway spruce (*Picea abies* [L.] Karst.) is an essential component of various European natural forest ecosystems and represents the most important commercial timber species. It is also found at lower elevations outside of its natural range, where it is subjected to intense drought and heat due to global warming (Jansson et al. 2013; Střelcová et al. 2013)**.**

Several studies (Menzel et al. 2006; Bertin 2008) demonstrated the impact of GCC on plant phenology near the end of the twentieth century, as shown by rapid temperature and precipitation variations. GCC affects ecological changes in ecosystems in numerous European regions, including species interactions, community structures, and biodiversity protection (Kirschbaum 2000).

The decrease is analogous to a complex disease produced by a synergistic interplay of abiotic, biotic, and anthropogenic factors. Yellowing, defoliation, decrease in radial increment, and death of individual trees and groups at varying ages, in some cases with final biotic mortality factors present (*Armillaria* spp., *Ips typographus*, *Ips duplicatus*, *Pityogenes chalcographus*, etc.), in others, no recognized identifiable mortality factors (*Armillaria* spp., *Ips typographus*, *Ips duplicatus, pityogenes* (Rybníček et al. 2010).

Stressed spruces, like other conifers, shedold needles to save resources. It is a natural process that helps the tree cope with the stress. Even trees whose physiology does not work adequately due to pathogens or the weakness of the roots exhibit this reaction.

On the other hand, the process is continually verified from the natural aging of the needles (loss of the needles' physiological activity), during which even the oldest needles turn brown and are expelled. In moments of increased stress (weather conditions, root weakness) this process occurs more quickly. When multiple needles are tapped simultaneously, the symptoms become more visible (Dubach et al. 2023). The result can be a sparse canopy (defoliation), and in addition to the damage from an ecological point of view, there is also damage to the landscape function.

Summer heatwaves and abnormally hot temperatures are commonly related to GCC, exacerbating all types of extreme weather, including frost events after the spring warmth has begun (Zohner et al. 2020).

Depending on the time of year, the metabolism of the spruce adapts to the surrounding climate, allowing the tree to survive critical temperatures ranging between -5 and -37 °C. Particularly vulnerable are the freshly sprouted small leaves/needles and assimilatory organs which can be easily damaged by late frosts in spring. Even the early frosts that occur in autumn can cause damage to the shoots of plants that are not yet or insufficiently lignified due to spruce's sensitivity to frost (Zurigo, 1993). A few hot days following during the winter season can be sufficient to trigger a progressive lowering of the plants' defense capacity, thus exposing them to damage caused by sudden frosts. The hardening process of plant tissues is very complex from a biochemical point of view and is characterized by an increase in the sugar content of the cells, which lowers their freezing point, a phenomenon combined with a transformation that takes place at the level of the cell membrane which is in a better condition to resist lower temperatures and tension deficits of water absorption they cause.

The symptoms of visible frost damage, such as redness and browning of the needles, are visibly obvious. In the case of minor damage, only the younger tissues more exposed to cold temperatures are affected. In the event of more intense frosts, redness or browning can affect entire twigs (or the needles) from previous years, or even the entire foliage (Engesser et al. 2002).

2.3. GCC impact on European beech

The recent rise in temperatures due to the GCC has had a negative effect on beech growth, which in some cases has decreased due to the increased susceptibility of beech to higher temperatures and drier conditions (Bosela et al. 2018). Prolonged periods of intense aridity and waterlogging conditions affect beech radial growth and its competitiveness (Geßler et al. 2007).

In fact, beech is considered vulnerable to drought (Walthert et al. 2021), even more than late frosts, influencing the radial growth of the beech and its diffusion in Europe. Several studies have found that beech trees, especially at low altitudes, suffer considerably from drought. It follows that the distribution of the beech is closely correlated to drought/aridity, as the need for a humid summer does not allow its development, such as in southern Spain, Greece, and the driest areas of central and southern Italy (Magri 2008). It can be argued that water stress and, therefore, water availability limits the distribution of beech in the southernmost part of its distribution limit (Hacket-Pain and Friend 2017). Drought is linked to a wide range of climatic conditions, such as the increase in mean and maximum air temperatures, which affect the evapotranspiration rate, the reduction of precipitation, a greater amount of solar radiation, and high vapor pressure (Camarero et al. 2018). As with late frosts, summer drought and, therefore, the temperatures and rainfall of the summer months also have different influences depending on the altitude in which the species develops. The main effect of drought on beech is the reduction of plant radial growth, but it can also have other consequences. The damage caused by drought affects all organs and is directly proportional to the duration of the phenomenon. Some symptoms that demonstrate the presence of a drought are the yellowing of the foliage, the progressive decrease in the coverage of the foliage due to anticipated *phyllotopsis*, and the *microphyllia*, which, if the phenomenon persists for a long time, can lead to desiccation of the distal parts of the branches of the plant. Other damages can be the detachment of strips of bark, which can also occur due to the effects of sunburn induced by the canopy reduction (Ebone et al. 2012).

2.4. Czech temperate forests

The Czech Republic, located in Central Europe, occupies an area of 78,867 km^2 and has an altitudinal range between 115–1602 m a.s.l. (**Figure 2**). The major geological features in the country are the Bohemian Massif (in the western and central part) and Western Carpathians (in the eastern part) (Chytrý 2012).

The Czech forests cover an area of 34.1% (2.67 million ha) (Šimůnek et al. 2020), and from an ecological point of view, the forests are positioned in the temperate zone with coniferous and broadleaved species (**Figure 3**).

Deciduous broadleaved forests constitute a biome extending from lowlands up to 1000–1200 m a.s.l. and are absent in the arid and hot lowlands. The dominant zonal types of natural vegetation are *Fagus sylvatica* forests with an admixture of *Abies alba* in the middle and higher altitudes, while at low altitudes, *Carpinus betulus* grows. Other broadleaved trees like *Acer platanoides, A. pseudoplatanus, Alnus glutinosa, A. incana, Fraxinus excelsior*, *Quercus petraea, Q. robur, Tilia cordata, T. platyphyllos, Ulmus glabra,* and *U. laevis* are mainly present in sites where the tree species composition has changed due to the past forestmanagement or natural disturbances, as well as at sites with specific character (Viewegh et al. 2003; Chytrý 2012).

With regard to the coniferous forest, Norway spruce forms forests in the high mountains, although Norway spruce forms forests outside its natural range too, which is made possible by the peculiarity of habitats, e.g., inversion of vegetation zones in deep valleys (e.g., the Sázava river valley) (Huth et al. 2017).

The trees belonging to this zone-biome can reach a height of 30–40 m, and in the zone of the mixed forest, and in favorable conditions, they can even reach taller heights. A prime example is the tallest known spruce in the Boubín old-growth forest, which measures 59.5 m. A similar height was also achieved by spruce and fir trees in Šumava and Beskydy Mts. (Remeš 2018).

Nonetheless, the tallest measured tree in the Czech Republic presently is a 140-year-old Douglas fir that grows in a valley near Železný Brod and is over 64 m tall.

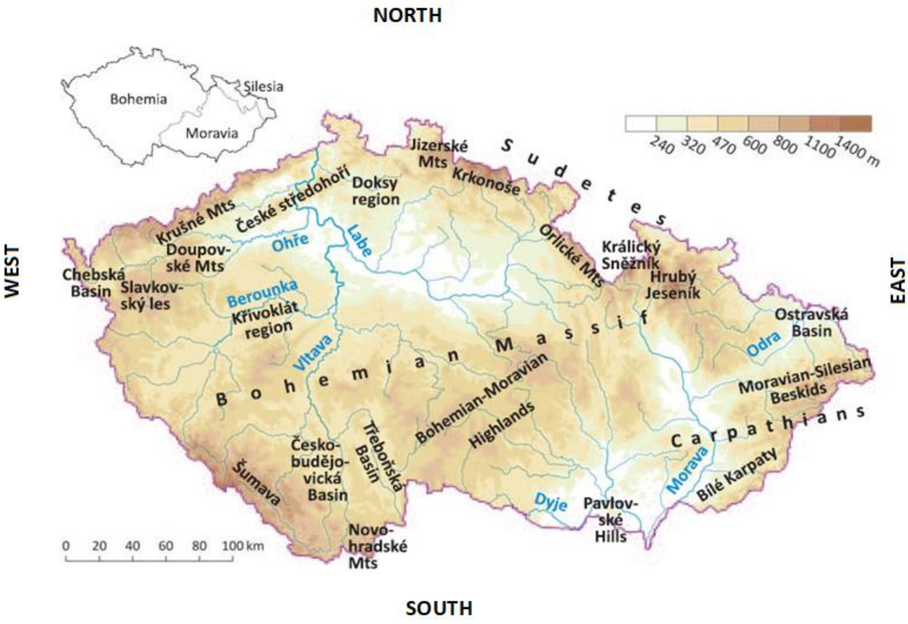

Figure 2. Basic topographic map and historical lands of the Czech Republic. This map was prepared by O. Hájek (Chytrý 2012).

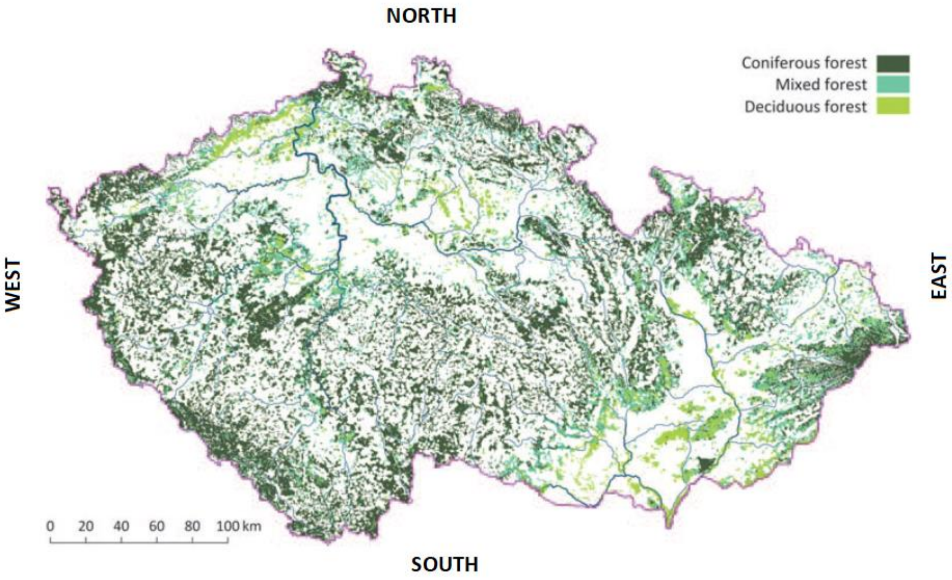

Figure 3. Forest cover of the Czech Republic. This map was prepared by O. Hájek (Chytrý 2012).

2.5. Italian temperate forests

Italy is in Southern Europe, a country that occupies an area of 302,068 km^2. The two main mountain ranges in Italy are the Alps, which constitute the natural border in the north, and the Apennines, which extend throughout the whole territory in the N-S direction.

The total forest area accounts for 36.7% of the national area; the forest coverage rate is 30.2%, and other forest areas account for 6.5% of the country area. Pure coniferous forest accounts for 12.8% of the area, while mixed conifers and broadleaves account for 10.1% of the forest area (and 6.1% of other wooded land area) (**Figure 4**) (Gasparini et al. 2022).

From an ecological point of view the forests are located in the temperate zone. Lower elevation forests are composed of sclerophyllous evergreen oaks, such as *Quercus ilex* (on limestone-derived soils), *Quercus suber* (on volcanic rock soils), and other deciduous species, such as *Quercus pubescens, Fraxinus ornus, Ostrya carpinifolia, Celtis australis, Acer monspessulanum, Carpinus orientalis,* and conifers like *Pinus pinaster, Pinus pinea,* and *Pinus halepensis.*

At mid-altitudes, the forests are primarily composed of deciduous oaks, such as *Quercus cerris, Quercus pubescens,* and *Quercus frainetto*, along with *Castanea sativa* and *Ostrya carpinifolia.*

At the highest altitudes, *Fagus sylvatica* dominates, together with other broadleaved species, such as *Acer pseudoplatanus, Acer obtusatum, Acer lobelii, Sorbus aria, Sorbus aucuparia, Sorbus torminalis, Ulmus glabra, Tilia platyphyllos, Populus tremula, Ilex aquifolium*, and conifers, such as *Taxus baccata* and silver fir (The Encyclopedia of Earth 2023) (**Figure 4**).

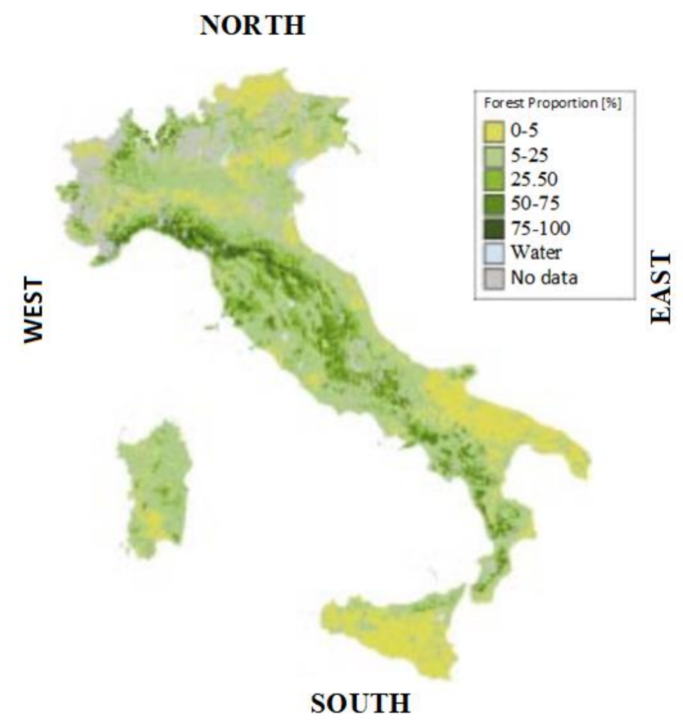

Figure 4. Map of broadleaved forests in Italy (Päivinen et al. 2001).

2.6. Studied species

2.6.1. Norway spruce (*Picea abies* [L.] Karst.)

The spruce areal is divided into two parts: a Northern (Baltic-Siberian) and a Central European areal. The separation occurs through a narrow corridor of Northern Poland; called "Polish disjunction," which distinguishes populations deriving from Russian and Asian glacial refugia from those deriving from Southeastern European ones.

The Baltic-Siberian range includes Siberia as far as the Pacific Ocean coast, then extends without interruption to nearly all of Fennoscandia, except for a strip along the western coast of Sweden, where the absence of the spruce is attributed to the climate being too Atlantic or to the incompleteness of postglacial re-expansion.

The Central European range includes the Alps and the eastern ranges with the Sudetes, the Carpathians, the Transylvanian Alps and the Rhodope Mountains on one side and the Dinaric Alps on the other (Bernetti 1995) (**Figure 5**).

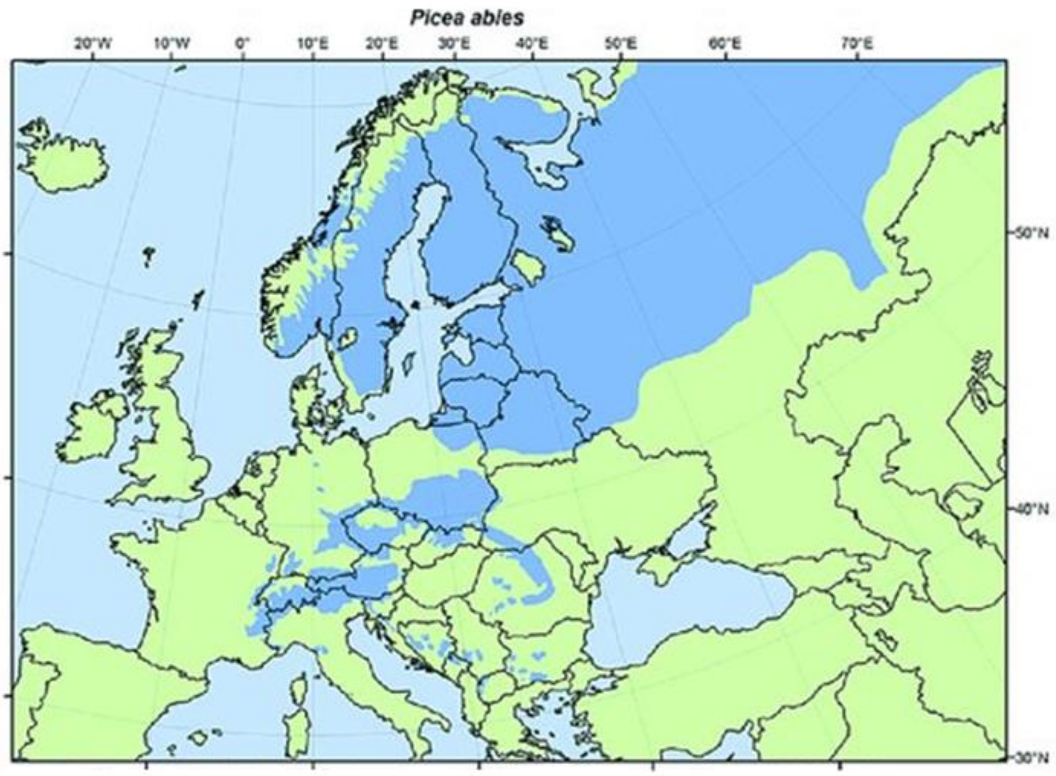

Figure 5. Native range of *Picea abies* L. in Europe (Jeger et al. 2017).

Norway spruce is a large tree, which can exceed the height of 50–60 m with a DBH of 2 m (Ballardini, 2013) and it is a very long-lived species that can exceed 500–600 years of age.

Norway spruce has a straight and slender trunk, slightly tapered; it is a monoecious species (the male and female flowers are located on the same branches) (Skrøppa 2003), and the foliage has a triangular shape with an intense green color but slightly lighter than the silver fir. The bark is thin and has a reddish color, and in young specimens, it flakes off into membranous scales, while the adult ones fissures into more or less rounded or irregularly quadrangular but not very thick plates (Romano and Grossoni 1996).

The leaves (needles) are needle-like acuminate with a rhomboidal section, dark green, 15–25 mm long, distributed in a spiral, and supported at the base by a raised bearing which remains adherent to the branch even after the fall of the leaves (Ballardini 2013).

As a monoecious tree, it has male reproductive structures formed into 8–10 mm ovoid cones, which form into groups in a terminal position on one-year-old branches. The color is initially reddish; when ripe, it is yellow ocher towards the end of spring. The female reproductive structures are formed into ovoid-elongated cones, initially erect, of a green color with a reddish hue, then, when ripe, they evolve into pendulous cones of a reddish-brown color 10–15 cm long. The cones have persistent imbricated, coriaceous scales with a wavy tip. The strobilus falls intact at maturity. The reddish-brown seed, of 2–5 mm, is provided with a large, trapezoidal wing, 4–5 times as long as the seed (Ballardini 2013). The production of seeds occurs late in the closed canopy, which happens around 50–60 years, while it is earlier in solitary plants at around 25–30 years of age. Seed years occur every 3–4 years, which rise to 8–10 years in the coldest places. The spruce is propagated not only by seed but also by offshoots, by grafting and by cuttings. By offshoot, the spruce tree multiplies naturally when the low branches that touch the ground spontaneously produce roots. This makes possible the survival of this species, especially at higher altitudes, where the production of fertile seeds occurs occasionally (Romano and Grossoni 1996).

Spruce has a superficial root system, which makes it very sensitive to aridity. Spruce prefers northern exposures, leaving the sunniest exposures to Scots pine or larch (Bernetti 1995).

In Central Europe, spruce stands are dominant in mountain regions. Norway spruce is a species of continental climate, and its optimum conditions for growth are perhumid, in the locations where annual precipitation exceeds 800 mm and the annual temperature does not exceed 6 °C (Rybníček et al. 2012b).

It is also a species that is susceptible to late frosts, which can cause damage to the blossoms by compromising the full maturation of the seed. As far as the edaphic conditions are concerned, the spruce has no particular soil requirements, although loose and well-aerated soils can promote a deeper development of the roots. Cultivation on agricultural land, however, has often given disappointing results with a higher susceptibility to root rot (Bernetti 1995).

Its natural range is located above all in the high-mountain and sub-alpine belts, but it can also grow in favorable climatic conditions in submontane areas, usually due to human action.

While artificial spruce forests grow at lower altitudes, in this case, they are considerably stressed. However, their resistance can be encouraged through thinning.

The wide diffusion of the spruce highlights its plasticity, a character exploited by the man who let it spread almost everywhere, favoring it for its particularly valuable timber.

The plasticity of the spruce derives from the fact that at higher altitudes, it does not seem limited by rigid temperatures, which it tolerates well.

On the other hand, it may be limited by the lack of conditions needed for the completion of the growing season, causing negative consequences for reproduction and renewal. In fact, spruce requires at least two and a half months with mean day temperatures greater than 10 °C to complete vital activities. The optimal conditions would be 3.5 months with temperatures above 14 °C. Another limiting factor of spruce is the precarious water balance in the winter period, during which it has water losses due to cuticular transpiration not compensated by adequate absorption from the frozen ground. The frequent freezing cycles also seem to be limiting thaw in the leaves, especially if they occur during the beginning of spring (as reported above), which significantly increases the incidence of frost damage. The wide diffusion of the spruce depends on its adaptability to different types of soil (see above) regardless of the nature of the substrate, but it can grow on both carbonate and silicate substrates (Ballardini 2013).

Currently, the Czech Republic is among the countries with the highest disturbance for spruce, which was formerly due to air pollution load in mountain areas and now due to the effect of change towards unsuitable climate in the lowlands (Šimůnek et al. 2020). Presently, spruce is suffering from ongoing climate change in the Czech Republic, especially long-term drought, extreme climate events, and (secondary) effects of bark beetle outbreaks (Toth et al. 2020; Hlásny et al. 2021).

2.6.1.1. Main adversities

Norway spruce is susceptible to a variety of diseases, some of which can cause alarming problems.

2.6.1.2. Fungal infections

2.6.1.2.1. Root rot caused by *Heterobasidion annosum*

Heterobasidion annosum is among the most widespread and damaging agents of root and butt rot in trees, especially conifers (Puddu et al. 2003). In the case of spruce, the infection advances along the roots and causes the death of their distal portion up to the central part of the woody cylinder (Ballardini 2013).

2.6.1.2.2. Burlap disease of conifers *Herpotrichia juniperi*

The fungus *Herpotrichia juniperi* causes a disease in the needles of conifers, which can lead to the death of seedlings and lower branch dieback of larger trees. The pathogen can cause significant losses, especially in young plantations when there is sufficient snow, which can delay or inhibit natural regeneration in subalpine forests (Ballardini 2013).

2.6.1.2.3. *Stereum sanguinolentum*

Stereum sanguinolentum is a fungus in the family Stereaceae. It is a plant pathogen that produces red heart rot, causing red staining on conifers such as spruces and Douglas-firs. Fruit bodies form on dead wood or, in rare cases, on dead branches of live trees. They are a thin, leathery crust on the surface of the wood. If a fresh fruit body is damaged, it will bleed a red-colored liquid, giving rise to the common names: bleeding *Stereum* and bleeding conifer parchment. *Tremella encephala*, a parasitic jelly fungus, may live on it (Zugmaier et al. 1994).

2.6.1.3. Insects

2.6.1.3.1. Bark beetle (*Ips typographus* L.)

In temperate and boreal forests, bark beetle (*Ips typographus* L.) is the most predominant insect nuisance factor affecting mainly spruce (*Picea abies* [L.] Karst.) (Sommerfeld et al. 2021).

The attack of the bark beetle (with the destruction of the phloem and of the inoculum of fungal agents) determines the death of the plant within a few weeks. The symptoms are already evident at the beginning of summer. The crowns of the affected trees take on a reddish color, followed by their defoliation. While the stems have thousands of holes from which the resin often comes out (Ballardini 2013).

2.6.1.3.2. Gypsy moth (*Lymantria monacha* L.)

Lymantria monacha L. is the most dangerous defoliator of coniferous forests (Stancă-Moise et al. 2018). The larvae feed on needles, causing direct damage. There may be a widespread mortality within the affected forest following the strong defoliation (Ballardini 2013).

2.6.1.3.3. Spruce miner torx (*Epinotia tedella* Clerck 1759)

This miner torx feeds exclusively on the spruce. Adult plants generally do not perish following an attack: even if they show symptoms such as an evident reddening, especially in the part of the crown exposed to the sun in late summer or in autumn, while in the spring, only inconspicuous discolorations are highlighted (Ballardini 2013).

2.6.1.3.4. Spruce root knot aphid (*Chermes viridis* Ratzeburg; *Chermes abietis* L.)

Chermes viridis is a common aphid that carries out a dioecious cycle with the spruce as its primary host and the larch as a secondary guest. As far as the spruce is concerned, the damage is caused by the bites caused on the buds by the wintering nymphs (Marcon et al. 2006).

2.6.1.3.5. Weevil (*Hylobilus abietis* L.)

Hylobilus abietis is a weevil beetle that, in its adult stage, can be very harmful to spruce woods as it feeds on the green bark of young plants (Ballardini 2013). It represents one of the most critical damaging factors for regeneration of forest tree species, especially in connection with clear-cutting.

2.6.2. European beech

The genus *Fagus* is part of the Fagaceae family native to North America, temperate Europe, and Asia. The genus is divided into two distinct subgenera, *Engleriana* and *Fagus* (Renner et al. 2016).

Fagus sylvatica L. is a large tree that can exhibit a variable shape and often has a height of about 30–40 m, occasionally 50 m. Its bark has a silvery-gray color, often tinged with green by epiphytic algae, and is smooth. The leaves are alternate, from ovate to elliptical. It is a monoecious species wind-pollinated, and most of the seed falls below the mother tree but is also dispersed by birds and mammals. It has a superficial to fasciate root system susceptible to drought (Packham et al. 2012). It goes much deeper compared to spruce, though.

The natural range of the *Fagus sylvatica* covers more than 910,000 km^2 (Leuschner 2020) and it extends from southern Italy to the south of the Scandinavian peninsula and from the Iberian peninsula to Crimea (San-Miguel-Ayanz et al., 2016; Preston and Hill, 1997), and defines the distribution of *Fagus sylvatica* as European Temperate (**Figure 6**).

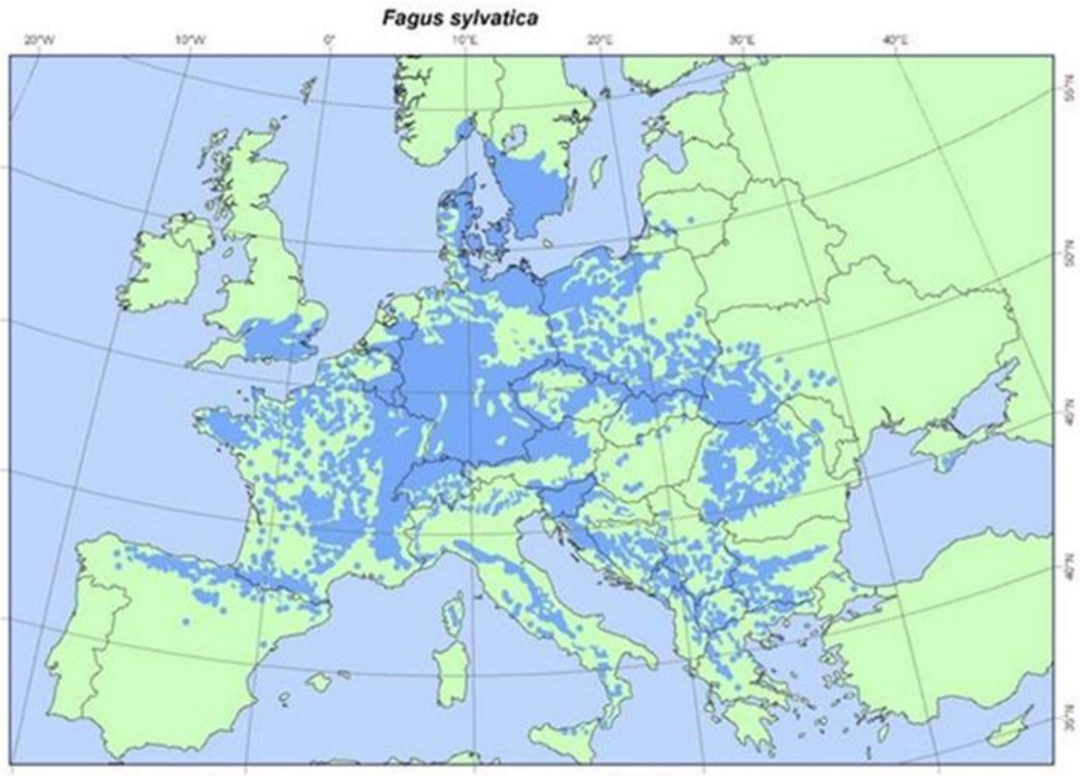

Figure 6. Natural range of *Fagus sylvatica* in Europe (Blanc-Jolivet et al., 2011).

Fagus sylvatica L.; subgenus *Fagus* is the most common deciduous broadleaved species in Central Europe (Pretzsch et al. 2013; Sharma et al. 2017; Štefančík et al. 2018b) and is widely managed for its valuable hardwood (Mader et al. 2019).

This species is crucial not only from an economic point of view but also from its ecological aspect (Podrázský et al. 2014; Bulušek et al. 2016; Štefančík et al. 2018a). It is an important timber species for many countries of Central Europe, surpassed only by some conifers such as Norway spruce and Scots pine (Leuschner 2020).

Many factors can influence the radial growth of European beech forests. The most important are temperature and precipitation (Remeš et al. 2015; Gallo et al. 2017; Vacek et al. 2019), air pollution (Breckle and Kahle 1992; Králíček et al. 2017), game damage (Slanař et al. 2017; Vacek 2017), habitat conditions (Dittmar et al. 2003; Vacek et al. 2015; Hájek et al. 2020), including the competition of weed species in the initial phase of growth (Gallo et al. 2018), previous land use (Rozas 2003; Cukor et al. 2017), and silvicultural interventions (Sharma et al. 2019; Vacek et al. 2020).

European beech (*Fagus sylvatica* L.) is a drought sensitive species (Fischer and Neuwirth 2013). From numerous dendrochronological and ecophysiological studies, it has emerged that European beech is more sensitive to drought than other Central European hardwood species, such as oaks (*Quercus petraea* [Matt.] Liebl. and *Q. robur* L.), ash (*Fraxinus excelsior* L.), hornbeam (*Carpinus betulus* L.), linden (*Tilia cordata* L.), and conifers such as Norway spruce (*Picea abies* [L.] Karst.) (Köcher et al. 2009; Zang et al. 2014; Zimmermann et al. 2015).

It is also sensitive to excessive light intensities, especially in conjunction with drought (Leuschner 2020). It does not tolerate dryness very well and conditions of heat, fire, and floods (Mishra et al. 2018). It needs sufficient humidity during the summer and mild temperatures during the winter (Bolte et al. 2007; Packham et al. 2012; Rasztovits et al. 2014; Leuschner and Ellenberg 2017).

European beech requires a mean annual temperature of 4.5–6.0 °C, with a mean of the warmest month of 13–20 °C and a mean of -2.3 °C for the coldest month (Pezzi et al. 2008). All this corresponds to a growing season of 110–150 days with maximum daily temperatures of 10 °C or more (Lausi and Pignatti 1973). *F. sylvatica* is very shade-tolerant species susceptible to spring frosts (Packham et al. 2012) and less tolerant than other beech species to extreme winter temperatures (it can survive extreme minimum temperatures of -30 °C while *F. grandifolia* can survive even temperatures of -42 °C) (Peters 1997).

Its distribution range is located in the more oceanic parts of Europe (Dulamsuren et al. 2017). It is absent in the continental areas of Eastern Europe (Packham et al. 2012). However, of the ten species of genus beech, *F. sylvatica* together with *F. orientalis*, are the species that most frequently advance towards dry climates (Fang and Lechowicz 2006).

Fagus sylvatica prefers well-drained soils (Stace 2010). It is unable to grow on wet clay soils where other species, such as common oak (*Quercus robur*) and hornbeam (*Carpinus betulus*), thrive (Mitchell 1996). In Europe, beech grows on a wide variety of soils with a pH between 3.5 and 8.5 (Rameau et al. 1989) but does not grow naturally on more acidic soils.

Under optimal growing conditions such as those of Central Europe, it can outcompete all the remaining tree species, forming monospecific stands in which the other broadleaved tree species cannot easily establish themselves due to shading (Ellenberg and Leuschner 2010).

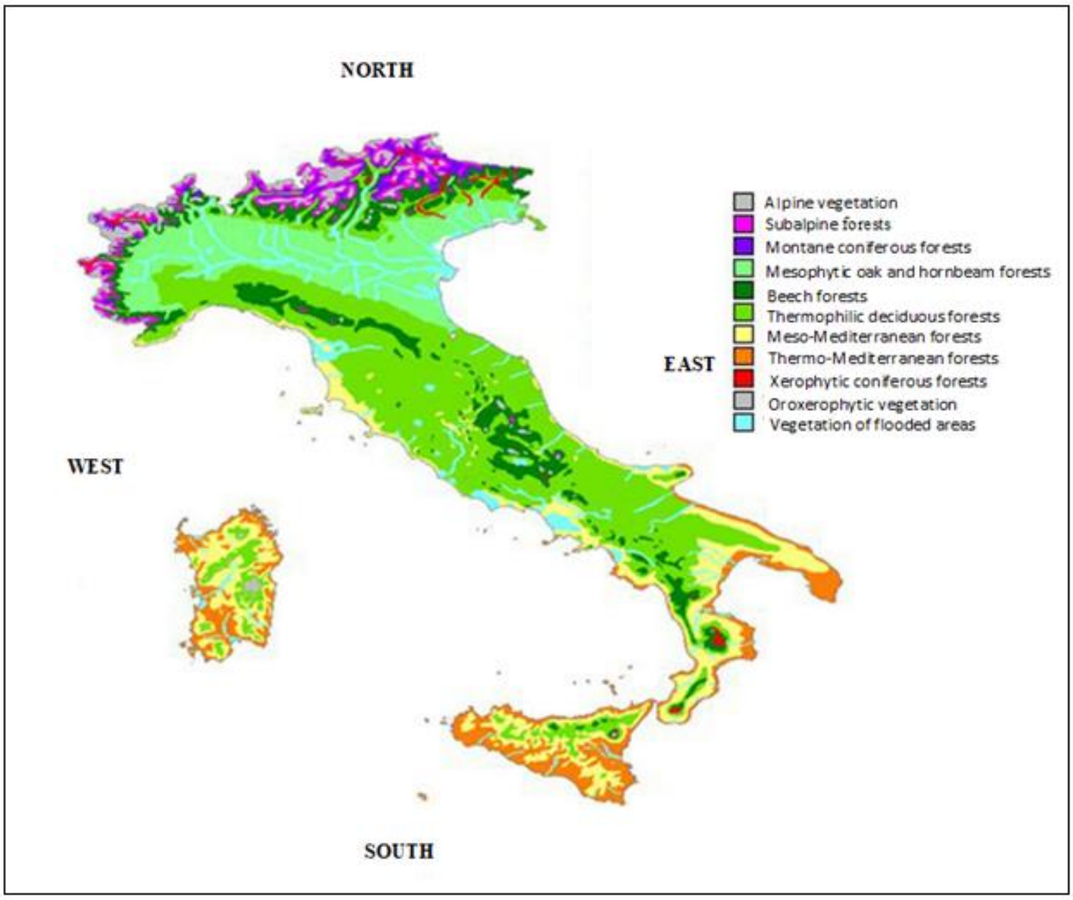

Figure 7. Beech representation in Italy. The map was modified from (Pignatti 2011).

2.6.2.1. Main adversities

No disease normally causes plant death. Several fungi cause leaf spots but generally do not create alarming problems:

2.6.2.2. Fungal infections

2.6.2.2.1. Beech anthracnose (*Apiognomonia errabunda*)

This pathogen is rarely harmful and generally affects the lower part of the canopy. This fungus causes the leaves and shoots to dry out (Ebone et al. 2012).

2.6.2.2.2. *Phytophtora* spp.

The pathogen settles in the plant through the root system and goes up to the base of the stem, where it causes necrotic areas under the bark and progressive desiccation of the foliage. The pathology manifests itself more in plants that grow in unsuitable soil conditions, such as asphyxiated soils or with water stagnation (Ebone et al. 2012).

2.6.2.3. Insects

2.6.2.3.1. *Dasychira pudibunda*

This moth produces only one generation per year and can cause intense defoliation in the beech forest. The larvae continuously gnaw the edges of the leaves until the end of the growing season, when they ascend in the litter (Nicolotti et al. 2002).

2.6.2.3.2. *Lymantria monacha*

This species prefers conifers, chiefly fir and larch, but can cause intense defoliation on beech (Nicolotti et al. 2002).

2.6.2.3.3. *Nadigella formosanta*

The *Nadigella* is an orthoptera that causes extensive defoliation from the juvenile stages. It prefers numerous essences, both shrubby and herbaceous of the undergrowth such as *Rubus ulmifolius*, *Corylus avellana*, *Sambucus nigra*, *Cornus mas*, or *Urtica dioica*, and trees such as beech, birch, linden, hornbeam, oak, chestnut, maple, ash, apple, peach, and cherry (Regionale 2018).

2.6.2.3.4. Attacks by aphids (*Cryptococcus fagisuga*)

Cryptococcus fagisuga is a bug that forms waxy colonies on the trunk where the bark browns; these damages facilitate the entry of *Nectria* spp., responsible for cankers (Ebone et al. 2012).

2.6.2.3.5. Attacks of egosoma (*Aegosoma scabricorne*)

This is a reddish-brown cerambycid beetle with robust and wrinkled antennae. It can reach 5 cm in length in the adult stage; it lays its eggs preferably on old hardwood specimens, including beech, where the larvae, with a cycle of several years, dig tunnels in the wood of the trunk (Ebone et al. 2012).

2.6.2.3.6. Attacks of agrilus (*Agrilus viridis*)

It is a buprestid beetle that frequently attacks perishing plants by digging tunnels under the bark (Ebone et al. 2012).

2.6.2.3.7. Morimo scabroso attacks (*Morimus aspers*)

It is a cerambycid beetle of a polyphagous nature and it attacks many deciduous and coniferous trees; the larvae damage the wood by digging tunnels even in depth (Ebone et al. 2012).

2.6.2.3.8. Attacks of yellow woodruff (*Zeuzera pyrina*)

It is a polyphagous moth. The larvae dig tunnels both in the branches and in the stem, damaging them from a mechanical and technological point of view (Ebone et al. 2012).

2.7. Remote sensing

Remote sensing is considered indispensable for various applications in the environmental and ecological fields and now is competitive, in terms of time and cost, with traditional terrestrial investigation techniques thanks to the continuous technological developments of shooting tools, image analysis, and interpretation methodologies. Satellite data are broadly available and may allow "*near real-time*" assessments of changes in forest health over large geographic areas

(McDowell et al. 2015). Multispectral sensors include spectral bands from visible and infrared wavelengths which may be combined to provide vegetation indices (Brown et al. 2006).

Remote-based vegetation indices may report information that exhibits a greater spatial extent and temporal resolution, which can range from daily to yearly, compared to traditional ground-based surveys. Satellite data are synoptic; that is, they enable us to observe wide geographical areas simultaneously.

Regular and frequent observations of the same portion of territory provide continuous control of the environmental conditions and its dynamics (for example, monitoring vegetation and water), and offer the possibility of quickly producing thematic maps using up-to-date data and digital systems (Gomarasca 2003).

The choice of satellite remote sensing for the study of vegetation is widely documented in various fields of application, in particular for forest inventories (Boyd and Danson 2005), to discriminate between different vegetation covers and classify land use and land cover (Clark et al. 2001), for the study of biological parameters, such as the leaf area index (Wang et al. 2005), for the prediction of agricultural productions (Clevers and Van Leeuwen 1996), and the monitoring of fires (Li et al. 2001).

Remote sensing measures the energy reflected from the surfaces of different objects to determine a correspondence between the amount and type of energy and the nature and status of the reflecting bodies or surfaces from which this energy comes. A parameter is used to describe the amount of reflected radiation, called reflectance, that is, the percentage of incident radiant energy reflected by a given surface of a body. The reflectance depends on the nature of the surface and the matter of which it consists. By analyzing the reflectance value of a surface, a characteristic curve called the spectral signature can be obtained (Trotta 2008). Each type of surface, such as vegetation, water, soil, and snow, has its own average spectral signature. Vegetation exhibits very high reflectance in the near-infrared and visible red bands: this can distinguish vegetation from bare ground. In particular, chlorophyll highly absorbs light in the visible spectrum, mainly red, which it uses during the photosynthetic process. Light in the near-infrared, on the other hand, is reflected because it is not useful to the plant at all. Thus, the reflectance by vegetation in the near-infrared and visible spectral intervals varies considerably (**Figure 8**).

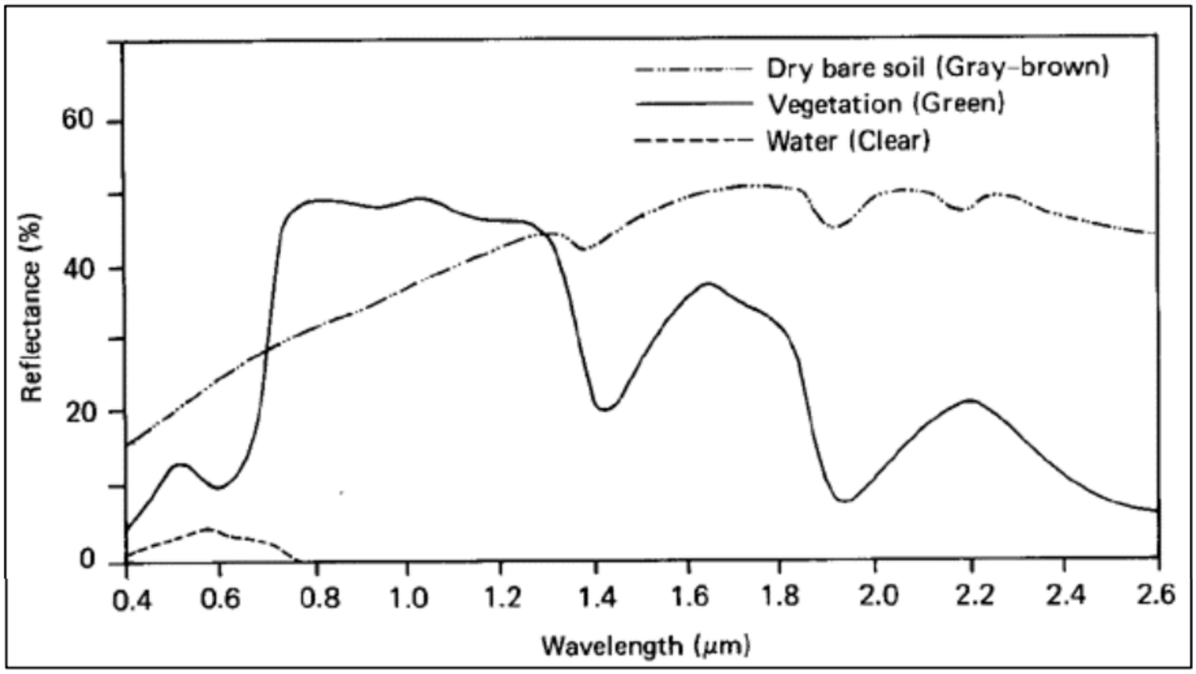

Figure 8. Reflectance of some elements of the territory, soil, vegetation, and water as the wavelength varies (Trotta, 2008).

The reflectance curve can vary according to the type of vegetation, its density, the phenological phase in which the plant species are found, and the stresses to which these plants can be subjected (Gomarasca 1997).

However, even remote sensing shows shortcomings, such as the lack of a long-time series of satellite observations. The data detected remotely exhibit adequate temporal resolution and have been widely accessible since 1980 (i.e., NOAA-AVHRR satellites). Additionally, other satellite datasets cover a shorter period of time (about 20 years) (e.g., MODIS) or have temporal gaps (e.g., Landsat).

For example, the World Resources Institute's Global Forest Watch initiative (WRI 2023) is a critical tool for detecting temporal shifts in forest cover connected to disturbances or mortality.

However, it has a spatial resolution of 30 m, which constitutes a limit to its application, precluding physiological background evaluation processes.

It is well known that the available spatial resolution of satellite data is often excessively coarse to be directly related to the growth data of small forest areas, thus making the availability of sufficient information about the tree ring a key constraint. However, the emergence of other technologies, such as LiDAR, allows for monitoring of single trees on larger scales (e.g., Asner et al., 2016). This feature could bridge the gap between tree-level and booth-scale information. Combining information from multiple levels of monitoring can be seen as the real challenge.

Table 1. Advantages and disadvantages of remote sensing (source SpatialPost, 2023).

Aspect	**Advantages**	**Disadvantages**
Geographical Coverage	Remote sensing is a perfect tool for environmental monitoring and disaster response since it efficiently collects data from broad geographic regions in a short amount of time.	The accessibility of remote sensing is sometimes constrained by the high implementation and maintenance costs.
Data Timeliness	Remote sensing is a useful tool for managing and responding to disasters because it may give real-time or near-real-time data that enables speedy decision-making and action in emergency circumstances.	The accessibility of remote sensing is sometimes constrained by the high implementation and maintenance costs.
Accessibility	Remote sensing is a useful tool for environmental monitoring and obtaining military information because it can collect data from locations that are challenging or hazardous to access, such as conflict zones, places affected by volcanic eruptions, or locations with toxic pollutants.	The accuracy and utility of remote sensing data can be constrained by air conditions and sun angle in particular applications.
Imaging Capability	For geological investigation, agricultural management, and animal monitoring, remote sensing may capture photos from a variety of wavelengths and angles, giving crucial layers of information on a specific location.	Some features, such as underground resources or deep ocean features, cannot be accurately identified using remote sensing techniques, making it difficult to gain a complete picture of certain areas.
Environmental Applications	Remote sensing is an effective tool for monitoring and analyzing environmental changes, such as deforestation, land-use changes, glacier retreat, and air pollution, making it	The resolution and quality of remote sensing data can be limited by technical constraints, such as the sensor’s spatial and spectral resolution and the quality of the

	valuable for environmental management and planning.	image, affecting its usefulness in some applications.
Disaster Response	Remote sensing can help with disaster response and management by providing real-time data and information on the extent of damage and changes in the affected area, making it a valuable tool for emergency services and aid organizations.	Remote sensing technology is constantly evolving, requiring updates and changes to equipment and software, which can be costly and time-consuming, affecting its compatibility and interoperability.
Agricultural Applications	Remote sensing can provide valuable data for monitoring crop growth and predicting yields, making it useful for agricultural management and planning, improving food security, and reducing waste.	Remote sensing raises ethical concerns and legal considerations, particularly when used for surveillance purposes, limiting its accessibility in some areas.
Geological Exploration	Remote sensing can help identify geological features and mineral deposits, making it an important tool for geological exploration and mining, improving the efficiency and sustainability of resource extraction.	The subjectivity in the interpretation of remote sensing data can lead to differing results between analysts, affecting its reliability and usefulness in some applications.
Urban Planning	Remote sensing can provide valuable information for urban planning and land-use management, such as identifying areas for development, infrastructure planning, and management of natural resources, improving the efficiency and sustainability of urban development.	Large data sets produced by remote sensing can be difficult to handle, store, and analyze since they need specialist technology and software, which limits their usability and accessibility in particular applications.
Water Resource Management	In order to better manage and save water, remote sensing may be used to monitor and manage water resources, including water quality, availability, and changes in water levels.	The amount of detail and frequency of data gathered by remote sensing can be restricted by geographical and temporal resolutions, which can have an impact on the utility and accuracy of the data in specific applications.

2.7.1. MODIS

The MODIS (Moderate Resolution Imaging Spectroradiometer) is a sensor installed on two NASA satellites put into orbit in December 1999 and May 2002: the Terra (EOS-AM 1) and Aqua (EOS-PM 1) (Altobelli et al. 2008) satellites which scan through the vast wages of the Earth (8 and 16-day cycles), providing data with high radiometric sensitivity (12 bit) in 36 spectral bands with lengths wavelengths from 0.4 to 14.4 μm: 11 in the visible, nine in the near-infrared (NIR), four in mid-infrared (MIR), six in thermal infrared (TIR), and six in far-infrared. It has an observation width of 2330 km and screens the entire surface of the Earth every one or two days (Maccherone 2023).

The first two bands (red at 620–670 nm and NIR at 841–876 nm) are acquired at resolution nominal 250 m, the next five bands (blue [459–479 nm], green [545–565 nm], NIR [1230–1250 nm] and SWIR [1628–1652 nm, 2105–2155 nm]) at 500 m resolution and finally the last 29 bands have a resolution of 1000 m (Deplano 2008). In this study, we used MODIS version 13, with a resolution storm of 16 days and a space of 250 m. The reflectance values are corrected, removing distortion caused by the camera angle and texture surface (Deplano 2008).

Therefore, among the indices that can be obtained from MODIS, there is the daytime temperature surface (LSTD) and nocturnal (LSTN); the mid-infrared associated with the water content (MIR); the NDVI (Normalized Difference Vegetation Index) and the EVI (Enhanced Vegetation Index) (Deplano 2008).

2.7.2. Normalized Difference Vegetation Index (NDVI)

Multispectral sensors can provide us with different vegetation indices by combining the spectral bands of the visible and infrared wavelengths (Brown et al. 2006). The most commonly used indicator of vegetation greenness/vitality is the Normalized Difference Vegetation Index (NDVI) (Rita et al., 2020). This index is used in many ecological studies (Pettorelli et al. 2005). The NDVI assesses the presence of photosynthetic activity as it correlates to the red spectrum, in which there is absorption by chlorophyll, and the near-infrared spectrum, in which leaves reflect light by activating energy dissipation processes. (Justice et al. 1985; Pettorelli et al. 2005): it ranges between -1 and +1 (Pettorelli et al. 2005), with higher values indicating a higher level of photosynthetic activity, while negative values coincide with an absence of vegetation (Sellers 1985; Tucker et al. 1991; Myneni et al. 1995). The NDVI is widely recognized as a valuable proxy for investigating the climatic influence on the phenology and productivity of vegetation, as it has a close relationship with vegetative activity, canopy cover, and greeness (Liu et al. 2013; Gazol et al. 2018a).

Different researchers, such as Running et al. (2004) and Hasenauer et al. (2012), report the feasibility of estimating net primary production (NPP) from the NDVI; further, Pettorelli et al. (2005) report the strong correlation of NDVI with the Leaf Area Index (LAI).

The NDVI is also widely used to investigate the negative impacts of severe drought (Rita et al. 2020; Wang et al. 2022), fire (Gemitzi and Koutsias 2022; Morante-carballo and Bravo-montero 2022; Wang et al. 2022), frost (Tait and Zheng 2003; Pettorelli et al. 2005; Nolè et al. 2018; Bojórquez et al. 2021), and flood (Verma, SunitaRapid flash flood calamity in Chamoli et al. 2022; Wu et al. 2022).

Remote sensing is a widely recognized tool for investigating intra-annual changes in canopy greenness, and, thus, the relation with radial growth. For instance, a positive correlation has been reported between summer NDVI and tree ring width from multiple studies, such as (Berner et al. 2011) and (Kaufmann et al. 2004).

2.7.3. Normalized Difference Vegetation Index (NDVI) limitations

NDVI has three major limitations:

- The NDVI signal is likely to saturate in high-cover vegetation areas, and therefore, the Enhanced Vegetation Index (EVI), including the blue wave band to enhance its sensitivity, is more widely used in such applications (Matsushita et al., 2007);

- NDVI is sensitive to snow in conifer-dominated boreal biomes (Jönsson et al. 2010) **(Figure 9)**;

- This index detects the presence of green leaves but not the photosynthesis itself (Camps-Valls et al., 2021).

The calculation of the NDVI value is sensitive to a series of troubling factors such as atmospheric effects, clouds, ground, and anisotropic effects.

Atmospheric effects: the actual composition of the atmosphere, and in particular the water vapor and aerosol (**Figure 10),** can significantly affect the measurements obtained from space. Consequently, the latter can be misinterpreted if these effects are not adequately considered. For example, this is the case when NDVI is calculated directly based on raw measurements.

Clouds: Deep, optically thick clouds **(Figure 11)** can be very noticeable in satellite images and produce characteristic NDVI values that facilitate their discernment. While small, i.e., those with a smaller diameter than the surface sampled by the sensor can significantly contaminate measurements.

Cloud shadows: Areas that do not appear bright can also affect NDVI values and lead to misinterpretations. All these considerations can be minimized by forming composite imagery using everyday captures. Composite NDVI images have led to many new applications where NDVI vegetation or photosynthetic capacity varies over time.

Soil effects: Soils tend to darken when wet, and consequently, their reflectance becomes a direct function of the water content. If the ghostly result of humidification is not the same in the two spectral bands, the value of the NDVI of an area may appear to have changed due to variations in soil moisture (precipitation or evaporation) and not because of changes in vegetation (Lettieri 2012).

Furthermore, in areas with poor vegetative cover, the reflectance of the soil is very high and the NDVI values could be altered (Fabrizi 2020).

Anisotropic effects: all surfaces, whether natural or artificial, reflect light differently in different directions. This form of anisotropy is usually spectrally dependent, although the general trend may be similar in these two spectrum bands. As a result, the NDVI value may depend on the particular anisotropy of the target and the angular geometry of illumination and observation (at the time of measurements), and therefore, from the position of the target inside the band of the instrument (or the time the satellite passes through the site). That is particularly important in an AVHRR data analysis since the orbit of NOAA platforms tended to drift over time. At the same time, the use of composite NDVI images minimizes these considerations and has resulted in a series of NDVI time data worldwide for more than 25 years.

Figure 9. Snow canopy (Hoving and Notaro 2015).

Figure 10. Fog around Cukrak (Photo: Giuseppe D'Andrea).

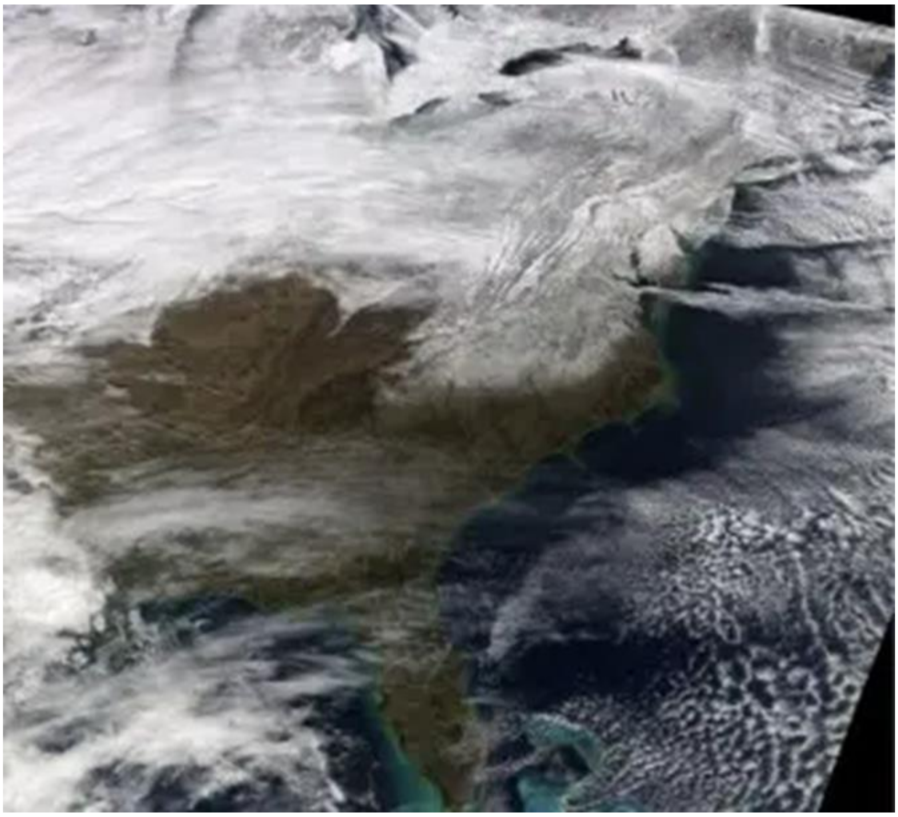

Figure 11. Clouds (GIS Resources 2022).

3. MATERIAL AND METHODS

3.1. Research area of Norway spruce

The spruce study area consists of six forest complexes (30 × 30 m) located in three regions of the central part of the Czech Republic: Karlštejn (1–2), Cukrák (1–2), and Kostelec (1–2) (**Figure 12**); all the forest complexes fall within the colline zone as they have an altitude between 319 and 425 m a.s.l. (**Table 2**) and are located on terrain with a 0–25° slope and mainly a northwest exposure.

The geological characteristics determine the predominant soil type, which is Cambisol (Němeček et al. 2001); various sites fall under the edaphic series of nutrient and acidic sites (Viewegh et al. 2003).

The study area is characterized by hot, dry summers and cool, dry winters with a narrow annual temperature range (Cfb) according to the Köppen climate classification (Köppen 1936).

Most precipitation occurs from June to August, while the least falls in the winter months (Pekařová 2007). The maximum monthly temperature occurred in July, while the minimum was in January with only one month with temperatures below zero.

The average length of the growing season (Tmax ≥ 10 °C) is 158–165 days (Bílek et al. 2009), while the average number of days with snow cover is 37, that of ice days (Tmax < 0 °C) is 24, of arctic days (Tmax < -10 °C) is one, and number of tropical days (Tmax ≥ 30 °C) is 12, according to the Czech Hydrometeorological Institute (CHMU) reports. The age of the forest stands ranged from 80 to 129 years (**Table 2**).

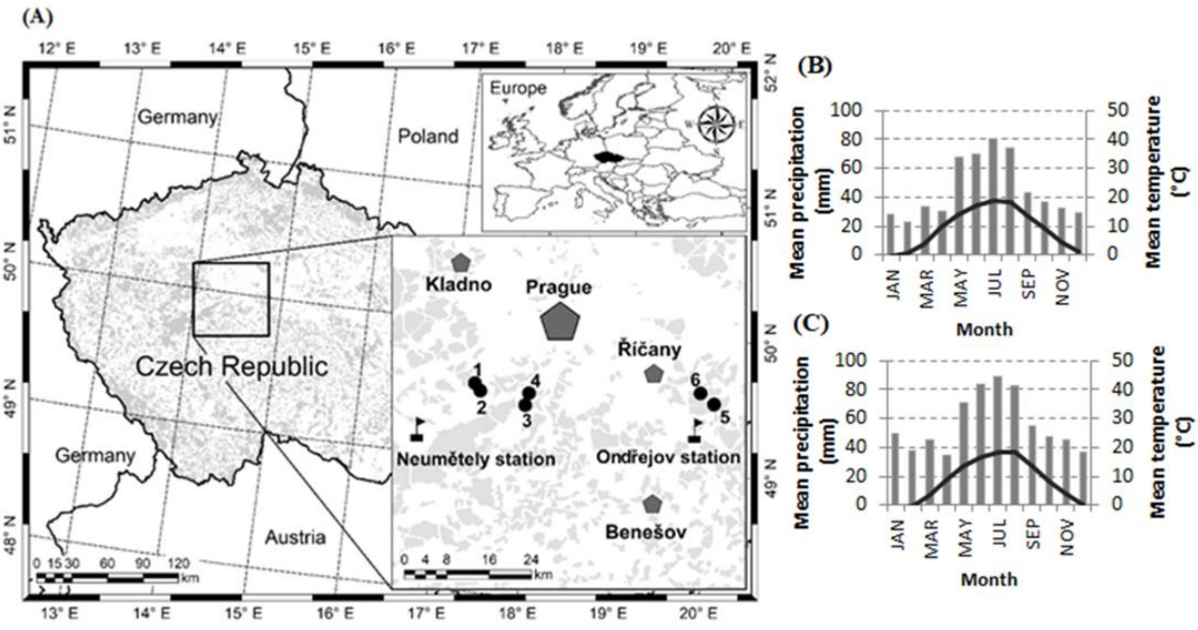

Figure 12. Location of Norway spruce stands on research plots (●) in the study areas of Karlštejn (1–2), Cukrák (3–4), and Kostelec (5–6); meteorological stations (⚑) (**A**); pentagons depict big cities; the shadowed areas are forested areas; the map was made in ArcGIS 10 software (Esri). Climogram for Karlštejn and Cukrák research plots (**B**); Climogram for Kostelec research plots (**C**). The map was rendered by D'Andrea et al. (2022).

Table 2. Overview of the sites and stand characteristics of spruce research plots. The table was rendered by D'Andrea et al. (2022).

Plot Name	GPS Coordinates	Altitude [m]	Exp.	Stand densities	Slope [%]	Age of Tree Layers [years]	Height [m]	DBH [cm]	Forest Type*
Karlštejn 1	49°56'51.3''N, 14°12'05.6''E	422	N-W	0.96	5–10	93	26	36	3B
Karlštejn 2	49°56'41.6''N, 14°12'19.6''E	406	W	0.91	<5	83	24	32	2H
Cukrák 1	49°56'14.2'N, 14°21'13.4''E	402	N-W	0.97	20–25	83	23	29	3K
Cukrák 2	49°56'51.3''N, 14°21'25.1''E	319	N-W	0.96	5-10	80	26	30	3I
Kostelec 1	49°57'55.9''N, 14°48'58.9''E	423	N-W	0.93	<5	96	31	46	3S
Kostelec 2	49°58'33.5''N, 14°47'20.9''E	425	N-E	0.95	10-15	129	30	35	3I

Notes:* Forest site type classification: 3B—Querceto-Fagetum trophicum, 2H—Fageto-Quercetum illimerosum trophicum, 3K2—Querceto-Fagetum acidophilum, 3I—Querceto-Fagetum illimerosum acidophilum, 3S—Querceto-Fagetum mesotrophicum (Viewegh et al. 2003).

The first study site, KA, is located approximately 22 km SW of Prague and is part of the Karlštejn National Nature Reserve (NNR), which is part of the Český Kras Protected Landscape Area (PLA) in Central Bohemia (Vacek et al. 2018b).

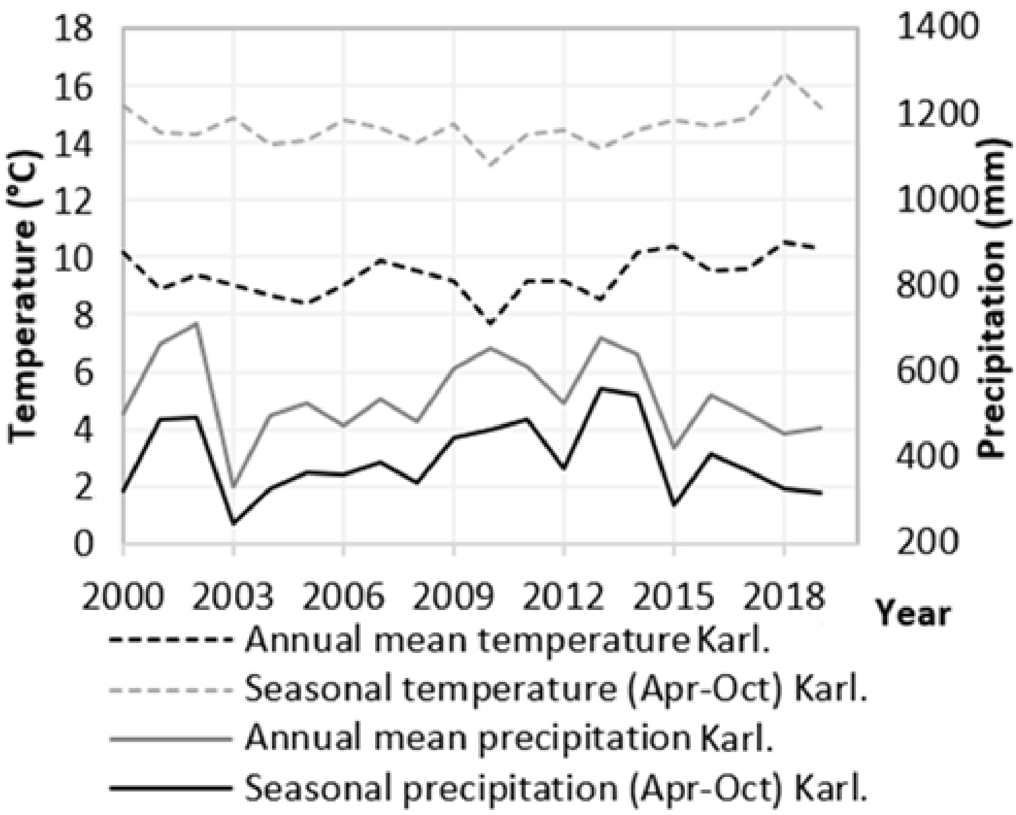

Figure 13. Dynamics of annual and seasonal temperature and annual and seasonal precipitation for the Karlštejn and Cukrák sites, according to nearby meteorological stations, for the period 2000–2018. Note: Karl.—Karlštejn research plot. The figure was taken by D’Andrea et al. (2022).

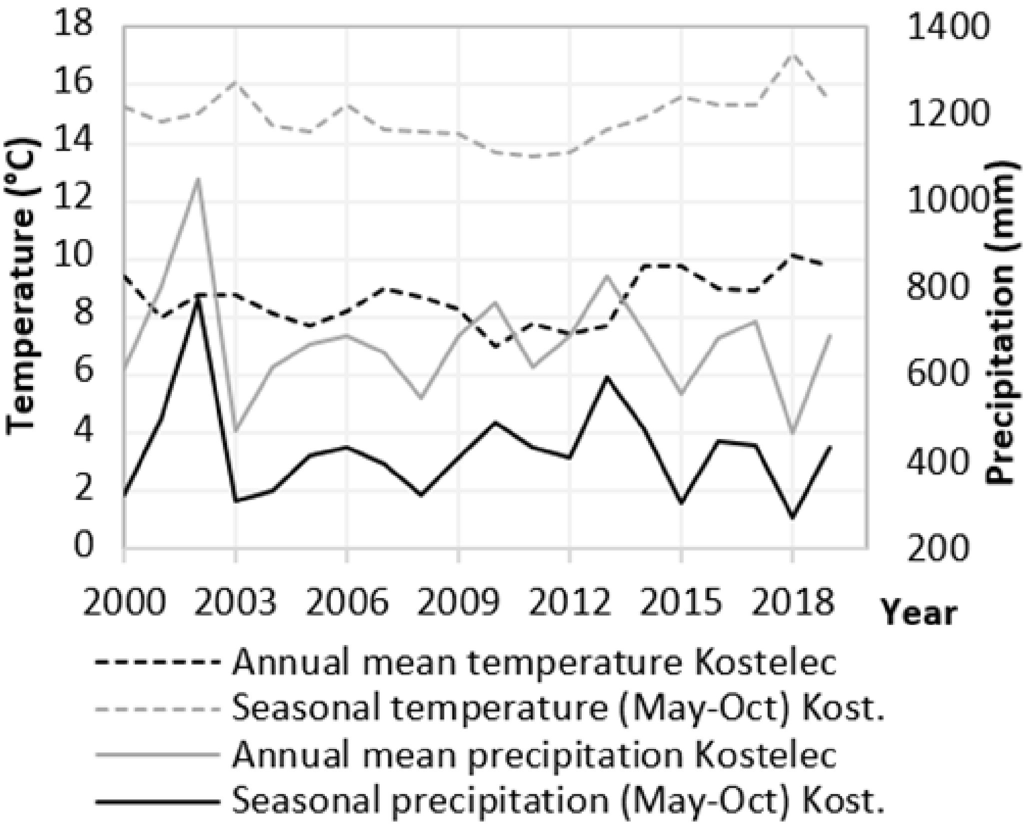

Figure 14. Dynamics of annual and seasonal temperature and annual and seasonal precipitation for the Kostelec sites, according to nearby meteorological stations, for the period 2000–2018. Note: Kost.—Kostelec research plot. The figure was taken from D'Andrea et al. (2022).

From a geological point of view, the prevailing rock substrates are gray and red limestone (Karlštejn). The average annual temperature range is between 8–9 °C, and precipitation is approximately 560 mm (CHMU 2020) (**Figure 13**). The forest is classified as Fageto-Quercetum illimerosum trophicum and Querceto-Fagetum trophicum (Viewegh et al. 2003).

The second study site, CU, is located approximately 18 km SW of Prague and consists of private forests. The two study plots lie on the Kopanina hill (maximum altitude of 411 m a.s.l.) which is located between the Vltava and Berounka rivers. The thermo-pluviometric data come from the same meteorological station at the KA location (**Figure 13**). The forest is classified as Querceto-Fagetum acidophilum and Querceto-Fagetum illimerosum acidophilum (Viewegh et al. 2003).

The third study site, KO, is located 25–30 km SE of Prague in the Voděradské bučiny NNR. It is part of the forest complexes managed by the Kostelec nad Černými lesy School Forest Enterprise (Czech University of Life Sciences Prague). From a geological perspective, the bedrock is formed by granites of different textures (Bílek et al. 2009), while from a meteorological standpoint, the climate can be defined as moderately hot and arid, with an average annual temperature of 8 °C and an average annual precipitation of 655 mm (Remeš and Podrázský 2006) (**Figure 14**). The forest is classified as Querceto-Fagetum mesotrophicum and Querceto-Fagetum illimerosum acidophilum (Viewegh et al. 2003).

All study sites are historically used for timber production and were established by artificial regeneration of Norway spruce and renewed by clear-cutting and replanting.

Figure 15. Karlštejn 1 Forest plot (Photo: Giuseppe D'Andrea).

Figure 16. Karlštejn 2 forest plot (Photo: Giuseppe D'Andrea).

Figure 17. Soil profile Karlštejn 2 (Photo: Giuseppe D'Andrea).

Figure 18. Cukrák 1 forest plot (Photo: Giuseppe D'Andrea).

Figure 19. Cukrák 2 forest plot (Photo: Giuseppe D'Andrea).

Figure 20. Kostelec 1 forest plot (Photo: Giuseppe D'Andrea).

Figure 21. Kostelec 2 research plot (Photo: Giuseppe D'Andrea).

3.2. Research area of *Fagus sylvatica*

The study areas are located in Poland, the Czech Republic, and Italy (**Figure 22**) and were selected by the major representation of beech (forest stands with a 100% share of European beech). All study sites (50 × 50 m) are in non-intervention areas, where no harvesting operations have taken place since at least 1985. The basic site and stand characteristics are given in **Table 3**. Precipitation and temperature conditions are different for the Czech Republic/Poland and Italy, as described in **Figure 23** and **Figure 24**.

The Polish/Czech plots are located in the national parks of the Krkonoše (Giant) Mountains, i.e., in the Cross-border Krkonoše/Karkonosze Biosphere Reserve. The plots in the Krkonoše Mountains were established and selected in 1980 for long-term research, while the Italian plots are located in the southern Apennines and are part of the Appennino Lucano National Park.

In total, six research plots were evaluated, the first is in Poland in portion of the Krkonoše Mountains called Chojnik 1, near the town of Sobieszów (approximately 1 km). The second study site, Rýchory 2, and the third study site, Rýchory 27, are in the Czech Republic and are located in eastern Krkonoše Mountains, in Rýchory massif, not far from the town of Žacléř (approximately 1.5 km), while the last three are in southern Italy. Sellata research plot is located 3.5 km from Abriola. The La Lama research plot is situated 6 km from the Marsico Nuovo, and the Monte Volturino research plot is located 3.5 km from the Marsicovetere.

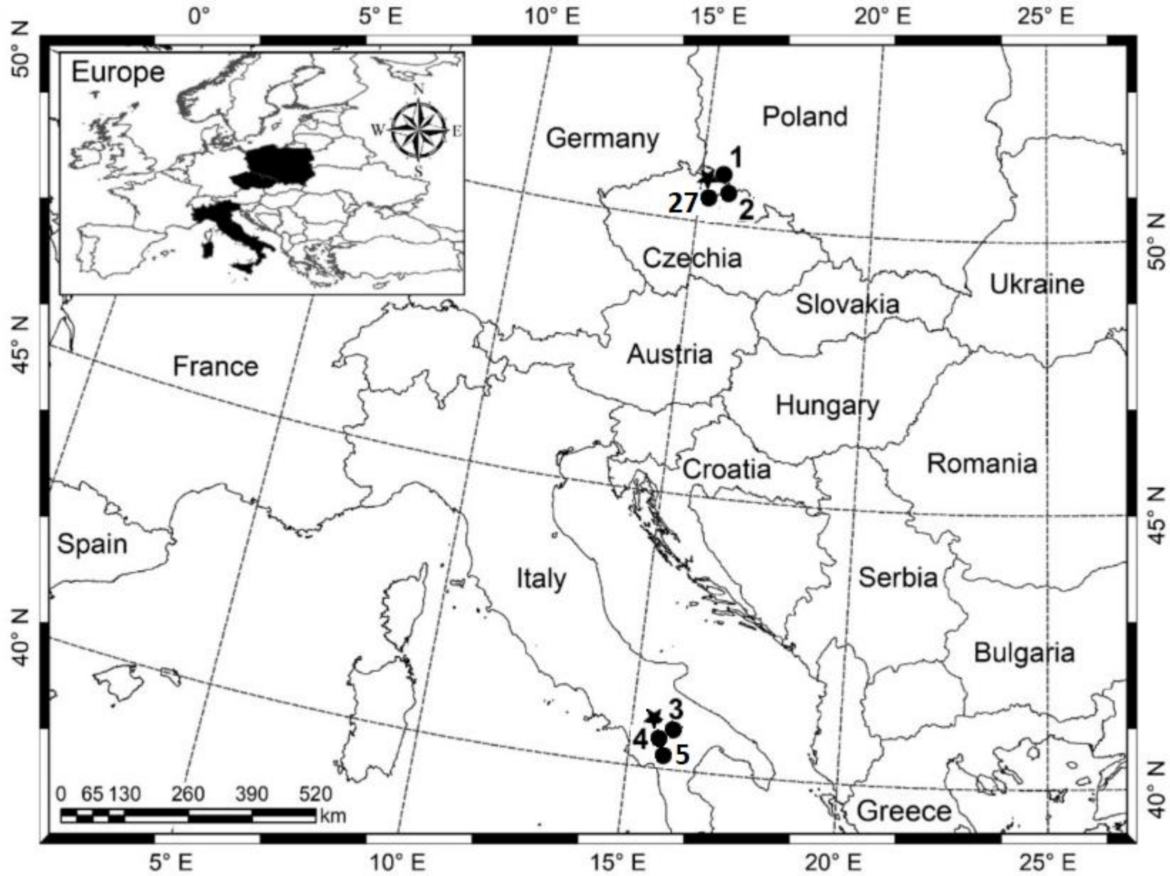

Figure 22. Research plots (black dots) of European beech in Central and Southern Europe. Black stars indicate the meteorological stations in Bedřichov (Czech Republic) and Potenza (Italy).

The mean annual temperature for CH1, RY2, and RY27 is 5.3 °C, the mean annual precipitation is 1300 mm, the mean number of vegetation days is around 120 days, and the number of days with snow cover reaches 117 (Šimůnek et al. 2019). The study area is characterized by a humid continental climate, with hot and humid summers and cold to very cold winters (classification symbol Dfb) according to the Köppen climate classification (Tolasz 2007).

While the mean annual temperature for the Italian plots is 13.7 °C, the mean annual precipitation is 707 mm, and the mean number of vegetation days is 135 days (same period for snow cover) (Piovesan et al. 2003). The study area is characterized by a mediterranean climate, with hot and dry summers and mild, rainy winters (classification symbol Csa).

Table 3. Overview of basic site and stand characteristics of beech research plots in 2019

Plot name	GPS Coordinates	Altitude [m]	Exp.*	Stand densities	Slope [%]	Height [m]	DBH [cm]	Age of tree [years]	Soil type
Chojnik 1	50°50'12.1"N 15°38'27.8"E	510	N-W	0.89	16	23	39	127	Modal Cambisol
Rýchory 2	50°39'57.7"N 15°53'05.2"E	760	N-E	0.81	27	29	44	155	Eutrophic Cambisols
Rýchory 27	50°38'44''N 15°52'14''E	1030	W	0.83	3	15	30	84	Cryptopodzols
Sellata 3	40°32'21.5"N 15°47'39.9"E	1275	E	0.90	26	33	60	123	Epileptic Phaeozems
La Lama 4	40°28'22.5"N 15°45'35.2"E	1340	S-E	0.82	7	29	52	185	Haplic Phaeozems
Monte Volturino 5	40°24'28.9"N 15°48'47.4"E	1740	E	0.91	25	23	45	185	Epileptic Phaeozems

Notes: * NW—northwest; NE—northeast; W—west; E—east; SE—southeast.

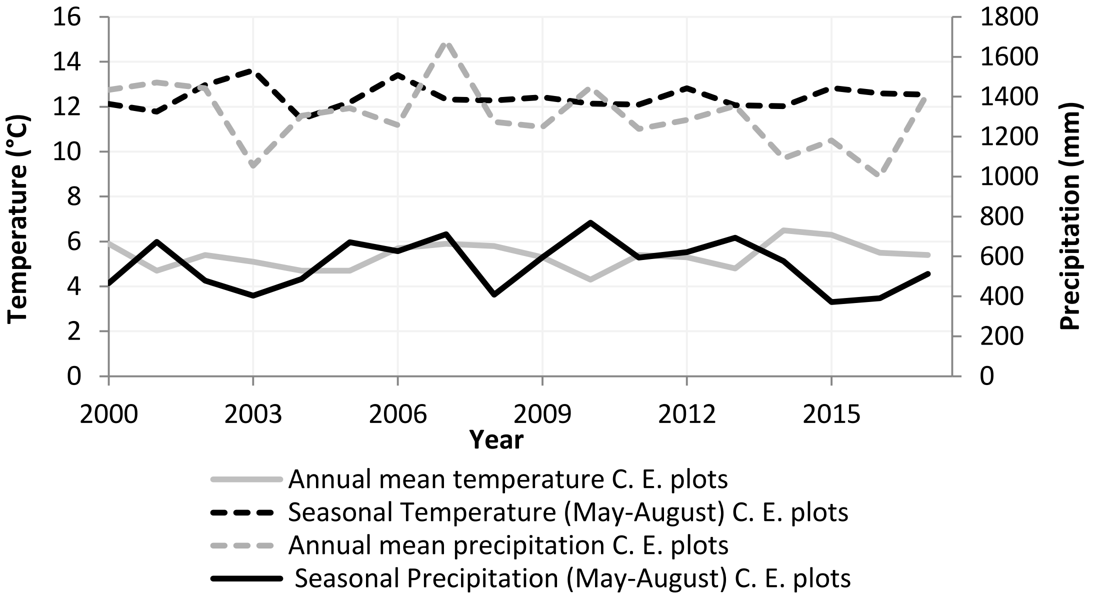

Figure 23. Dynamics of annual and seasonal temperature and annual and seasonal precipitation for the Central European sites (C. E.), according to nearby meteorological stations, for the period 2000–2017.

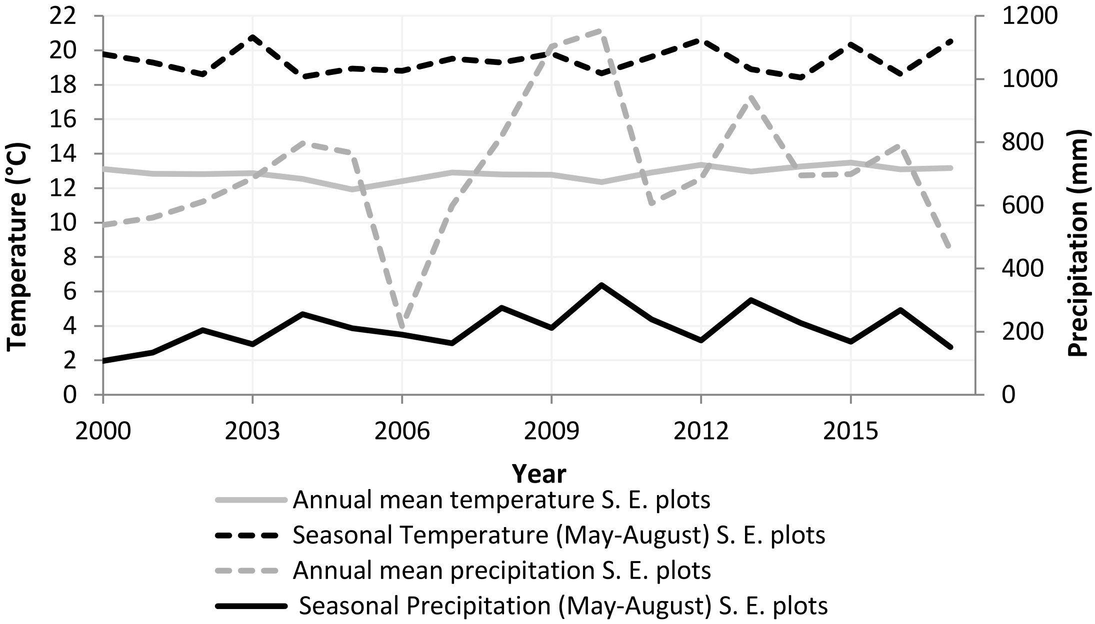

Figure 24. Dynamics of annual and seasonal temperature and annual and seasonal precipitation for the Southern European sites (S. E.), according to nearby meteorological stations, for the period 2000–2017.

3.3. Data collection

3.3.1. NDVI data

To obtain NDVI MODIS (MOD13Q1 collection 6 product) time series collections (from 2000 to 2018 in the spruce study and from 2000 to 2017 in the beech study) to discuss the possible imbalance in NDVI models across different sites, we used Climate Engine, an open source tool (Huntington et al. 2017).

This tool uses the Google Earth Engine cloud-computing platform to process satellite data on-demand using a web browser. We decided to use the MOD13Q1 product from the beginning of our research (250 × 250 m spatial resolution and 16-day composition periods). The final data from the MOD13Q1 product are calculated from atmospherically corrected bi-directional surface reflectance masked for disrupting factors such as water, clouds, heavy aerosols, and cloud shadows.

It supplies NDVI, obtained using the formula NDVI=(NIR-RED)/(NIR+RED) (Essaadia et al. 2022), values on a per-pixel basis. Pre-processing of the data set included cropping images in study areas and spatial averaging of the NDVI pixel values.

The NDVI values obtained were subsequently averaged for the entire growing season for both maximum and mean values. The resulting NDVI values were used for comparison with annual tree-ring growth.

3.3.2. Dendrochronological data

For dendrochronological analysis, 180 spruce and 180 beech core samples were taken by a Pressler borer, i.e., 30 samples per research plot.

Tree-ring samples were collected at breast height (1.3 m), perpendicular to the slope, following standard dendrochronological procedures (Schweingruber et al. 1990); each core was air-dried at room temperature, positioned, glued with vinyl-based glue, mounted on wooden slats, and polished with progressively finer sandpaper (we used three types of finer sandpaper; first, 100 grit, then 400 grit, and the last, 600 grit; sometimes we also used 1000 grit (by hand) in some cases.

The cross-dating procedure was performed by Cdendro software (CybisElectronik & Data), while tree-ring widths were measured by LINTAB (Rinntech) with an Olympus binocular magnifier. Samples were measured from bark to the pith on a scale of 0.01 mm and measuring of tree-ring data sets was processed with TSAP-Win software (Rinntech (2010)).

3.3.3. Climate data

3.3.3.1. Climate data for spruce forest plots

For the locations KA and CU, the climate data (monthly air temperatures and precipitation sums) were taken from the CHMU Neumětely meteorological station located at an altitude of 322 m a.s.l. (49°51'00"N, 14°02'24"E) and situated approximately 16 km from the KA research plot and approximately 25 km from the CU research plots. For the KO research areas, climate data, monthly air temperatures, and the sum of precipitation, were taken from the nearest CHMU meteorological station, Ondřejov (49°54'36"N, 14°46'48"E) located at an altitude of 485 m a.s.l. and situated approximately 7 km from the research areas.

The range of climate data collected was set for 2000–2018. The growing seasons for KA and CU locations are from April to October, while for the KO location, the growing season is from May to October.

In the KO location, due to the geolocation and position of the study plots and the greater extension of the forest area territory than the forest area at the KA and CU locations, where the temperature is different. In fact, the mean annual temperature at the KO site is lower than the average temperature at the KA and CU locations, and the total annual precipitation at the KA and CU locations is lower than at the KO location.

Furthermore, the KA and CU locations are drier due to the arid winds that blow in the area and the soil characteristics. Therefore, the growing season in the KO location starts later.

3.3.3.2. Climate data for beech forest plots

Climate data for all study sites were obtained from the nearest thermo-pluviometric station. In particular, the data for Central Europe forest plots were given by Bedřichov station (50°47'30.7"N, 15°08'31.7"E) located at an altitude of 780 m a.s.l.; the station is 35.5/54.3 km away from the research plots in the Czech Republic and Poland; while for the plots in southern Italy, the climate data were provided by the meteorological station in Potenza (40°37'47.9"N; 15°48'00.2"E), located at an altitude of 720 m a.s.l.

The distance between the meteorological station and SE, LL, and MV is 10, 18, and 25 km, respectively; the range of climate data collected was set for 2000–2017. The growing season for

Czech locations is from May to August and for Italian sites it is 15 days longer due to the different geolocation of the study plots.

3.3.3.3. Data analysis

Measured tree-ring width series were analyzed by using R software (R Core Team, 2018) with dplR package (Zang et al. 2018). Tree-ring chronology data sets were detrended to remove age trend and other stand-related trends and was used the negative exponential detrendation.

The detrending removes the age-related trends while preserving the low-frequency climatic variations (Shumilov et al. 2011).

The dendrochronological indicators were calculated using R software in dplR package instructions (Bunn 2018; Bunn and Mikko 2018). To indicate the reliability of chronology, the expressed population signal (EPS) was calculated (Fritts 1976b). To make dendrochronological results more precise, an "EPS cutoff" was used to reduce the dendrochronological time series. The population signal (EPS) was calculated to indicate the reliability of the chronology (Fritts 1976a). The EPS dendrochronological data set results for every research plot were EPS > 0.85 to preserve a strong climatic signal in the used chronology.

We also computed signal-to-noise ratio (SNR), which represents the strength of chronology and R-bar inter-series correlations (Fritts 1976b).

Spectral analyses for detrended radial growth were calculated using Statistica 13 software (StatSoft. 2013).

The calculation was carried out using the "Single Furier (Spectral) Analysis" function, with the output "Periodogram" plotted by "Period." The same software was also used to calculate correlation coefficients and cross-correlations. To study a multivariate spatial process between tree-ring width index and NDVI, Cross-periodograms were used (Lim and Stein 2008).

4. RESULTS

4.1. Trend of radial growth in spruce forest plots

Dendrochronological data indicated a significant limit of EPS (≥0.95) for all study sites and showed high R-bar values (≥0.39; **Table 4**). The SNR indicated that the best dendrochronological pattern (without any noise) was found in the youngest forest stand, CU2 (40.14), while the poorest was found in the oldest forest stand, i.e., in KO2 (17.68). Equally, the highest and lowest variability were observed on the same research sites. The largest mean value of tree-ring width was found at the second oldest research site, KO1 (2.26 mm), which was also nutrient-rich with the highest soil moisture content among all plots compared to compacted acid soils on the KO2 (1.45 mm), the oldest plot.

Table 4. Characteristics of tree-ring chronologies for Norway spruce in study plots. The table was prepared by D'Andrea et al. (2022).

Plot Name	No. Trees	Mean RW (mm)	Mean min—max RW (mm)	Age (Years)	Std. (mm)	ar1	R-Bar	EPS	SNR
Karlštejn 1	27	1.79	1.29–2.58	93	0.87	0.55	0.59	0.97	32.75
Karlštejn 2	30	1.61	0.99–2.25	83	0.94	0.66	0.53	0.97	28.90
Cukrák 1	31	1.65	1.09–2.63	83	0.82	0.60	0.46	0.96	22.14
Cukrák 2	27	1.94	1.15–3.20	80	1.11	0.57	0.62	0.98	40.14
Kostelec 1	28	2.26	1.22–3.34	96	0.96	0.65	0.47	0.96	21.29
Kostelec 2	30	1.45	1.03–2.17	129	0.69	0.73	0.39	0.95	17.68

Notes: No. trees—number of trees, Age—age of youngest and oldest sample trees, Mean RW—mean tree-ring width, Std.—standard deviation, ar1—first order autocorrelation, R-bar—inter-series correlation, EPS—expressed population signal, SNR—signal-to-noise ratio.

Regarding the tree-ring width index (RWI), very low increments were found for 2000, 2007, 2017, and 2018 at the KA and CU sites. At the KO location, tree-ring chronology showed the highest depression for the years 2000, 2004, 2017, and 2018. On the other hand, the highest RWI values were observed in 2002, 2012, and 2014 for all study plots except for the KO2 location. Concerning the dynamics of RWI, the highest similarity between study plots was found in KA, while the highest variability was observed in KO.

4.2. Trend of radial growth in beech forest plots

Dendrochronological data showed a significant limit of EPS (≥0.88) for all research plots and indicated high R-bar values (≥0.24; **Table 5**). The SNR showed that the best dendrochronological pattern (without any noise) was found in CO1 (16.65), and the poorest was found in RY27 (7.94). The highest mean value of tree-ring width was found in SE (2.33 mm), while the smallest value of tree-ring width was found in RY27 (1.01 mm; **Table 5**).

Table 5. Characteristics of tree-ring chronologies for beech in research plots.

Plot Name	No. Trees	Mean RW (mm)	Age (Min/Max)	Std. (mm)	R-Bar	EPS	SNR
Chojník 1	29	1.99	90–123	1.05	0.40	0.94	16.65
Rýchory 2	33	1.05	103–182	0.52	0.25	0.91	11.34
Rychory 27	34	1.01	96–189	0.48	0.29	0.88	7.94
Sellata 3	40	2.33	94–152	1.08	0.25	0.94	18.81
La Lama 4	38	1.73	125–247	0.84	0.34	0.92	12.39
Monte Volturino 5	41	1.34	109–244	0.63	0.24	0.89	8.70

Notes: No. trees—number of trees, Mean RW—mean tree-ring width, Age—age of youngest and oldest sample trees, Std.—standard deviation, R-bar—inter-series correlation, EPS—expressed population signal, SNR—signal-to-noise ratio.

Dynamics of tree-ring width index (RWI) did not show similar increments for all plots. The year 2011 indicated less radial growth for RY2 (RWI = 0.433) and RY27 (RWI = 0.570), while 2003 is the year with the lowest radial growth for CO1 (RWI = 0.559). On the other hand, the highest

RWI was observed in years 2001 for RY2 (RWI = 1.473) and RY27 (RWI = 1.517), while 2013 was the year with the highest RWI for CO1 (RWI = 1.381).

Regarding the dynamics of the RWI Italian plot, the year 2016 indicated less radial growth for SE (RWI = 0.462) and MV (RWI = 0.595), while 2013 was the year with the lowest radial growth for LL (RWI = 0.499). On the other hand, the highest RWI was observed in years 2010 for SE (RWI = 1.488) and LL (RWI = 1.455), while 2009 was the year with the highest RWI for MV (RWI = 0.595).

4.3. Relationships between tree-ring growth and NDVI in spruce forest study

RWI and NDVI (**Figure 25**) did not show a common trend in the data. In fact, low values of NDVI did not occur in equal years among single study plots and locations, an example being the years 2009 and 2012, where lower values of NDVI were registered.

These NDVI time values from 2009 to 2012 were completely different from the concurrent RWI values across the research areas.

There was no similarity in trend between the NDVI and RWI values, although, in one location, CU1, the mean of the NDVI and RWI values over the period 2013 to 2018 showed similar decreasing values.

Also, for the CU2 site, the mean NDVI and RWI values were similar for the period 2012 to 2014.

The differences in dynamics of NDVI and RWI were most pronounced in the KO1 study site from 2008 to 2018, where the maximum NDVI had completely reversed values to RWI.

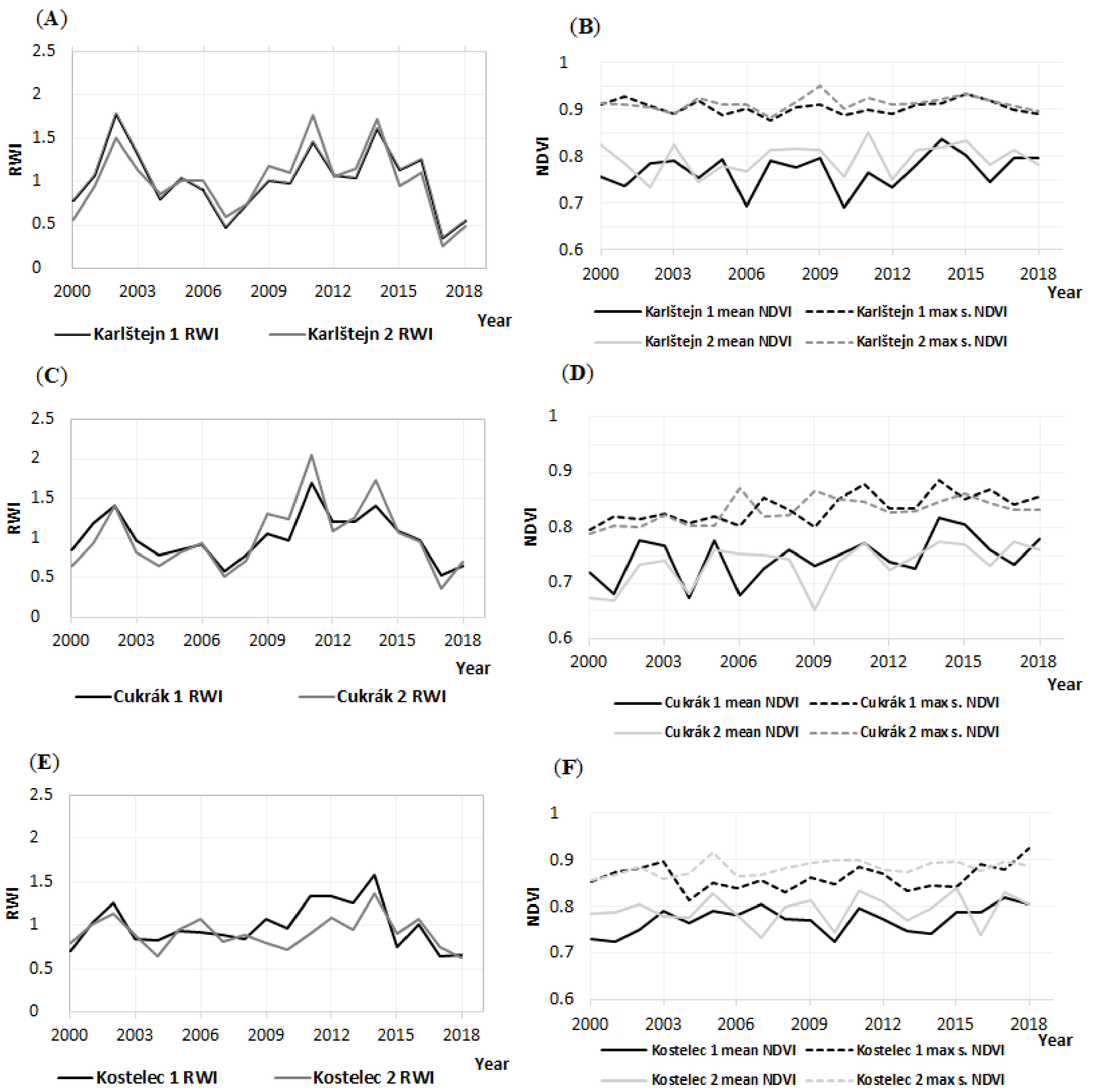

Figure 25. Description of tree-ring width index (RWI) and normalized difference vegetation index (NDVI) for the period 2000–2018. (**A**): RWI for 2000–2018, Karlštejn 1 and 2; (**B**): mean and maximum NDVI values for 2000–2018, Karlštejn 1 and 2. (**C**): RWI for 2000–2018, Cukrák 1 and 2; (**D**): mean and maximum NDVI values for 2000–2018, Cukrák 1 and 2. (**E**): RWI for 2000–2018, Kostelec 1 and 2; (**F**): mean and maximum NDVI values for 2000–2018, Kostelec 1 and 2. Notes: s.—growing season. The figure was provided by D'Andrea et al. (2022).

Concerning the relationship between RWI and NDVI, maximum seasonal NDVI values during the growing season from all study sites were more correlated with each other, in relation to the correlation and *p*-value, than mean NDVI values, but the correlation was not significant ($p < 0.05$; **Table 6**). NDVI reported higher *p*-values that were far from the limit of significance ($p < 0.05$). The KO1 and KO2 research plots showed the lowest correlation coefficients with NDVI values, while the KO1 location indicated opposite results (negative correlation coefficients) compared to the other study plots. Maximum seasonal NDVI values correlated with higher opposite radial growth values more than with temperatures at the KA and CU study plots (but these were only four study plots out of six). In some cases, correlation coefficients for maximum seasonal NDVI were higher compared to the temperatures, and the maximum seasonal NDVI had a lower *p*-value. For this spruce study, were also calculated cross-correlation variants with +5-year and -5-year lag, but the results of this analysis indicated no significant relationship between NDVI and RWI in the study plots.

Table 6. Correlation coefficients for tree-ring width index (RWI) at research plots to NDVI, temperature, and precipitation. Significant correlation values are in bold; correlations are significant at $p < 0.05$. The table was provided by D'Andrea et al. (2022).

Plot Name	Mean NDVI	Mean Seasonal NDVI	Max Seasonal NDVI	Annual Temperature	Seasonal Temperature	Annual Precipitation	Seasonal Precipitation
Karlštejn 1 RWI	0.36	0.10	0.29	-0.11	-0.28	0.40	0.44
p-value	*0.13*	*0.68*	*0.23*	*0.64*	*0.25*	*0.09*	*0.06*
Karlštejn 2 RWI	0.01	0.10	0.33	-0.24	-0.40	**0.49**	0.59
p-value	*0.95*	*0.68*	*0.17*	*0.33*	*0.09*	***0.03***	*0.08*
Cukrák 1 RWI	0.29	0.18	0.26	-0.13	-0.30	**0.55**	**0.62**
p-value	*0.23*	*0.45*	*0.29*	*0.61*	*0.22*	***0.02***	***0.01***
Cukrák 2 RWI	0.16	0.15	0.39	-0.13	-0.30	**0.57**	**0.67**
p-value	*0.55*	*0.54*	*0.10*	*0.60*	*0.22*	***0.01***	***0.01***
Kostelec 1 RWI	-0.36	-0.26	-0.08	-0.30	**-0.53**	**0.50**	**0.59**
p-value	*0.13*	*0.28*	*0.75*	*0.21*	***0.02***	***0.03***	***0.01***
Kostelec 2 RWI	0.06	0.22	0.01	0.04	-0.15	0.43	**0.50**
p-value	*0.80*	*0.37*	*0.95*	*0.87*	*0.55*	*0.07*	***0.03***

4.4. Relationships between tree-ring growth and NDVI in beech forest study

RWI and NDVI did not show a common trend in the data for the entire time frame (**Figure 26**; **Figure 27**). In most years, low NDVI values did not occur in the same years between individual research plots and locations, for example, in 2010 or 2013, when the low NDVI values were recorded. These NDVI values were completely different from the simultaneous RWI values in the research areas.

Exceptionally, for short periods, such as from 2014 to 2016 in the case of CO1, from 2014 to 2017 for RY2 and RY27, from 2004 to 2008 for LL, from 2000 to 2003 for CO1, RY2, and MV, and from 2011 to 2014 for the Italian locations, the mean of NDVI and RWI had similar values.

In addition, the mean seasonal NDVI and RWI had similar values from 2014 to 2017 in the case of RY2 and RY27, from 2003 to 2006 for RY27, and from 2015 to 2017 for SE. In general, the mean NDVI was more correlated for more periods than the seasonal mean NDVI, and the maximum NDVI had opposite values to RWI.

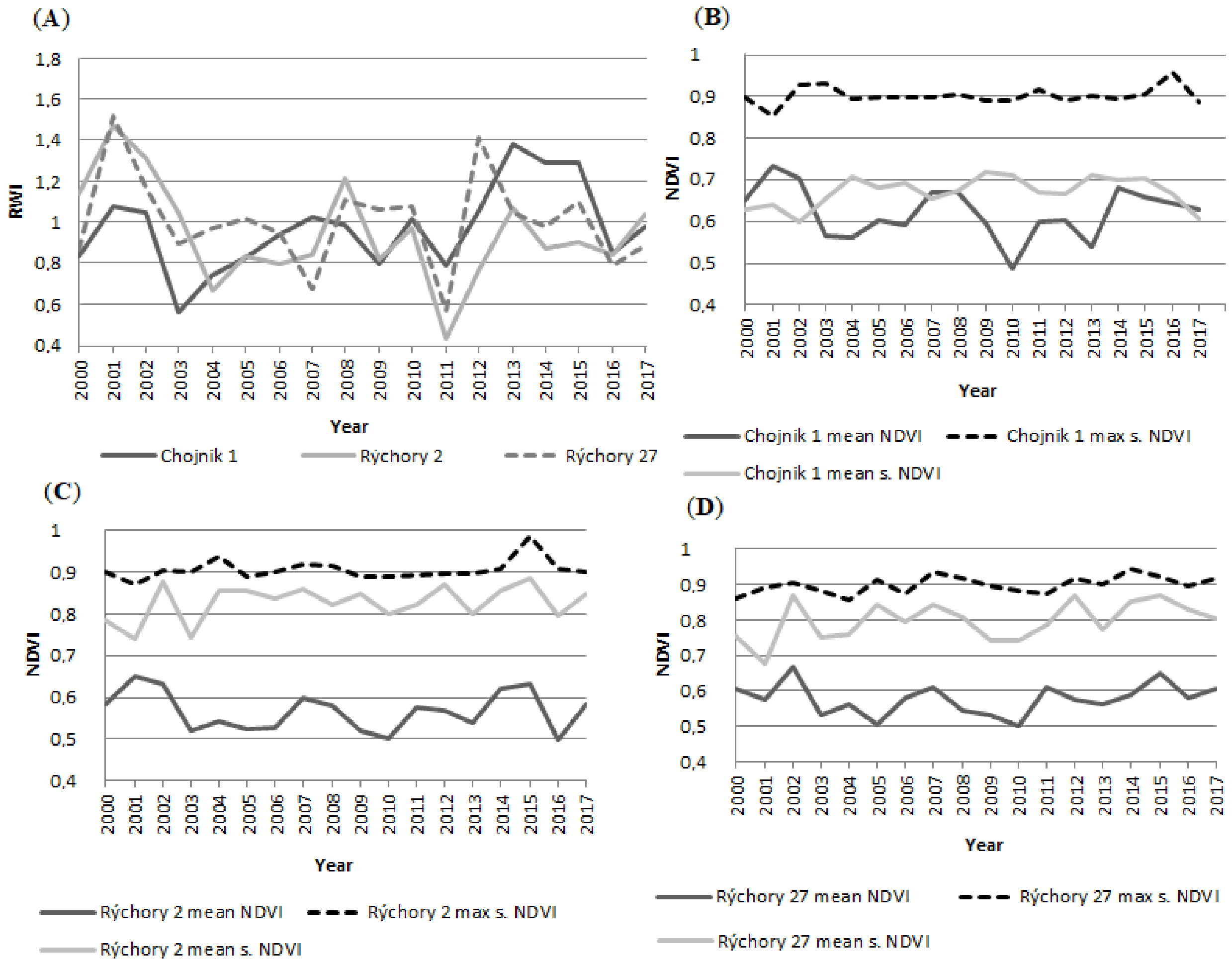

Figure 26. Description of tree-ring width index (RWI) and normalized difference vegetation index (NDVI) for 2000–2017. (**A**): RWI for 2000–2017, Chojnik 1, Rýchory 2, and Rýchory 27; (**B**): mean and maximum NDVI values for 2000–2017, Chojnik 1. (**C**): mean and maximum NDVI values for 2000–2017, Rýchory 2. (**D**): mean and maximum NDVI values for 2000–2017, Rýchory 27. Notes: s.—growing season.

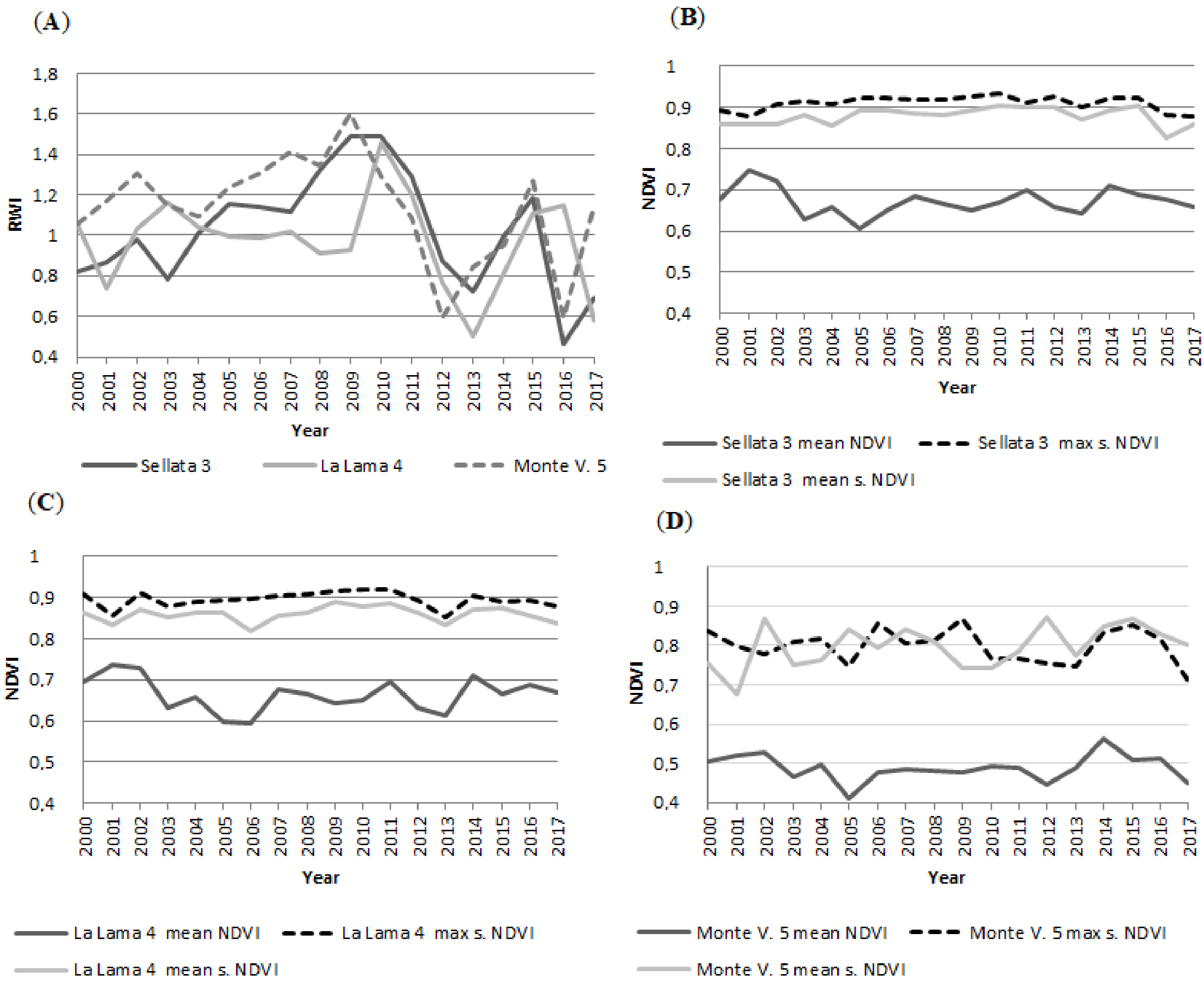

Figure 27. Description of tree-ring width index (RWI) and normalized difference vegetation index (NDVI) for 2000–2017. (**A**): RWI for 2000–2017, Sellata 3, La Lama 4, and Monte Volturino 5; (**B**): mean and maximum NDVI values for 2000–2017, Sellata 3. (**C**): mean and maximum NDVI values for 2000–2017, La Lama 4. (**D**): mean and maximum NDVI values for 2000–2017, Monte Volturino 5. Notes: Monte V.— Monte Volturino; s.—growing season.

Regarding the relationship between RWI and NDVI, according to the correlation, maximum seasonal NDVI values from all sites were more correlated with each other than mean NDVI values, but the correlation was significant only for SE and LL sites ($p < 0.05$; **Table 7**). These two Italian plots also showed significant correlations between RWI and mean seasonal NDVI. While the Czech sites did not show any significant correlations between RWI and NDVI, RY2 and RY27 in particular, indicated the lowest correlation coefficients with NDVI. Regarding the correlations between RWI and temperature and precipitation, the results did not show any significant correlations. However, the values of annual mean precipitation were positively correlated (but not significant) compared with annual mean temperature, where all values were negative (except for CO1).

Table 7. Correlation coefficients for tree-ring width index (RWI) at research plots to NDVI, temperature, and precipitation. Significant correlation values are in bold; correlations are significant at $p < 0.05$.

Plot Name	Mean NDVI	Mean Seasonal NDVI	Max Seasonal NDVI	Annual Mean Temperature	Seasonal Mean Temperature	Annual Mean Precipitation	Seasonal Precipitation
Chojnik 1 RWI	0.24	0.17	-0.28	0.29	-0.18	0.18	0.25
Rýchory 2 RWI	0.41	-0.40	-0.22	-0.09	0.04	0.30	-0.10
Rýchory 27 RWI	-0.11	-0.12	0.13	-0.28	-0.03	0.11	0.14
Sellata RWI	-0.03	**0.74**	**0.75**	-0.41	-0.10	0.35	0.30
La Lama RWI	0.05	**0.54**	**0.64**	-0.31	-0.14	0.21	0.25
Monte Volturino RWI	-0.09	0.06	0.31	-0.42	0.01	0.06	-0.09

4.5. Effect of climate on radial growth in spruce forest study

In general, when comparing NDVI, temperature, and precipitation with RWI, the highest correlation was found for precipitation in the growing season, except for the KA location (higher correlation for annual precipitation). Regarding temperature, RWI showed only one significantly ($p < 0.05$) negative correlation with temperature during the growing season. Regarding the significant correlation coefficient values, precipitation values showed a major effect on RWI for spruce, and furthermore, the correlation coefficients that were not significant showed high r and had low *p*-values.

Relevant changes in the RWI of spruce are recorded in **Figure 28**. The pointer years reported fluctuations in the RWI of spruce. Positive and negative growth periods alternated after four to seven years. The KA1 study site reported the highest number of pointer years (only negative ones). For KA1, the negative pointer years were 2007, 2017, 2018, and 2019. KA2 also recorded negative pointer years in 2017 and 2018. The negative pointer year 2018 was historically the hottest growing season since 1941 (10.5 °C; long-term mean annual temperature 8.5 °C) with less precipitation (454 mm; mean 543 mm).

For the CU1 location, 2017 was the only negative pointer year, while CU2 had only two pointer years, 2011 (positive) and 2017 (negative). The latter negative pointer year (2017) corresponds with the same year when there was a similarity between mean NDVI and spruce growth. Similarly, 2017 was below average in terms of precipitation and above average in terms of temperature (501 mm, 9.6 °C), especially during the growing season.

KO1 reported only one negative pointer year, 2015, while KO2 did not show any pointer years.

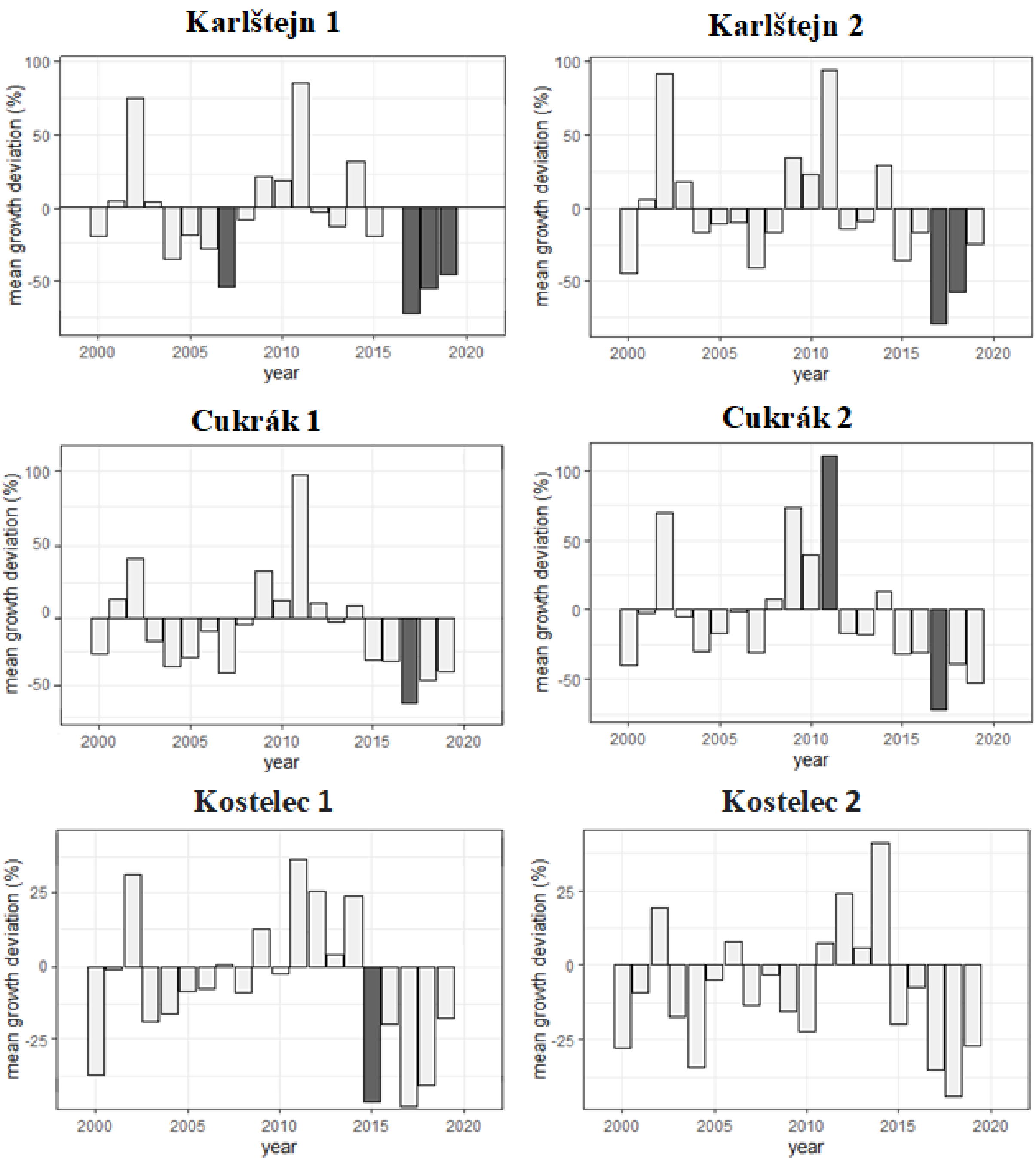

Figure 28. Pointer years (relative growth change) for Norway spruce (2000–2018); dark gray bars—pointer years; light gray bars—mean growth deviation. The figure was taken from D’Andrea et al. (2022).

4.6. Effect of climate on radial growth in beech forest study

Relative changes in the growth of European beech tree rings are recorded in **Figure 29**. The pointer years indicated fluctuations in the radial growth of beech. The only negative pointer year was 2012 for MV. This year was the year with the least radial growth for the location.

For all study sites, the year with the least radial growth coincides with negative pointer years, but they were not significant.

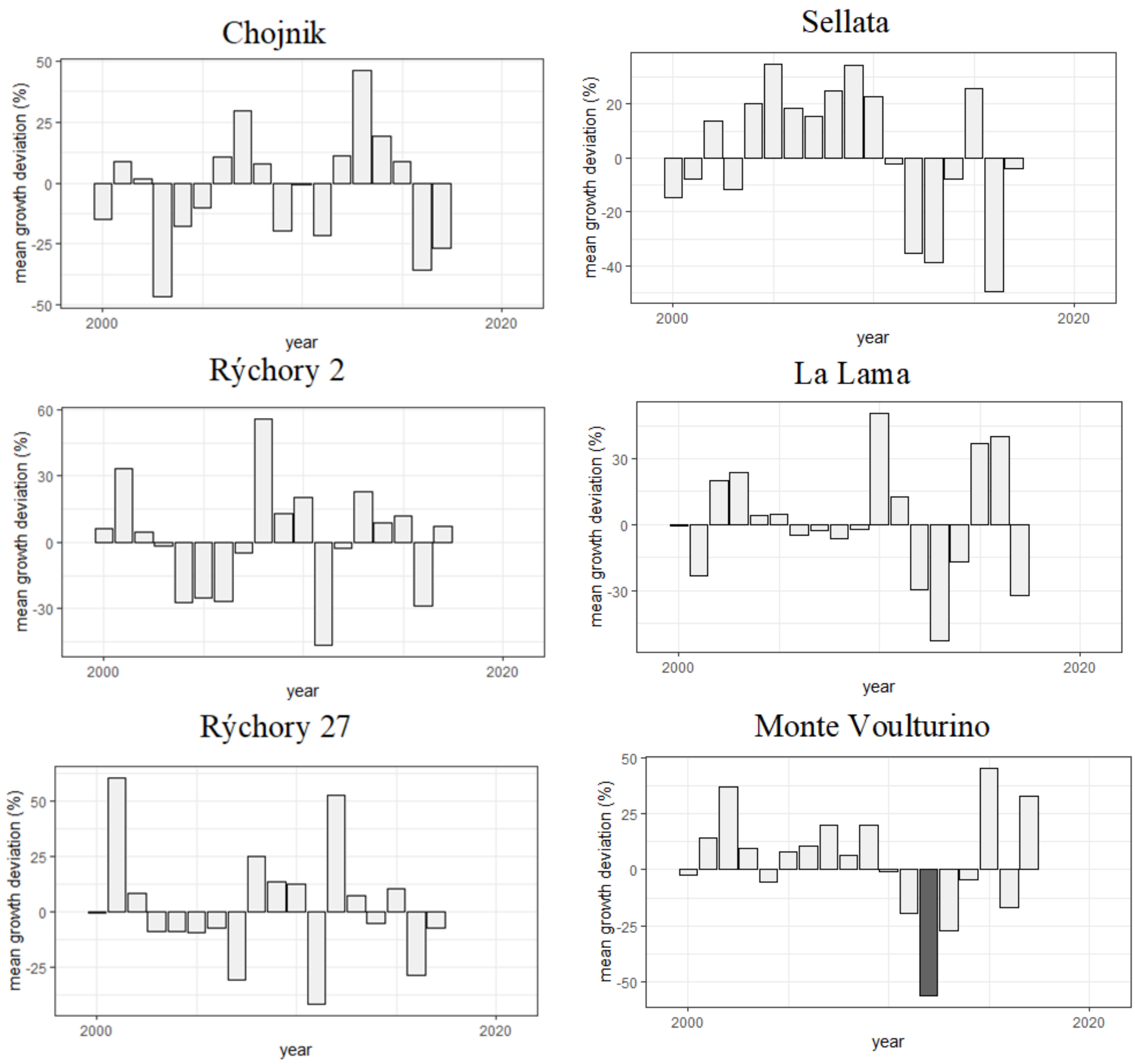

Figure 29. Pointer years (relative growth change) for European beech (2000–2017); dark gray bars—pointer years; light gray bars—mean growth deviation.

5. DISCUSSION

5.1. Trend in radial growth of spruce forests

The RW of spruce sites studied ranged from 1.45 to 2.26 mm, whereas the highest radial growth was obtained at the location with the best soil water stock (KO1). For comparison, a significantly higher mean RW of spruce (mean 2.41 mm) was gotten in the Krkonoše Mountains in a mixed stand of similar age (with mean annual precipitation of 1200 mm) (Hájek et al. 2021). Norway spruce, in general, prefers cool and humid climatic conditions (Tjoelker et al. 2007; Caudullo et al. 2016), due to its features, this economically precious tree species may hardly be affected in the case of intense warming (Bugmann et al. 2014).

In most of the research forest sites, radial growth indicated 2017 as the year with the least growth (except for the KO2 location). This result can be explained by the discoveries of Rita et al. (2020), who recorded that from mid-July 2017, many countries in Europe were exposed to a long period of drought. In the KO1 location, 2003 was the year with the least radial growth, and that year (for Central Europe) was also the year with the warmest summer in the last 500 years until 2010 (Schär et al. 2004; Ciais et al. 2005; Garcia-Herrera et al. 2010).

A decrease in tree ring growth happens also in the year following one in which water stress followed (Rybníček et al. 2012a). The year 2004 could be an example of this situation for the KA, CU, and KO2 study sites. As mentioned above, the summer of 2003 was the hottest in over 500 years for Central Europe, which probably had consequences for radial growth in the following year. Furthermore, this also corresponds with the data obtained from thermo-pluviometric stations. Indeed, precipitation in the year 2003 reached only 60 percent of normal, which was 334 mm over the entire year and 249 mm over the growing season for the KA and CU locations, and 472 mm over the whole year and 309 mm over the growing season for the KO location. These values are well below the optimum amount of precipitation for the growth of spruce (Caudullo et al. 2016).

In this GCC context, we need by management options to increase the biodiversity (from monospecific to polyspecific stands) to enhance their resistance and resilience, especially in forests most vulnerable to drought.

In fact, spruce in mixed stands is more tolerant to unfavorable environmental circumstances such as pollution and climate extremes than monospecific stands. In terms of GCC, it is essential to strengthen forest tolerance to extreme weather events by enhancing structural variety and preserving species richness (Vacek et al. 2019).

5.2. Trend in radial growth of beech forests

In Central Europe, beech stands have shorter growing seasons than in the Mediterranean, reflected in the radial growth size. The tree-ring width of European beech in the studied areas in Central Europe ranged from 1.01 to 1.99 mm, while in Southern Europe ranged from 1.34 to 2.33 mm. The highest radial growth in Southern Europe plots was reached at the site SE (2.33 mm), while in Central European plots, the highest radial growth was reached in CH1 (1.99 mm).

European beech had a considerable increment of radial growth in sites at lower altitudes compared to sites located at higher altitudes; moreover, radial growth decreases with increasing altitude in both in the Central European and Southern European study sites.

These results are unexpected in this scenario of GCC because due to the increase in temperature, the growing season at higher altitudes will be prolonged and this should be beneficial for forests located at higher altitudes, but our study showed the opposite results.

In fact, higher-altitude sites showed less radial growth in comparison to sites at lower altitudes. This result was also corroborated by Dittmar et al. (2003), who analyzed growth-climate relationships of 36 beech stands in Central Europe and discovered that almost all sites showed a reduction of radial growth rate at higher altitudes and an increase of radial growth rate at lower altitudes. The author reports that it seems that beech forests at higher altitudes during the growing season over the last couple of decades are more sensitive against late frost than previously (Tonelli et al. 2023) and unfavorable conditions of weather like cold, wet, and cloudy (Dittmar et al. 2003).

Moreover, we expected higher increments in plots in Central Europe than plots in Southern Europe, yet in our case, the research showed the opposite results.

An important factor that influenced the radial growth consistency at both Central European plots and Southern European plots is altitude, in fact, a higher value of radial growth, and it was found in areas situated at lower altitudes compared to those at higher altitudes.

For comparison, a very similar beech RW mean (mean 2.2 mm) like at the Sellata locations was reached in a study conducted in Slovenia for a forest stand of European beech (called Mašun), with mean annual precipitation of 1609 mm, which takes into consideration the three wettest years of the period 1960–2016; while the same RW mean of MV (mean 1.3 mm) was reached in a location called Idrija, with mean annual precipitation of 2090 mm from the same study mentioned above, but in this case, the three driest years of the same period (1960–2016) were considered. In Central European plots, the highest radial growth was reached in CH1 (mean 1.99 mm) and similar RW (mean 2.1 mm) was reached in a location called Javornik with mean annual precipitation of 1514 mm from the same study conducted in Slovenia. However, in Slovenia, the three wettest years of the same period (1960-2016) were considered, while similar RW mean of RY27 was reached in a location called Mašun (mean 1.1 mm) where the driest three years of the period (1969–2016) were considered. All Slovenian plots have a similar altitude between 904 and 958 m a.s.l. (Arnič et al. 2021).

In most of the Central European studied forest stands, the documentation of the radial growth showed that 2011 was the year with the least radial growth, except for the CH1 location, where 2011 was the year with the least radial growth following 2003 and 2004. This result can be explained by the report of Šimůnek et al. (2019), who documented that from May 3 to May 8 in 2011, the air temperature was -8 °C, these extreme frosts that occurred in late spring seriously damaged the fresh budding leaves, and consequently, negatively affected the entire growth of the European beech in the 2011 season.

In the CH1 location, the year with the least radial growth was 2003. This result can be explained by Garcia-Herrera et al. (2010) who documented that in Europe, 2003 was the year with the hottest summer in the last 500 years. Furthermore for the CH1 location, 2003 shows a very low value of mean seasonal precipitation (403 mm) and the highest values of seasonal temperature (13.7 °C) of the entire period (2000–2017); these values are well below the optimal temperature for beech growth (Pezzi et al. 2008).

The warmest summer in over 500 years that occurred in year 2003 in Central Europe, as previously mentioned, had repercussions for radial growth in the following year. As a matter of fact, 2004 was the year with the least radial growth after 2003 for CH1. The excessive drought occurred in 2003 when most of the annual wood production of the same year was already completed (Dulamsuren et al. 2017).

In most of the Southern European forest stands studied, the description of the radial growth showed that 2016 had the lowest value of RWI except for the LL site, where 2013 experienced the lowest value of radial growth, followed by 2017. This result can be explained by comparing it with the report of Nolè et al. (2018), who documented that a late spring frost disturbance occurred during spring 2016 in southern Italy that affected montane beech forests.

Furthermore, not all plants and forests suffer the same amount of damage as a result of an extreme weather event. Actually, the potential damage of a late frost is strongly correlated with specific sites, minimum temperatures, and the phenological status of the affected plant (Dittmar et al. 2006).

In the LL location mentioned above, 2013 had the least radial growth; an explanation for the lowest radial growth could be the low value of precipitation during the growing season (172 mm) of 2012, accompanied by high seasonal temperatures (of the previous year 2012) (20.6 °C). 2012 had the highest value of seasonal temperature, second only to 2003 (seasonal temperature 20.7 °C). As mentioned above, 2003 was characterized by the hottest summer in over 500 years.

In the LL location, 2017 was the second year with the lowest radial growth after 2013; this result can be explained by what Rita et al. (2020) reported, who recorded that, from mid-July 2017, many European countries were affected by a prolonged period of drought. Moreover, this also coincides with the data provided by thermo-pluviometric stations. In 2017, the seasonal temperature was 20.5 °C, while seasonal precipitation reached only 150.6 mm. These values are well below the optimal amount of precipitation for beech.

Interestingly, in Southern Europe, beech reaches its growth optimum at sites where the annual precipitation exceeds 1500 mm, while values around 800 mm per year are considered the minimum limit (Ebone et al. 2012), and in our study, the recorded value is 457 mm. This value is far below the minimum value that beech requires.

In most of the Southern European forest stands studied, the description of RWI showed that 2010 was the year with the highest radial growth (except for the MV location, where 2009 was the year with the highest value of radial growth). This result can be explained by values of annual mean precipitation (1153.8 mm) and by the value of seasonal precipitation (347.8 mm); these values are the highest of the observed period (2000–2017).

The year 2009 showed the highest value of RWI for the MV location. Moreover, in 2009, the value of annual mean precipitation (1102.8 mm) was the second highest only after 2010.

Levanič et al. (2023) reported the best radial growth of *Fagus sylvatica* is found on the plots characterized by high levels of precipitation (and summers characterized by moderately hot temperatures); in particular, the rainfall during July positively influences the radial growth of beech (Adamič et al. 2023). However, other variables affect beech radial growth, such as soil type, nutrient presence, masting events, competition, and insect infestation most of which are very difficult to predict (Martinez et al. 2022).

In this GCC setting, especially in drought-prone forests, it is clear that silvicultural operations and management approaches must be applied to create polyspecific stands in order to prevent damage and safeguard and preserve the forest for future generations. It is known that mixed forests reduce the sensitivity of beech to drought, especially during the growing season (Novosadová et al., 2023).

5.3. Low similarity between tree-ring growth and NDVI in spruce forests

The relationship between the growing process and NDVI depends on the period range considered. During specific periods in the growing season, radial increment—as reported by precedent works – may show higher correlations (Andreu-Hayles et al. 2011). In our study, maximum seasonal NDVI values in the growing season were more correlated than mean NDVI for most study sites. Nevertheless, there was not any significant correlation found between NDVI and annual ring width.

As observed by several authors, the relationships between these two indicators are unclear. Vicente-Serrano et al. (2016) focused on relationships between NDVI and tree-ring growth from 155 plots worldwide using data from the "International Tree Ring Data Bank" and GIMMS3g NDVI time series. The authors found a generally positive correlation but also high site-to-site inhomogeneity, due to the diversity in local climate and forest typologies (D'Arrigo et al. 2000). However, other authors (Lawrence et al. 2005; Beck et al. 2013) found an insignificant correlation between NDVI and RWI.

Our results agree with the findings reported by Rita et al. (2020) that the NDVI led us to discover the areas most sensitive to drought. In our study sites most vulnerable to drought (KA and CU) were found to show a higher correlation with NDVI data in comparison to the less arid locations (KO), even if the correlation was statistically insignificant.

The NDVI is normally applied in phenological studies within different buffer zones. NDVI values are sensitive to certain types and quantities of vegetation (Martinez and Labib 2023). Nevertheless, NDVI has its limits; the (relatively) short-term (since 2000) monitoring of this indicator, when data was usable from the MOD13Q1, can exhibit serious limitations. NDVI can be influenced by background problems, path radiance, and saturation effects, particularly in dense canopies (Hmimina et al. 2013). The mentioned differences in insufficient time series and surface irradiance could be one possible explanation for the lack of correlation between NDVI data and RWI data. Study sites in this work have enough density, characterized by dense canopies that are appropriate for studying correlations between NDVI data and spruce radial growth. However, this tree species must be highlighted when compared to NDVI for its relevance in Central European countries. The relationship between RWI and NDVI is different throughout various landscapes and between tree types (coniferous versus deciduous), spatial resolutions, cumulative NDVI periods, and bioclimatic zones (Testa et al. 2014). The insignificant correlations between NDVI and annual radial growth could also suggest that this indicator is unsuitable for Norway spruce. In fact it is a coniferous evergreen tree that gets stressed for an extended time period, and thus, the differences in the annual reflectance of the tree crowns may not be visible enough. A characteristic example can be observed with other tree species, particularly broadleaved ones such as *Betula papyrifera*, which shows a high correlation between NDVI data and RWI (Bumann et al. 2019), as well as for *Quercus* spp. (Wang et al. 2004).

5.4. Relationships between tree-ring growth and NDVI in beech forests

The relationship between tree-ring growth and NDVI depends on the time interval. During specific periods in the growing season, radial increment—as demonstrated by previous works—may show higher correlations (Andreu-Hayles et al. 2011).

In our case, NDVI values differ between locations in Central and Southern Europe. In particular, Italian plots show positive values of maximum seasonal NDVI and mean seasonal NDVI, while the Italian plots located at lower altitudes also have significant correlations compared to Central European plots.

The inconsistent correlations between NDVI and RWI in Central European plots could also indicate that this index is not reliable for the study of forests located in non-arid areas, such as those of southern Italy. Our results coincide with the findings reported by (Rita et al. 2020). Likewise, our study found higher correlations in southern Italian plots (more susceptible to drought).

The effects of drought were also evident in the relationship between NDVI and RWI in study plots. For example, drought in 2003 was reflected in the summer NDVI signal, whereas there was no clear correlation between summer NDVI and RWI in non-drought years. The same results were also found by Meyer et al. (2020).

We did not find a clear relationship between RWI and NDVI values in the years where beech plots were affected by frost, such as in 2011 for RY2 and RY27, while for 2016, where the SE site was affected by frost, we found a clear relationship between RWI and NDVI; a clear relationship between NDVI and frost was also found by Nolè et al. (2018) in the Mediterranean beech forest. Our results may also indicate that this index is unsuitable for European beech forests located in non-arid area such as the studied forests in Southern Europe.

Although beech forests have a high resilience in terms of development capacity in response to late spring frost (Príncipe et al. 2017), the combination of successive severe occurrences may significantly impair the species resistance.

The impacts of spring frost may have a detrimental effect on forest carbon absorption due to defoliation of the forest, NDVI is used as a proxy for forest productivity. According to recent reports by Bascietto et al. (2018) and Príncipe et al. (2017), the observed decline in NDVI and the shortening of the growing season may diminish forest production by 7–14%. Additionally, a second flush of buds during the same growth season causes the plant's carbon supply to become depleted. Thus, in the mountainous Mediterranean area, the increasing occurrences and duration of extreme events, such as the spring frost of 2016 followed by the summer heat wave of 2017 (Di Giuseppe et al. 2017), can reduce forest productivity while also affecting species resilience.

5.5. Radial growth and climatic conditions for spruce forests

The highest correlation was found between radial growth and precipitation, compared to temperature or NDVI. Precipitation in the growing season had the most profound effect on the growth of spruce. Water deficit causes the formation of stricter tree rings. Inadequate precipitation causes a reduction in net photosynthesis as nutrient transfer slows down, and accordingly, growth and cell division are also slowed (Fritts 1966; Bhuyan et al. 2017). Adequate precipitation allows trees to use the nutrients utilized in the initial development of the formation of tree rings. During the growing season, precipitation is more of a limitative factor at lower and middle elevations than at higher ones (Rybníček et al. 2012b). However, the limiting effect of low temperatures is more important at higher elevations (Mäkinen et al. 2002; Králíček et al. 2017).

In our case, air temperature during the growing season indicated a significantly negative correlation with radial growth. High temperatures during the growing season cause moisture stress and, hence, a decrease in growth (Barber et al. 2000; D'Arrigo et al. 2004; Miyamoto et al. 2010; Aakala and Kuuluvainen 2011). With high temperatures, raised evapotranspiration causes plants to minimize water losses, close stomata, and decrease net photosynthesis (Kozlowski and Pallardy 2002). An increment of more than 3 °C in average monthly temperature during the growing season is dangerous (Grabařová and Martinková 2000).

The results of spectral analysis of pointer years for Norway spruce also indicated that the most negative years were recorded at study plots with a low level of water supply (Karlštejn followed by Cukrák), while on the KO locations with higher moisture, had recorded for just one pointer year. The period from 2015 to 2018 recorded the most negative pointer years, when the Czech Republic was at the beginning of the bark beetle outbreak due to increased salvage logging caused by long-term dryness with extremely high temperatures (Vacek et al. 2018a; Šimůnek et al. 2020). In general, the frequency of negative pointer years increased during the later years of our study. Equally, an increasing number of negative pointer years with very low radial growth was found for spruce in the Krkonoše Mts. in relation to the scenario of GCC (Hájek et al. 2021). Norway spruce is a species sensitive to drought and changes in groundwater due to its shallow root system (Caudullo et al. 2016). The vitality of the root system accordingly derives from the disposability of water during the growing season of the previous year (Kolář et al. 2020).

5.6. Radial growth and climatic conditions for beech forests

We found a positive correlation between radial growth and annual mean precipitation in all plots (correlations were not significant) and negative correlations between RWI and annual mean temperature except CH1 (also here, correlations were not significant). Precipitation during the growing season had the most significant effect on radial growth in beech stands. Our results are in line with other studies which reported that the main growth driver of European beech in Europe is water availability (Hacket-Pain et al. 2016; Cavin and Jum 2017; Roibu et al. 2017, 2022; Arnič et al. 2021; Camarero et al. 2021; Dorado-liñán et al. 2022; Martinez et al. 2022).

It is well known that elevated temperatures cause an increase in evapotranspiration, thus affecting the physiological mechanisms of tree growth (Leuschner 2020). In the case of increased evapotranspiration and lack of water availability during the growing season, there are reductions in radial growth and vitality that directly affect the cell development, xylem embolism, phloem velocity, or indirectly, the activity of photosynthesis, transpiration, and nutrition of the tree (Dorado-Liñán et al. 2017)

Furthermore, air temperatures during the previous summer period and precipitation from the previous year may trigger masting events in the following season, reducing stem growth by decreasing tree carbohydrates (Hacket-Pain et al. 2016). It is well known that beech trees, during long periods of drought, deplete the water reserves of the soil very quickly, increasing the stress caused by drought (Leuschner 2020).

Similar patterns have been found in the region of Bavaria (Meyer et al. 2020), Moldavia, and eastern Romania (Roibu et al. 2017) and also in southern populations on the borderline of the species distribution (Camarero et al. 2021). Furthermore, long periods of drought are known to induce metabolic imbalances by mobilizing soluble sugars (NSCs) from starch stores to protect cells from dehydration and defend trees against pathogen attacks (Leuschner 2020).

The increase in the frequency of very long drought periods depletes these reserves, causing reduced radial growth in the current year. Furthermore, even dry soils could be an additional stress factor for the beech roots, which are damaged and consequently, due to the reduction in hydraulic conductivity, also affect the stem growth (Liese et al. 2019).

6. CONCLUSION

The present study focused on the main coniferous and broadleaves species in the Czech Republic, specifically Norway spruce and European beech, in the current context of the GCC.

In particular, the overall goals of the study were:

1) to investigate the dynamics of radial growth of Norway spruce forests located at lower altitudes and the beech forests in different vegetation zones;
2) to investigate the effect of climate factors (temperature and precipitation) on radial growth of studied species;
3) to analyze the relations between NDVI and RWI.

Regarding the goals, our findings are as follows:

1) Despite the low altitudes, if the Norway spruce grows on soils with an adequate water availability (whether it derives from the particular microsite character or from sufficient precipitation), as in the case of the KO1 site, a satisfactory growth is reported.

   European beech had substantial values of radial growth in sites located at lower altitudes compared to the sites located at higher altitudes. Therefore, radial growth decreases with increasing altitudein both Central European and Southern European study sites.

   Despite the dryer study plots in southern Italy than the plots in the Czech Republic and Poland, they showed a higher radial growth than the rest of the study sites. This result shows us that despite the GCC, beech forests at low altitudes have shown higher values of radial growth. Future studies are needed to verify if the affected plots have an optimal microclimate for beech radial growth or if there are other factors that we have not taken into consideration that could have positively influenced the radial growth of the trees.

2) In the studied lowland forests, it was observed that precipitation during the growing season had a positive effect on spruce radial growth, while temperature during the growing season had a negative effect on radial growth. In the case of beech located at different vegetative belts observed in selected sites, the same results (for the major part of the study plots) were found (but the correlations in this case were not significant).

3) As for the relationship between remote data (NDVI) and field data (RWI) of Norway spruce, the maximum NDVI values of the growing season tended to be more correlated than the mean NDVI values for most sites. The higher correlations were found in sites susceptible to drought, but despite of the general view, the correlation was not significant.

   In the case of beech, the most significant positive correlations to RWI were observed with maximum seasonal NDVI in Southern European plots located at lower altitudes.

   In general, the study confirmed that the relationship between NDVI and RWI is more correlated in drier locations, such as the Mediterranean ones, and further studies are needed to state whether NDVI is also a valid indicator for less arid locations like those of Central Europe, and to state whether it is a reliable index for both deciduous and coniferous trees.

7. RECOMMENDATION FOR RESEARCH

Our proposal emerged from the obtained results regarding the relationship between remote data (NDVI) and field data (RWI). It should be investigated by specific studies to state whether NDVI is a reliable index only on temperate broadleaved forests, as Hlásny et al. (2015) suggest or if it is a reliable index for both coniferous and deciduous forests located in arid sites. Further studies have been announced to confirm or deny the reliability of the NDVI on both coniferous and deciduous forests at low and high altitudes and highlighting both locations suffering due to high temperatures and low precipitation, as is the case of the Mediterranean area and also in locations with an adequate availability of water in the soil.

For future research evaluating the correlations between NDVI and RWI, we recommend using a different methodology. In fact, instead of MODIS, it will besuggested to use Landsat 8 since the latter has a spatial resolution of 30 × 30 meters (Yang and Acharya 2015) greater than the spatial resolution of MODIS (250 × 250 meters) and the same temporal resolution of 16 days as MODIS. The only disadvantage of Landsat 8 is the availability of data, which has been available since 2013. But despite everything, even if we do not have a considerable time interval, the available data will only serve to verify if the NDVI is a reliable indicator not only for arid regions such as the Mediterranean, which resulted from this research, but also for less arid locations such as Central Europe.

Moreover, if we want to evaluate a particular event, such as a fire, frost, or a particularly dry year, we must know that the NDVI value is not constant throughout the year and is closely linked to the varietal phenology of the species. Consider, for example, the deciduous species, which are inactive to photosynthesis in winter, but in this case, the forest will have a very low NDVI value in winter (mainly due to visible soil) with a rapid increase in spring. Subsequently, the index tends to “saturate,” not detecting substantial changes in the summer period.

After the rapid spring increase, the NDVI values reach a plateau and remain stable until an autumn decline. Therefore, in monitoring the variation of the NDVI of a single event, it is necessary to choose a range of dates not too distant from each other and that fall within the summer phase, with stable NDVI values, so that the phenology does not influence the results and we can isolate the effects of the damaging event (Moraca and Pepe 2018).

8. LITERATURE

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9. ANNEX

Annex-I (Published Articles)

forests

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Article

Mismatch between Annual Tree-Ring Width Growth and NDVI Index in Norway Spruce Stands of Central Europe

Giuseppe D'Andrea [1,*], Václav Šimůnek [1], Maria Castellaneta [2], Zdeněk Vacek [1], Stanislav Vacek [1], Osvaldo Pericolo [2], Rosa Giada Zito [3] and Francesco Ripullone [2]

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Abstract: Presently, the forests of one of the most economically important tree species in Europe—Norway spruce [*Picea abies* (L.) Karst.]—have been disrupted and are in rapid decline due to a combination of several natural factors: extreme drought, heatwaves, and secondary damage caused by bark beetle outbreaks. The vulnerability of these forests has increased considerably over the past decade, and remote sensing methods can theoretically improve the identification of endangered forest stands. The main objective was to determine the relationship between remotely sensed characteristics of vegetation (using the normalized difference vegetation index—NDVI) and annual tree-ring growth in 180 trees through precipitation and air temperature. The research was conducted at six research plots in lowland spruce forests (319–425 m a.s.l.) in the central Czech Republic. No significant correlation between NDVI and annual ring width was observed. The primary factor limiting radial growth was lack of precipitation in the growing season; subsequently, spruce trees reacted negatively to air temperatures. A higher correlation with NDVI was observed on sites susceptible to drought, but overall, NDVI and RWI did not show similarities. This result describes that NDVI is a poor indicator for identifying low radial growth in Norway spruce stands on non-native localities in the studied area.

Keywords: *Picea abies*; remote sensing; temperature; precipitation; Czech Republic

Citation: D'Andrea, G.; Šimůnek, V.; Castellaneta, M.; Vacek, Z.; Vacek, S.; Pericolo, O.; Zito, R.G.; Ripullone, F. Mismatch between Annual Tree-Ring Width Growth and NDVI Index in Norway Spruce Stands of Central Europe. *Forests* **2022**, *13*, 1417. https://doi.org/10.3390/f13091417

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forests

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Article

Growth Response of Norway Spruce (*Picea abies* [L.] Karst.) in Central Bohemia (Czech Republic) to Climate Change

Giuseppe D'Andrea [1,*], Václav Šimůnek [1], Osvaldo Pericolo [2,3], Zdeněk Vacek [1], Stanislav Vacek [1], Roberto Corleto [1], Lukáš Olejár [1] and Francesco Ripullone [2]

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Abstract: Norway spruce (*Picea abies* (L.) Karst.) is a significant conifer tree species in Europe that holds significant economic and ecological value. However, it remains one of the most sensitive to climate change. This study describes the climate–growth relationship, focusing on dendroecology in hilly spruce forests (319–425 m a.s.l.) located in Bohemia, the Czech Republic, during 1950–2018. The results confirmed that the highest radial increment was obtained in locations with higher precipitation (Kostelec), while the lowest growth was observed in locations with lower precipitation (Karlstejn). Tree-ring growth shows very low increments for the years 1964 and 1976 for all plots, and the years with the least growth were confirmed by the negative pointer year analysis. This study confirmed precipitation as the main factor that affects the growth of spruce at lower altitudes. The radial growth for all study sites shows a statistically significant positive correlation with precipitation during the growing season, while no statistically significant values between radial growth and temperature were obtained. This study demonstrates that Norway spruce is affected more by precipitation than temperature, and the results indicate that this conifer is seriously affected by the lack of precipitation at lower altitudes in the Czech Republic, where the species is not native.

Keywords: climate change; Czech Republic; tree-ring width; temperature; precipitation

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Citation: D'Andrea, G.; Šimůnek, V.; Pericolo, O.; Vacek, Z.; Vacek, S.; Corleto, R.; Olejár, L.; Ripullone, F. Growth Response of Norway Spruce (*Picea abies* [L.] Karst.) in Central Bohemia (Czech Republic) to Climate Change. *Forests* **2023**, *14*, 1215. https://doi.org/10.3390/f14061215

Annex-II (Conferences)

D’Andrea, G., Šimůnek, V., Podrázský, V., Travascia, D., Castelleneta, M., Ripullone, F. 2023: Relationships between field data and NDVI data of beech forests in Czech Republic and southern Italy. In IV Convegno AISSA # Under 40. Salerno (Italy) 12-13 July.

Attestato di partecipazione al

IV Convegno AISSA#under40 svoltosi presso il Campus Università degli Studi di Salerno

12 - 13 luglio 2023

rilasciato a **GIUSEPPE D’ANDREA**

Fisciano, 14/07/2023

Il responsabile del convegno

Prof. Ronga Domenico

AISSA#UNDER40 12 luglio- 13 luglio – anno 2023 Campus Università degli Studi di Salerno- Fisciano