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TITLE

“*Integrated approach for monitoring the vulnerability of Mediterranean forests affected by drought-induced dieback* ”

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Cycle XXXIV

Nature is the source of all true knowledge

(Leonardo da Vinci)

To *myself,*
to sacrifices and perseverance
that allowed me to achieve this goal

ABSTRACT

Rising aridity, mostly driven by higher temperatures and reduced precipitation, will likely undermine the health status of forest ecosystems. Experiments and observations point to the likelihood that if climate changes proceed at its current rate, the resilience of many forests will be threated by altering their structure and functions and reducing their capability to provide ecosystem services. Such increasing drought conditions, coupled to other biotic and abiotic drivers, are synergistically leading to responses in tree morphology, physiology, growth, reproduction, and forest mortality in different areas of the Mediterranean Basin. However, our understanding of vegetation dynamics in response to climate changes is still lacking, as a robust comprehension relies on the need to obtain insights at multiple temporal and spatial scales. In this context, we sought to forecasting vegetation response to climate stressors, particularly during dieback episodes when tree vulnerability is exacerbated. The first section of this study focused on tree and shrub populations exhibiting recent dieback phenomena in Italy (*Quercus pubescens*, *Quercus frainetto*) and Spain (*Pinus sylvestris*, *Juniperus phoenicea*). The general aim was to investigate how remotely sensed measures of vegetation activity and radial growth (BAI, basal area increment) responded to climate extreme events. To this purpose, we compared trees and nearby stands showing different vigor, *i.e.*, dieback *vs* non-dieback, assessed as growth decline, elevated canopy defoliation and rising tree mortality rate. To disentangle growth and NDVI responses to drought, we accounted for two components of drought, namely elevated vapor pressure deficit (VPD) and low soil moisture. As a whole, the response of the investigated species to VPD increase was characterized by growth reduction. In Scots pine, high VPD was linked to a loss of growth in declining individuals which did not respond to changes in soil moisture. Oaks responded mostly to soil moisture, whereas the juniper was the most negatively affected by higher VPD.

Indeed, the different hydraulic strategies (anisohydric *vs.* isohydric species) could partially explain the contrasting growth responses to drought proxies. We also found that dieback stands exhibited lower NDVI values than non-dieback stands. In most cases, NDVI and BAI was positively correlated and such relation likely relied on specific time windows. In the second part of the thesis, the phenological behavior of Mediterranean oak forest stands (*Quercus cerris*, *Quercus pubescens*, and *Quercus frainetto*), showing evident decline symptoms, are investigated by using a satellite-based approach. We explored how a phenological (PPI, Plant Phenology Index) index would be capable to reflect the seasonal vegetative dynamics of forests affected by dieback phenomena. We found that dieback forest stands - characterized by a higher ratio of crown-defoliated trees - showed distinct phenological performance as compared to non-dieback stands. In detail, our results revealed that dieback stands lengthened the growing season by delaying autumn leaf senescence. Nevertheless, both seasonal amplitude and productivity were found to have higher values for non-dieback stands as compared to dieback stands. Furthermore, it was highlighted that non-dieback stands experienced either greening up or senescence periods more rapidly than dieback ones. Overall, our framework demonstrated that the effects of climate extremes on vegetation can be detected either in terms of canopy greenness or radial growth reductions, thus hinting at the opportunity to both employ remotely sensed data as a stand-level indicator of vegetation stress and to scaling up informations from tree to stand levels by using the maximum growing season NDVI and tree-ring width data taken at the individual scales. Our findings also highlighted how patterns of vegetation response to climate extremes may depend on both the water use strategies of trees and shrubs and site-specific climatic conditions. Hence, coupling proxies of forest productivity (NDVI, BAI) may be employed for retrospective modeling of the impact of drought stress on forest productivity and tree growth, enhancing our knowledge and forecast of drought-induced dieback phenomena in woody plant communities.

Furthermore, the second part of the work revealed the phenological behaviour of Mediterranean forest populations showing clear symptoms of decline. We speculated that the lengthened growing season may be related to the dieback trees' effort to compensate for the reduction in whole-plant photosynthesis, associated to canopy decline. Increased photosynthesis during the season under higher temperatures and increased light availability, due to global warming, provided a possible explanation for the greater seasonal amplitude and productivity of healthier stands. Our findings may provide new insights on phenological response to climate change in semi-arid regions, highlighting how trees, showing clear symptoms of decline, may keep their vital activities by changing their phenological performance. What described above leads to a crucial question concerning the potential implications of observed phenological shifts on the global carbon and water balance of terrestrial ecosystems under future climate change. Hence, in the coming years, this study could provide a more comprehensive overview on climate-vegetation interactions, mainly in the Mediterranean Basin, where intensified global warming and aridification trends are expected. Nonetheless, more investigations on the interactive effects among different environmental factors, are needed to improve our understanding of the underlying mechanisms affecting vegetation response.

Keywords: climate change, forest dieback, Mediterranean area, radial growth, satellite-based vegetation indices.

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DEFINITIONS

AI	Aridity index
BAI	Basal area increment
CMI	Climate moisture index
D	Dieback or Declining
MODIS	Moderate Resolution Imaging Spectroradiometer
ND	Non-dieback or Non-declining
NDVI	Normalized Difference Vegetation Index
P	Precipitation
PET	Potential evapotranspiration
PPI	Plant phenology index
SPEI	Standardized Precipitation Evapotranspiration Index
VPD	Vapor pressure deficit

READING GUIDE

A brief guideline on the contents of each chapter is summarized to facilitate the readability of this thesis.

- **Chapter 1** reports an overview of forest dieback phenomena in the Mediterranean region, with a brief focus on forest health monitoring approaches.

- **Chapter 2** provides a comprehensive evaluation of how interannual variation of NDVI and radial growth of four tree and shrub species, that undergo drought-induced decline, respond to extreme climate events.

- **Chapter 3** gives an assessment of phenological dynamics in oak forests, exhibiting clear symptoms of die-off, through the use of remotely sensed vegetation index that is demonstrated to be excellent proxy for the phenological status of forest vegetation.

- **Chapter 4** provides a short overview of the outcomes, emphasizing the key findings.

PUBLICATIONS

The chapters provided in this thesis were formatted as scientific articles to allow publishing in academic journals.

- **Chapter 1** was authored on my own;

- **Chapter 2** has been published:

Castellaneta, M., Rita, A., Camarero, J. Julio, Colangelo, M., Ripullone, F., 2021. *Declines in canopy greenness and tree growth are caused by combined climate extremes during drought-induced dieback*. Science of The Total Environment. doi.org/10.1016/j.scitotenv.2021.152666

- **Chapter 3** is being prepared for the next submission:

Castellaneta, M., Rita, A., Borghetti M., Ripullone, F. *Canopy cover dynamics in dieback affected oak forests captured by phenological behavior.*

- **Chapter 4** was authored on my own.

During my PhD, I have been involved and worked on the following manuscripts that are not included in this thesis:

Pergola, M., Saulino, L., **Castellaneta, M.,** Rita, A., Pecora, G., Cozzi, M., Moretti, N., Pericolo, O., Pierangeli, D., Romano, S., Viccaro, M., Ripullone, F., 2022. *Toward a sustainable management of forest residues in the southern Apennine Mediterranean mountain forests. A scenario-based approach.* Annals of Forest Science. Accepted

D'Andrea, G., Šimůnek, V., **Castellaneta, M.**, Vacek, Z., Vacek, S., Pericolo, O., Zito, R.G., Ripullone, F., 2022. *Mismatch between annual tree ring-widths and NDVI index in Norway spruce stands of Central Europe*. European Journal of Forest Research. Submitted

Pergola, M., Rita, A., Tortora, A., **Castellaneta**, **M.**, Borghetti, M., De Franchi, A. S., Lapolla, A., Moretti, N., Pecora, G., Pierangeli, D., Todaro, L., Ripullone, F., 2020. *Identification of suitable areas for biomass power plant construction through environmental impact assessment of forest harvesting residues transportation*. Energies,13(11), 2699. doi.org/10.3390/en13112699

POSTERS

The research outcomes of the PhD activities have been presented in scientific posters:

Castellaneta, **M.**, Rita, A., Borghetti, M., Ripullone, F., 2022. *Evaluation of canopy cover dynamics using phenological and productivity indices: the case of Mediterranean oak forests affected by dieback.* In EGU General Assembly Conference Abstracts. Abstract accepted

Castellaneta, **M.**, Rita, A., Camarero, J.J., Colangelo, M., Ripullone, F., 2022. *Integrating canopy greenness and growth to assess the vulnerability of woody vegetation to drought during dieback.* In XIII° Congresso Nazionale SISEF. Abstract accepted

Castellaneta, **M.**, Rita, A., Camarero, J.J., Colangelo, M., Ripullone, F., 2021. *Assessment of the climate change-induced impact on forest vegetation in the Mediterranean Basin using an integrated approach*. In EGU General Assembly Conference Abstracts (pp. EGU21-13511).

Castellaneta, **M.**, Rita, A., Camarero, J. J., Colangelo, M., Nolè, A., Ripullone, F., 2020. *Assessing and monitoring the vulnerability to drought and climate anomalies of Mediterranenan oak forests by using NDVI.* In EGU General Assembly Conference Abstracts (p. 17113).

Castellaneta, M., Rita, A., Colangelo, M., Ripullone, F., 2019. *Vegetation Response to Climate Anomalies: a case study for Italy using Landsat NDVI time series analysis*. In XII° Congresso Nazionale SISEF . Palermo (Italia) 12-15 November.

During my PhD, I was involved in research activities, leading to the outcomes presented in the following posters, which are partially related to my PhD objectives:

Avanzi, C., Pericolo, O., Assini, S. P., Bagnoli, F., Barcella, M., Borghetti, M., Bracco, F., **Castellaneta**, **M.**, Marchi, M., Pinosio, S., Rodolfi, M., Romiti, E., Storchi, T., Vendramin, G. G., Piotti, A., Ripullone, F., Nola, P., 2022. *Alle radici del deperimento della farnia nei boschi planiziali lombardi: ResQ, un progetto multidisciplinare per la selezione di risorse genetiche resistenti.* In XIII° Congresso Nazionale SISEF. Abstract accepted

Rita, A., Piovesan, G., Borghetti, M., Baliva, M., **Castellaneta**, **M.**, Colangelo, M., De Vivo, G., Di Filippo, A., Gentilesca, T., Lapolla, A., Pericolo, O., Schettino, A., Ripullone, F., 2019. *La cronologia dendro-anatomica millenaria di Pinus leucodermis*. In XII° Congresso Nazionale SISEF. Palermo (Italia) 12-15 November.

DISSEMINATION ARTICLES

Castellaneta, **M.**, Borghetti, M., Colangelo, M., Lapolla, A., Rita, A., Ripullone, F., 2021. *SilvaCuore: un'App per monitorare lo stato di salute delle foreste italiane*. Forest@ 18, 74-78. doi: 10.3832/efor3993-018.

Castellaneta, **M.**, 2021. *SilvaCuore: l'App che ha a cuore i nostri boschi.* SmartGreenPost (online magazine).

Castellaneta, **M.**, 2021. *Il monitoraggio dello stato di salute delle foreste: dalla cellula ai satelliti.* Agrifoglio n. 104.

Castellaneta, **M.**, 2020. *La ricerca al servizio delle foreste: il loro futuro è nelle nostre mani.* SmartGreenPost (online magazine).

Agata, M., **Castellaneta**, **M.**, 2020. *L'Ultima foresta incantata: un progetto per salvare il bosco igrofilo del Pantano di Policoro.* Agrifoglio n. 97.

CHAPTER 1 – General Introduction

Preface

Forest ecosystems cover 31% of the Earth's land surface (FAO, 2020), thus contributing significantly to the global carbon cycle as sequestration sinks (Körner, 2017; Pan et al., 2011). Forests hold the majority of biodiversity in terrestrial ecosystems, perform an essential role in climate mitigation and provide a wide range of environmental and economic benefits to society. In the last decades, some of those functionalities could be endangered by climate change: higher temperatures and reduced precipitation are leading to more intense and frequent droughts and heat waves (Anderegg et al., 2020), with consequent impacts on the complexity, structure, and functioning of forest ecosystems (McDowell et al., 2020). Climate stressors may affect forest species and their dependent communities' dynamics either in the short-term, *e.g.*, by influencing 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). Consequently, as a response to the exacerbation of such phenomena, the resilience of many ecosystems will likely be exceeded (IPPC, 2014), although some forest populations are more adapted to tolerate seasonal drought periods and/or irregular rainfall regimes (Gazol et al., 2018a). The Mediterranean region is an extremely important biodiversity hotspot, which is likely to experience increasingly arid conditions that can contribute to increasing forests vulnerability (Camarero et al., 2021a; Lloret et al., 2021, among others). Evidence is reporting that the health of forest communities is treated by climate extremes, which are leading to tree decline and mortality due to impairment of plant hydraulics, and reductions in carbon uptake (Gaylord et al., 2013; Hartmann et al., 2015).

1.1 Forest dieback and mortality

Climate-induced forest mortality is an emerging global phenomenon (Allen et al., 2015), at both regional and local scales (Anderegg et al., 2020; Hartmann et al., 2018; Senf et al., 2020), leading to major implications for the functioning of these key ecosystems (Anderegg et al., 2013). Reported increases in tree mortality indicate an intensifying forests vulnerability worldwide under warming temperatures and prolonged and more intense droughts associated with increased climate variability (IPPC, 2018). Recently, several local surveys reported an increased rate of tree mortality in response to drought throughout Europe (Buras et al., 2018; Peñuelas et al., 2001, among others). On that note, Caudullo and Barredo (2019) reported 293 severe forest mortality events in Europe for the period 1970-2019. Die-off phenomena as a consequence of severe water shortages have been reported mostly in drought-prone ecosystems such as Mediterranean forests (Allen et al., 2010; Hartmann, 2011). Different studies carried out in deciduous and coniferous forests highlighted the widespread occurrence of these phenomena in the Iberian Peninsula: *e.g.*, *Abies alba* Mill. and *Pinus sylvestris* L. (Pellizzari et al., 2016; Voltas et al., 2013), *Pinus pinaster* Aiton. (Gea-Izquierdo et al., 2019; Moreno-Fernàndez et al., 2021), *Quercus robur* L., *Quercus pubescens* Willd. and *Fagus sylvatica* L. (Camarero et al., 2021b), *Quercus frainetto* Ten. and *Quercus canariensis* Willd. (Sánchez-Salguero et al., 2020a), *Pinus nigra* J. F. Arnold (González De Andrés et al., 2020). Even several juniper species exhibited widespread dieback over the last years, although they are supposedly better adapted to tolerate low water availability periods compared to co-existing tree species such as pines (Camarero et al., 2020; Gazol et al., 2017; Sánchez-Salguero et al., 2020b). In addition, Gentilesca et al. (2017) provided an overview of this phenomenon's extent for oaks located in the western Mediterranean Basin, focusing on Italy and Spain.

In Italy, isolated oak decline cases have been observed since the end of the last century: at first, the phenomenon was detected in the northeastern area, mainly affecting *Quercus robur* L.; it, subsequently, became widespread in central and southern Italy, mostly involving *Quercus cerris* L., *Quercus frainetto* Ten., and *Quercus pubescens* Willd. in either pure or mixed forests (Barzanti et al., 2001; Di Filippo et al., 2010). Recent investigations carried out in identified forest stands in Valle d'Aosta revealed several dieback and mortality cases affecting *Pinus sylvestris* L. (Castagneri et al., 2015; Vacchiano et al., 2012). Moreover, Pollastrini et al. (2019) outlined the impact of the 2017 summer drought on the populations of several representative species occurring in central Italy (*Fagus sylvatica* L., *Quercus pubescens* Willd, *Quercus cerris* L., *Quercus ilex* L., and *Phillyrea*), highlighting their different responses and recovery capacity after disturbance phenomenon. Evidence of oak forests, showing clear evidence of foliage losses, growth decline, and mortality, is reported also in the Southern Apennines, for which dendro-isotopic and wood-anatomy investigations are already underway: namely, the Gorgoglione mixed forest, which is dominated by *Quercus cerris* L. and *Quercus pubescens* Willd. (Colangelo et al., 2018), and the high forests of San Paolo Albanese and Oriolo, both characterized by *Quercus frainetto* Ten. (Colangelo et al., 2017a, 2017b; Ripullone et al., 2020). The widespread phenomena of forest decline and mortality have also been affecting the lowland oak forests over the last years. In the past, these forest populations have been intensively exploited, reducing their extent and fragmenting their natural distribution, thus making the entire ecosystem extremely vulnerable to climate change. Currently, the multiple significance and relevance of lowland oak forests are broadly understood. Many scientific activities and projects have been carried out in recent years in different forest populations, *e.g.*, the Regional Oriented Reserve “Bosco Pantano” in the Policoro territory and the Ticino Park: that is, the research activities aim to explore and assess the underlying causes and mechanisms of the decline of *Quercus robur* L.

Overall, dieback symptoms typically consist of a marked reduction in tree vigor (*e.g.*, shoot death and leaf drop, epicormic shoot production), growth decline, and high mortality rates. Two major mechanisms are involved in tree dieback and mortality: hydraulic failure and carbon starvation (Choat et al., 2018; McDowell et al., 2011). Hydraulic failure is related to the conductivity loss induced by embolism: that is, it occurs when the transpiration water loss is higher than the absorption by the roots, leading to pressure in the xylem becoming increasingly negative. Beyond a given threshold value, the pressure reduction causes the formation of gas bubbles in the xylem conduits (cavitation), which then diffuse into the vascular system (embolism), thereby impeding water transport. Meanwhile, carbon starvation occurs as a consequence of prolonged stomatal closure, resulting in a negative carbon balance (McDowell et al., 2008; Sevanto et al., 2014).

The influence of drought on forest structural and functional conditions may be sensitive to tree size: *i.e.*, enhanced mortality of smaller trees may affect future forest succession, whereas mortality of larger individuals leads to disproportionate carbon stock losses (Lindenmayer et al., 2012). Smaller trees, as reported for instance by Zhang et al. (2017), may be more prone to water stress as their roots are shallower, resulting in limited access to water in deeper soil layers. In contrast, larger trees might be most affected negatively by drought owing to higher evapotranspiration rates and more water demand, as compared to smaller individuals (Bennett et al., 2015).

1.2 Forest health monitoring

Assessing the state of health and vitality of forest ecosystems, through monitoring of dieback and mortality phenomena, is fundamental to develop and implement measures for climate impacts mitigation, as well as recovery and adaptation strategies. The vegetative status conditions of forests can be evaluated either by ground-based surveys or through remote sensing, using images captured by drones and satellites.

Tree-ring samplings provide information on the amount of wood being formed from the stem, which may be related directly to biomass gain and carbon uptake (Babst et al., 2014; Van Breugel et al., 2011). For instance, TRWIs (Tree ring width indices) are widely applied as long-term predictors of past forest productivity, *i.e.*, gross primary production (GPP), as reported by Xu et al. (2017). Tree growth rates are highly influenced by climate and many studies have examined tree growth response to climate patterns and its interannual variability in different forest species (Babst et al., 2012; Gao et al., 2018, among others). The advantages of growth data include high temporal resolution, providing long-term series, and accurate dating. In contrast, due to their limited spatial resolution (*tree level*), these data can only give insights about forest response to climate at local scales. Moreover, although retrospective and reliable estimates of tree growth and productivity are achieved, tree rings require intense field labor to collect wood samples, as well as time-consuming laboratory work to cross-date and measure woody material. These issues constrain the potential exploitation of such approach for real-time monitoring of forest growth on large spatial scales.

Conversely, 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).

Remotely sensed vegetation indices may report information that exhibits a greater spatial extent and temporal resolution, that can range from daily to yearly, as compared to traditional dendro-chronological surveys. One of the most widely used remote sensing indices, the Normalized Difference Vegetation Index (NDVI), which measures the fractional absorbed photosynthetically active radiation (Myneni et al., 1995), is widely recognized as a valuable proxy for exploring the influence of climate variability on vegetation productivity and phenology, owing to its tight relationship with vegetative activity and canopy cover and greenness (Gazol et al., 2018b; Liu et al., 2013). For instance, NDVI has been applied to evaluate the detrimental effects of severe drought events on forests on global scale, which are more pronounced in water-limited areas and for species exhibiting poor hydraulic safety margins (Wu et al., 2018). Further, different researches, such as Hasenauer et al. (2012), have reported the feasibility of estimating net primary production (NPP) derived from NDVI. However, the NDVI signal is likely to saturate in high cover vegetation areas, and therefore the Vegetation Enhancement Index (EVI), including the blue wave band to enhance its sensitivity, is more widely used in such applications (Matsushita et al., 2007). There are several papers focused on employing vegetation indices to either explore seasonal changes and vegetation dynamics (*e.g.*, Ivits et al., 2013, among others) or to assess and evaluate climate effects on forest ecosystems (*e.g.,* Anderegg et al., 2019). One possible gap may be represented by the lack of long-time series of satellite observations. Continuous remotely sensed data, exhibiting suitable temporal resolution, have been widely accessible since the 1980s (*i.e.*, NOAA-AVHRR satellites). As well, other satellite datasets either cover shorter periods (approx. 20 years) (*e.g.*, MODIS) or exhibit significant temporal gaps (*e.g.*, Landsat).

For instance, the World Resources Institute's Global Forest Watch initiative (http://www.globalforestwatch.org) represents a valuable instrument for detecting temporal shifts in forest cover, related to disturbance or mortality; but the spatial resolution (30 m) constitutes a limitation to its application, precluding evaluations of underlying physiological processes. Significantly, the available spatial resolution of satellite data is frequently overly coarse to be directly related to growth data of small forest areas, thus rendering the availability of sufficient tree ring information a key constraint. The deployment of emerging technologies, as LiDAR, allowing the monitoring of single trees over broader patches (*e.g.*, Asner et al., 2016), might bridge the gap between tree-level *versus* stand-scale information. Combining insights from multiple monitoring levels represents the real challenge.

1.2.1 Ground observations and satellite data: complementary views

Ground-based data and satellite-derived measures may provide complementary insight into forest health. It is crucial to validate the remotely-sensed information through testing the coupled/uncoupled relationship with the most reliable dendro-anatomical traits which provide long-term records of radial growth and are used as proxies for hydraulic conductivity and carbon uptake. Field observations yield information at the individual plant level, and can be scaled to the variety, provenance, and species-level; in addition, individual trees are observed within a specific micro-environment, which is more or less known. Remote sensing, on the other hand, gives area-averaged information which emphasizes the vegetation's prevailing components and is based on, *e.g.*, greenness, and relative reflectance. Combining the strengths of either approach has great potential to be able to address scaling issues among individual plant and ecosystem responses (Bunn et al., 2013; Vicente-Serrano et al., 2016; Wang et al., 2004).

Accordingly, remote sensing is a reliable, widely recognized tool for investigating intra-annual changes in canopy greenness, and thus the relation with radial growth (Decuyper et al., 2020). In this way, we enhance our understanding of ecological strategies employed by tree species to cope and withstand drought stress conditions, by combining data from radial growth and remote sensing (Pompa-García et al., 2021; Vicente-Serrano et al., 2020).

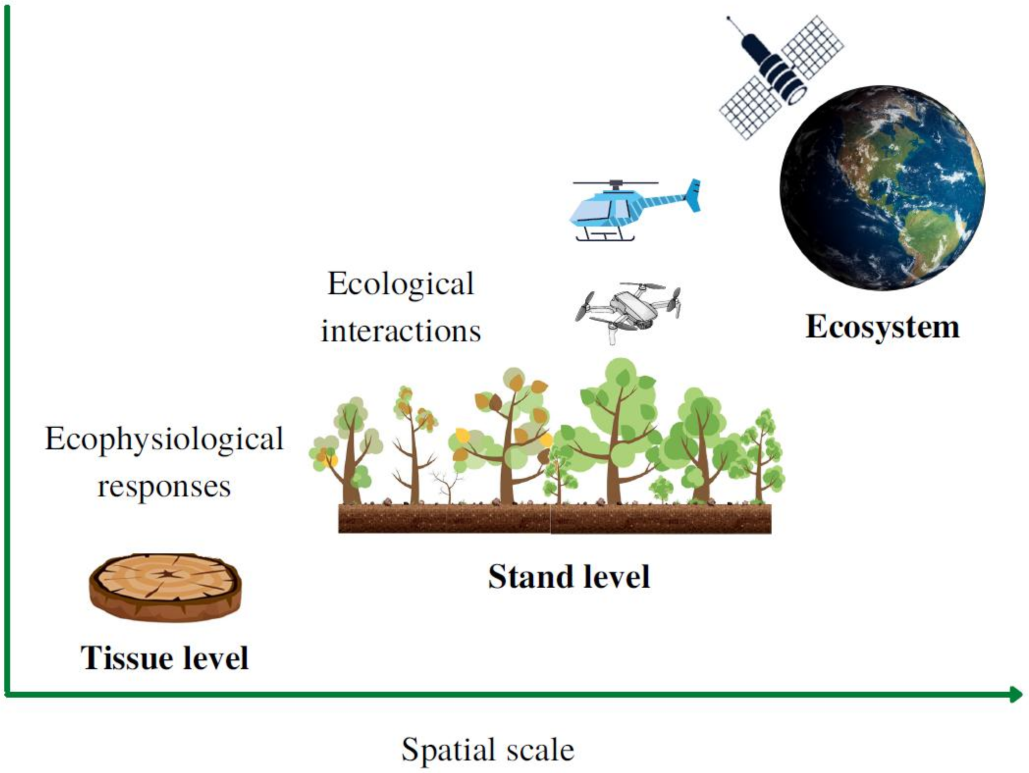


Figure 1. Spatial scales of vegetation health monitoring

For instance, a positive correlation has been reported among summer NDVI and tree ring width from multiple studies, such as Berner et al. (2015) and Kaufmann et al. (2004). The timing of the relationship among ground-based data and vegetation indices, as reported by Kaufmann et al. (2008), may differ spatially (*e.g.*, latitude effects) and can be related to vegetation types (*e.g.*, broadleaf *vs* coniferous); in addition, these changes can enable the identification of climatic controls on tree growth.

Establishing an optimal link between satellite observations and tree growth (*i.e.*, determining the optimal time window during which they strongly correlate) is critical, as it may better allow subsequently upscaling of growth measurements (*e.g.*, Xu et al., 2019, among others) at the ecosystem scale. Additionally, the examination of tree growth and its relationship to remotely sensed metrics can provide a key tool for exploring the condition of high elevation forest ecosystems and understanding the ongoing impacts of climate change on growth, distribution, and function. As an example, Correa-Diaz et al. (2019) combined tree-ring measurements and remotely sensed data to investigate how forests responded to climate variability across altitudinal gradients.

Lastly, Xu et al. (2018) explored the potential linkage among canopy height and forest responses to drought, based on multi-source data: notably, they revealed that the percentage of tree mortality and reductions in both stem growth and leaf growth was linked to canopy height. Hence, we can deduce that the negative effects of severe droughts on forests might be mitigated through the active management of forest structure.

1.2 Forest dieback networking

Many research institutions worldwide are undertaking concrete initiatives and scientific projects which are focused both on mapping and monitoring the forest decline phenomenon but also to relating it to other environmental drivers. For instance, the International Union of Forest Research Organizations (IUFRO) Task Force is carrying out activities to develop a global multi-disciplinary monitoring network. *Tree Alert* is an application that was developed in Great Britain by the Forestry Research Institute, aiming to evaluate the current forests health status and to forecast their future dynamics.

A further good example is provided by the *AlertaForestal* application, promoted by CREAF (Research Center on Ecological and Forestry Applications), which aims to reach the same objectives in Catalonia. The need to monitor these phenomena for understanding the future dynamics of forests has led also to the *SilvaCuore*’s development, the first App designed in Italy to survey declining forest sites and collect data that can be used as a baseline for planning research activities and management measures. *SilvaCuore* was developed from an idea of a group of researchers from the University of Basilicata, aiming to offer a new tool to detect declining forest sites in Italy and to contribute to the development of a valuable scientific database. The *SilvaCuore* App allows both researchers and citizens to contribute to reporting the forests' health status. Therefore, it is a Citizen Science project, which focuses on citizens’ direct engagement, thus enabling them to become the real protagonists of scientific research. Through a user-friendly interface, the App leads the users through a simplified reporting procedure.

1.3 Research objectives

Increasing temperatures coupled with extreme drought events are having notable impacts on forest ecosystems, triggering dieback and mortality phenomena worldwide. In this context, the overall goal of the research activity during this PhD was to investigate the forest responses to climate stressors, through integration of canopy foliage dynamics and radial growth data. The investigation was focused in the Mediterranean basin, with a particular emphasis on local phenomena affecting the Iberian and Italian peninsulas, *i.e.*, Pyrenees and Southern Apennines. The detailed aims can be summarized as follows:

PART I

The general objective of work, described in **Chapter 2**, was to explore how remotely sensed measures of vegetation activity and radial growth responded to climate extremes. Our study focused on tree and shrub populations showing recent dieback phenomena; climate extremes were evaluated using two components of drought, namely high vapor pressure deficit (VPD) and low soil moisture.

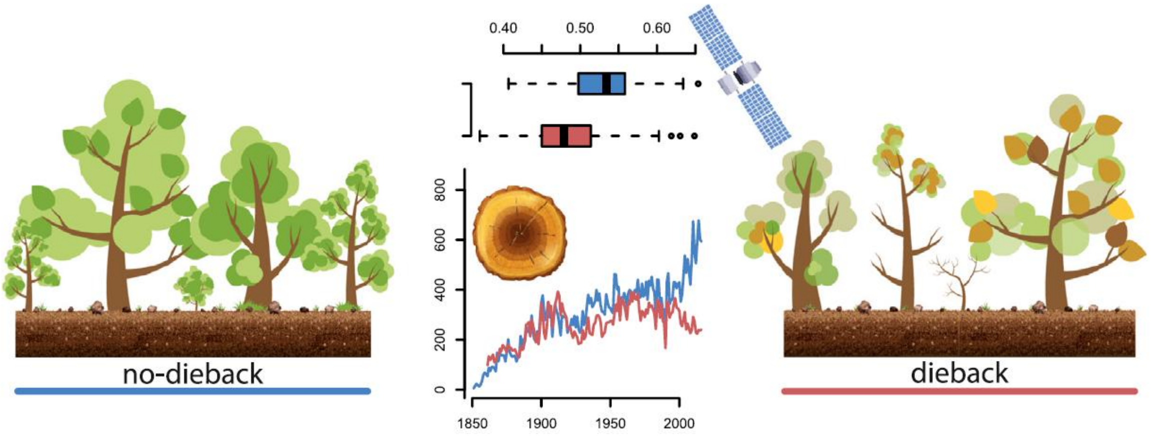
PART II

The goal of the work, presented in **Chapter 3**, was to investigate phenological behavior of Mediterranean forest stands exhibiting evident decline symptoms. Through a satellite-based approach, we aimed to assess how a phenological index is able to reflect the seasonal vegetative dynamics of oak forests affected by dieback.

PART I

CHAPTER 2 - Declines in canopy greenness and tree growth are caused by combined climate extremes during drought-induced dieback

Graphical abstract



Abstract

Several dieback episodes triggered by droughts are revealing the high vulnerability of Mediterranean forests, manifested as declines in growth, increased defoliation, and rising mortality rates. Understanding forest responses to such climate extreme events is of high priority for predicting their future vegetation dynamics. We examined how remotely sensed measures of vegetation activity (NDVI, Normalized Difference Vegetation Index) and radial growth (BAI, basal area increment) responded to climate extreme events. We considered tree (*Pinus sylvestris*, *Quercus pubescens*, *Quercus frainetto*) and shrub (*Juniperus phoenicea*) populations from Italy and Spain showing recent dieback phenomena.

Two components of drought, namely elevated atmospheric demand (VPD, vapor pressure deficit) and low soil moisture were analyzed in nearby stands showing or not showing dieback symptoms. Dieback stands exhibited lower NDVI values than non-dieback stands. NDVI and BAI were positively related in all sites except for the dieback trees of *Q. frainetto* that was negatively related. Such NDVI-BAI linkages were related to specific time windows, which could be useful for identifying when climatic conditions have the greatest influence on vegetation. Growth decline occurred in response to increasing VPD, but responses differed among species. *J. phoenicea* was the most negatively impacted by higher VPD, whereas oaks responded to soil moisture. A high VPD was related to stronger growth reduction in dieback *P. sylvestris* trees regardless of soil moisture changes. We highlighted that coupling between proxies of forest productivity (NDVI, BAI) allows better understanding and forecasting of drought-induced dieback phenomena in forests and shrublands. Scaling up from tree to stand levels might be feasible when using the maximum growing season NDVI, which can be applied for retrospective modeling of the impact of drought stress on forest productivity and tree growth.

Kewwords: drought stress, dieback, radial growth, Mediterranean forests, MODIS NDVI

2.1 Introduction

Forest ecosystems and tree species distributions have been altered by the impact of climate warming worldwide since the middle of the 20th century as a result of increased atmospheric water demand and reduced soil moisture (IPCC, 2014). In recent decades, dieback episodes and tree mortality phenomena, related to heat stress and drought spells, have been reported across all biomes affecting several tree and shrub species (Allen et al., 2015; Hartmann et al., 2018; Senf et al., 2020). Such events could lead to rapid modification of community composition and function with negative feedbacks in terms of productivity and carbon stocks (Anderegg et al., 2015). Indeed, negative impacts of prolonged heat and drying events on forests have been interpreted considering the impairment of hydraulic function and carbon use (Adams et al., 2017; McDowell et al., 2008). As drought has been remarked in recent years to be a major driver of tree growth (Babst et al., 2019; Colangelo et al., 2017a; Gazol et al., 2018b), detecting growth responses to this climate stressor provides a useful tool for assessing vegetation dynamics, particularly during forest dieback episodes when tree vulnerability is amplified (Hereş et al., 2014). However, we lack integrative, retrospective approaches to disentangle the underlying climatic triggers of dieback episodes and how they impact basic attributes such as tree cover and growth, which are proxies of productivity.

Several studies have evaluated the impacts of climate anomalies on vegetation via retrospective approaches based on a variety of proxies such as remote sensing and radial growth data. Tree-ring analyses have been widely used in natural conditions to assess the growth decline of mature trees and to predict tree death (*e.g.*, Bigler and Bugmann, 2004; Sanchez-Salguero et al., 2017; Cailleret et al., 2017, 2019). Authors, such as Pasho et al. (2011) and Vicente-Serrano et al. (2014), reported evidence that the time lag among the water deficit and the impact on growth differed significantly among forest types and tree species; thus, the existence of a gradient in the growth response to drought may describe the different ability to cope with water shortages of variable magnitude and severity.

Other studies suggest the possibility of employing remote-sensing derived vegetation indices to explore seasonal changes and vegetation dynamics (*e.g.,* Wu et al., 2021). As such, spectral data exhibit a clear potential to highlight the impact of climate anomalies on forest vegetation, as reported by different works (*e.g.,* Liu et al., 2021; Moreno-Fernandez et al., 2021, among others). Combining remote sensing and tree-ring data may be useful to evaluate underlying factors of forest vulnerability to climate anomalies. Therefore, it is crucial to validate the remotely sensed data by testing their linkages with ground-based radial growth assessments. In the last decade, research efforts have allowed relating remotely sensed variables with field-based dendrochronological data (*e.g.,* Gazol et al., 2018a; Correa-Diaz et al., 2019; Decuyper et al., 2020; Vicente-Serrano et al., 2020) although the relationships between these indicators are often weak and still not sufficiently understood. It is unclear yet how the changes in photosynthetic activity and canopy cover and greenness, as expressed by remotely sensed indices, are related to stem wood formation. For instance, the relationship between inter-annual values of widely used vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and tree growth differs between forest biomes and environmental conditions (Vicente-Serrano et al., 2020). For instance, Zhou et al. (2020) combined radial growth and remote sensing data to assess the responses of *Pinus yunnanensis* forests to climatic variability across altitudinal gradients: both variables showed strong climate response throughout the growing season, but the response varied under dry climate conditions. Therefore, we must better understand how NDVI and growth covary under drought conditions, which promotes tree dieback. To disentangle NDVI-growth responses to drought, in this work we considered two compound climatic extremes causing drought stress, namely elevated vapor pressure deficit (VPD) and low soil moisture (Grossiord et al., 2020; Vicente-Serrano et al., 2020). These components constitute key drivers to better understand the coupling of soil moisture dynamics to hydraulic function and atmospheric water demand (Zweifel et al., 2021).

Accordingly, these two variables are related to dieback mechanisms during drought including hydraulic impairment and depletion of carbohydrate reserves (McDowell et al., 2008). Such mechanisms define the so-called "*physiological drought*", which is linked to the tree's mechanism for regulating water use *e.g.*, isohydric *vs*. anisohydric species in response to decreasing soil water potential (Mitchell et al., 2013; Roman et al., 2015). In this regard, Poyatos et al. (2008) reported differential response to water deficits of *Pinus sylvestris* L. and *Quercus pubescens* Willd. under soil moisture deficits and high evaporative demand. Hence, it appears key to determine how vegetation indices can be used congruently with growth measurements to evaluate spatial and temporal patterns of ecological parameters. Improving our knowledge on these aspects is a critical step for the Mediterranean area, where there is an intensification of heating and drying processes (Giorgi and Lionello, 2008). The aim of the present study is an overall evaluation of how the interannual variation of NDVI and radial growth of four tree and shrub species, that experienced drought-triggered dieback, react to extreme climate events. To this purpose, we selected four sites located in Italy and Spain, two climate change hotspots (Giorgi and Lionello, 2008) to address the following questions: i) is there a difference in terms of NDVI or radial growth at nearby stands showing contrasting vigor, *i.e*. dieback *vs*. non-dieback stands or individuals?; ii) are NDVI and growth responses to drought linked?, and iii) how NDVI or growth respond to extreme climate events defining droughts, *i.e*. elevated VPD and reduced soil moisture?

We hypothesized that i) declining forest patches - characterized by a high frequency of dieback trees - would be discriminated from non-declining ones via differential photosynthetic activity and canopy greenness, as expressed by NDVI; ii) the linkage between NDVI and tree growth would be different depending on different species' physiological strategies whereas site-specific conditions could impair such a coupled/uncoupled relationship.

2.2 Materials and methods

2.2.1 Study sites and species

Tree and shrub populations were selected based on previously reported dieback symptoms including high rates of leaf shedding or browning and elevated mortality after recent severe droughts (Table 1, Figs. 2, 3). Two sites are located in northeastern Spain. The first site, Yaso, is an open scrubland dominated by *Juniperus phoenicea* subsp. *turbinata* (Guss.), located in the ‘Sierra y Canones de Guara’ Natural Park in Aragon. There are scattered trees (*Quercus faginea* Lam., *Quercus ilex* L., *Arbutus unedo* L.), but the landscape is dominated by shrubs such as *Quercus coccifera* L., *Buxus sempervirens* L., *Salvia rosmarinus* (L.) Schleidand, and *Juniperus oxycedrus* L. The site is characterized by continental Mediterranean climate conditions with cold winters and dry summers (mean annual temperature is 12.6 °C, total annual precipitation is 532 mm). The soil is basic and characterized by a rocky substrate. The shrub die-off episodes occurred in response to severe droughts which affected most of the Iberian Peninsula (1994-1995, 2005, 2012, and 2015). The estimated mortality rate of junipers was 66% and dead junipers showed lower growth rates than living conspecifics (Camarero et al., 2020). The second Spanish site is the Corbalán mixed forest, which is dominated by *Pinus sylvestris* L. and is characterized by a continental Mediterranean climate (mean annual temperature is 11.8 °C, total annual precipitation is 406 mm). The soil is mostly loamy. This forest is located near the southernmost European distribution limit of species and in a xeric site (Fig. 4), which potentially makes this population very sensitive to water shortage. The site presents marked canopy defoliation, with sparse defoliated and dead trees on the dominant layer. Declining Scots pine trees show a lower growth rate compared to non-declining trees since the 1980s (Camarero et al., 2015). In this site, the low growth rates, the high defoliation (90-95%), and the high growth responsiveness to drought suggest a chronic drought-induced dieback process (Camarero et al., 2015).

Camarero et al. (2018) point out also that the growth reduction as a result of successive drought is more pronounced in declining than in non-declining individuals. Other tree species present on the site are *Pinus nigra* L., *Q. ilex*, *Q. faginea*, and *Juniperus thurifera* L.. The other two sites are located in southern Italy and are oak forests. The Gorgoglione high forest is dominated by *Quercus cerris* L. (71%), followed by *Quercus pubescens* Willd. (25%) and other broadleaf species. The site is characterized by a Mediterranean climate with dry-warm summers and wet-mild winters (mean annual temperature is 11.6 °C, total annual precipitation is 722 mm). The soil consists of a mixture of sand, silt, and clay. The oak dieback was characterized by conspicuous leaf shedding and high mortality rates. Oak mortality rate in the study area shifted from 5% to 10% from 2002 to 2004. Considering the period 1950–2016, non-declining individuals presented slightly higher growth rates than declining individuals (Colangelo et al., 2018). The San Paolo Albanese high forest is located in the Pollino National Park. The dominant species is *Quercus frainetto* Ten. The climate of the area is Mediterranean (mean annual temperature is 16.4 °C, total annual precipitation is 742 mm).The soil is composed of sands and clays. The site shows dieback symptoms since the early 2000s and the most affected areas encompass ca. 250 ha. The frequency of trees showing crown-transparency levels above the 50% threshold is 80% (Colangelo et al., 2017a).

Table 1. Characteristics of the four study sites.

Site	**Species**	**Status**	**Latitude** (N)	**Longitude** (-W, +E)	**Elevation** (m a.s.l.)	**References**
Yaso	*J. phoenicea*	D	42.209	-0.126	694	Camarero et al., 2020
		ND	42.223	-0.108	650	
Corbalán	*P. sylvestris*	D	40.442	-0.987	1303	Camarero et al., 2015, 2018
		ND	40.440	-0.984	1250	
Gorgoglione	*Q. pubescens*	D	40.369	16.171	800-850	Colangelo et al., 2018
		ND	40.451	16.133	900-1000	
San Paolo Albanese	*Q. frainetto*	D	40.016	16.347	950	Colangelo et al., 2017a, 2017b
		ND	40.026	16.349	850-950	

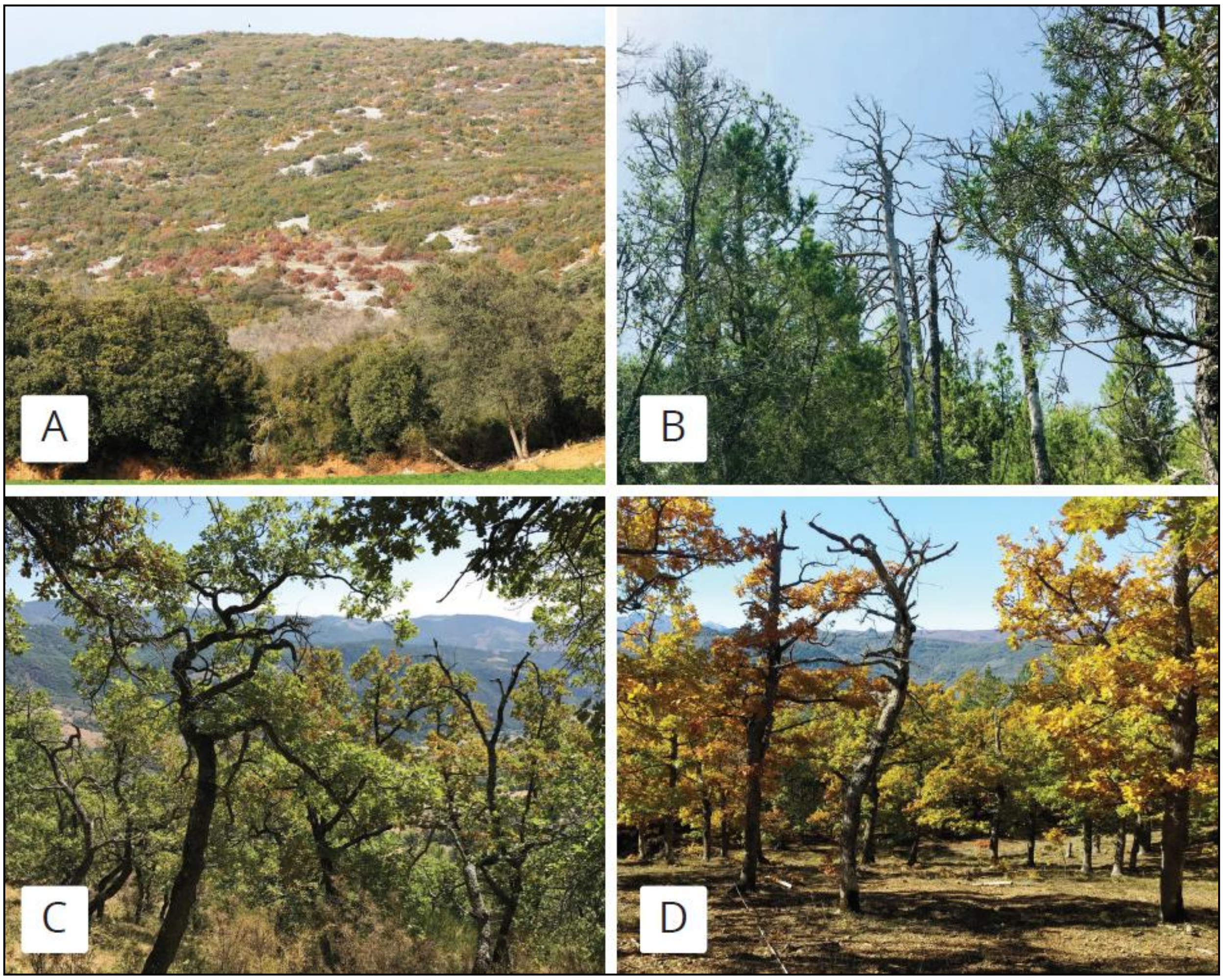


Figure 2 . Photographies showing the studied forest and shrubland dieback episodes across selected study sites: (A) Yaso, *J. phoenicea* shrubland; (B) Corbalán, *P. sylvestris* mixed forest; (C) Gorgoglione, *Q. pubescens* mixed forest; and (D) San Paolo Albanese, *Q. frainetto* pure forest.

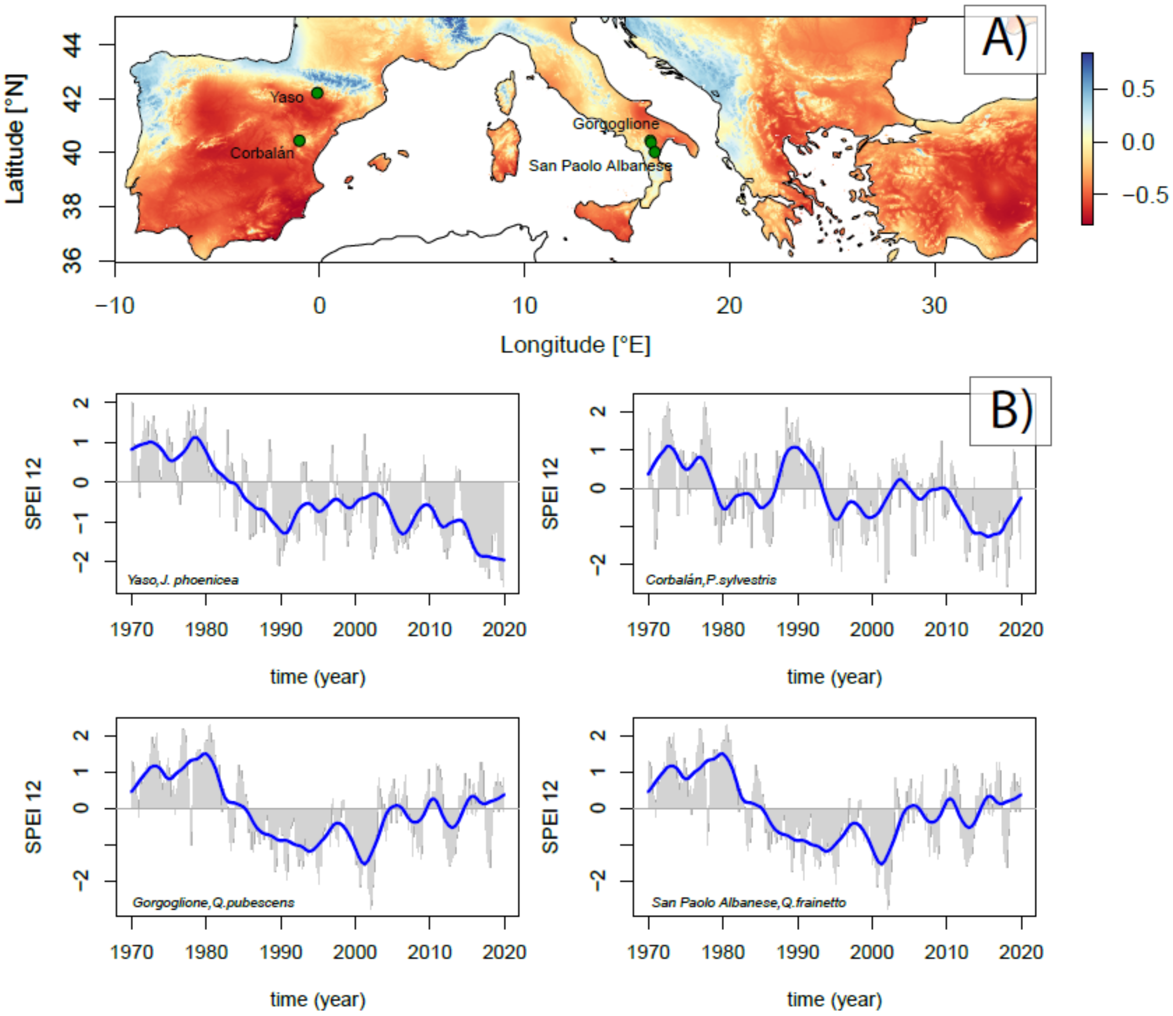


Figure 3. (A) Map showing a climate moisture index (CMI = P / PET) with wet and dry sites climates showing positive or negative CMI values, respectively across southern Europe. Green dots show the location of the four study sites. (B) Time series of the SPEI-12 drought index for each study site during 1970–2019. The SPEI varies from −3 to 3, being categorized as extremely wet (2.00 and above), very wet (1.50 to 1.99), moderately wet (1.00 to 1.49), near normal (−0.99 to 0.99), moderately dry (−1.00 to −1.49), severely dry (−1.50 to −1.99), and extremely dry (−2.00 and less).

2.2.2 Field sampling protocols

Declining or dieback (D) individuals showing dieback were considered those with crown transparency or defoliation higher than 50%, whereas non-declining or non-dieback (ND) individuals were those with crown transparency lower than 50%. The stem diameter was measured with tapes in all sampled individuals (at the base in shrubs and 1.3 m in trees), and crown transparency was evaluated by a visual assessment performed by two independent observations on the same tree using binoculars (Dobbertin, 2005). Pairs of neighboring D and ND individuals were selected. Within each couple, trees were located 10–15 m apart. In the case of shrubs, declining and non-declining patches were compared. The ecological and site-specific conditions (*e.g.*, soil type) of compared individuals or stands are similar. A similar ND-D comparison was carried out at the site level in the case of NDVI values.

2.2.3 NDVI data

The Normalized Difference Vegetation Index (NDVI) consists of the normalized ratio of reflectance in the red (R) and near-infrared (NIR) spectral wavelengths, *i.e*., NDVI = (NIR-R / (NIR + R) (Gorelick et al., 2017). This is one of the most used vegetation indices, and it is related to vegetation amount and photosynthetic activity and considered a proxy of productivity in drought-prone Mediterranean biomes (Vicente- Serrano et al., 2020). The NDVI values and trends reflect the relative abundance and activity of vegetation with positive (*greening*) or negative (*browning*) trends showing cover changes as a result of the modification in the level of vegetation photosynthetic activity over time (Pettorelli et al., 2005). MODIS vegetation indices dataset from the Terra (MOD13Q1) and Aqua (MYD13Q1) satellites were used in this study. These satellites acquire global images on a daily basis and, to avoid data gaps due to clouds and other atmospheric contamination, they are composed within a temporal window of 16-days (Didan et al., 2015).

From these products, we extracted NDVI time series with a temporal resolution of 8 days and a 250-m spatial resolution for each site from the Google Earth Engine platform via '*rgee*' (Aybar et al., 2020) bridge in the R software v.4.0.0 package (R Core Team, 2020). We aggregated the raw NDVI time series to either monthly or yearly maximum and decomposed NDVI time series into seasonal, trend, and irregular components using moving averages via R '*stats*' package. To identify and test for changes in vegetation indices, we applied non-parametric Theil-Sen (TS) regression on site-specific maximum annual NDVI ($NDVI_{max}$) time-series using the '*mblm*' R package (Komsta, 2019) because the $NDVI_{max}$ is less affected by outliers than the NDVI. Trends were estimated using the median values and are therefore less susceptible to noise and outliers (Sen, 1968; Theil, 1950). The significance of vegetation greening/browning trends was evaluated using the non-parametric Mann-Kendall test and statistical significance at the confidence of 95% ($p < 0.05$) was considered.

2.2.4 Tree radial growth data

To quantify radial growth, increment cores were extracted at breast height (1.3 m) using 5 mm Pressler increment borers in the case of trees, whereas basal sections were taken in the case of *J. Phoenicea* shrubs. In the Spanish Yaso shrubland site, basal stem cross-sections were collected from living (n = 28 individuals) and dead (n = 30 individuals) junipers. Pairs of neighboring, dominant living, and recently dead junipers were sampled as described by Camarero et al. (2020). Recently dead junipers still retained stem bark and fine branches but have lost most of their leaves. Concerning the Spanish Corbalán forest, 39 dominant and mature *P. sylvestris* trees (21 D trees and 18 ND trees) were selected and sampled (Camarero et al., 2018). In the Italian Gorgoglione site, one increment core per tree was sampled, due to restrictions imposed by forest managers for preserving the population; whereas for San Paolo Albanese two cores from each tree were used for tree-ring analyses.

A total of 38 individuals (17 D trees and 21 ND trees) of *Q. pubescens* were sampled in Gorgoglione, while 97 dominant *Q. frainetto* trees with contrasting vigor (35 D trees and 62 ND trees) were sampled at San Paolo Albanese (Colangelo et al., 2018, 2017a). Ring width series for all sampled materials were measured along two opposite radii per section, avoiding measuring eccentric parts. In the laboratory, the wood samples were air-dried and carefully sanded until ring boundaries were visible. Tree-rings were first visually cross-dated and then measured with a minimum precision of 0.01 mm using a binocular microscope coupled to a computer with the LINTAB package (Rinntech, Heidelberg, Germany). The cross-dating accuracy was finally checked with the program COFECHA (Holmes, 1983) which calculates moving correlations between each individual series and the average tree-ring width series. To quantify and compare growth trends between living and dead trees for each site, ring widths were converted into basal area increments (BAI) to account for geometrical effects of stem enlargement on growth using '*bai.in*' function from the "*dplR*" package (Bunn et al., 2021) in R environment (R Core Team, 2020). To obtain the mean value chronology for each site, the function "*chron*" via the "*dplR*" R package (Bunn et al., 2021) was applied.

2.2.5 Climate data

To classify the study sites according to their water balance, we obtained the climate moisture index (CMI, which ranges from −1 to +1) from the ENVIREM dataset v1.0 with a spatial resolution of ~5 km^2 (Title and Bemmels, 2018). The CMI is based on the methodology developed by Willmott and Feddema (1992), who calculated CMI as the ratio between annual precipitation (P) and annual potential evapotranspiration (PET) depending on P and PET value, *i.e.* (P / PET) - 1 when P < PET; and 1 - (PET / P) when P ≥ PET. In this way, wet and dry climate conditions correspond to positive or negative CMI values, respectively (Vörösmarty et al., 2005).

We got the vapor pressure deficit (VPD) and soil moisture data covering the period 1958-2020 from the TerraClimate dataset (http:// www.climatologylab.org/terraclimate.html), estimated using a Thornthwaite Mather climatic water-balance model (Willmott et al., 1985) and extractable soil water storage capacity data (Wang-Erlandsson et al., 2016). TerraClimate is a high-spatial-resolution (~ 4 km) dataset of monthly climate and climatic water balance for the global land surfaces, which is a combination of spatial climatology data from WorldClim and CRU TS4.0 climate datasets (Abatzoglou et al., 2018). To quantify the variability of drought impacts on tree growth, we also downloaded the Standardized Precipitation Evapotranspiration Index (SPEI) at a time scale of 12 months and a 0.5° spatial resolution. The SPEI was obtained from the Global Drought Monitor webpage (http://spei.csic.es/index.html). The SPEI is a multi-scalar drought index, which considers the effects of temperature and evapotranspiration on drought severity and indicates wet (positive SPEI values) and dry (negative SPEI values) conditions (Vicente-Serrano et al., 2010). The use of a longer SPEI time resolution is relevant to quantify the effects of droughts, mainly for forests that experience semi-arid conditions, as demonstrated by Vicente-Serrano et al. (2020). We plotted the climatic space of each species by retrieving their occurrence sites in Europe from the Global Biodiversity Information Facility (de Vries and Lemmens, 2021) via the '*rgbif*' R package (Chamberlain and Boettiger, 2017). Then, we obtained VPD and soil moisture for all species' sites and each study location. Soil moisture was plotted against VPD to detect if study sites were situated in locations characterized by extreme climate conditions *i.e.*, very high VPD, very low soil moisture, or both.

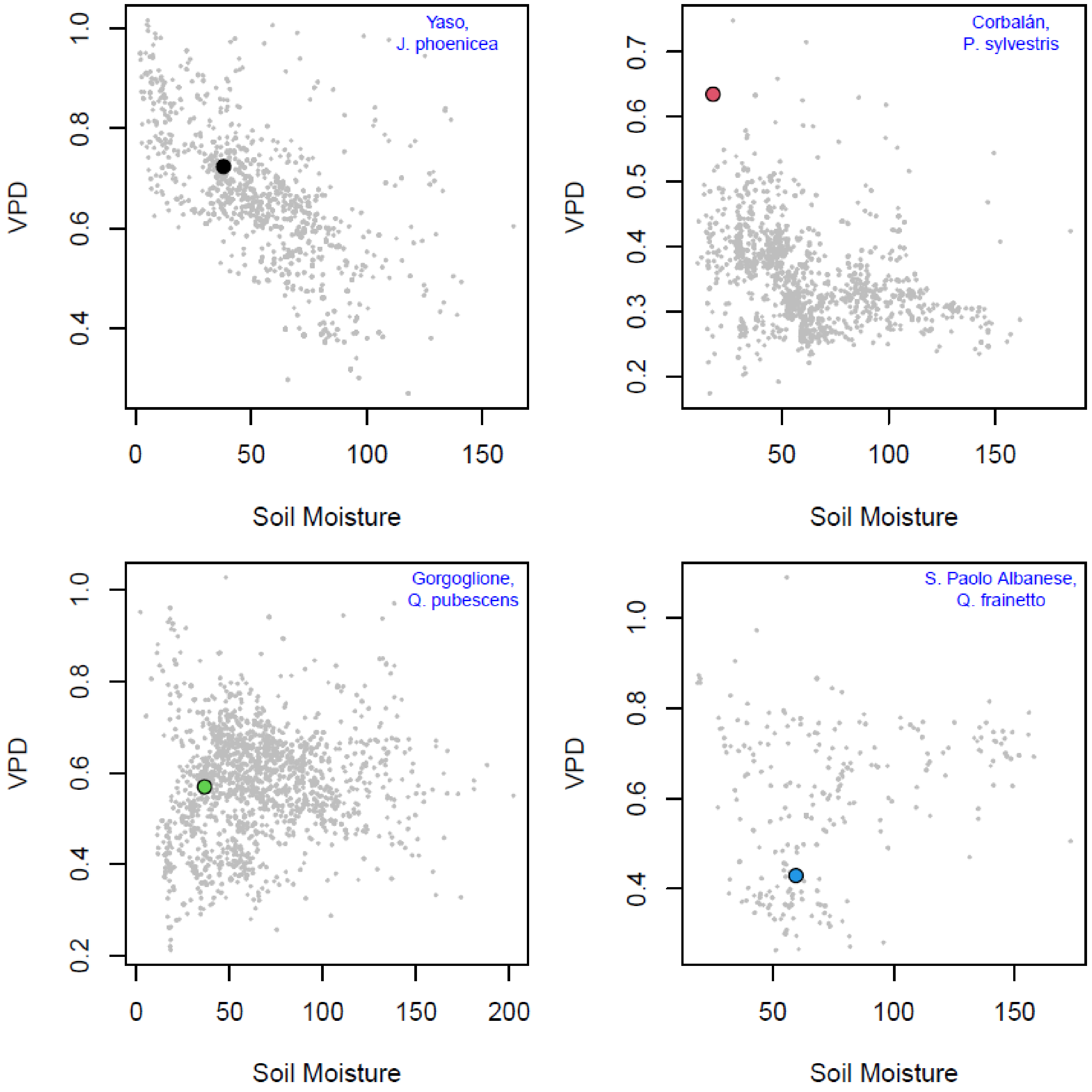


Figure 4 . Representation of each studied species in the climatic space. The grey dots represent values of mean annual VPD (in kPa) and total soil moisture (in mm) where the species are present in Europe while the marked dots in the graph indicate the location of the sampled tree populations of each species.

2.2.6 Data analyses

Relationships between yearly BAI with the growing season (May-June) maximum NDVI and yearly maximum NDVI ($NDVI_{max}$) were investigated through Spearman correlations using the "*rcorr*" function in the R package '*Hmisc*' (Harrell, 2020). Then for each site, linear mixed-effects models were fitted to assess the effects of VPD, soil moisture (dummy coded "low" and "high", based on the interannual average value cutoffs), diameter, individual vigor status (D *vs* ND), and their interactions (fixed factors) on growth (log (BAI)), where individuals were considered as random effects to account for repeated measure within site. Fixed terms were centered and scaled to improve parameter estimates and allow direct comparisons of the regression coefficients. We then optimized the random-effect structure of the model testing if including extra random-effects terms (*i.e.*, diameter as random slopes) improved the fit of the model; different random structures were compared through a likelihood ratio test (Zuur et al., 2009). When comparing models that varied in their random structure but not fixed effects, the models were fitted using restricted maximum likelihood to avoid biased estimators for the variance terms. Model estimation was performed using the '*lme4*' package (Bates et al., 2015) from R software (R Core Team, 2020). Marginal and conditional R^2 values (Nakagawa and Schielzeth, 2013) were calculated to examine the variation explained by fixed and fixed plus random factors using the '*r.squaredGLMM* ' function in the "*MuMIn*" package. Furthermore, we evaluated the linkage of the stand-specific maximum annual NDVI with the VPD and soil moisture, and their interactions via linear regressions. The diagnosis of residuals was performed to check the validity of the models' assumptions (normality and homoscedasticity of residuals) and the absence of temporal autocorrelation. Subsequently, the '*emtrends*' function from the '*emmeans*' R package (Lenth, 2021) was used to test the difference in terms of NDVI or radial growth at nearby stands showing contrasting vigor *i.e.*, dieback *vs.* non-dieback stands by comparing differences of site-specific slopes of fitted lines through Tukey post-hoc test.

To detect potential asynchrony between radial growth and NDVI and climate (VPD), cross-correlation of a log-transformed bivariate time series for selected species/stands were performed using the function ‘*cc.test’* of the ‘*testcorr*’ (Dalla et al., 2021) R package.

2.3 Results

2.3.1 Climate trends

The study sites are located in some of the driest sites for their respective species' distribution areas in Europe (Figs. 3 and 4), particularly in the case of the *P. sylvestris* site. More importantly, aridification trends are noticeable in the four study sites with very negative SPEI values in the 1980s, 1990s, and 2010s in the Spanish sites, and in the 1980s, 1990s, and early 2000s in the Italian sites (Fig. 3B). In the Spanish sites, VPD has steadily increased during the last decades, particularly after the 1990s, whereas soil moisture has decreased (Fig. S1), whilst the changes in these climate variables are of lower magnitude in the wetter Italian sites.

2.3.2 NDVI patterns and trends

Overall, a synchronic NDVI pattern is found for all sites over the period 2001-2019, with lower NDVI values in dieback stands (Fig. 5). A rather common $NDVI_{max}$ pattern is also shared between D and ND patches in both Gorgoglione and San Paolo Albanese oak sites where the increasing $NDVI_{max}$ trend (*greening*) was significant ($p<0.05$). For the Yaso shrubland site, the $NDVI_{max}$ trend exhibited a significant positive slope (*greening*) only for the D stand, whereas the Corbalán D stand had a significant negative (*browning*) trend. In this site, differences between D and ND stands become increasingly consistent over the years.

2.3.3 Growth patterns

The annual BAI pattern showed a clear divergence between D and ND individuals in all analyzed species with lower values in D individuals, as expected (Fig. 6). In particular, the BAI trends of D and ND individuals started to diverge in the 1990s in the case of *J. phoenicea* and in the 1980s in the case of *P. sylvestris*. Trends in BAI were always lower in D than in ND individuals from 2000 onwards for both oak species. For each specific site, interestingly, the onset of the ND-D growth divergence coincided with dry years characterized by very negative SPEI values (Fig. 3B).

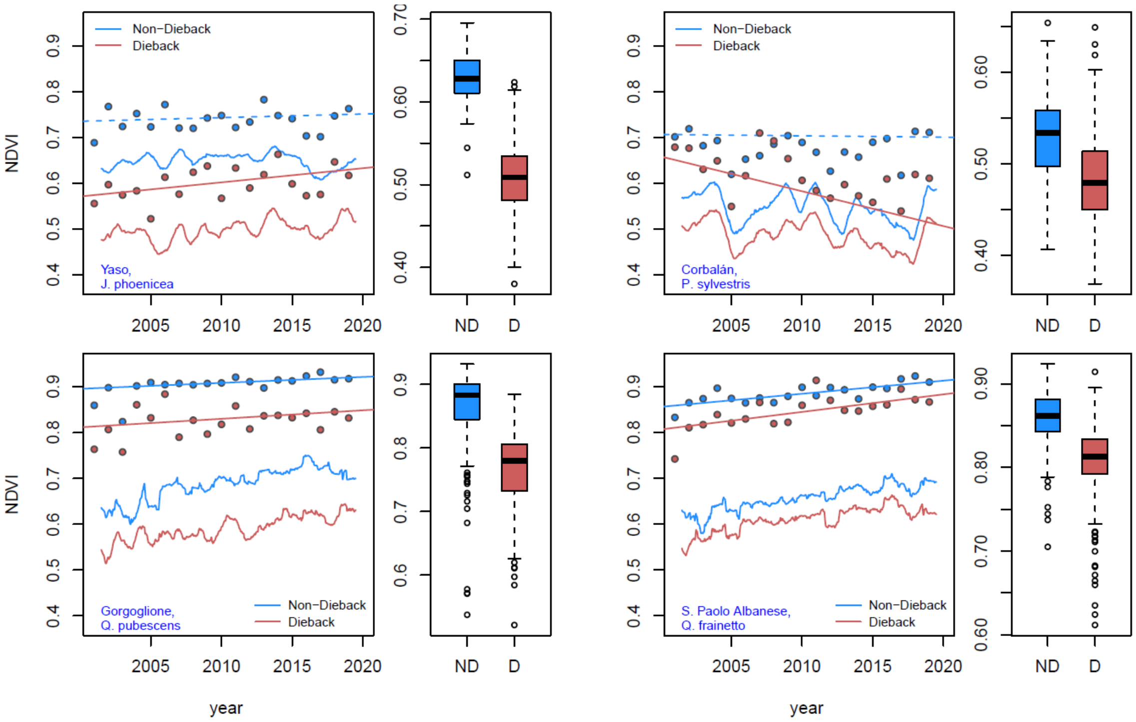


Figure 5 . NDVI linear trends from decomposed 8-day composite time series from 2001 to 2019 for non-dieback (ND, blue symbols and lines) and dieback (D, red symbols and lines) stands. Points represent the annual maximum NDVI value and fitted straight lines are the estimated Theil-Sen (TS) regression, where full and dashed lines are for significant ($p < 0.05$) and not significant slopes, respectively. Boxplots refer to the annual growing season (May to June) NDVI values for ND and D sites. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers. Y-axes show different scales.

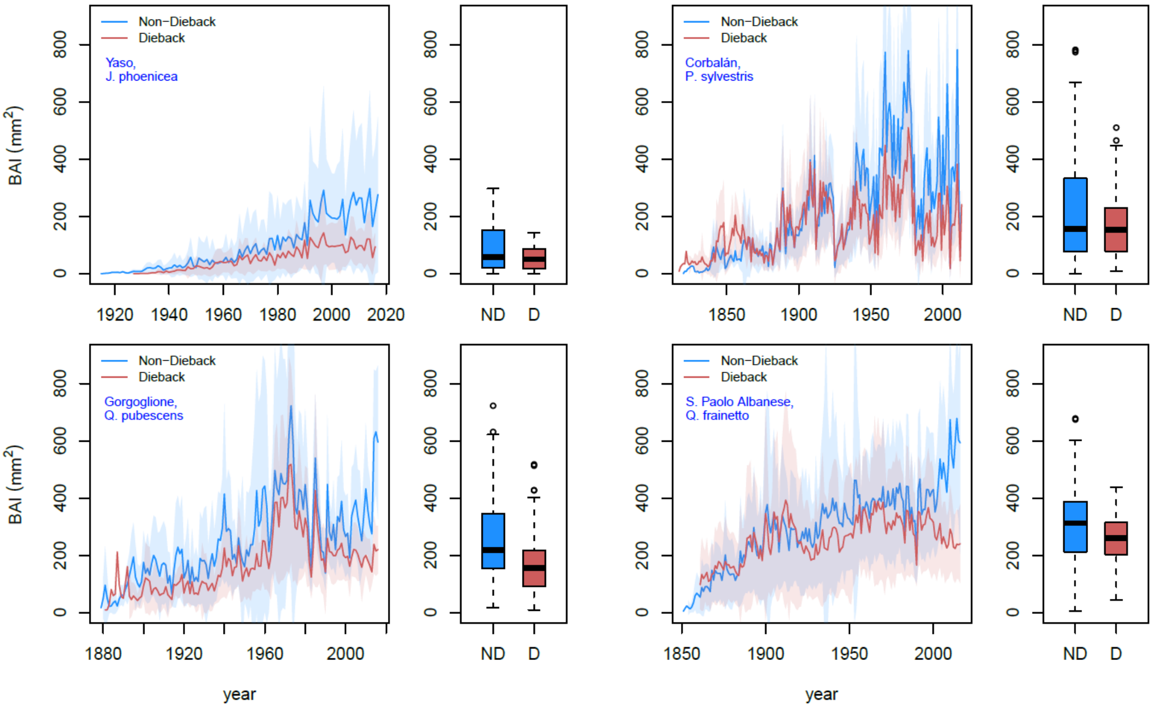


Figure 6 . Basal area increment (BAI) time series for non-dieback (ND) and dieback (D) individuals (lines). The shaded area represents the standard deviation of the mean. Boxplots of the BAI distribution for ND and D individuals. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

2.3.4 Relationships between NDVI and tree growth

There was a stronger relationship of NDVI and BAI between May to June (growing season) for pine and juniper stands than for oak stands, particularly for dieback individuals (Table 2). In most cases, BAI and NDVI were positively related. For the Yaso juniper stand, the growth values of both D and ND trees were found to be positively and significantly correlated with NDVI. A positive and significant relationship was also observed for the Corbalán stand, with a moderately higher value for D trees. Regarding the Gorgoglione stand, the BAI-NDVI relationship was positive but not significant.

For the San Paolo Albanese stand, the growth of ND trees exhibited a positive and significant correlation with NDVI, while correlation was slightly negative for D trees. Examination of the association between BAI and annual maximum NDVI indicated similar associations in oaks. However, for pine and juniper stands, the correlations were again positive but not significant ($p > 0.05$).

Table 2. Spearman correlation coefficients calculated between basal area increment (BAI) and May to June maximum NDVI, and annual maximum NDVI ($NDVI_{max}$). Bold values are significant at $p < 0.05$.

Site	Status	BAI – NDVI	BAI – $NDVI_{max}$
Yaso	Dieback	**0.54**	0.22
	No-dieback	**0.53**	0.34
Corbalán	Dieback	**0.69**	0.13
	No-dieback	**0.65**	0.20
Gorgoglione	Dieback	0.31	0.31
	No-dieback	0.43	0.43
San Paolo Albanese	Dieback	-0.05	-0.18
	No-dieback	**0.63**	**0.60**

2.3.5 Climatic influences on NDVI and growth

While VPD was negatively associated with $NDVI_{max}$ in both D and ND *P. sylvestris* stands (Fig. 7), we found a decoupling between the effects of soil moisture on the NDVI-VPD relationships of the other species. For instance, the relationship between VPD and $NDVI_{max}$ under low soil moisture conditions is significant neither for *J. phoenicea* nor for *Q. pubescens* stands. A different picture emerges for *Q. frainetto*, where the VPD - $NDVI_{max}$ relationship becomes positive and significant under low soil moisture conditions (Fig. 7, and Supplementary Table S1).

Regarding the influence of drought on growth (BAI), we observed a significant ($p<0.05$) decrease of growth in response to increasing VPD in *J. phoenicea* (Fig. 8, and Supplementary Table S2). For the P. *sylvestris* stand, a significant negative trend of BAI at increasing VPD was detected only for D trees under more humid soil conditions *i.e.*, growth response to varying soil moisture depended on vigor class. For both *Q. frainetto* and *Q. pubescens* BAI decreased at a similar rate as VPD increased regardless of vigor class or soil moisture, but *Q. frainetto* D trees did not show a decline in growth in years characterized by high soil moisture. No peculiar legacy effects were found between BAI and $NDVI_{max}$, but *Q. frainetto* in the San Paolo Albanese site, nor between $NDVI_{max}$ and VPD (Supplementary Figs. S2 and S3).

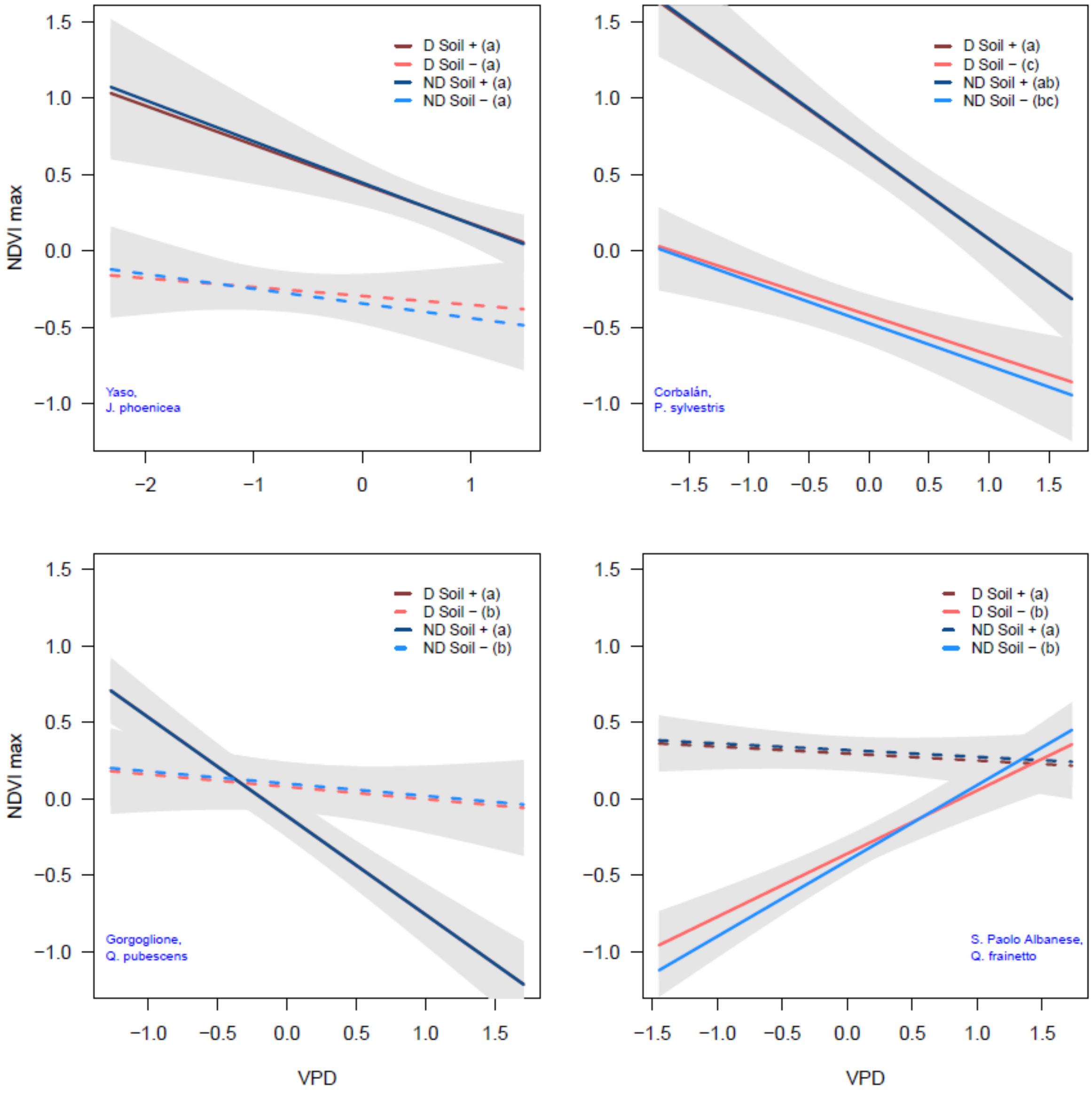


Figure 7 . Fitted slopes of $\mathrm{NDVI}_{\mathrm{max}}$ against atmospheric vapor pressure deficit (VPD) for dieback (D) and non-dieback (ND) sites in years characterized by low (−) and high (+) soil moisture. The interannual average value was used as cutoffs to determine "low" (−) and "high" (+) soil moisture. Straight lines represent a significant ($p < 0.05$) slope, while dashed lines do not. Shaded areas represent the confidence interval of predicted values. Different letters indicate differences among site specific slopes.

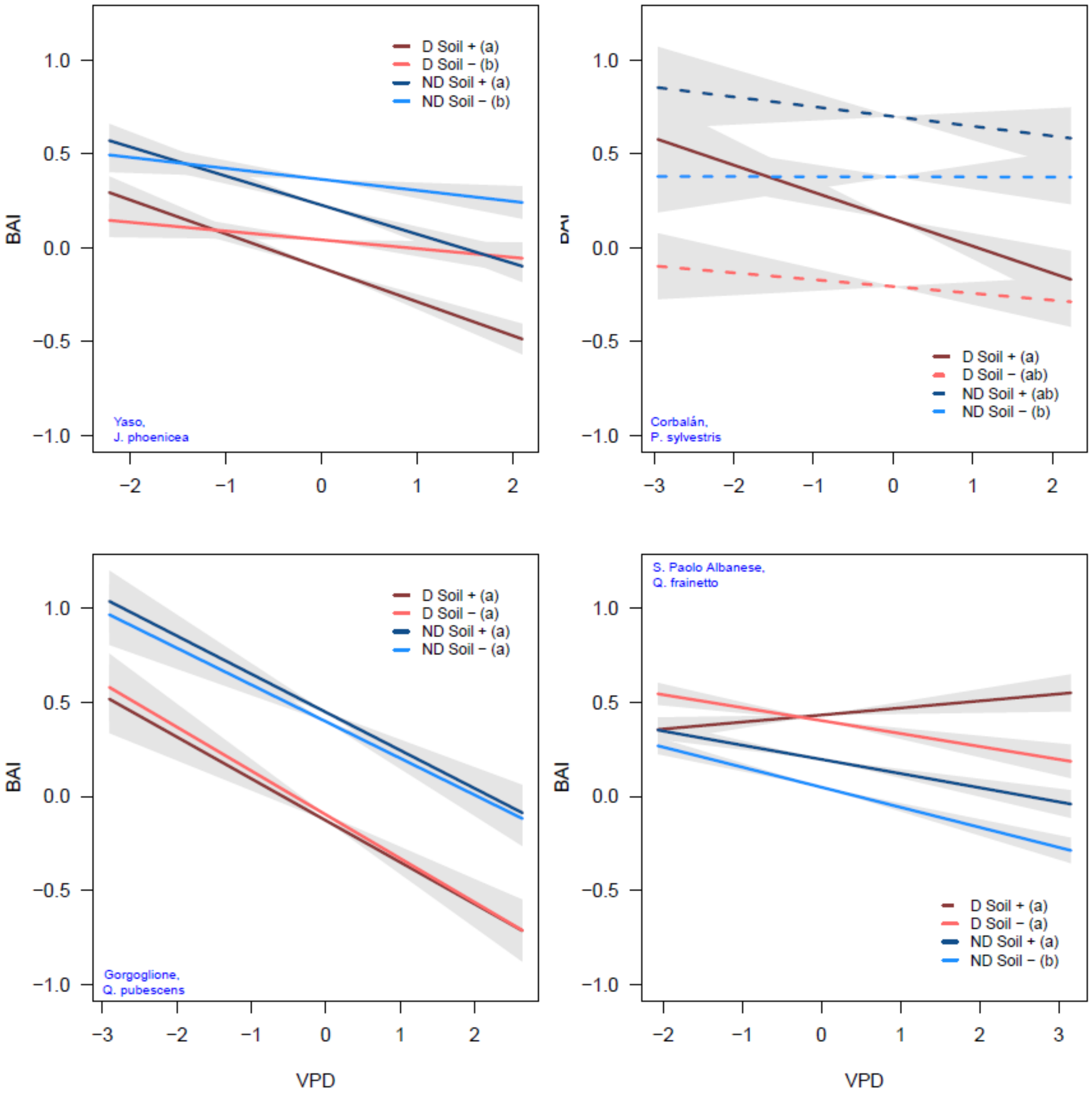


Figure 8 . Fitted slopes of the basal area increment (BAI) against atmospheric vapor pressure deficit (VPD) for non-dieback (ND) and dieback (D) individuals in years characterized by low (−) and high (+) soil moisture. The interannual average value was used as cutoffs to determine “low” (−) and “high” (+) soil moisture. Straight lines represent a significant ($p<0.05$) slope, while dashed not. Shaded areas represent the confidence interval of predicted values. Different letters indicate differences among site-specific slopes.

2.4 Discussion

2.4.1 Coupling radial growth and NDVI at multiple spatial and temporal scales improve dieback assessment

Our findings highlight the striking different responses to drought between sites, stands, or individuals showing different vigor in terms of canopy greenness and radial growth. As hypothesized, dieback stands presented lower NDVI values than non-dieback ones. This marked difference would suggest that individuals in dieback stands exhibit a lower performance, affecting not only their radial growth but also increasing their vulnerability to other abiotic (*e.g.,* frost) and biotic (*e.g.,* insect defoliators, fungal pathogens) stress factors. Although expected, this result emphasizes the significant contribution of remotely sensed indices to identify and discriminate forests and shrublands characterized by dieback symptoms and their use in ecosystem health monitoring. This would suggest that scaling up from tree to stand levels might be feasible when using the maximum growing season NDVI, which can be applied for retrospective modeling of the impact of drought stress on forest productivity in woody plant communities over large areas. Using vegetation indices from satellite data, prior studies successfully upscaled from individual- to forest-scale processes, especially for monitoring vegetation response to drought by coupling ground-measured growth data and remotely sensed data (*e.g.,* Vicente-Serrano et al., 2013, 2016; Correa-Diaz et al., 2019). This approach allowed to overcome the major restriction of satellite-time series for monitoring tree physiology *i.e*., the relatively limited temporal coverage compared with the long-term record of tree growth at multi-decadal time scales. Radial growth patterns of trees from stands showing dieback and for all surveyed species showed significant reductions in the last decades as previously reported by Camarero et al. (2015, 2018, 2020) and Colangelo et al. (2017a, 2017b, 2018). Growth trends of dieback and non-dieback trees and shrubs exhibit a characteristic divergence, which widened towards the present.

The onset of this divergence occurs in distinct years, particularly after droughts, and could be attributed either to the species-specific response to drought or local characteristics related to soil type or competition among neighbors (Camarero et al., 2015; Cailleret et al., 2017). Our results indicate that such growth divergence between trees of different vigor may be attributed to climate extreme events related to drought stress such as very high vapor pressure deficit (VPD) or very low soil moisture triggering an irreversible loss in vigor and growth decline. Indeed, over the last decades, extreme climate events such as heat stress and drought spells have affected the growth of trees in these sites, leading to a declining pattern that has persisted until today, especially in most vulnerable dieback individuals and stands (Camarero et al., 2018). The different species' physiology also is found to significantly influence the patterns of the relationship between NDVI and tree growth (Moreno-Fernandez et al., 2021). Differing outcomes of this work revealed coupled significant relationship between the growing season maximum NDVI values and radial growth (BAI) for pine and juniper stands. Interestingly, the Spanish conifer populations were located in sites characterized by high VPD and low soil moisture (Fig. 4), indicating a strong response to evaporative demand and rising temperatures. However, the Italian oak sites were characterized by low soil moisture conditions suggesting a great dependence on soil water availability in agreement with their anisohydric strategy characterized by a weak regulation of stomatal conductance and a high dependence on deep soil water sources during the dry summer (Ripullone et al., 2020). For the Spanish stands, the relationships observed between BAI-NDVI and BAI-$NDVI_{max}$ agree with several studies demonstrating a tight link between canopy greenness and tree-ring growth reflecting associations between carbon uptake and productivity (Moreno-Fernandez et al., 2021). However, NDVI and growth data are most inter- correlated in specific time windows of the year, as reported Vicente- Serrano et al. (2020).

Specifically, radial growth appears to be more related to the maximum NDVI of the growing season rather than the summer maximum NDVI, which corresponds to the maximum greenness peak of the growing season before the summer water deficit. These results underline the possibility that the timing of the correlation may allow detecting periods in which the climatic factors influence tree growth (Kaufmann et al., 2008). We acknowledge that the non-significant association between NDVI and BAI for the *Q. frainetto* dieback stand may be related to either asynchrony between radial growth and NDVI or site-specific conditions such as low tree density and non-uniform canopies coverage. In the first case, the two-year time lag between the radial growth and NDVI for declining trees might partly reflect an adaptation of trees to environments with more severe water stress *i.e.*, they carry over fixed carbon from 2 years to subsequent years (*e.g.*, McDowell et al., 2008). Instead, the one-year time lag between BAI and NDVI would be a likely consequence of reduced radial growth after canopy loss leads to lower productivity. In the second case, the reflectance of background components such as understory vegetation and soil may have had a significant effect on the canopy reflectance when the canopy cover is low (Huemmrich and Goward, 1997). Additionally, the scale mismatch of poor replicated tree ring data (individual level) and coarse resolution of MODIS NDVI (250 m) data could further affect uncertainty in our results. It is therefore hard to discern the distinct response of forest species within the mixed stand such as Gorgoglione site. All this points to an inevitable weakness of our study, related to the potential confounding of inter-site variation with an inter-species variation. Future research is needed, primarily in terms of eco-physiological implications.

2.4.2 Climate influences on NDVI and tree growth

One of the main results of our study is that an increased VPD leads to a reduction in growth, supporting findings that Mediterranean vegetation productivity is tightly linked to atmospheric water demand (Vicente-Serrano et al., 2014). In this context, recent surveys recognized the importance of VPD as one of the most crucial key drivers of drought-induced dieback and tree mortality across forest biomes (Grossiord et al., 2020), although some tree species might be able to tolerate more variable and higher atmospheric evaporative demand than others (Martinez-Vilalta et al., 2014). Remarkably, tree radial growth is more constrained by high VPD values than by low soil moisture in temperate forests subjected to seasonal drought (Zweifel et al., 2021). As hypothesized, the considered tree and shrub species showed different growth responses to VPD and soil moisture which may be partially explained by their water use strategy, which probably affected tree growth responses to drought. The strong dependence of juniper growth on VPD would be explained by its vulnerability to elevated summer temperatures enhancing transpiration which is not compensated by water uptake from the uppermost soil horizon (Baquedano and Castillo, 2007). In this species, the less affected non-dieback individuals showed a stronger growth reduction in response to rising VPD than dieback individuals (see crossing blue and red lines in Fig. 8), and this response was not related to soil water availability. Such a behavior could be due to the differential response to increasing atmospheric aridity and hotter droughts because dieback individuals show a stronger water loss through leaves and lower growth than non-dieback individuals which probably have better access to soil water (Camarero et al., 2020). Conversely, we did not find any significant growth patterns in response to increasing VPD in *P. sylvestris* individuals of different vigor, which is probably linked to its isohydric behavior and tight control of stomatal conductance. Indeed, as water soil potential decreases and VPD increases, this species reduces stomatal conductance to prevent xylem cavitation (Roman et al., 2015).

Such a strong stomatal control keeps trees maintaining the leaf water potential within a constant threshold (Martinez-Vilalta et al., 2014), although it may affect photosynthesis leading to carbon starvation at the tissue level (Mitchell et al., 2013). One of the most interesting findings we presented is that increased VPD affected pine growth more in dieback than in non-dieback trees, particularly when trees experienced high soil moisture conditions. Although this might appear rather counterintuitive, we argue that in this stand tree dieback growth is more affected by atmospheric aridity rather than soil water availability. Dieback pine trees are less plastic, in terms of growth and potential hydraulic conductivity, in response to higher water availability compared to non-dieback trees as suggested by wood anatomical studies (Pellizzari et al., 2016). This would correspond to a long-term deterioration in the hydraulic performance of declining individuals in this stand which lose responsiveness to climate. Indeed, the divergence between dieback and non-dieback trees was observed after the 1950s (Fig. 6), when the site water balance steadily started to decrease. We expected that oaks were comparatively more drought-tolerant given their anisohydric strategy than pine. Oaks tolerate more leaf water potential reduction by keeping higher stomatal conductance and photosynthetic rates compared to isohydric pines (Poyatos et al., 2008). Hence, oaks should exhibit less dependency on soil moisture fluctuations. Indeed, we did not observe soil moisture co-variability in response to increasing VPD in *Q. pubescens*. That is, this species is able to maintain a high transpiration rate even though soil moisture deficit occurs, as a result of its capacity to extract water from deeper soil layers, particularly in the case of non-dieback trees, during the peak of summer drought (Ripullone et al., 2020). This is supported by Roman et al. (2015) reporting that oaks were more resilient to the severe drought of 2011-2012 due to their anisohydric hydraulic regulation strategy. Additionally, multiple evidence reported that species-specific response may impair the local macroclimate effect of trees growing within the same geographical area (*e.g.*, Camarero et al., 2021c).

In this context, *Q. frainetto* is less drought-tolerant and more sensitive to soil water availability than *Q. pubescens* (Siam et al., 2008) and this might help to explain its null growth response to increasing VPD in years with higher soil moisture. What described above opens an important question regarding the possible implication of the coordination between hydraulic traits and water use spectrum in light of climate change and on how trees can tolerate and recover from drought stress. In particular, one would expect tree species to respond hydraulically to drought in predictable ways, *i.e.*, following isohydric *vs*. anisohydric strategies (McDowell et al., 2008; Hartmann et al., 2013). Such framework would rank tree species according to their post-drought resistance and resilience, where anisohydric species having small safety margins (Anderegg et al., 2015) and limited recovery rate during low-intensity or short duration droughts compared to isohydric ones (*e.g.*, Mitchell et al., 2013). However, many caveats complicate such a mechanistic representation of species behavior (see Hochberg et al., 2018, and references therein), among others the interactions between multiple environmental conditions (*e.g.*, both soil water supply and atmosphere demand) and plant traits (*e.g.*, hydraulic architecture and root depth) that can strongly influence plant hydraulic behavior at relatively fast timescales making a species shifting from partial isohydric to extreme anisohydry (*e.g.*, Guo et al., 2020).

2.5 Conclusion

In the context of climate warming, our study provided an evaluation of the impacts of climate extremes on tree and shrub species that exhibited drought-induced dieback. Severe droughts have been recognized as the main contributing driver of tree and shrubs dieback in the Mediterranean Basin. A crucial insight comes out in this paper by comparing not only dieback and non-dieback trees, but also stands showing contrasting degrees of defoliation and canopy vigor. The effects of climate extremes on vegetation can be found both in terms of canopy greenness and radial growth losses, suggesting the possibility of: i) employing remotely sensed data as a stand-level indicator of climatic stress, and ii) scaling up from tree growth to stand NDVI. In most cases, we detected a positive correlation between BAI and NDVI. In addition, our analysis revealed that this inter-relationship is probably affected by the specific time window of the year. We speculate that this may be useful to characterize the timing in which climate extremes most closely affect growth. The overall response of the studied species to increased vapor pressure deficit was characterized by growth reduction. But, the different hydraulic strategies of anisohydric *vs.* isohydric species may lead to different growth responses to high vapor pressure deficit and low soil moisture. The pronounced response to increased VPD of the juniper was related to its vulnerability to maximum air temperatures. In the case of the pine, located at a very xeric site, the increase in VPD had the strongest influence on the growth of the dieback trees, thus also confirming its likely long-term deterioration of hydraulic performance. The oaks, as hypothesized, were found to have a lower dependency on soil moisture fluctuations compared to pine and juniper. Our findings also show how changes in vegetation response to climate extremes may depend on both the water use strategies of trees and shrubs and site specific climate conditions. Nevertheless, additional local factors related to biotic interactions or soil features may have affected NDVI and growth and may explain underlying mechanisms affecting vegetation responses to extreme climate events during dry spells.

Our framework shows how scaling up from tree to stand levels might be feasible when using the maximum growing season NDVI and tree-ring width data taken at the individual scales. Coupling such variables may be used for retrospective modeling of the impact of drought stress on forest productivity in woody plant communities and over large areas, particularly in drought “*hotspots*” or stands severely impacted by water shortage.

2.6 Supplementary materials

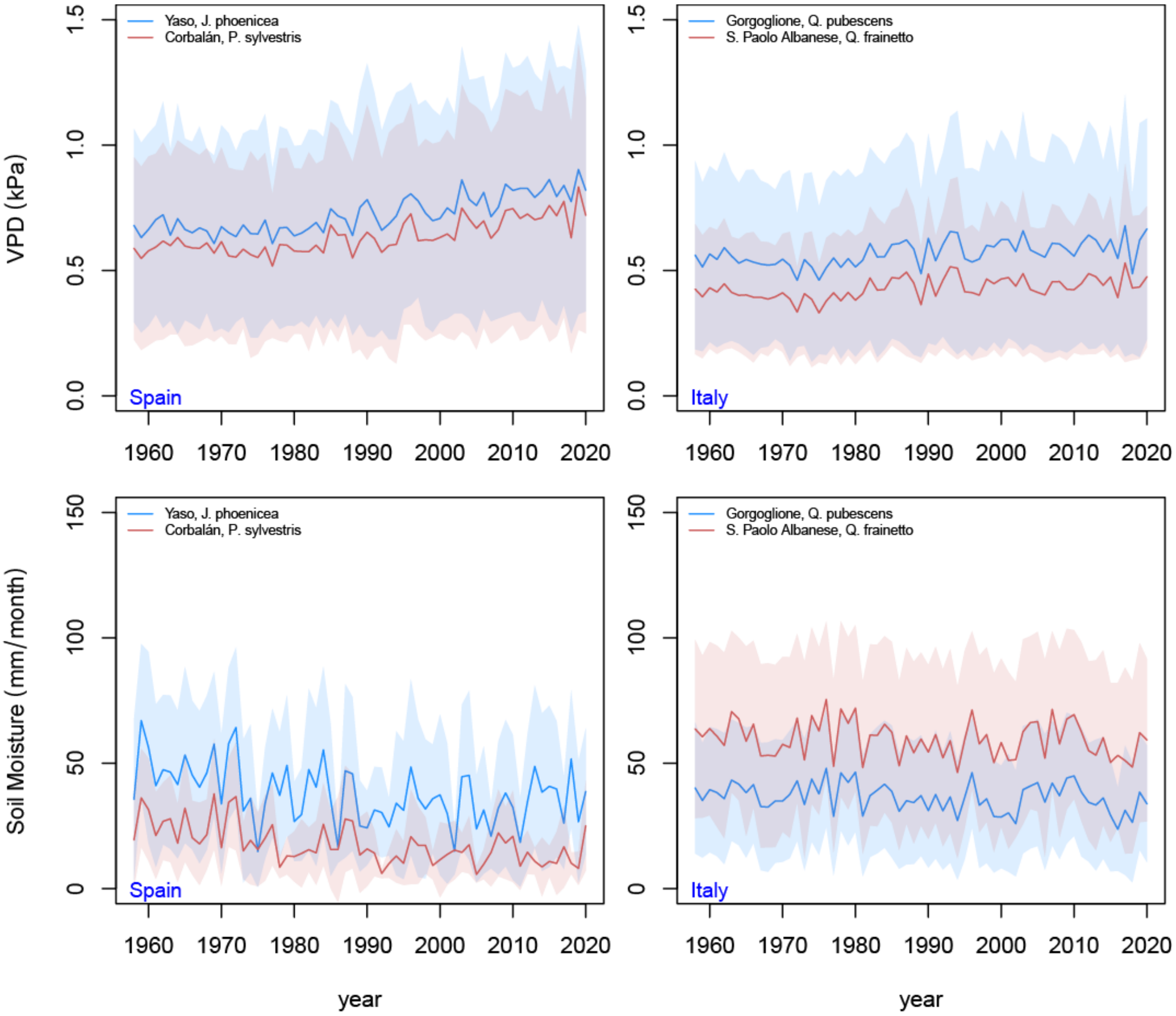


Figure S1. Temporal patterns of vapor pressure deficit (VPD) and monthly soil moisture for selected study sites and considering the 1958-2020 period.

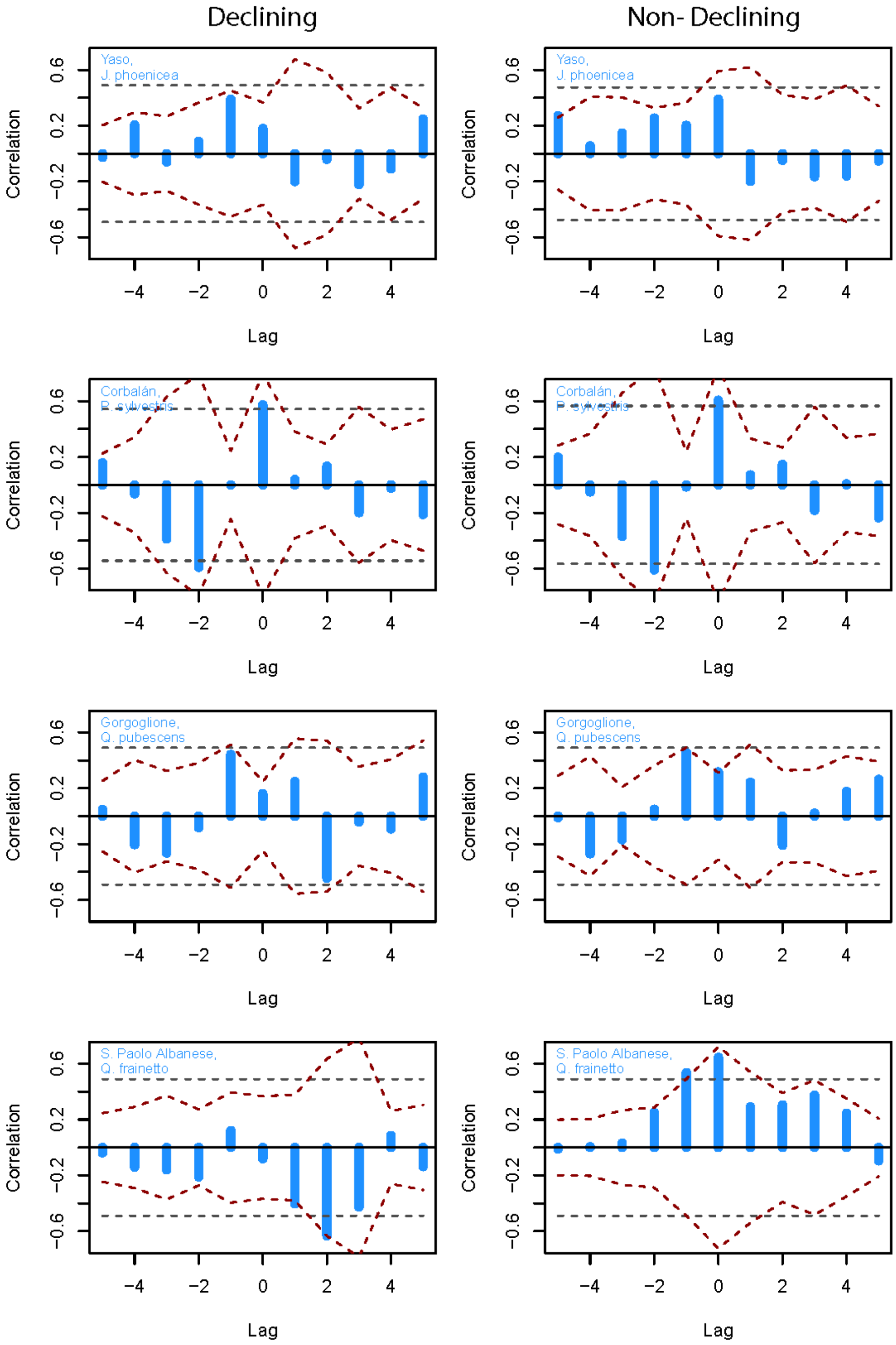


Figure S2. Cross-correlation of a bivariate time series *i.e.*, log(BAI) and log(NDVI$_{max}$) for selected species using the function "*cc.test*" of the testcorr (Dalla et al., 2021) R package. In the correlogram, dashed lines represent the 95% confidence band for standard (grey) and robust (red) statistics for non-significance of correlation. Left and right panels are declining and non-declining, respectively.

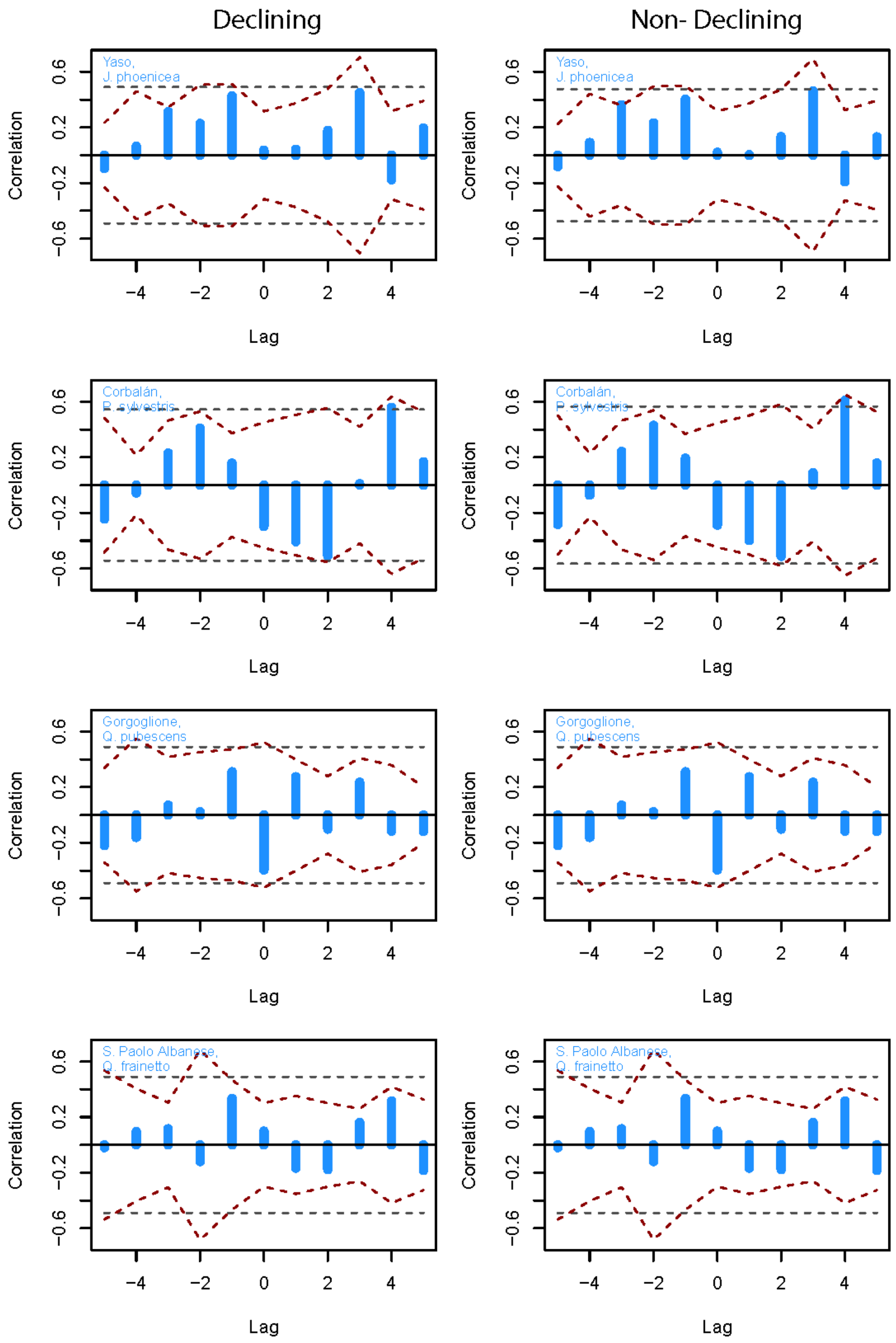
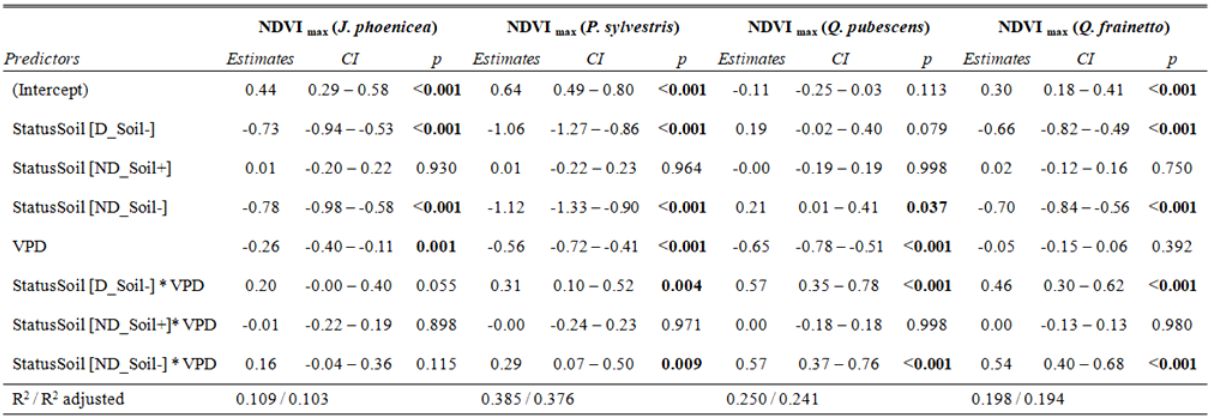


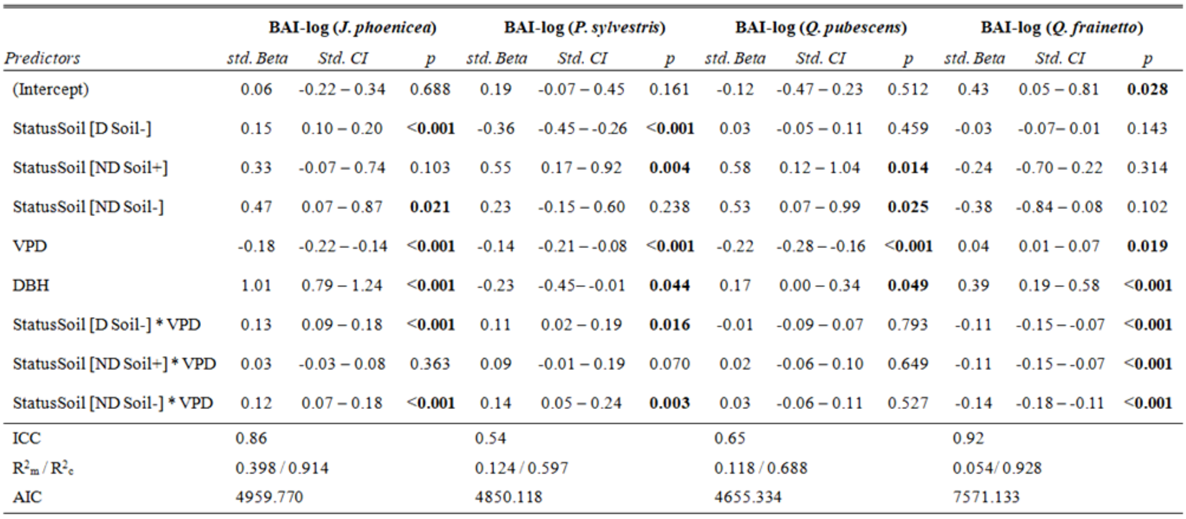
Figure S3. Cross-correlation of a bivariate time series i.e., log(NDVI$_{max}$) and log(VPD) for selected species using the function "*cc.test*" of the testcorr (Dalla et al., 2021) R package. In the correlogram, dashed lines represent the 95% confidence band for standard (grey) and robust (red) statistics for non-significance of correlation. Left and right panels are declining and non-declining, respectively.

Table S1. Standardized estimates of the linear models fitted to $NDVI_{max}$ data as a function of vapor pressure deficit (VPD), soil moisture condition (+ high, - low), and individual vigor status (D, ND) in the four study sites. Standardized estimates, std. Beta; Standardized confidence interval, std. CI; the last row the R^2 and the adjusted R^2. Significance levels: $p \leq 0.05$, $p < 0.01$, $p < 0.001$.



	NDVI $_{max}$ (*J. phoenicea*)			**NDVI $_{max}$ (*P. sylvestris*)**			**NDVI $_{max}$ (*Q. pubescens*)**			**NDVI $_{max}$ (*Q. frainetto*)**		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.44	0.29 – 0.58	<**0.001**	0.64	0.49 – 0.80	<**0.001**	-0.11	-0.25 – 0.03	0.113	0.30	0.18 – 0.41	<**0.001**
StatusSoil [D_Soil-]	-0.73	-0.94 – -0.53	<**0.001**	-1.06	-1.27 – -0.86	<**0.001**	0.19	-0.02 – 0.40	0.079	-0.66	-0.82 – -0.49	<**0.001**
StatusSoil [ND_Soil+]	0.01	-0.20 – 0.22	0.930	0.01	-0.22 – 0.23	0.964	-0.00	-0.19 – 0.19	0.998	0.02	-0.12 – 0.16	0.750
StatusSoil [ND_Soil-]	-0.78	-0.98 – -0.58	<**0.001**	-1.12	-1.33 – -0.90	<**0.001**	0.21	0.01 – 0.41	**0.037**	-0.70	-0.84 – -0.56	<**0.001**
VPD	-0.26	-0.40 – -0.11	**0.001**	-0.56	-0.72 – -0.41	<**0.001**	-0.65	-0.78 – -0.51	<**0.001**	-0.05	-0.15 – 0.06	0.392
StatusSoil [D_Soil-] * VPD	0.20	-0.00 – 0.40	0.055	0.31	0.10 – 0.52	**0.004**	0.57	0.35 – 0.78	<**0.001**	0.46	0.30 – 0.62	<**0.001**
StatusSoil [ND_Soil+]* VPD	-0.01	-0.22 – 0.19	0.898	-0.00	-0.24 – 0.23	0.971	0.00	-0.18 – 0.18	0.998	0.00	-0.13 – 0.13	0.980
StatusSoil [ND_Soil-] * VPD	0.16	-0.04 – 0.36	0.115	0.29	0.07 – 0.50	**0.009**	0.57	0.37 – 0.76	<**0.001**	0.54	0.40 – 0.68	<**0.001**
R^2 / R^2 adjusted	0.109 / 0.103			0.385 / 0.376			0.250 / 0.241			0.198 / 0.194		

Table S2. Standardized estimates of the linear mixed-effects models fitted to annual radial growth (basal area increment) data as a function of vapor pressure deficit (VPD), soil moisture condition (+ high, - low), diameter at breast height (DBH), individual vigor status (D, ND) in the four study sites. Standardized estimates, std. Beta; Standardized confidence interval, std. CI; the last three rows show the intraclass correlation coefficient (ICC), the Akaike information criteria (AIC), and the R^2m and R^2c, which correspond to the marginal and conditional R^2 values accounting for the variance explained by fixed and fixed plus random effects, respectively. Significance levels: $p \leq 0.05$, $p < 0.01$, $p < 0.001$.

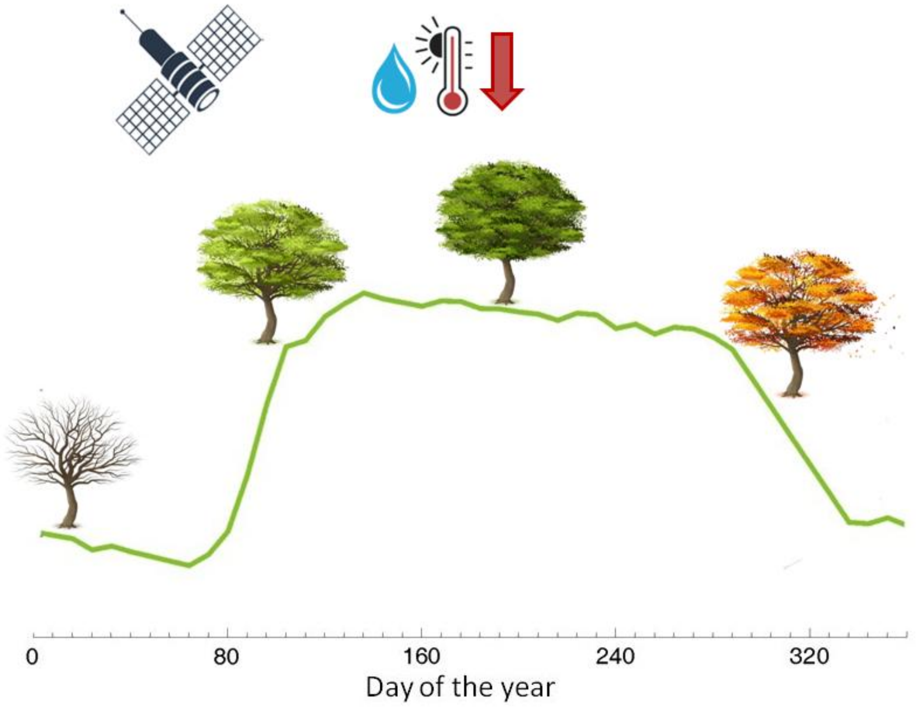


	BAI-log (*J. phoenicea*)			**BAI-log (*P. sylvestris*)**			**BAI-log (*Q. pubescens*)**			**BAI-log (*Q. frainetto*)**		
Predictors	*std. Beta*	*Std. CI*	*p*	*std. Beta*	*Std. CI*	*p*	*std. Beta*	*Std. CI*	*p*	*std. Beta*	*Std. CI*	*p*
(Intercept)	0.06	-0.22 – 0.34	0.688	0.19	-0.07 – 0.45	0.161	-0.12	-0.47 – 0.23	0.512	0.43	0.05 – 0.81	**0.028**
StatusSoil [D Soil-]	0.15	0.10 – 0.20	<**0.001**	-0.36	-0.45 – -0.26	<**0.001**	0.03	-0.05 – 0.11	0.459	-0.03	-0.07– 0.01	0.143
StatusSoil [ND Soil+]	0.33	-0.07 – 0.74	0.103	0.55	0.17 – 0.92	**0.004**	0.58	0.12 – 1.04	**0.014**	-0.24	-0.70 – 0.22	0.314
StatusSoil [ND Soil-]	0.47	0.07 – 0.87	**0.021**	0.23	-0.15 – 0.60	0.238	0.53	0.07 – 0.99	**0.025**	-0.38	-0.84 – 0.08	0.102
VPD	-0.18	-0.22 – -0.14	<**0.001**	-0.14	-0.21 – -0.08	<**0.001**	-0.22	-0.28 – -0.16	<**0.001**	0.04	0.01 – 0.07	**0.019**
DBH	1.01	0.79 – 1.24	<**0.001**	-0.23	-0.45– -0.01	**0.044**	0.17	0.00 – 0.34	**0.049**	0.39	0.19 – 0.58	<**0.001**
StatusSoil [D Soil-] * VPD	0.13	0.09 – 0.18	<**0.001**	0.11	0.02 – 0.19	**0.016**	-0.01	-0.09 – 0.07	0.793	-0.11	-0.15 – -0.07	<**0.001**
StatusSoil [ND Soil+] * VPD	0.03	-0.03 – 0.08	0.363	0.09	-0.01 – 0.19	0.070	0.02	-0.06 – 0.10	0.649	-0.11	-0.15 – -0.07	<**0.001**
StatusSoil [ND Soil-] * VPD	0.12	0.07 – 0.18	<**0.001**	0.14	0.05 – 0.24	**0.003**	0.03	-0.06 – 0.11	0.527	-0.14	-0.18 – -0.11	<**0.001**
ICC	0.86			0.54			0.65			0.92		
R^2_m / R^2_c	0.398 / 0.914			0.124 / 0.597			0.118 / 0.688			0.054/ 0.928		
AIC	4959.770			4850.118			4655.334			7571.133		

PART II

CHAPTER 3 - Canopy cover dynamics in dieback affected oak forests captured by phenological behavior

Graphical abstract



Abstract

Climate change influences the structure and function of forest ecosystems and plays an impactful role in forest health status. Vegetation phenology has been comprehensively recognized as a major tool for tracking the timing of seasonal activities of plants and animals, as well as changes in forest ecosystems in response to climate change. In this work, we sought to detect the phenological behavior of Mediterranean forest stands showing evident die-off symptoms. We investigated how a phenological spectral index for *Quercus cerris*, *Quercus pubescens*, and *Quercus frainetto* stands would be able to reflect the seasonal vegetative dynamics of forests affected by dieback.

To this purpose, we compared nearby stands exhibiting different vigor, *i.e.*, dieback *vs* non-dieback, assessed as severe defoliation growths decline, and higher tree mortality rate. Phenological metrics of Plant Phenology Index (PPI) were derived from Sentinel 2 satellite. Our results indicated peculiar site-specific phenological patterns. We found that dieback forest stands - characterized by a high percentage of trees showing canopy defoliation - exhibited different phenological behavior compared with non-dieback stands. Our findings revealed that dieback stands extended the growing season by delaying autumn leaf senescence. However, both seasonal amplitude and productivity were found to have higher values for non-dieback stands, as compared to dieback ones. Also, it was highlighted that non-dieback stands exhibited either greening up or senescence periods more rapid than dieback stands. Overall, our framework evidenced that trees, showing clear decline symptoms, would maintain their vital activities by changing their phenological performance.

The above results lead to a salient question concerning the implications of observed phenological shifts on the global carbon and water balance of terrestrial ecosystems under future climate change. Thus, the evaluation of proxies for phenological status of forest vegetation may improve our comprehension of climate-vegetation interactions, mainly in semi-arid regions such as the Mediterranean Basin.

Keywords: climate change, forest dieback, Mediterranean forests, remote-sensing, vegetation phenology.

3.1 Introduction

Ongoing global climate change impacts forest productivity and ecosystems functioning worldwide (Hartmann et al., 2018) with implications on the forest species' growth and resilience. Globally, air temperatures are expected to rise for the next several decades: this, coupled with a decrease in the amount of rainfall, may lead to enhanced evapotranspiration rates (IPCC, 2018). The balance between precipitation and evapotranspiration has a key function in the ecosystem's performance in many areas of the world. Hence, forest populations, mainly in the most water stress-prone areas such as the Mediterranean basin, can be extremely vulnerable to water deficit increases, thus affecting tree growth and canopy condition (Liu et al., 2018), as well as increasing their vulnerability to other abiotic (*e.g.* frost, drought spell, heatwave) and biotic (*e.g.*, insect defoliators, fungal pathogens) stress factors (Anderegg et al., 2015). Consequently, the productivity of the Mediterranean forest will exhibit a severe decline in response to increasing global temperatures, with negative feedback on tree physiology, leading to carbohydrate reserves starvation and/or hydraulic failure issues (Adams et al., 2017). Therefore, investigating and monitoring the state of health and growth of forest populations is crucial to predicting response to future climate scenarios.

Vegetation phenology is strongly sensitive to climate change, so it may be assumed to be a key factor influencing forest growth and productivity (Richardson et al., 2010). Leaf phenology refers to the biological events that characterize annually plant leaves, such as flowering, growth, senescence, and dormancy, and this is tightly related to tree growth and reproduction, influencing forest productivity (Vitasse et al., 2018). Phenological behavior may differ according to tree species and environmental conditions (Aragones et al., 2019); that is, phenology exhibits adaptive capacity by being able to model the length of the growing season through the adaptation of the seasonal life cycle to local conditions (Chuine et al., 2013).

Hence, monitoring vegetation phenology is becoming an ever more valuable tool for assessing and tracking the underlying mechanisms of vegetation interactions and response to changes in climate. Numerous studies have pointed to the direct effects of climate change on spring phenology at different spatial scales (Badeck et al., 2004; Keenan et al., 2014). Interestingly, Vitasse et al. (2018), in their work based on observations of the leaf-out date of common temperate tree species located at different elevations in the European Alps, pointed out that the elevation-induced phenological shift has significantly declined in the last few years due to global warming. Furthermore, several research efforts also explored how different climatic factors (*i.e.,* temperature, precipitation, and many others) can lead to the interannual variability of spring phenology (*e.g.,* Yang et al., 2017; Wipf et al., 2009). For instance, leaf unfolding has advanced for the majority of tree and shrub species in response to increasing spring temperatures (*e.g*., Menzel et al., 2020; Wang et al., 2015). Also, Morin et al. (2010) evaluated the response of deciduous and evergreen species to experimental warming treatments of +1.5 °C and +3.0 °C: both advanced the leaf-out by 8 and 13 days, respectively. Recently, however, Fu et al. (2015) detected in recent years a slowdown in the advancement of spring phenology. Overall, earlier leaf unfolding results in a longer growing season and thereby more assimilates and higher biomass production; this may also lead to an enhanced risk of frost damage. Specifically, frost resistance is low during leaf unfolding, and consequently, trees are particularly vulnerable to frost damage as temperatures drop below species-specific critical values (Hufkens et al., 2012). In addition, the earlier leaf unfolding, as reported by Fu et al. (2014) for two common tree species as *Quercus robur* L. and *Fagus sylvatica* L., may also translate into earlier senescence, thus partially compensating the lengthening of the growing season. Moreover, increased temperatures can either advance or delay budburst dates, depending on their timing.

In a recent study, Malyshev (2020) demonstrated that differential impacts of upcoming extreme warming events on spring phenology will probably depend on non-linear responses of bud dormancy depth to warming. Warming-induced changes in bud dormancy depth will likely depend on the timing of warming events and the species-specific timing of bud dormancy induction and release. Despite temperature being widely recognized as a key factor for most species' phenology, precipitation, through its influence on soil moisture, may influence growing season length and/or affect flowering phenology (Peñuelas et al., 2002, 2004). Increased precipitation, as reported by Shen et al. (2015), could advance the greenup date, reducing the water stress impact on vegetation growth, mainly in arid and semi-arid areas. Yun et al. (2018) also investigated the relationship between winter precipitation and spring phenology (*i.e.*, start of growing season), reporting that increased winter precipitation may attenuate strong advancing trends in spring vegetation growth response to global warming, for temperature-limited ecosystems as well.

Previous studies have also reported that global warming is affecting, although to a lesser extent, the autumn leaf senescence, leading to a delay (Fu et al., 2019; Ge et al., 2015). As suggested by Gallinat et al. (2015), environmental triggers of autumn phenology are still poorly understood. Multiple drivers, as highlighted by several authors (Liu et al., 2019; Vitasse et al., 2021, among others), may affect autumn phenology concurrently, including, *e.g.*, nutrient availability, temperature, drought, light conditions.

To date, these aspects are not sufficiently understood for forest populations showing decline symptoms; in such cases, slight alterations of phenological timing may affect the forest' growth and functioning. Hence, we need to better investigate how climatic stressor factors might impact vegetation phenology, mainly in the Mediterranean area, as reported in Gordo et al. (2009).

To improve our knowledge on how forest health status may affect phenological response to climate variations, in this work we focused on forest stands, located in Southern Italy, that have exhibit dieback symptoms for the last several decades (Colangelo et al., 2017, 2018; Ripullone et al., 2020). In addition, a recently published paper has also evaluated how remotely sensed measures of vegetation activity and radial growth responded to extreme climate events (high vapor pressure deficit and low soil moisture) by examining the same forests. It was found that dieback stands exhibited lower NDVI values than non-dieback stands, thus suggesting the possibility of scaling up from tree to stand levels for monitoring vegetation response to climate change. The study further revealed that the increase in vapor pressure deficit led to a reduction in growth.

The objective of this work is to untangle the phenological dynamics of dieback *vs.* non-dieback stands through the use of a remotely sensed vegetation index that is demonstrated to be an excellent proxy for the phenological and productive status of forest vegetation. Specifically, this study represents the first effort to highlight the phenological characteristics of forest populations showing clear symptoms of decline. To this purpose, we aim to address the following questions: i) is there a difference in terms of phenological metrics between nearby stands showing contrasting vigor, *i.e.* dieback and non-dieback stands in the short term?; ii) are phenological differences also being reflected in tree productivity?

We hypothesized that i) dieback forest stands - characterized by a high percentage of trees showing clear symptoms of decline - could exhibit different phenological behavior than non-dieback stands; ii) differences between nearby stands showing contrasting vigor, *i.e.* dieback and non-dieback stands are also observed in terms of productivity.

3.2 Materials and methods

3.2.1 Study sites

Our study focused on selected oak populations, located in southern Italy. The high forest at Gorgoglione site is mostly dominated by *Quercus cerris* L. (71%), followed by *Quercus pubescens* Willd. (25%) and other broadleaf species. The climate of the area is Mediterranean with average annual temperature of about 11.6 °C and annual total precipitation of about 722 mm. The soil is composed of sand, silt, and clay. The San Paolo Albanese high forest, located in the Pollino National Park, is mainly constituted by *Quercus frainetto* Ten., representing the dominant species. The site is characterized by Mediterranean climate (mean annual temperature is about 16.4 °C, annual total precipitation is about 742 mm). The soil is characterized by sands and clays. Selected forest sites, as reported in previous works (Colangelo et al., 2017, 2018), are characterized by conspicuous leaf shedding and high mortality rates (as can be observed in Fig. 9), and this can be observed since the early 2000s. For each sites, nearby stands showing (D, *dieback*) or not showing (ND, *non-dieback*) decline symptoms were selected. The ecological and site-specific conditions (*e.g.*, elevation, slope, aspect) of compared stands were similar (Tab. 3).

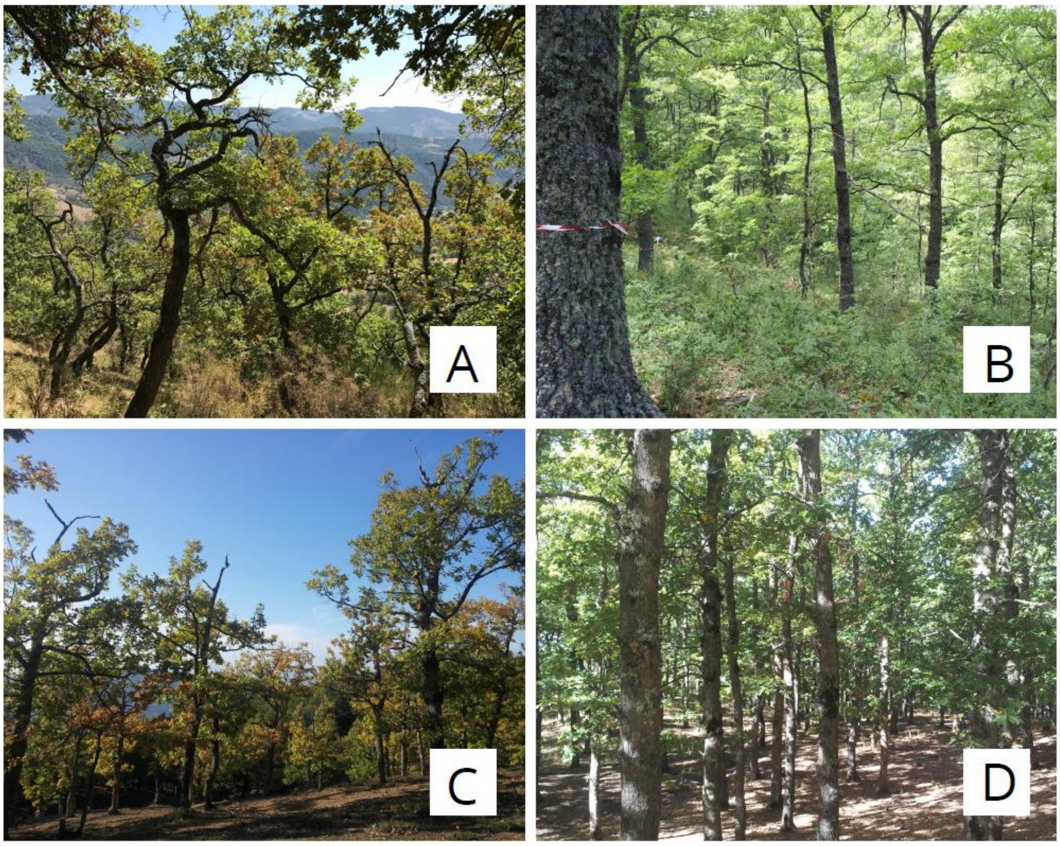


Figure 9. Photographies showing the studied forest dieback sites: A (Dieback) – B (Non-dieback), Gorgoglione, *Q. cerris* - *Q. pubescens* mixed forest; and C (Dieback) – D (Non-dieback), San Paolo Albanese, *Q. frainetto* pure forest.

Table 3. Characteristics of the two study sites

Site	Species	Status	Latitude (N)	Longitude (-W, +E)	Elevation (m a.s.l.)	Slope (%)	Aspect	References
Gorgoglione	*Q. cerris* *Q. pubescens*	D	40.369	16.171	807	65	NE	Colangelo et al., 2018
		ND	40.384	16.161	704	67	E-NE	
San Paolo Albanese	*Q. frainetto*	D	40.016	16.347	1018	27	O-SO	Colangelo et al., 2017
		ND	40.019	16.355	1093	55	O-SO	

3.2.2 Satellite data

In this work, phenology products were acquired from Copernicus dataset (www.wekeo.eu) and they are derived from the Sentinel-2 (Sentinel -2A and Sentinel - 2B) with a revisit time of 5 days. Phenological metrics are obtained from Plant Phenology Index (PPI) seasonal trajectories. Plant Phenology Index, proposed by Jin et al. (2014), is derived from radiative transfer equations (Hapke, 1993) and it has strong correlation with gross primary productivity (Jin et al., 2017). This index also exhibits an approximately linear relationship with the green LAI (it has the same unit, m^2*m^{-2}), and that is of crucial relevance since the green LAI is the most dynamic canopy visual indicator during the phenological cycle.

3.2.3 Climate data

To classify the study sites according to their water deficit condition, we obtained the Aridity Index (AI, which ranges from 0 to 100) from the ENVIREM dataset v1.0 with a spatial resolution of ~5 km^2 (Title and Bemmels, 2018). The AI is based on the methodology developed by Thornthwaite (1948), who calculated AI as the ratio between the water deficiency (d) and the water need (n), *i.e.*, 100d/n. This index indicated the degree of water deficit below water need at any given station and thus it si useful for recording the evolution of the drought phenomenon. To evaluate the variability of climate impacts on forests stands, we downloaded the Standardized Precipitation Evapotranspiration Index (SPEI) at a time scale of 12 months and a 0.5° spatial resolution. The SPEI was obtained from the Global Drought Monitor webpage (http://spei.csic. es/index.html). The SPEI is a multi-scalar drought index, which combine the effects of temperature and evapotranspiration on drought severity and points to wet (positive SPEI values) and dry (negative SPEI values) conditions (Vicente-Serrano et al., 2010).

The use of a longer SPEI time resolution is relevant to quantify the effects of droughts, mainly for forests that experience semi-arid conditions, as demonstrated by Vicente-Serrano et al. (2020).

3.2.4 Analyses

We used Analysis of Variance (ANOVA, function ‘*aov*’) to evaluate the influence of vegetation condition *i.e,* dieback and non-dieback forests patches on the phenological indices, followed by a post-hoc Tukey’s HSD (Honest Significant Difference; function ‘*TukeyHSD*’) for a pair-wise comparison of means using R software (R Core Team, 2020).

3.3 Results

3.3.1 Climate trends

The study sites are located in areas characterized by high water stress conditions (Fig. 10 A). Particularly, very negative SPEI values are evident in the 1990s, and early 2000s for either site. Since then, SPEI changes of lower magnitude have occurred, even within the period (2017 - 2020) covered by this work (Fig. 10 B).

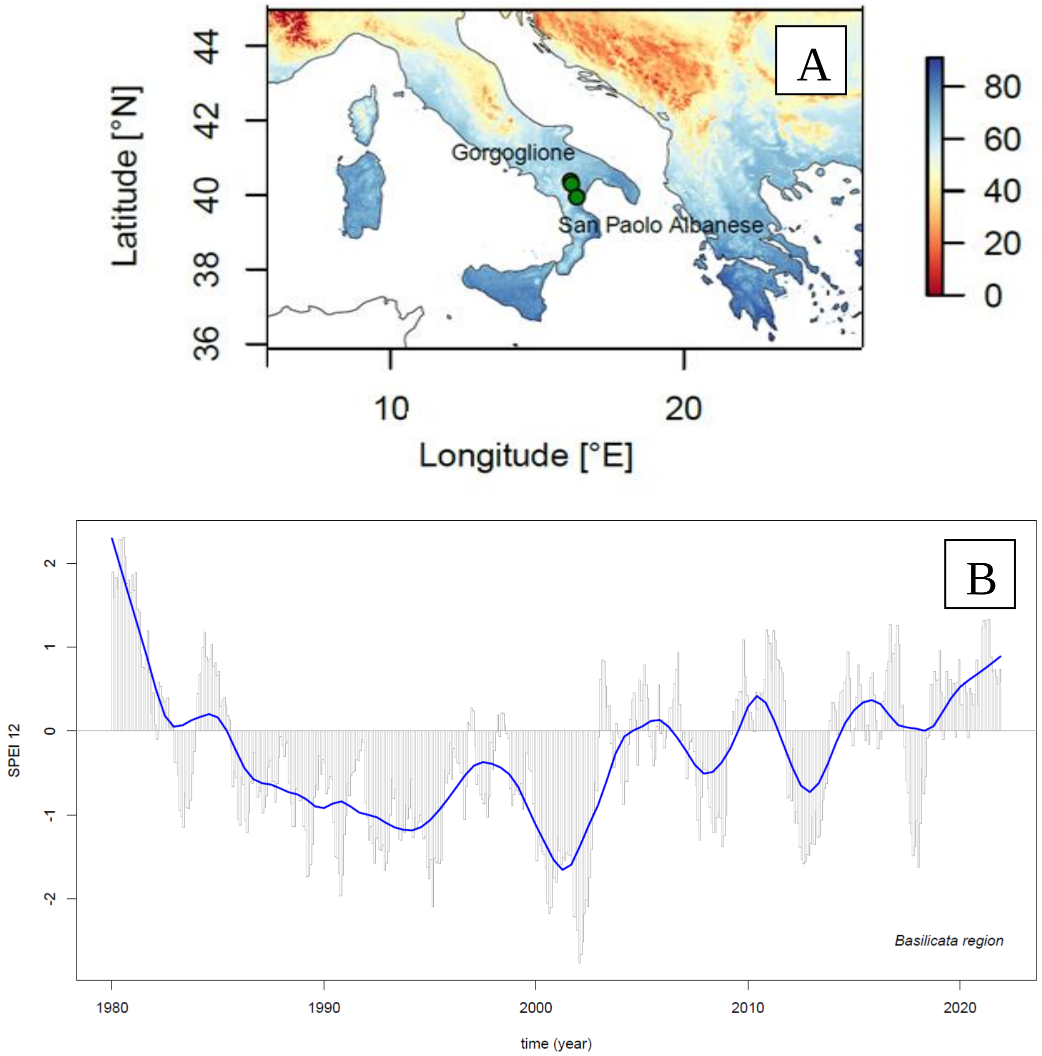


Figure 10. (A) Map showing an aridity index (AI=100d/n) with higher and lower values showing more and less water stress conditions, respectively, in Italian Peninsula. Green dots show the location of the two study sites. (B) Time series of the SPEI-12 drought index for each study site during 1990–2021. The SPEI varies from−3 to 3, being categorized as extremely wet (2.00 and above), very wet (1.50 to 1.99), moderately wet (1.00 to 1.49), near normal (−0.99 to 0.99), moderately dry (−1.00 to−1.49), severely dry (−1.50 to−1.99), and extremely dry (−2.00 and less).

3.3.2 Phenological metrics evaluation

Overall shifts in the growing season were found for either site over the period 2017-2020, with a lengthening of the vegetative season in the dieback stands. In particular, a common delay in the end of the growing season was reported for dieback stands in both sites (as can be observed in Fig. 11). A slight delay in the onset of the growing season for dieback stand was observed only for the San Paolo Albanese site (Supplementary Fig. S4).

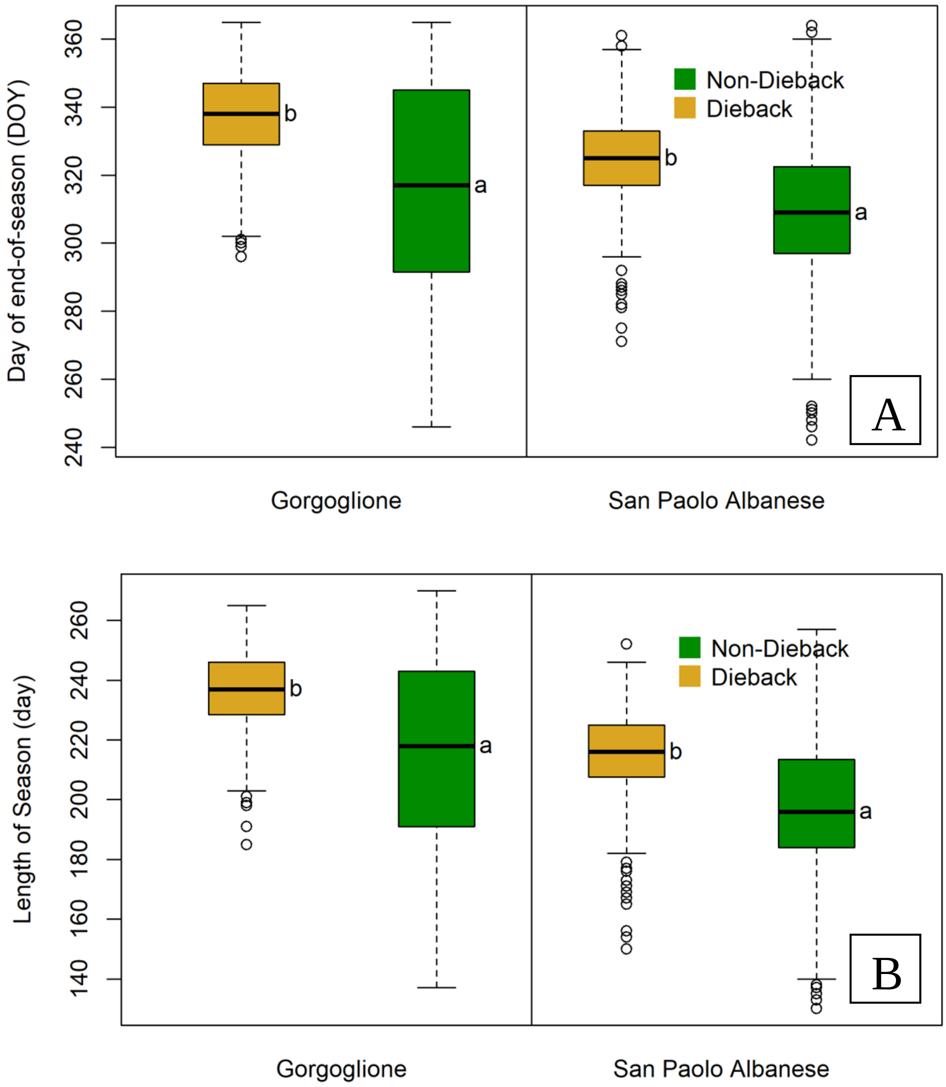


Figure 11. Boxplots of (A) the day of end of season (DOY) and (B) the length of the season (day) for D and ND stands for each site. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

Conversely, we found a greater seasonal amplitude for non-dieback stands *vs* dieback ones in both Gorgoglione and San Paolo Albanese sites (Fig.12). That is, non-dieback stands exhibited a higher vegetation index value at the peak of the season (Supplementary Fig. S5). An analogous picture emerged for productivity, either seasonal or total, for which higher values are observed for non-dieback stands as compared to dieback ones (Fig. 12 and Supplementary Fig. S5). For both sites, non-dieback stands exhibited higher positive (*greening*) and negative slopes (*browning*) in comparison to diebacks (Fig. 13).

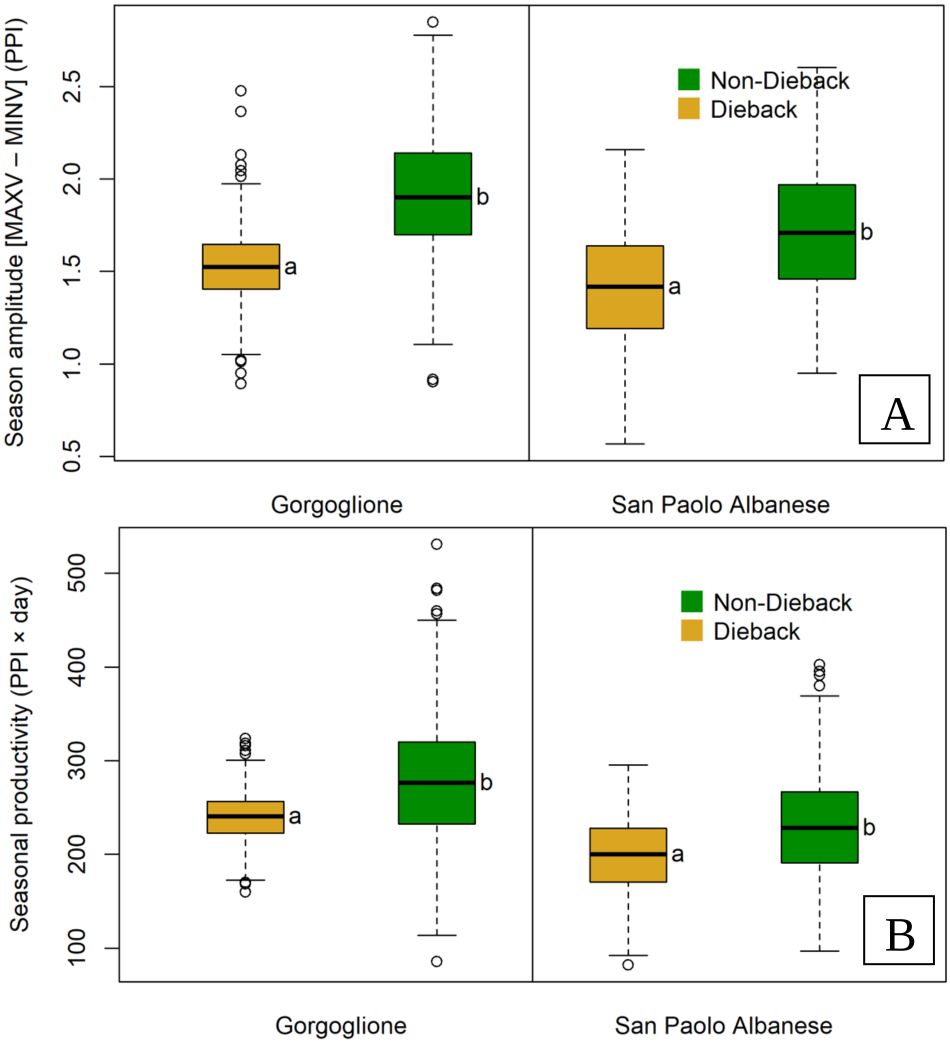


Figure 12. Boxplots of (A) season amplitude [MAXV – MINV] (PPI) and (B) seasonal productivity (PPI x day), for D and ND stands for each site. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

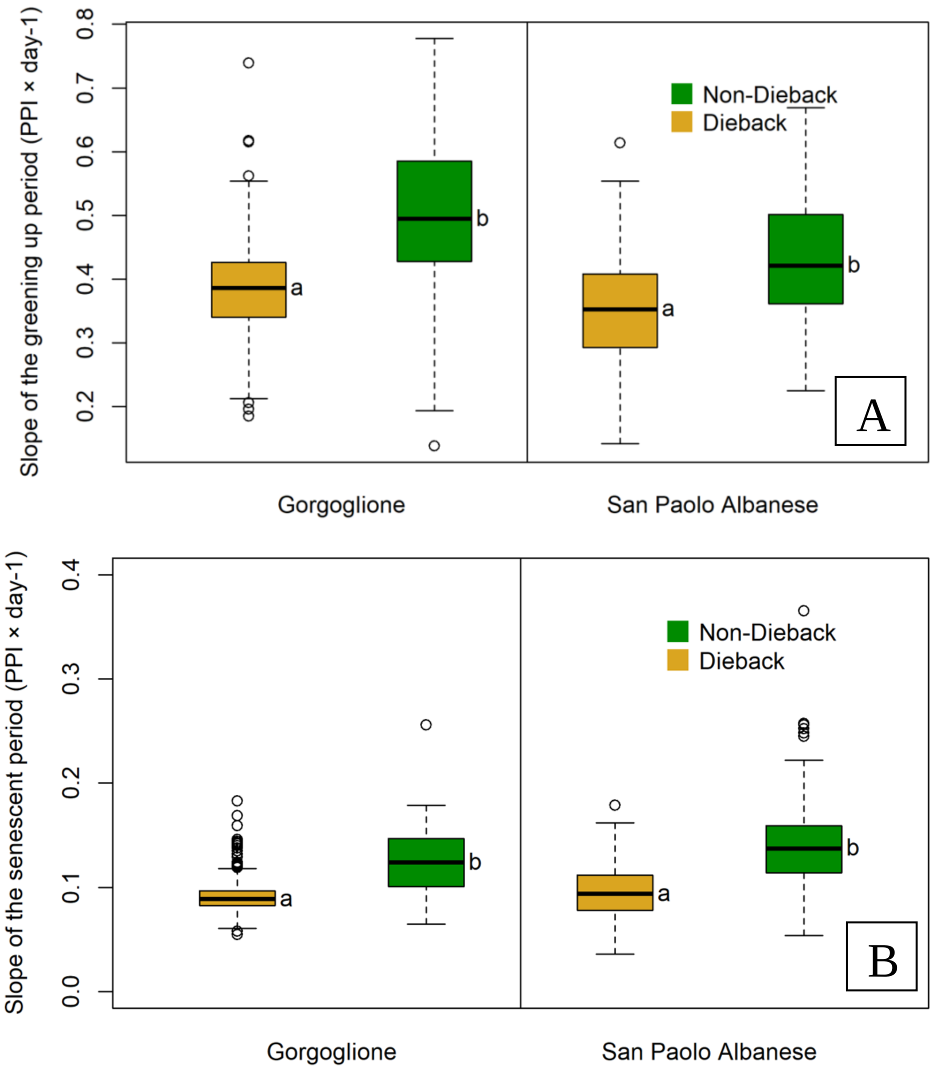


Figure 13. Boxplots of (A) the slope of the greening up period (PPI x day^{-1}) and (B) the slope of the senescent period (PPI x day^{-1}), for D and ND stands for each site. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

3.4 Discussions

To our knowledge, the present study provides the first attempt to detect the phenological behavior of Mediterranean forest stands exhibiting evident decline symptoms. Selected forest sites are exposed to high temperatures and limited precipitation during the summer dry period, contributing to reduced soil water availability and increased atmospheric vapor demand. The effect of water shortage coupled with heat stress can be observed as widespread yellowing of canopies, foliage loss, thus reducing tree photosynthetic capacity and biomass accumulation at these sites. These phenomena are increasingly common in drought-prone areas, such as Mediterranean basin, affecting a multitude of temperate forest species, including those most adapted to these conditions. Such occurrences can persist on either small or large spatial scales, and are known as *diebacks*. By employing a satellite-based approach, here, we document the phenological dynamics of dieback *vs.* non-dieback oak stands.

Our results highlight different phenological behavior among dieback and non-dieback stands. In detail, we found that forest stands showing clear evidence of decline (as can be observed in Fig. 9) extend the growing season delaying the leaf autumn senescence, as compared to those not affected by the decline in either site. To date, consistent results have documented that delaying leaf senescence has either a direct effect on C uptake or an indirect effect on nutrient reabsorption (*e.g.*, Estiarte et al., 2015), thus changing their nutrient availability for the following year. For instance, Gunderson et al. (2012) highlighted a delay in autumn senescence, related to ongoing warming, for different forest species, *e.g.*, *Quercus rubra*, via temperature-controlled experiment. Wu et al. (2021) further pointed out, referring to four dominant European tree species, that the correlation is mainly positive among pre-season temperature and leaf senescence; but, radiation may accelerate the senescence dynamics as it reduces the temperature sensitivity of leaf senescence. In contrast, a delayed end of the growing season could also increase the potential risk of early autumnal frosts (Schreiber et al., 2013).

Oaks, due to their anisohydric strategy, can maintain high stomatal conductance and high photosynthetic rates even with reduced water potential. Mortality occurs predominantly from hydraulic failure (McDowell et al., 2008). However, as a result of canopy decline, whole-plant photosynthesis and thus C supply can be reduced (Anderegg et al., 2014). Such a condition may likely explain the lengthening of the growing season of dieback stands to compensate for this decrease. Camarero et al. (2016) also reported that summer drought impairs xylem phenology in Mediterranean forests; accordingly, non-dieback trees are likely to be able to more efficiently photosynthesize under severe climate conditions during the growing season. In contrast, delayed leaf autumn senescence allows the dieback trees to exploit "*extra*" days of assimilation, allowing more time for photosynthesis and transpiration without summer constraints. The capability of dieback trees to perform biological functions in stressful conditions by modifying the uptake and consumption of essential elements is evidenced, for instance, by Nejad et al. (2021): they found that dieback oaks had higher leaf contents of P and Ca and a lower N/P ratio as compared to non-dieback ones. Although spring and autumn phenological timing is well recognized to impact forest productivity as defining the length of the growing season (Wu et al., 2013, among others), seasonal amplitude represents another major driver. One of the most interesting findings we presented is that non-dieback stands exhibited greater seasonal amplitude, and this resulted in higher productivity. Potential mechanism underlying the observations may also be related to the *sink-limitation* hypothesis, proposed by Zani et al. (2020). They demonstrated that the increased spring and summer productivity, related to enhanced photosynthesis during the growing season under ongoing high temperature conditions and increased light availability, led to the earlier leaf senescence as a result of a likely impairment of plants' source/sink balance.

So this mechanism may additionally explain the observed phenomenon; that is, non-dieback stands exhibited earlier autumn leaf senescence as compared to dieback stands, which experienced impaired photosynthetic capacity. For instance, Moreno-Fernández et al. (2021) have likewise reported a larger photosynthetic capacity of the healthier stands compared to declining ones for *Pinus pinaster*. Confirming the possible enhanced photosynthetic rate during the growing season, our results indicate also that non-dieback stands exhibited a more rapid greening up period, probably linked also to a different concentrations of leaf pigments as compared to dieback ones. As highlighted by Liu et al. (1997) and Nejad et al. (2021), declining trees have been found to have lower foliar chlorophyll concentrations than non-declining ones. Pigment content reduction may be considered a typical symptom of oxidative stress (Smirnoff, 1993), as it may be the consequence of the destruction of chlorophyll by chlorophllase and peroxidase activity. Tongo et al. (2021) similarly observed reductions in chlorophyll pigments and carotene in Q. *brantii* as defoliation rate increased, likely coupled to a reduction in leaf water content. Another key finding in this study was that the non-dieback stands also exhibited a quicker senescent period as compared to the dieback stands. This would confirm that non-declining stands complete the growing season more rapidly, thus corroborating assumptions from our previous results.

Overall, it can be argued that climate change leads to significant changes in vegetation phenology, thereby influencing species distribution and competition, and the performance of forest ecosystems and their related services (Cleland et al., 2007; Way, 2011). Hence, vegetation phenology can provide a valuable predictor of climate-vegetation interactions (*e.g.*, Menzel et al., 2006; Zeng et al., 2020), which may either directly or indirectly regulate water and carbon flux cycles in terrestrial global ecosystems, by altering physiological and structural properties including, *i.e*., photosynthetic rates, canopy conductance (Richardson et al., 2013; Wang et al., 2018, among others).

Our discussion above leads to an interesting and relevant question concerning the possible implications associated with the detected phenological shifts . Remarkably, some studies have found that lengthening the growing season had a direct effect on net ecosystem productivity (Wu et al., 2013, among others). For instance, Cheng et al. (2021) pointed out that a delayed end of season would lead to an increase in mean daily GPP in the grassland ecosystem across the Tibetan Plateau. Even, Keenan et al. (2014) found, by matching different scales (organism, ecosystem, landscape) of long-term phenological observations, that the trend toward later leaf senescence in recent decades has been leading to increased GPP and net carbon uptake in autumn in temperate forests. In contrast, other authors, such as Richardson et al. (2010) and Lempereur et al. (2015), have reported that an extended period of growth does not inevitably lead to enhanced net ecosystem productivity.

Given that knowledge about the link between phenological variables from remote sensing, *e.g.*, season onset, season length, or seasonal amplitude, and drought-prone forest decline is lacking to date, the identification of the phenological dynamics, characterizing the dieback phenomenon, may contribute to the geographical delineation of the most affected areas. In addition, this may provide better insight on the forest ecosystem response to upcoming climate changes. We acknowledge that the interaction among differing environmental factors may complicate our understanding of changing phenological behavior of vegetation.

3.5 Conclusion

Over the last years, the study of phenology has received considerable attention as the changing rhythm of different phenological events is recognized as a key predictor of climate change. To our knowledge, this work is the first to reveal the phenological behaviour of Mediterranean forest populations showing clear symptoms of decline. A key insight is revealed in this work not only by comparing stands exhibiting contrasting vigor status, but also through the employment of a vegetation index that is expected to provide the best performance in evaluating phenological dynamics. According with our expectations, nearby forest stands showing contrasting vigor exhibited distinct phenological patterns. The dieback process in the study forest sites is mostly evidenced by a delay in the growing season, whereas our results revealed no significant changes in growing season onset. Thus, dieback stands exhibited a longer growing season compared to stands not showing decline. We speculate that this may be related to dieback trees' effort to offset the reduction in whole-plant photosynthesis, related to canopy decline. Non-dieback stands, as hypothesized, were found to show greater seasonal amplitude, and consequently higher productivity. Likewise, our findings also showed that non-dieback stands exhibited either a more rapid green-up period, probably related also to a different concentrations of leaf pigments, or a quicker senescence period. Our findings highlighted how trees, exhibiting die-off symptoms, may keep their vital activities by modifying their physiological performance. The discussion above points to a critical question relating to the potential impacts of detected phenological shifts on the global carbon and water balance of forest ecosystems under future climate change. Surveys of vegetation phenological dynamics may therefore represent a key factor to assess forests' response in the face of climate change. Nonetheless, we recognize that interactions among multiple environmental drivers may affect our comprehension of phenological behavior changes in vegetation.

3.6 Supplementary materials

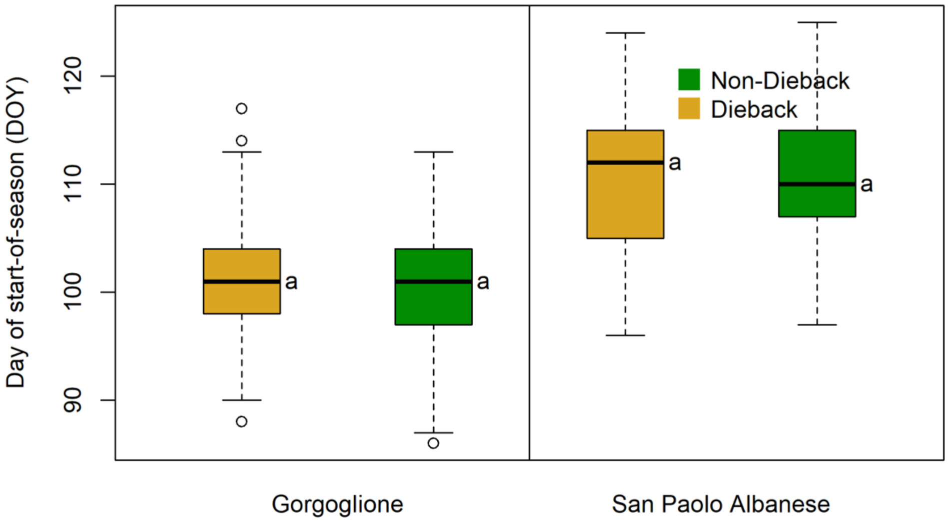


Figure S4. Boxplots of the start of the growing season (DOY) for D and ND stands for each site. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

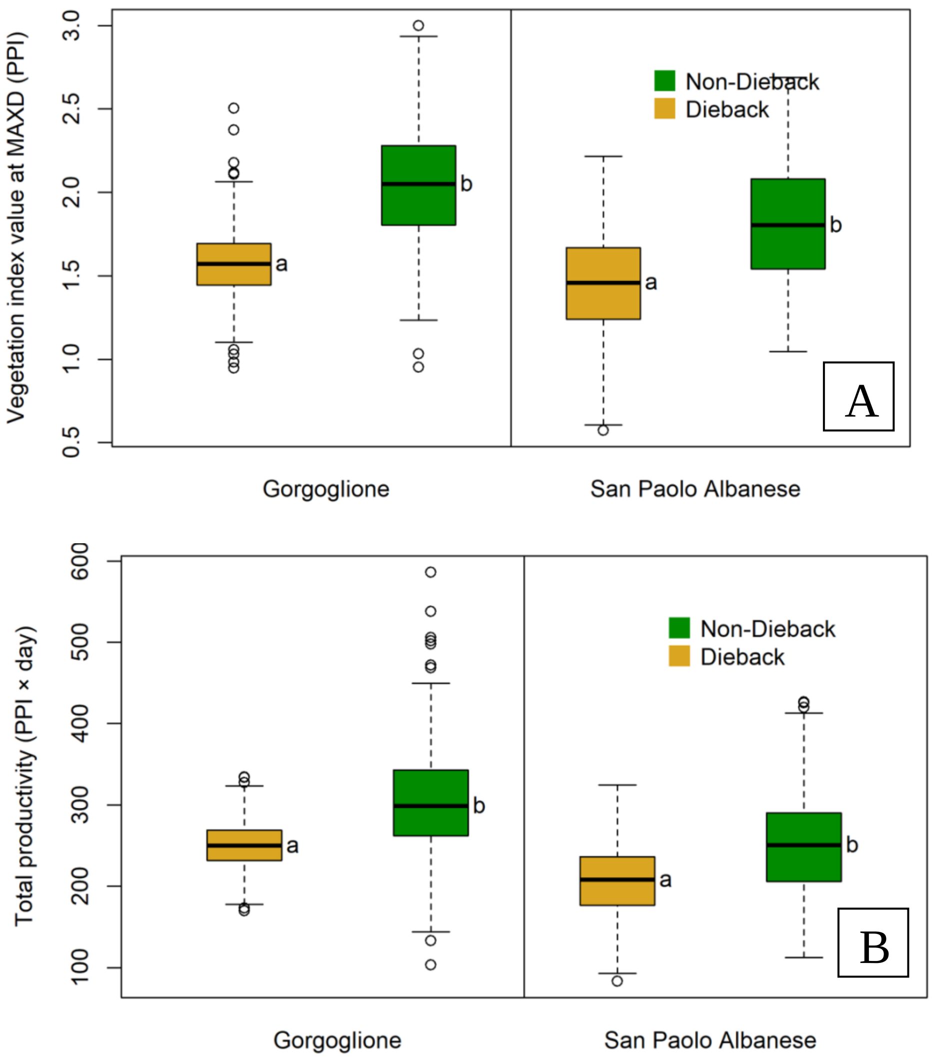


Figure S5. Boxplots of (A) the vegetation index value at growing season peak (PPI) and (B) total productivity (PPI x day), for D and ND stands for each site. Each box shows the 75th to 25th percentiles, and the line inside the box represents the median; upper and lower marks are the largest to smallest observation values, which are less than or equal to the upper and lower quartile plus 1.5 times the length of the inter-quartile range; circles outside the mark ranges are outliers.

CHAPTER 4 - SUMMARY

General conclusions

The overall goal of this study was to investigate the Mediterranean forest responses to climate stressors.

The part I evaluated the response of dieback affected forest populations to climate extremes through a combined approach. The major findings were as follows:

- NDVI and growth were positively related in all sites, except for the dieback stand of *Q. frainetto* that was negatively related.
- *J. phoenicea* and *P. sylvestris* growth showed a strong dependence on vapor pressure deficit.
- *Q. pubescens* and *Q. frainetto* growth depended on soil moisture.
- Coupling radial growth and NDVI at multiple spatio-temporal scales improves dieback assessment.

In general, the study confirmed that impacts of climate extremes on vegetation can be evaluated either in terms of canopy greenness or ground-based growth data, suggesting the possibility of: i) up-scaling, from tree to stand level, allows to evaluate climate stress on forest ecosystems; ii) down-scaling, from the satellite data at broader spatial resolution, provides the phenomenon's investigation on a local scale. In addition, the relationships among NDVI and BAI, which are likely influenced by the specific time window, may be useful in identifying the timing of climate extremes that most affect growth.

In Part II of this thesis, the phenological behavior of Mediterranean forest stands exhibiting symptoms of decline was explored.

Here there are the main findings:

- Dieback stands in either site exhibited a lengthening of the growing season, associated with a delay of leaf autumn senescence.
- Non-dieback stands have been found to have greater season amplitude, and subsequent higher productivity as compared to diebacks.
- Non-dieback stands exhibited either a more rapid greening or senescence period compared to dieback stands in both sites.

Our study revealed new insights into the phenological response of forests to climate change in semi-arid regions, demonstrating that trees, exhibiting symptoms of dieback, may maintain their biological activities by modifying their phenological performance. Thus, the study can provide an understanding of climate-vegetation interactions, primarily in the Mediterranean Basin, where enhanced global warming and aridification trends are projected.

References

Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A., Hegewisch, K.C., 2018. *Terraclimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958-2015*. Sci. Data, 5, 170191. doi.org/10.1038/sdata.2017.191.

Adams, H.D., Zeppel, M.J.B., Anderegg, W.R.L., et al., 2017. *A multi-species synthesis of physiological mechanisms in drought-induced tree mortality*. Nat. Ecol. Evol. 1, 1285-1291. doi.org/10.1038/s41559-017-0248-x.

Allen, C.D., Breshears, D.D., McDowell, N.G., 2015. *On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene*. Ecosphere, 6(8), 1-55. doi.org/10.1890/ES15-00203.1

Allen, C.D., Macalady, A., Chenchouni, H. et al., 2010. *A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests*. For. Ecol. Manag., 259, 660–684. doi.org/10.1016/j.foreco.2009.09.001

Anderegg, W.R., Trugman, A.T., Badgley, G., Konings, A.G., Shaw, J., 2020. *Divergent forest sensitivity to repeated extreme droughts*. Nature Climate Change, 10(12), 1091-1095. doi.org/10.1038/s41558-020-00919-1

Anderegg, W.R., Anderegg, L.D., Huang, C.Y., 2019. *Testing early warning metrics for drought-induced tree physiological stress and mortality*. Global change biology, 25(7), 2459-2469. doi.org/10.1111/gcb.14655

Anderegg, W.R., Hicke, J.A., Fisher, R.A., Allen, C.D., Aukema, J., Bentz, B., et al., 2015. *Tree mortality from drought, insects, and their interactions in a changing climate*. New Phytol., 208, 674-683. doi.org/10.1111/nph.13477.

Anderegg, W.R.L., Anderegg, L.D.L., Berry, J.A., Field, C.B., 2014. *Loss of whole-tree hydraulic conductance during severe drought and multi-year forest die-off.* Oecologia, 175,11-23. doi. org/ 10. 1007/ s00442- 013-2875-5

Anderegg, W.R., Kane, J.M., Anderegg, L.D., 2013. *Consequences of widespread tree mortality triggered by drought and temperature stress*. Nature climate change, 3(1), 30-36. doi.org/10.1038/nclimate1635.

Aybar, C., Wu, Q., Bautista, L., Yali, R., Barja, A., 2020. *rgee: an R package for interacting with Google Earth Engine*. J. Open Source Softw., 5, 2272. doi.org/10.21105/joss.02272.

Aragones, D., Rodriguez-Galiano, V.F., Caparros-Santiago, J.A., Navarro-Cerrillo, R.M., 2019. *Could land surface phenology be used to discriminate Mediterranean pine species*?. International Journal of Applied Earth Observation and Geoinformation, 78, 281-294. doi.org/10.1016/j.jag.2018.11.003

Asner, G.P., Brodrick, P.G., Anderson, C.B., Vaughn, N., Knapp, D.E., Martin, R.E., 2016. *Progressive forest canopy water loss during the 2012-2015 California drought.* Proceedings of the National Academy of Sciences, USA. 113, 249-255. doi.org/10.1073/pnas.1523397113.

Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M.P., Frank, D.C., 2019. *Twentieth century redistribution in climatic drivers of global tree growth*. Science Advances, 5(1), eaat4313. doi:10.1126/sciadv.aat4313

Babst, F., Bouriaud, O., Papale, D., Gielen, B., Janssens, I.A., Nikinmaa, E., et al., 2014. *Aboveground woody carbon sequestration measured from tree rings is coherent with net ecosystem productivity at five eddy-covariance sites*. New Phytol., 201, pp. 1289-1303. doi.org/10.1111/nph.12589.

Babst, F., Carrer, M., Poulter, B., Urbinati, C., Neuwirth, B., Frank, D., 2012. *500 years of regional forest growth variability and links to climatic extreme events in Europe*. Environ. Res. Lett., 7, 045705. doi:10.1088/1748-9326/7/4/045705

Badeck, F.W., Bondeau, A., Böttcher, K., Doktor, D., Lucht, W., Schaber, J., Sitch, S., 2004. *Responses of spring phenology to climate change*. New phytologist, 162(2), 295-309. doi.org/10.1111/j.1469-8137.2004.01059.x

Barzanti, G.P., Capretti, P., Ragazzi, A., 2001. *Characteristics of some Phytophthora species isolated from oak forest soil in central and northern Italy.* Phytopathologia Mediterranea, 40,149-156. doi:10.1400/14466

Baquedano, F.J., Castillo, F., 2007. *Drought tolerance in the Mediterranean species Quercus coccifera, Quercus ilex, Pinus halepensis and Juniperus phoenicea*. Photosynthetica, 45, 229-238. doi.org/10.1007/s11099-007-0037-x.

Bates, D., Machler, M., Bolker, B., Walker, S., 2015. *Fitting linear mixed-effects models using lme4*. J. Stat. Softw., 67, 1-48. doi.org/10.18637/jss.v067.i01.

Batllori, E., Lloret, F., Aakala, T., Anderegg, W.R., Aynekulu, E., Bendixsen, D.P., et al., 2020. *Forest and woodland replacement patterns following drought-related mortality*. Proceedings of the National Academy of Sciences, 117(47), 29720-29729. doi.org/10.1073/pnas.2002314117

Bennett, A.C., Mcdowell, N.G., Allen, C.D., Anderson-Teixeira, K.J., 2015. *Larger trees suffer most during drought in forests worldwide*. Nat. Plants, 1 15139. doi.org/10.1038/nplants.2015.139

Berner, L.T., Beck, P.S.A., Bunn, A., Lloyd, A., Goetz, S.J., 2015. *High-latitude tree growth and satellite vegetation indices: Correlations and trends in Russia and Canada (1982-2008)*. J. Geophys. Res. Biogeosci., 116, 321-342. doi.org/10.1029/2010JG001475.

Bigler, C., Bugmann, H., 2004. *Predicting the time of tree death using dendrochronological data*. Ecol. Appl. 14, 902-914. doi.org/10.1890/03-5011

Brown, M.E., Pinzon, J.E., Didan, K., Morisette, J.T., Tucker, C.J., 2006. *Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-vegetation, SeaWiFS, MODIS, and Landsat ETM+ sensors.* IEEE Transactions on geoscience and remote sensing, 44(7), 1787-1793.
doi: 10.1109/TGRS.2005.860205.

Bunn, A., Korpela, M., Biondi, F., Campelo, F., Merian, P., Qeadan, F., Zang, C., 2021. *dplR: Dendrochronology Program Library in R.* R package version 1.7.2. https:// CRAN.R-project.org/package=dplR.

Bunn, A.G., Hughes, M.K., Kirdyanov, A.V., Losleben, M., Shishov, V.V., Berner, L.T., Oltchev, A., Vaganov, E.A., 2013. *Comparing forest measurements from tree rings and a space-based index of vegetation activity in Siberia*. Environ. Res. Lett., 8, 035034. doi:10.1088/1748-9326/8/3/035034

Buras, A., Schunk, C., Zeiträg, C., Herrmann, C., Kaiser, L., Lemme, H., et al., 2018. *Are Scots pine forest edges particularly prone to drought-induced mortality?.* Environmental Research Letters, 13(2), 025001. doi.org/10.1088/1748-9326/aaa0b4

Cailleret, M., Dakos, V., Jansen, S., Robert, E.M., Aakala, T., Amoroso, M.M., Antos, J.A., et al., 2019. *Early-warning signals of individual tree mortality based on annual radial growth*. Front. Plant Sci., 9, 1964. doi.org/10.3389/fpls.2018.01964.

Cailleret, M., Jansen, S., Robert, E.M.R., Desoto, L., Aakala, T., Antos, J.A., Beikircher, B., Bigler, C., Bugmann, H., Caccianiga, M., Čada, V., et al., 2017. *A synthesis of radial growth patterns preceding tree mortality*. Glob. Chang. Biol. 23, 1675-1690. doi.org/10.1111/gcb.13535.

Camarero, J.J., Gazol, A., Sánchez-Salguero, R., 2021a. *Effects of global change on tree growth and vigor of Mediterranean pines. In Pines and Their Mixed Forest Ecosystems in the Mediterranean Basin*. Springer, Cham. pp. 237-249. doi.org/10.1007/978-3-030-63625-8_12

Camarero, J.J., Colangelo, M., Gazol, A., Azorín-Molina, C., 2021b. *Drought and cold spells trigger dieback of temperate oak and beech forests in northern Spain*. Dendrochronologia, 66, 125812.
doi.org/10.1016/j.dendro.2021.125812

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Vergarechea, M., Alfaro-Sánchez, R., Cattaneo, N., Vicente-Serrano, S.M., 2021c. *Tree growth is more limited by drought in rear-edge forests most of the times*. For. Ecosyst., 8, 25. doi.org/10.1186/s40663-021-00303-1

Camarero, J.J., Gazol, A., Sánchez-Salguero, R., Sangüesa-Barreda, G., Díaz-Delgado, R., Casals, P., 2020. *Dieback and mortality of junipers caused by drought: Dissimilar growth and wood isotope patterns preceding shrub death.* Agricultural and Forest Meteorology, 291, 108078. doi.org/10.1016/j.agrformet.2020.108078

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Cantero, A., Sanchez-Salguero, R., Sánchez-Miranda, A., et al., 2018. *Forest growth responses to drought at short-and long-term scales in Spain: squeezing the stress memory from tree rings*. Front. Ecol. Evol., 6, 9. doi.org/10.3389/fevo.2018.00009.

Camarero, J.J., Guada, G., Sánchez-Salguero, R., Cervantes, E., 2016. *Winter drought impairs xylem phenology, anatomy and growth in Mediterranean Scots pine forests*. Tree Physiology, 36(12), 1536-1549. doi.org/10.1093/treephys/tpw077

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., Vicente-Serrano, S.M., 2015. *To die or not to die: early warnings of tree dieback in response to a severe drought*. J. Ecol., 103, 44-57. doi.org/10.1111/1365-2745.12295.

Castagneri, D., Bottero, A., Motta, R., Vacchiano, G., 2015. *Repeated spring precipitation shortage alters individual growth patterns in Scots pine forests in the Western Alps*. Trees, 29(6), 1699-1712. doi.org/10.1007/s00468-015-1250-z

Caudullo, G., Barredo, J.I., 2019. *A georeferenced dataset of drought and heat-induced tree mortality in Europe*. OE 4, e37753. doi.org/10.3897/oneeco.4.e37753

Chamberlain, S.A., Boettiger, C., 2017. *R python, and ruby clients for GBIF species occurrence data*. PeerJ, PrePrints. doi.org/10.7287/peerj.preprints.3304v1.

Cheng, M., Jin, J., Jiang, H., 2021. *Strong impacts of autumn phenology on grassland ecosystem water use efficiency on the Tibetan Plateau.* Ecological Indicators, 126, 107682.7. doi.org/10.1016/j.ecolind.2021.107682

Choat, B., Brodribb, T.J., Brodersen, C.R., Duursma, R.A., Lopez, R., Medlyn, B.E., 2018. *Triggers of tree mortality under drought*. Nature, 558(7711), 531-539. doi.org/10.1038/s41586-018-0240-x

Chuine, I., de Cortazar-Atauri, I.G., Kramer, K., Hänninen, H., 2013. *Plant development models.* In Phenology: an integrative environmental science (pp. 275-293). Springer, Dordrecht.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M.D., 2007. *Shifting plant phenology in response to global change.* Trends in ecology & evolution, 22(7), 357-365. doi.org/10.1016/j.tree.2007.04.003

Colangelo, M., Camarero, J.J., Borghetti, M., Gentilesca, T., Oliva, J., Redondo, M.A., Ripullone, F., 2018. *Drought and Phytophthora are associated with the decline of oak species in southern Italy*. Frontiers in plant science, 9, 1595. doi.org/10.3389/fpls.2018.01595

Colangelo, M., Camarero, J.J., Battipaglia, G., Borghetti, M., De Micco, V., Gentilesca, T., Ripullone, F., 2017a. *A multi-proxy assessment of dieback causes in a Mediterranean oak species*. Tree physiology, 37(5), 617-631. doi.org/10.1093/treephys/tpx002

Colangelo, M., Camarero, J.J., Borghetti, M., Gazol, A., Gentilesca, T., Ripullone, F., 2017b. *Size matters a lot: drought-affected Italian oaks are smaller and show lower growth prior to tree death.* Frontiers in Plant Science, 8, 135. doi.org/10.3389/fpls.2017.00135

Correa-Diaz, A., Silva, L.C.R., Horwath, W.R., Gómez-Guerrero, A., Vargas-Hernández, J., et al., 2019. *Linking remote sensing and dendrochronology to quantify climate induced shifts in high-elevation forests over space and time*. J. Geophys. Res. Biogeosci., 124, 166-183. doi.org/10.1029/2018JG004687

Dalla, V., Giraitis, L., Phillips, P.C.B., 2021. *testcorr : Testing Zero Correlation*. R package version 0.2.0. https://CRAN.R-project.org/package=testcorr.

Decuyper, M., Chavez, R.O., Čufar, K., Estay, S.A., Clevers, J.G., Prislan, P., et al., 2020. *Spatio-temporal assessment of beech growth in relation to climate extremes in Slovenia– an integrated approach using remote sensing and tree-ring data*. Agric. For. Meteorol., 287, 107925. doi.org/10.1016/j.agrformet.2020.107925

Didan, K., Munoz, A.B., Solano, R., Huete, A., 2015. *MODIS Vegetation Index User's Guide (MOD13 Series)*. University of Arizona: Vegetation Index and Phenology Lab, USA.

Di Filippo, A., Alessandrini, A., Biondi, F., Blasi, S., Portoghesi, L., Piovesan, G., 2010. *Climate change and growth decline: Dendroecology and stand productivity of a Turkey oak (Quercus cerris L.) old stored coppice in Central Italy*. Annals of Forest Science, 67,706-710. https://doi.org/10.1051/forest/2010031

Dobbertin, M., 2005. *Tree growth as indicator of tree vitality and of tree reaction to environmental stress: a review*. Eur. J. For. Res., 124 (4), 319-333. doi.org/10.1007/s10342-005-0085-3.

Estiarte, M., Peñuelas, J., 2015. *Alteration of the phenology of leaf senescence and fall in winter deciduous species by climate change: effects on nutrient proficiency*. Global change biology, 21(3), 1005-1017. doi.org/10.1111/gcb.12804

FAO. 2020. *The State of the World's Forests 2020*. In: Forests, biodiversity and people. Rome: FAO.

Fu, Y.H., Piao, S., Delpierre, N., Hao, F., Hänninen, H., Geng, X., Peñuelas, J., Zhang, X., Janssens, I.A., Campioli, M., 2019. *Nutrient availability alters the correlation between spring leaf-out and autumn leaf senescence dates*. Tree Physiology, 39(8), 1277-1284. doi.org/10.1093/treep hys/tpz041

Fu, Y.H., Zhao, H., Piao, S., Peaucelle, M., Peng, S., Zhou, G., et al., 2015. *Declining global warming effects on the phenology of spring leaf unfolding*. Nature, 526, 104-107. doi: 10.1038/nature15402

Fu, Y.S., Campioli, M., Vitasse, Y., De Boeck, H.J., Van den Berge, J., AbdElgawad, H., et al., 2014. *Variation in leaf flushing date influences autumnal senescence and next year's flushing date in two temperate tree species.* Proceedings of the National Academy of Sciences, 111(20), 7355-7360. doi.org/10.1073/pnas.1321727111

Gallinat, A.S., Primack, R.B., Wagner, D.L., 2015. *Autumn, the neglected season in climate change research*. Trends in Ecology & Evolution, 30, 6, 364. doi.org/10.1016/j.tree.2015.01.004

Gao, S., Liu, R., Zhou, T., Fang, W., Yi, C., Lu, R., Zhao, X., Luo, H., 2018. *Dynamic responses of tree-ring growth to multiple dimensions of drought.* Glob. Chang. Biol., 24(11), 5380-5390. doi.org/10.1111/gcb.14367.

Gaylord, M.L., Kolb,T.E., Pockman,W.T., Plaut, J. A., Yepez, E. A., Macalady, A. K., Pangle, R. E., McDowell, N. G., 2013. *Drought predisposes pinon-juniper woodlands to insect attacks and mortality*. New Phytol., 198(2), 567-578. doi:10.1111/nph.12174.

Gazol, A., Camarero, J.J., Vicente-Serrano, S.M., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., et al., 2018a. *Forest resilience to drought varies across biomes*. Global Change Biology, 24(5), 2143-2158. doi.org/10.1111/gcb.14082

Gazol, A., Camarero, J.J., Sangüesa-Barreda, G., Vicente-Serrano, S.M., 2018b. *Post-drought resilience after forest die-off: shifts in regeneration, composition, growth and productivity*. Front. Plant Sci., 9, 1546. doi.org/10.3389/fpls.2018.01546.

Gazol, A., Sangüesa-Barreda, G., Granda, E., Camarero, J.J., 2017. *Tracking the impact of drought on functionally different woody plants in a Mediterranean scrubland ecosystem*. Plant Ecology, 218(8), 1009-1020. doi.org/10.1007/s11258-017-0749-3.

Ge, Q., Wang, H., Rutishauser, T., Dai, J., 2015. *Phenological response to climate change in China: A meta-analysis*. Global Change Biology, 21(1), 265-274. doi.org/10.1111/gcb.12648

Gea-Izquierdo, G., Férriz, M., García-Garrido, S., Aguín, O., Elvira- Recuenco, M., Hernandez-Escribano, L., et al., 2019. *Synergistic abiotic and biotic stressors explain widespread decline of Pinus pinaster in a mixed forest.* Sci Total Environ., 685, 963-75. doi.org/10.1016/j.scitotenv.2019.05.378.

Gentilesca, T., Camarero, J.J., Colangelo, M., Nole, A., Ripullone, F., 2017. *Drought-induced oak decline in the western Mediterranean region: an overview on current evidences, mechanisms and management options to improve forest resilience*. iForest-Biogeosciences and Forestry, 10(5), 796. doi.org/10.3832/ifor2317-010

Giorgi, F., Lionello, P., 2008. *Climate change projections for the Mediterranean region*. Glob. Planet. Chang. 63 (2–3), 90–104. doi.org/10.1016/j.gloplacha.2007.09.005.

González de Andrés, E., Camarero, J.J., 2020. *Disentangling Mechanisms of Drought-Induced Dieback in Pinus nigra Arn. from Growth and Wood Isotope Patterns.* Forests, 11(12), 1339. doi.org/10.3390/f11121339

Gordo,O., Sanz,J.J., 2009. *Long-term temporal changes of plant phenology in the Western Mediterranean.* Global Change Biology, 15(8), 1930-1948. doi: 10.1111/j.1365-2486.2009.01851.x

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. *Google Earth Engine:planetary-scale geospatial analysis for everyone*. Remote Sens. Environ., 202, 18-27. doi.org/10.1016/j.rse.2017.06.031.

Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T., et al., 2020. *Plant responses to rising vapor pressure deficit*. New Phytol., 226, 1550-1566. doi.org/10.1111/nph.16485.

Gunderson, C.A., Edwards, N.T., Walker, A.V., O'Hara, K.H., Campion, C.M., Hanson, P.J., 2012. *Forest phenology and a warmer climate - growing season extension in relation to climatic provenance*. Global Change Biology, 18(6), 2008-2025. doi. org/10.1111/j.13652486.2011.02632.

Guo, J.S., Hultine, K.R., Koch, G.W., Kropp, H., Ogle, K., 2020. *Temporal shifts in iso/ anisohydry revealed from daily observations of plant water potential in a dominant desert shrub*. New Phytol., 225, 713-726. doi.org/10.1111/nph.16196.

Hapke, B., 1993. *Theory of reflectance and emittance spectroscopy*. Cambridge University Press.

Harrell, F.E., 2020. *Hmisc: Harrell Miscellaneous*. R package (version 4.0-1) with contributions from Charles Dupont and many others, 2017.

Hartmann, H., Moura, C.F., Anderegg, W.R., Ruehr, N.K., Salmon, Y., Allen, C.D., et al., 2018. *Research frontiers for improving our understanding of drought-induced tree and forest mortality.* New Phytologist, 218(1), 15-28. doi.org/10.1111/nph.15048

Hartmann, H., Adams, H.D., Anderegg, W.R., Jansen, S., Zeppel, M.J., 2015. *Research frontiers in drought-induced tree mortality: crossing scales and disciplines*. doi.org/10.1111/nph.13246

Hartmann, H., Ziegler, W., Trumbore, S., 2013. *Lethal drought leads to reduction in non structural carbohydrates in Norway spruce tree roots but not in the canopy*. Funct. Ecol., 27 (2), 413427. doi.org/10.1111/1365-2435.12046.

Hartmann, H., 2011. *Will a 385 million year-struggle for light become a struggle for water and for carbon?- How trees may cope with more frequent climate change-type drought events*. Glob. Change Biol., 17,642-655 doi.org/10.1111/j.1365-2486.2010.02248.x

Hasenauer, H., Petritsch, R., Zhao, M., Boisvenue, C., Running, S.W., 2012. *Reconciling satellite with ground data to estimate forest productivity at national scales.* Forest ecology and management, 276, 196-208. doi.org/10.1016/j.foreco.2012.03.022.

Hereş, A.M., Camarero, J.J., Lopez, B.C., Martinez-Vilalta, J., 2014. *Declining hydraulic performances and low carbon investments in tree rings predate Scots pine drought induced mortality*. Trees 28 (6), 1737-1750. doi.org/10.1007/s00468-014-1081-3.

Hochberg, U., Rockwell, F.E., Holbrook, N.M., Cochard, H., 2018. *Iso/anisohydry: a plant-environment interaction rather than a simple hydraulic trait*. Trends Plant Sci., 23 (2), 112120. doi.org/10.1016/j.tplants.2017.11.002.

Holmes, R.L., 1983. *Computer-assisted quality control in tree-ring dating and measurement*. Tree-Ring Bull. 43, 69-78.

Huemmrich, K.F., Goward, S.N., 1997. *Vegetation canopy PAR absorptance and NDVI: an assessment for ten tree species with the SAIL model.* Remote Sens. Environ., 61 (2), 254-269. doi.org/10.1016/S0034-4257(97)00042-4.

Hufkens, K., Friedl, M.A., Keenan, T.F., Sonnentag, O., Bailey, A., O'Keefe, J., Richardson, A.D., 2012. *Ecological impacts of a widespread frost event following early spring leaf-out.* Global Change Biology, 18(7), 2365-2377. doi.org/10.1111/j.1365-2486.2012.02712.x

IPCC, 2018. “IPCC 2018: summary of policymakers,” in Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, eds V. Masson-Delmotte, et al. (Geneva: World Meteorological Organization), 32.

IPCC, 2014. *Climate Change 2014: impacts, adaptation, and vulnerability*. Part A: global and sectoral aspects. In: Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., White, L. L., Estrada, Y. O. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Chang. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1132.

Ivits, E., Horion, S., Fensholt, R., Cherlet, M., 2013. *Drought footprint on European ecosystems between 1999 and 2010 assessed by remotely sensed vegetation phenology and productivity*. Global Change Biology, 20, 581-593. doi.org/10.1111/gcb.12393

Jin, H., Jönsson, A.M., Bolmgren, K., Langvall, O., Eklundh, L., 2017. *Disentangling remotely-sensed plant phenology and snow seasonality at northern Europe using MODIS and the plant phenology index*. Remote Sensing of Environment, 198, 203-212. doi.org/10.1016/j.rse.2017.06.015

Jin, H., Eklundh, L., 2014. *A physically based vegetation index for improved monitoring of plant phenology.* Remote Sensing of Environment, 152, 512-525. doi.org/10.1016/j.rse.2014.07.010

Kaufmann, R.K., D'arrigo, R.D., Paletta, L.F., Tian, H.Q., Jolly, W.M., Myneni, R.B., 2008. *Identifying climatic controls on ring width: the timing of correlations between tree rings and NDVI*. Earth Interact., 12 (14), 114. doi.org/10.1175/2008EI263.1.

Kaufmann, R.K., D'Arrigo, R.D., Laskowski, C., Myneni, R.B., Davi, N.K., 2004. *The effect of growing season and summer greenness on northern forests.* Geophys. Res. Lett., 31, 111-142. doi.org/10.1029/2004GL019608

Keenan, T. F., Gray, J., Friedl, M.A., Toomey, M., Bohrer, G., Hollinger, D.Y., et al., 2014. *Net carbon uptake has increased through warming-induced changes in temperate forest phenolog*y. Nature Climate Change, 4(7), 598-604. doi: 10.1038/nclimate2253

Komsta, L., 2019. *mblm: Median-Based Linear Models*. R package (version 0.12.1). https://CRAN.R-project.org/package=mblm.

Körner, C., 2017. *A matter of tree longevity.* Science, 355(6321), 130-131. doi: 10.1126/science.aal2449

Lempereur, M., Martin-StPaul, N.K., Damesin, C., Joffre, R., Ourcival, J.M., Rocheteau, A., Rambal, S., 2015. *Growth duration is a better predictor of stem increment than carbon supply in a Mediterranean oak forest: implications for assessing forest productivity under climate change*. New Phytologist, 207(3), 579-590. doi.org/10.1111/nph.13400

Lenth, R.V., 2021. *emmeans: Estimated Marginal Means, aka Least-Squares Means*. R package (version 1.5.4). https://CRAN.R-project.org/package=emmeans.

Lindenmayer, D.B., Laurance, W.F., Franklin, J.F., 2012. *Global decline in large old trees*. Science, 338(6112), 1305-1306. doi: 10.1126/science.1231070

Liu, F., Liu, H., Xu, C., Shi, L., Zhu, X., Qi, Y., He, W., 2021. *Old-growth forests show low canopy resilience to droughts at the southern edge of the taiga*. Glob. Chang. Biol., 27 (11), 2392-2402. doi.org/10.1111/gcb.15605.

Liu, G., Chen, X., Fu, Y., Delpierre, N., 2019. *Modelling leaf coloration dates over temperate China by considering effects of leaf season climate.* Ecological Modelling, 394, 34-43. doi.org/10.1016/j.ecolmodel.2018.12.020

Liu, D., Ogaya, R., Barbeta, A., Yang, X., Peñuelas, J., 2018. *Long-term experimental drought combined with natural extremes accelerate vegetation shift in a Mediterranean holm oak forest*. Env. Exp. Bot., 151, 1-11. doi: 10.1016/j.envexpbot.2018.02.008

Liu, G., Liu, H., Yin, Y., 2013. *Global patterns of NDVI-indicated vegetation extremes and their sensitivity to climate extremes.* Environmental Research Letters, 8(2), 025009. doi.org/10.1088/1748-9326/8/2/025009

Liu, X., Ellsworth, D.S., Tyree, M.T., 1997. *Leaf nutrition and photosynthetic performance of sugar maple (Acer saccharum) in stands with contrasting health conditions*. Tree Physiol., 17, 169-178. doi.org/10.1093/treephys/17.3.169

Lloret, F., Batllori, E., 2021. *Climate-induced global forest shifts due to heatwave-drought*. In Ecosystem Collapse and Climate Change. Springer, Cham. pp. 155-186.doi.org/10.1007/978-3-030-71330-0_7

Malyshev, A.V., 2020. *Warming events advance or delay spring phenology by affecting bud dormancy depth in trees.* Frontiers in Plant Science, 11, 856. doi.org/10.3389/fpls.2020.00856

Martinez-Vilalta, J., Poyatos, R., Aguade, D., Retana, J., Mencuccini, M., 2014. *A new look at water transport regulation in plants*. New Phytol. 204 (1), 105-115. doi.org/10.1111/nph.12912.

Matsushita, B., Yang, W., Chen, J., Onda, Y., Qiu, G., 2007. *Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-Density Cypress Forest*. Sensors, 7, 2636-2651. doi.org/10.3390/s7112636.

McDowell, N.G., Allen, C.D., Anderson-Teixeira, K., Aukema, B.H., Bond-Lamberty, B., Chini, L., et al., 2020. *Pervasive shifts in forest dynamics in a changing world.* Science, 368 (6494). doi:10.1126/science.aaz9463

McDowell, N.G., Coops, N.C., Beck, P.S.A., Chambers, J.Q., Gangodagamage, C., Hicke, J.A., Huang, C.Y., Kennedy, R., Krofcheck, D.J., Litvak, M., et al., 2015. *Global satellite monitoring of climate-induced vegetation disturbances.* Trends in Plant Science, 20, 114-123. doi.org/10.1016/j.tplants.2014.10.008

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., Stitt, M., 2011. *The interdependence of mechanisms underlying climate-driven vegetation mortality.* Trends Ecol Evol., 26(10), 523-532. doi.org/10.1016/j.tree.2011.06.003

McDowell, N., Pockman, W.T., Allen, C. D., Breshears, D.D., Cobb, N., Kolb, T., et al., 2008. *Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought?.* New phytologist, 178(4), 719-739. doi.org/10.1111/j.1469-8137.2008.02436.x

Menzel, A., Yuan, Y., Matiu, M., Sparks, T., Scheifinger, H., Gehrig, R., Estrella, N., 2020. *Climate change fingerprints in recent European plant phenology.* Global Change Biology, 26(4), 2599-2612. doi.org/10.1111/gcb.15000

Menzel, A., Sparks, T.H., Estrella, N., Roy, D. B., 2006. *Altered geographic and temporal variability in phenology in response to climate change.* Global Ecology and Biogeography, 15(5), 498-504. doi.org/10.1111/j.1466-822X.2006.00247.x

Mitchell, P. J., O'Grady, A. P., Tissue, D. T., White, D. A., Ottenschlaeger, M. L., Pinkard, E. A., 2013. *Drought response strategies define the relative contributions of hydraulic dysfunction and carbohydrate depletion during tree mortality*. New Phytol., 197 (3), 862-872. doi.org/10.1111/nph.12064.

Moreno-Fernández, D., Viana-Soto, A., Camarero, J.J., Zavala, M. A., Tijerín, J., García, M., 2021. *Using spectral indices as early warning signals of forest dieback: The case of drought-prone Pinus pinaster forests*. Science of The Total Environment, 148578. doi.org/10.1016/j.scitotenv.2021.148578

Morin, X., Lechowicz, M.J., Augspurger, C., O' Keefe, J., Viner, D., Chuine, I., 2010. *Leaf phenology in 22 North American tree species during the 21st century.* Global Change Biol., 15, 961-975. doi.org/10.1111/j.1365-2486.2008.01735.x

Myneni, R.B., Hall, F.G., Sellers, P.J., Marshak, A.L., 1995. *The meaning of spectral vegetation indices.* IEEE Trans. Geosci. Remote Sens., 33, pp. 481-486. doi: 10.1109/TGRS.1995.8746029.

Nakagawa, S., Schielzeth, H., 2013. *A general and simple method for obtaining R2 from generalized linear mixed-effects models*. Methods Ecol. Evol., 4 (2), 133-142. doi.org/10.1111/j.2041-210x.2012.00261.x.

Nejad, A.Z., Badehian, Z., Rezaei Nejad, A., Bazot, S., 2021. *Do soil properties and ecophysiological responses of oak (Quercus brantii Lindl.) correlate with the rate of dieback?.* Trees, 35(5), 1639-1650. doi.org/10.1007/s00468-021-02142-7

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W. A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., 2011. *A large and persistent carbon sink in the world's forests*. Science, 333, 988-993. doi: 10.1126/science.1201609.

Pasho, E., Camarero, J.J., de Luis, M., Vicente-Serrano, S.M., 2011. *Impacts of drought at different time scales on forest growth across a wide climatic gradient in north-eastern Spain*. Agric. For. Meteorol., 151, 1800-1811. doi.org/10.1016/j.agrformet.2011.07.018

Pellizzari, E., Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Carrer, M., 2016. *Wood anatomy and carbon-isotope discrimination support long-term hydraulic deterioration as a major cause of drought-induced dieback*. Global Change Biology, 22(6), 2125-2137. https://doi.org/10.1111/gcb.13227

Peñuelas, J., Filella, I., Zhang, X., Llorens, L., Ogaya, R., Lloret, F., et al., 2004. *Complex spatiotemporal phenological shifts as a response to rainfall changes*. New phytologist, 161(3), 837-846. doi.org/10.1111/j.1469-8137.2004.01003.x

Peñuelas, J., Filella, I., Comas, P., 2002. *Changed plant and animal life cycles from 1952 to 2000 in the Mediterranean region.* Global Change Biol., 8, pp. 531-544. doi.org/10.1046/j.1365-2486.2002.00489.x

Peñuelas, J., Lloret, F., Montoya, R., 2001. *Severe drought effects on Mediterranean woody flora in Spain.* For. Sci., 47, 214-218. doi.org/10.1093/forestscience/47.2.214

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., Stenseth, N.C., 2005. *Using the satellite-derived NDVI to assess ecological responses to environmental change.* Trends Ecol. Evol., 20, 503-510. doi.org/10.1016/j.tree.2005.05.011.

Poyatos, R., Llorens, P., Pinol, J., Rubio, C., 2008. *Response of Scots pine (Pinus sylvestris L.) and pubescent oak (Quercus pubescens Willd.) to soil and atmospheric water deficits under Mediterranean mountain climate.* Ann. For. Sci., 65 (1). doi.org/10.1051/forest:2008003.

Pollastrini, M., Puletti, N., Selvi, F., Iacopetti, G., Bussotti, F., 2019. *Widespread crown defoliation after a drought and heat wave in the forests of Tuscany (Central Italy) and Their Recovery - A Case Study From Summer 2017*. Frontiers in Forests and Global Change, 2, 74. doi.org/10.3389/ffgc.2019.00074.

Pompa-García, M., Camarero, J.J., Colangelo, M., González-Cásares, M., 2021. *Inter and intra-annual links between climate, tree growth and NDVI: improving the resolution of drought proxies in conifer forests*. Int J Biometeorol., 65, 2111-2121. doi.org/10.1007/s00484-021-02170-5

R Core Team, 2020. *R: A Language And Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O., Toomey, M., 2013. *Climate change, phenology, and phenological control of vegetation feedbacks to the climate system.* Agric. For. Meteorol., 169, pp. 156-173. doi.org/10.1016/j.agrformet.2012.09.012

Richardson, A.D., Black, T.A., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., et al., 2010. *Influence of spring and autumn phenological transitions on forest ecosystem productivity*. Phil. Trans. R. Soc. B., 365, 3227-3246. doi.org/10.1098/rstb.2010.0102

Ripullone, F., Camarero, J. J., Colangelo, M., Voltas, J., 2020. *Variation in the access to deep soil water pools explains tree-to-tree differences in drought-triggered dieback of Mediterranean oaks*. Tree physiology, 40(5), 591-604. doi.org/10.1093/treephys/tpaa026

Roman, D.T., Novick, K.A., Brzostek, E.R., Dragoni, D., Rahman, F., Phillips, R.P., 2015. *The role of isohydric and anisohydric species in determining ecosystem-scale response to severe drought.* Oecologia, 179, 641-654. doi.org/10.1007/s00442-015-3380-9.

Sánchez-Salguero, R., Colangelo, M., Matías, L., Ripullone, F., Camarero, J.J., 2020a. *Shifts in growth responses to climate and exceeded drought-vulnerability thresholds characterize dieback in two Mediterranean deciduous oaks.* Forests, 11(7), 714. doi.org/10.3390/f11070714

Sánchez-Salguero, R., Camarero, J.J., 2020b. *Greater sensitivity to hotter droughts underlies juniper dieback and mortality in Mediterranean shrublands*. Science of the Total Environment, 721, 137599. doi.org/10.1016/j.scitotenv.2020.137599

Sanchez-Salguero, R., Camarero, J.J., Gutierrez, E., Gonzalez Rouco, F., Gazol, A., Sangüesa-Barreda, G., et al., 2017. *Assessing forest vulnerability to climate warming using a process-based model of tree growth: bad prospects for rear-edges.* Glob. Chang. Biol., 23, 2705-2719. doi.org/10.1111/gcb.13541.

Schreiber, S.G., Ding, C., Hamann, A., Hacke, U.G., Thomas, B.R., Brouard, J.S., 2013. *Frost hardiness vs. growth performance in trembling aspen: an experimental test of assisted migration.* Journal of Applied Ecology, 50(4), 939-949. doi.org/10.1111/1365-2664.12102

Sen, P. K., 1968. *Estimates of the regression coefficient based on Kendall's tau*. J. Am. Stat. Assoc. 63, 1379–1389.

Senf, C., Buras, A., Zang, C.S., Rammig, A., Seidl, R., 2020. *Excess forest mortality is consistently linked to drought across Europe.* Nature communications, 11(1), 1-8. doi.org/10.1038/s41467-020-19924-1

Sevanto, S., McDowell, N.G., Dickman, L.T., Pangle, R., Pockman, W.T., 2014. *How do trees die? A test of the hydraulic failure and carbon starvation hypotheses*. Plant, Cell & Env, 37, 153-161. doi.org/10.1111/pce.12141

Shen, M., Piao, S., Cong, N., Zhang, G., Jassens, I.A., 2015. *Precipitation impacts on vegetation spring phenology on the Tibetan Plateau*. Global change biology, 21(10), 3647-3656. doi.org/10.1111/gcb.12961

Siam, A.M.J., Radoglou, K.M., Noitsakis, B., Smiris, P., 2008. *Physiological and growth responses of three Mediterranean oak species to different water availability regimes*. J. Arid Environ., 72, 583-592. doi.org/10.1016/j.jaridenv.2007.11.001

Smirnoff, N., 1993. *The role of active oxygen in the response of plants to water deficit and desiccation.* New Phytol., 125, 27-58

Theil, H., 1950. *A rank-invariant method of linear and polynomial regression analysis*. Indag. Math. 12, 173.

Title, P., Bemmels, J., 2018. *ENVIREM: ENVIronmental Rasters for Ecological Modeling Version 1.0* [dataset]. University of Michigan - Deep Blue Data. doi.org/10.1111/ecog.02880.

Thornthwaite, C.W. ,1948. *An approach toward a rational classification of climate*. Geographical Review, 38, 55-94. doi.org/210739

Tongo, A., Jalilvand, H., Hosseininasr, M., Naji, H.R., 2021. *Leaf morphological and physiological variations in response to canopy dieback of Persian Oak (Quercus brantii Lindl.).* Forest Pathology, 51(2), e12671. doi.org/10.1111/efp.12671

Vacchiano, G., Garbarino, M., Mondino, E.B., Motta, R., 2012. *Evidences of drought stress as a predisposing factor to Scots pine decline in Valle d'Aosta (Italy).* European Journal of Forest Research, 131(4), 989-1000. doi.org/10.1007/s10342-011-0570-9

Van Breugel, M., Ransijn, J., Craven, D., Bongers, F., Hall, J.S., 2011. *Estimating carbon stock in secondary forests: decisions and uncertainties associated with allometric biomass models*. For. Ecol. Manag., 262, pp.1648-1657. doi.org/10.1016/j.foreco.2011.07.018.

Vicente-Serrano, S.M., Martin-Hernandez, N., Camarero, J.J., Gazol, A., Sanchez-Salguero, R., Pena-Gallardo, M., et al., 2020. *Linking tree-ring growth and satellite derived gross primary growth in multiple forest biomes. Temporal-scale matters*. Ecol. Indic., 108, 105753. doi.org/10.1016/j.ecolind.2019.105753.

Vicente-Serrano, S.M., Camarero, J.J., Olano, J.M., Martin-Hernandez, N., Pena-Gallardo, M., Tomás-Burguera, M., et al., 2016. *Diverse relationships between forest growth and the Normalized Difference Vegetation Index at a global scale*. Remote Sens. Environ., 187, 14-29. doi.org/10.1016/j.rse.2016.10.001.

Vicente-Serrano, S.M., Camarero, J.J., Azorin-Molina, C., 2014. *Diverse responses of forest growth to drought timescales in the Northern Hemisphere*. Glob. Ecol. Biogeogr., 23, 1019-1030. doi.org/10.1111/geb.12183.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Begueria, S., Trigo, R., Lopez-Moreno, J.I., Azorin-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Moran-Tejeda, E., Sanchez-Lorenzo, A., 2013. *Response of vegetation to drought time-scales across global land biomes.* Proc. Natl. Acad. Sci., 110 (1), 52-57. doi.org/10.1073/pnas.1207068110.

Vicente-Serrano, S.M., Begueria, S., Lopez-Moreno, J.I., 2010. *A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index*. J. Clim., 23, 1696-1718. doi.org/10.1175/2009JCLI2909.1.

Vitasse, Y., Baumgarten, F., Zohner, C.M., Kaewthongrach, R., Fu, Y.H., Walde, M., Moser, B., 2021. *Impact of microclimatic conditions and resource availability on spring and autumn phenology of temperate tree seedlings*. New Phytologist. doi.org/10.1111/nph.17606

Vitasse, Y., Signarbieux, C., Fu, Y.H., 2018. *Global warming leads to more uniform spring phenology across elevations*. Proc. Natl. Acad. Sci., 115, pp. 1004-1008 https://doi.org/10.1073/pnas.1717342115

Voltas, J., Camarero, J.J., Carulla, D., Aguilera, M., Ortiz, A., Ferrio, J.P., 2013. *A retrospective, dual-isotope approach reveals individual predispositions to winter-drought induced tree dieback in the southernmost distribution limit of Scots pine*. Plant Cell Environ., 36, 1435-48. doi.org/10.1111/pce.12072.

Vörösmarty, C.J., Douglas, E.M., Green, P.A., Revenga, C., 2005. *Geospatial indicators of emerging water stress: an application to Africa*. Ambio 34, 230-236.

de Vries, H., Lemmens, M., 2021. *Observation.org, Nature data from around the World*. Observation.org. Occurrence dataset [dataset]. accessed via GBIF.org on 2021-07-01. doi.org/10.15468/5nilie.

Way, D.A., 2011. *Tree phenology responses to warming: spring forward, fall back?.* Tree physiology, 31(5), 469-471. doi.org/10.1093/treephys/tpr044

Wang, J., Wu, C., Zhang, C., Ju, W., Wang, X., Chen, Z., Fang, B., 2018. *Improved modeling of gross primary productivity (GPP) by better representation of plant phenological indicators from remote sensing using a process model.* Ecol. Ind. 88, 332-340. doi.org/10.1016/j.ecolind.2018.01.042

Wang, C., Cao, R., Chen, J., Rao, Y., Tang, Y., 2015. *Temperature sensitivity of spring vegetation phenology correlates to within-spring warming speed over the northern hemisphere*. Ecol. Indic., 50, pp. 62-68. doi.org/10.1016/j.ecolind.2014.11.004

Wang, J., Rich, P.M., Price, K.P., Kettle, W.D., 2004. *Relations between NDVI and tree productivity in the central great plains*. Int. J. Remote Sens., 16, 12. doi.org/10.1080/0143116032000160499

Wang-Erlandsson, L., Bastiaanssen, W.G., Gao, H., Jagermeyr, J., Senay, G. B., Van Dijk, A.I.J., Guerschman, J.P., Keys, P.W., Gordon, L.J., Savenije, H.H., 2016. *Global root zone storage capacity from satellite-based evaporation*. Hydrol. Earth Syst. Sci., 20, 1459-1481. doi.org/10.5194/hess-20-1459-2016.

Willmott, C., Feddema, J., 1992. *A more rational climatic moisture index*. Prof. Geogr. 44, 84-88. doi.org/10.1111/j.0033-0124.1992.00084.x.

Willmott, C.J., Rowe, C.M., Mintz, Y., 1985. *Climatology of the terrestrial seasonal water cycle*. J. Climatol. 5, 589–606. doi.org/10.1002/joc.3370050602.

Wipf, S., Stoeckli, V., Bebi, P., 2009. *Winter climate change in alpine tundra: plant responses to changes in snow depth and snowmelt timing.* Climatic change, 94(1), 105-121. doi:10.1007/s10584-009-9546-x

Wu, M., Vico, G., Manzoni, S., Cai, Z., Bassiouni, M., Tian, F., et al., 2021. *Early growing season anomalies in vegetation activity determine the large-scale climate-vegetation coupling in Europe*. J. Geophys. Res. Biogeosci. 126, e2020JG006167. doi.org/10.1029/2020JG006167.

Wu, X., Liu, H., Li, X., Ciais, P., Babst, F., Guo, W., et al., 2018. *Differentiating drought legacy effects on vegetation growth over the temperate Northern Hemisphere*. Global Change Biology, 24(1), 504-516. doi.org/10.1111/gcb.13920

Wu, C., Chen, J. M., Black, T.A., Price, D.T., Kurz, W.A., Desai, A.R., et al., 2013. *Interannual variability of net ecosystem productivity in forests is explained by carbon flux phenology in autumn*. Global Ecology and Biogeography, 22(8), 994-1006. doi.org/10.1111/geb.12044

Xu, P., Fang, W., Zhou, T., Zhao, X., Luo, H., Hendrey, G., Yi, C., 2019. *Spatial upscaling of tree-ring-based forest response to drought with satellite data.* Remote Sensing, 11(20), 2344. doi.org/10.3390/rs11202344

Xu, P., Zhou, T., Yi, C., Fang, W., Hendrey, G., Zhao, X., 2018. *Forest drought resistance distinguished by canopy height*. Environmental Research Letters, 13(7), 075003. doi.org/10.1088/1748-9326/aacadd

Xu, K., Wang, X., Liang, P., An, H., Sun, H., Han, W., Li, Q., 2017. *Tree-ring widths are good proxies of annual variation in forest productivity in temperate forests*. Scientific reports, 7(1), 1-8. doi.org/10.1038/s41598-017-02022-6.

Yang, B., He, M., Shishov, V., Tychkov, I., Vaganov, E., Rossi, S., et al., 2017. *New perspective on spring vegetation phenology and global climate change based on Tibetan Plateau tree-ring data*. Proceedings of the National Academy of Sciences, 114(27), 6966-6971. doi.org/10.1073/pnas.1616608114

Yun, J., Jeong, S.J., Ho, C.H., Park, C.E., Park, H., Kim, J., 2018. *Influence of winter precipitation on spring phenology in boreal forests*. Global change biology, 24(11), 5176-5187. doi.org/10.1111/gcb.14414

Zani, D., Crowther, T.W., Mo, L., Renner, S.S., Zohner, C.M., 2020. *Increased growing-season productivity drives earlier autumn leaf senescence in temperate trees*. Science, 370(6520), 1066-1071. doi: 10.1126/science.abd8911

Zeng, L., Wardlow, B.D., Xiang, D., Hu, S., Li, D., 2020. *A review of vegetation phenological metrics extraction using time-series, multispectral satellite data.* Remote Sens. Environ. 237, 111511. doi.org/10.1016/j.rse.2019.111511.

Zhang, Q., Shao, M.A., Jia, X., Wei, X., 2017. *Relationship of climatic and forest factors to drought- and heat-induced tree mortality*. PLoS ONE, 12(1), e0169770. doi.org/10.1371/journal.pone.0169770

Zhou, Y., Yi, Y., Jia, W., Cai, Y., Yang, W., Li, Z., 2020. *Applying dendrochronology and remote sensing to explore climate-drive in montane forests over space and time*. Quat. Sci. Rev., 237, 106292. doi.org/10.1016/j.quascirev.2020.106292.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. *Mixed Effects Models And Extensions in Ecology With R*. Springer Science & Business Media.

Zweifel, R., Sterck, F., Braun, S., Buchmann, N., Eugster, W., Gessler, A., et al., 2021. *Why trees grow at night.* New Phytol. doi.org/10.1111/nph.17552.

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