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Canopy spectral responses of temperate forests to late spring frost and hot drought events assessed with Sentinel-2 NDVI time series

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ABSTRACT

Extreme climatic events (ECEs) are projected to increase due to climate change, but we still have limited understanding of how these events affect the functioning of forest ecosystems. Each species may react differently to ECEs, depending on their ecology, but we lack a regional perspective on these responses. Here we tracked intra-annual changes in the canopy greenness (i.e. NDVI from Sentinel-2 imagery) of 16 tree species growing within 3000 km^2 *of forests of the Italian Alps. The study region was subject to a late spring frost event in May 2019, and a hot drought in July 2022, allowing us to quantify species responses to ECEs by comparison of seasonal trends in NDVI observed over the period 2018–2024. The effects of 2019 frost were very localized and mainly affected the canopy spectral response and phenology of* Fagus sylvatica L. *in areas around 1000 m a.s.l.. There, trees had developed buds and some juvenile leaves when frost occurred, resulting in the wilting or dropping of the earliest leaves, and slower green-up phase but no lasting impacts. The hot drought had its largest impact on* Quercus ilex L. *forests growing at low elevations: there was a clear decrease in canopy greenness from July onwards in 2022, but no residual impacts were observed the following years. At higher elevations, some species had unusually green canopies in response to the heatwave suggesting they benefitted from warmer conditions.*

1. Introduction

Extreme climate events (ECEs) are becoming more frequent due to climate warming events (Chan et al., 2020), with significant consequences for forest ecosystems. These events, including severe droughts, heat waves, their combination known as "hot droughts," and late spring frosts, impact forest growth, mortality, and regeneration processes (Breshears et al., 2005; Hufkens et al., 2012; Allen et al., 2015). Such changes contribute to shifts in forest distribution (Smith, 2011), with coniferous and boreal ecosystems particularly vulnerable (Seidl et al., 2017). Understanding how temperate forest canopies respond to ECEs is crucial for assessing ecosystem resilience and carbon dynamics. Extreme climatic events influence key physiological processes in trees, including transpiration, photosynthesis, and phenology, with consequences for forest structure and function. Studying these effects across multiple tree species and altitudinal gradients is essential to capture the full variability in forest responses. By leveraging remote sensing data, it is possible to track these impacts over large spatial and temporal scales, providing valuable insights into forest responses and recovery patterns.

Late spring frosts pose a significant threat to forests, affecting trees differently depending on their phenological stage. Frost events

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damage buds, flowers, and young leaves, disrupting budburst and flowering, reducing growth and reproductive success, and in severe cases, causing mortality (Zohner et al., 2020; Lamichhane, 2021). Climate warming alters leaf unfolding, spring temperatures, and frost event occurrences, with species-specific and geographical variations in frost risk (Ma et al., 2019). In the Swiss Alps, trees above 800 m elevation are particularly susceptible (Bigler and Bugmann, 2018). While lower-elevation temperate trees will likely face increased drought stress (Pederson et al., 2012), higher-elevation trees may experience heightened frost risk due to phenological shifts (Vitasse et al. 2018a, 2018b). Projections indicate that over one-third of European temperate forest areas will face rising frost damage (Zohner et al., 2020), with increasing impacts on temperate and boreal vegetation in mid-latitudes (Lamichhane, 2021). Research indicates that late spring frosts events reduce photosynthetic productivity by 13.6 % and delay subsequent spring phenology by approximately seven days, emphasizing the need for their integration into Earth system models (Wang et al., 2025). Moreover, warming winters may delay budburst through reduced chilling, which may cause plants to leaf out more slowly, thus decreasing spring freeze tolerance (Chamberlain and Wolkovich, 2021). Studies further highlight that late spring frosts can delay subsequent flowering, with late-leafing species exhibiting even greater sensitivity, suggesting that climate change affects phenological sequences rather than individual stages (Qiu et al., 2024). Additionally, frost events during early seedling stages pose a major challenge to forest regeneration, as high mortality rates and growth impairments can reduce competitive strength, despite some degree of frost acclimation over time (Muffler et al., 2024).

Projections suggest that hot droughts will intensify, become more frequent (Suarez-Gutierrez et al., 2023), and expand geographically (Ballester et al., 2010; Stott et al., 2016; McDowell et al., 2018). Over the past 30 years, severe droughts have been primary drivers of global gross primary productivity variations (Zscheischler et al., 2014), directly reducing carbon uptake. In Europe, the summer 2022 heatwave decreased net biospheric carbon uptake by 56–62 TgC (Van Der Woude et al., 2023), and similar extreme events occurred in South Europe in 2023 (Wolf and Paul-Limoges, 2023). Hot droughts limit photosynthesis through stomatal closure, cavitation, and leaf loss, while also reducing forest productivity, increasing tree mortality, and exacerbating fire risk (Seidl et al., 2017; Mishra et al., 2023).

Drought also alters vegetation phenology. While studies showed that global warming generally delays autumn date of foliar senescence (having positive implications for growing season length), drought can induce earlier dates of foliar senescence, especially in water-limited regions (Wu et al., 2022). Similarly, drought shifts the start of the growing season, advancing it in humid regions due to increased net radiation but delaying it in arid and semi-arid regions due to water deficits (Hu et al., 2025). These phenological shifts impact carbon cycling, shortening or lengthening the growing season and influencing ecosystem stability (Ding et al., 2024). In boreal forests, they also threaten plant-pollinator interactions, affecting biodiversity and resilience (Díaz-Calafat et al., 2025). In temperate forests like those in Siberia, earlier growing seasons may temporarily mitigate drought stress, but prolonged droughts could surpass species' physiological tolerances, ultimately reducing forest productivity (Arzac et al., 2021).

Satellite remote sensing provides a powerful tool for monitoring ECE, offering insights into forest response and post-event recovery at regional and continental scales. In particular, Sentinel-2 (S2), with its high temporal (5-day) and spatial (10 m) resolution, is revolutionizing our ability to detect vegetation changes and assess climate-induced forest decline. Sentinel-2 data were used to effectively capture fine-scale variations in forest health following the extreme drought of 2017 in South Italy (Coluzzi et al., 2020). Similarly, using multitemporal Sentinel-2 imagery a reduced photosynthetic activity and species-specific response strategies to drought were detected (Puletti et al., 2019). More broadly, remote sensing has emerged as a crucial tool for mapping temperate forests affected by extreme weather and climate events, such as droughts, storms, and late frosts, though challenges remain in distinguishing species-specific responses (Wegler and Kuenzer, 2024).

Thus, this study addresses the following questions: (1) how does the canopy spectral response to late spring frost varies across tree species and elevations in temperate forests? (2) how does the canopy spectral response to hot drought varies across tree species and elevations in temperate forests? To answer these questions, we analyse the effects of late spring frost and hot droughts on forest canopies using Sentinel-2 remote sensing data. The study focuses on sixteen tree species (both deciduous and evergreen) across a wide altitudinal range in the Italian Alps, encompassing sub-Mediterranean, temperate, and Alpine ecosystems.

2. Materials and methods

2.1. Study area

The study area encompasses the Province of Trento in Italy, located in the South-Eastern Italian Alps, spanning 6207 square kilometres, of which 55 % is covered by forests. The terrain within this region exhibits a complex topography, with altitudes ranging from 65 m a.s.l. to 3764 m a.s.l. Conifers, such as Silver Fir (*Abies alba* Mill.), Norway Spruce (*Picea abies* (L.) Karst.), European Larch (*Larix decidua* Mill.), Austrian Pine *(Pinus nigra* J.F.Arnold), and Scots Pine (*Pinus sylvestris* L.), dominate 67 % of the forested land. The remaining 33 % comprises broadleaf forests featuring European Beech (*Fagus sylvatica* L.), Hop hornbeam (*Ostrya carpinifolia* Scop.), various Oak species (*Quercus* ss.pp.), and Maples *(Acer* ss.pp.).

The species observed in our study area collectively reflect the complex and transitional bioclimatic conditions of the Province of Trento, which spans a wide range of altitudes and microclimates. The majority of the species, including *Abies alba*, *Larix decidua*, *Picea abies*, and *Fagus sylvatica*, are characteristic of the temperate and alpine biomes. However, the presence of species with a clear thermophilous or Mediterranean affinity is particularly noteworthy. Species such as *Ostrya carpinifolia*, *Fraxinus ornus*, and most significantly, *Quercus ilex*, are indicative of the warmer, southern-facing valleys where the influence of the Mediterranean climate is pronounced. The presence of *Quercus ilex* in a predominantly alpine context highlights a critical ecological transition zone, where Mediterranean flora penetrates and coexists with Central European forest species. This species is located almost exclusively in the surrounding Garda Lake, the largest lake of Italy, that creates a microclimate with mild winters that allows this species to survive. This rich mix of species from different biomes, along with the presence of introduced species like *Robinia pseudacacia*, underscores the phytogeographical complexity of the region and provides a crucial context for understanding local forest dynamics.

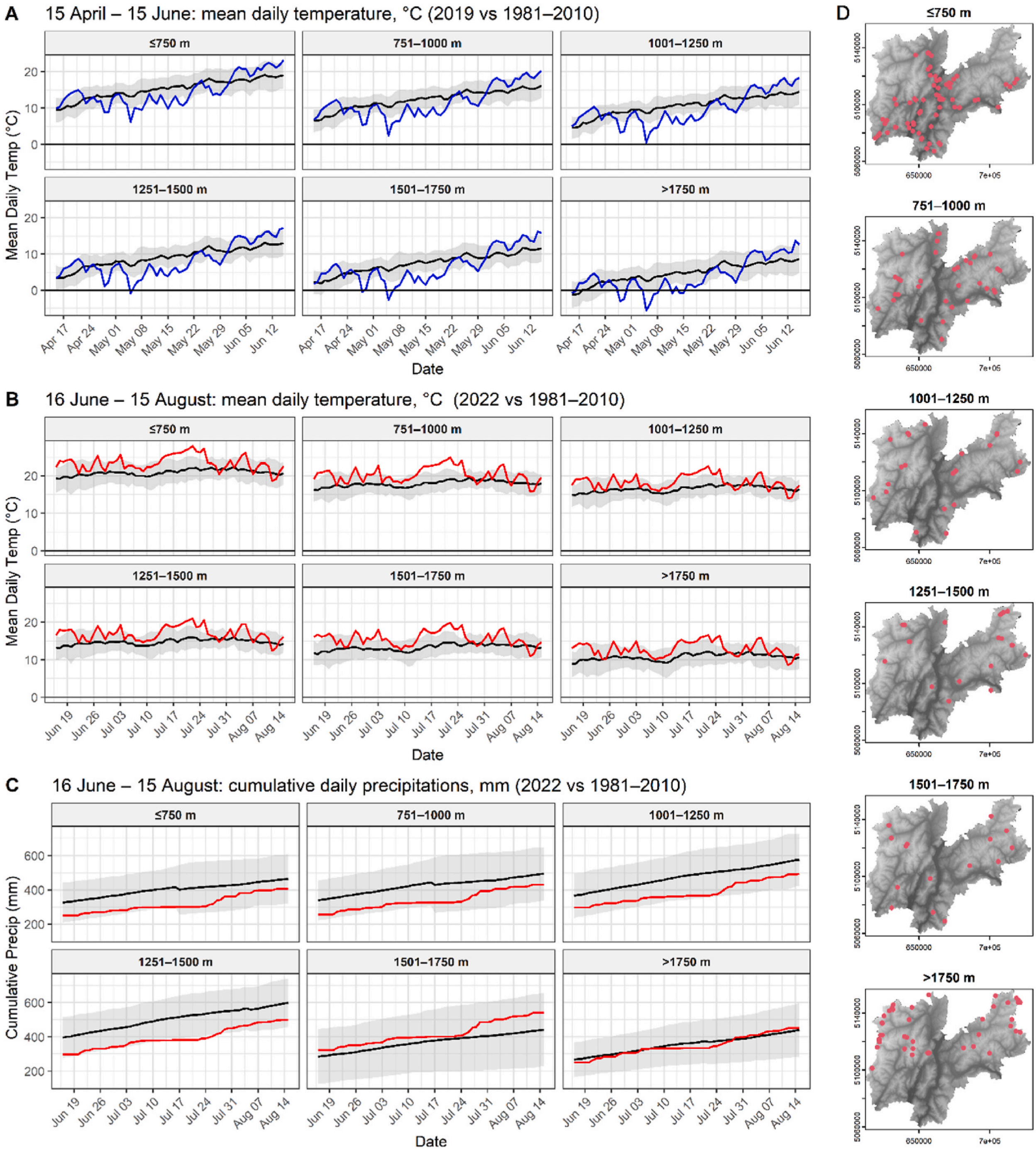

Fig. 1. Summary of data from 109 MeteoTrentino weather stations. (A) Mean daily temperature in 2019 (blue) compared with the 1981–2010 period (black: mean; grey: ±1 SD). (B) Mean daily temperature in 2022 (red) compared with the 1981–2010 period. (C) Mean cumulative precipitation from January 1, 2022 (red) compared with the 1981–2010 period. (D) Location of weather stations by altitude range.

2.2. Extreme climatic events analysed

May 2019 was one of the coldest May months on record in the study area, with mean monthly daily temperatures 3.2 °C below the average of the previous 30 year. On May 4–5, a cold front caused late spring frost and snowfall down to 500 m a.s.l., damaging agricultural crops and forest tree buds and leaves. During this event, 41 of 108 MeteoTrentino stations recorded mean daily temperatures below 0 °C ("Meteotrentino"). On the contrary, June 2019 was particularly warm with temperatures 2.2 °C above the monthly daily mean of the previous 30 years (Fig. 1).

The summer of 2022 was marked by extreme heat and drought. In Trento province, July temperatures were 1.6 °C above average, following an unusually dry period from mid-winter through summer (Fig. 1). A heatwave from July 13–26 brought peak temperatures around 38 °C, with mean daily temperatures exceeding 25 °C at 41 of 108 MeteoTrentino stations (Meteotrentino). Cumulative precipitation from January to July 2022 was significantly below the 1990–2020 average (410 mm vs. 529 mm, average of 96 MeteoTrentino stations). Due to this combination of heat and drought, we refer to the 2022 event as a 'hot drought.'

2.3. Sampling strategy

Using forest inventory maps from the forest management service, we selected forest parcels where a single predominant tree species made up over 70 % of the composition. Only species covering at least 100 ha across the study area were included. In this way we reduced the tree species from 45 to 16. To minimize edge effects from adjacent parcels with different species, we applied a 20-m negative buffer to each parcel. Within the trimmed parcels, sampling points were selected from a uniform 40-m grid, resulting in 212,327 points across 16 tree species (Table 1). The elevation of these points ranged from 112 m to 2369 m a.s.l. (Fig. 2).

2.4. Remote sensing data

We used Sentinel-2 data from the European Space Agency (ESA), which provides high spatial resolution optical imagery on a 5-day cycle. Each Sentinel-2 multispectral image includes 13 spectral bands, with different spatial resolutions: 4 bands at 10 m, 6 bands at 20 m, and 3 bands at 60 m resolution. We considered all images at the L2A processing level (Google Earth Engine product 'COPERNICUS/S2_SR_HARMONIZED') from 2018 to 2024. Data were accessed via the Google Earth Engine platform (Gorelick et al., 2017). We retained pixels classified as vegetation (SCL map value of 4) and excluded pixels with a cloud score (Google Earth Engine product 'GOOGLE/CLOUD_SCORE_PLUS/V1/S2_HARMONIZED') above 0.65 (Pasquarella et al., 2023).

To analyse vegetation status, we chose the Normalized Difference Vegetation Index (NDVI) because it is a widely used indicator of vegetation health and greenness (Huang et al., 2021). Bands 4 (red) and 8 (NIR), both at a 10 m spatial resolution, were used to compute NDVI for each available image. NDVI values for each sampling point were extracted from each image, generating an NDVI time series from 2018 to 2024 for every sampling point.

An important phase in land surface phenology analysis involves applying a smoothing technique to mitigate residual noise in the time series (Zeng et al., 2020). We opted for Generalized Additive Models (GAM), a method that has recently gained recognition in modelling land surface phenology (Grabska-Szwagrzyk and Tymińska-Czabańska, 2023). GAMs are capable of fitting phenological trajectories directly from the data, eliminating the need to impute missing values. Thin plate regression splines were used as the smoothing function, as described by Kowalski et al. (2020). For each sample and year under consideration, we applied the GAM function independently, considering the NDVI values above 0.1 from November of the year before to February of the year after.

Phenological status variables, including the start and end of green-up, the length of the green-up phase, and the length of the growing season, were estimated from the NDVI time series for each sampling point. These variables were computed using the *phenofit* package in R (Kong et al., 2022). Specifically, the fitting method by Zhang was applied, and the phenological variables were extracted

Table 1
Summary of the sampling points per species.

Species	Number of parcels	Average size of parcels (m^2)	Number of sampling points	Average points elevation (m)
Abies alba Mill.	598	17351.0	3352	1242.2
Alnus alnobetula (Ehrh.) K.Koch	1850	12775.8	2977	1461.2
Alnus incana (L.) Moench	148	4747.5	246	1935.3
Castanea sativa Mill.	55	8986.6	142	646.5
Corylus avellana L.	252	1563.9	99	1184.3
Fagus sylvatica L.	4777	19308.9	38461	1197.6
Fraxinus ornus L.	75	6360.5	163	838.2
Larix decidua Mill.	5513	21666.6	36865	1761.7
Ostrya carpinifolia Scop.	403	8965.9	1296	741.7
Picea abies (L.) H.Karst.	10815	38839.9	107074	1566.9
Pinus cembra L.	362	17642.4	2303	1969
Pinus mugo Turra	2393	18090.3	3826	1601.9
Pinus nigra J.F.Arnold	984	12504.1	3285	519.3
Pinus silvestris L.	2470	15299.4	11472	923.6
Quercus ilex L.	66	18016.5	432	487.8
Robinia pseudacacia L.	158	4983.7	334	665.5

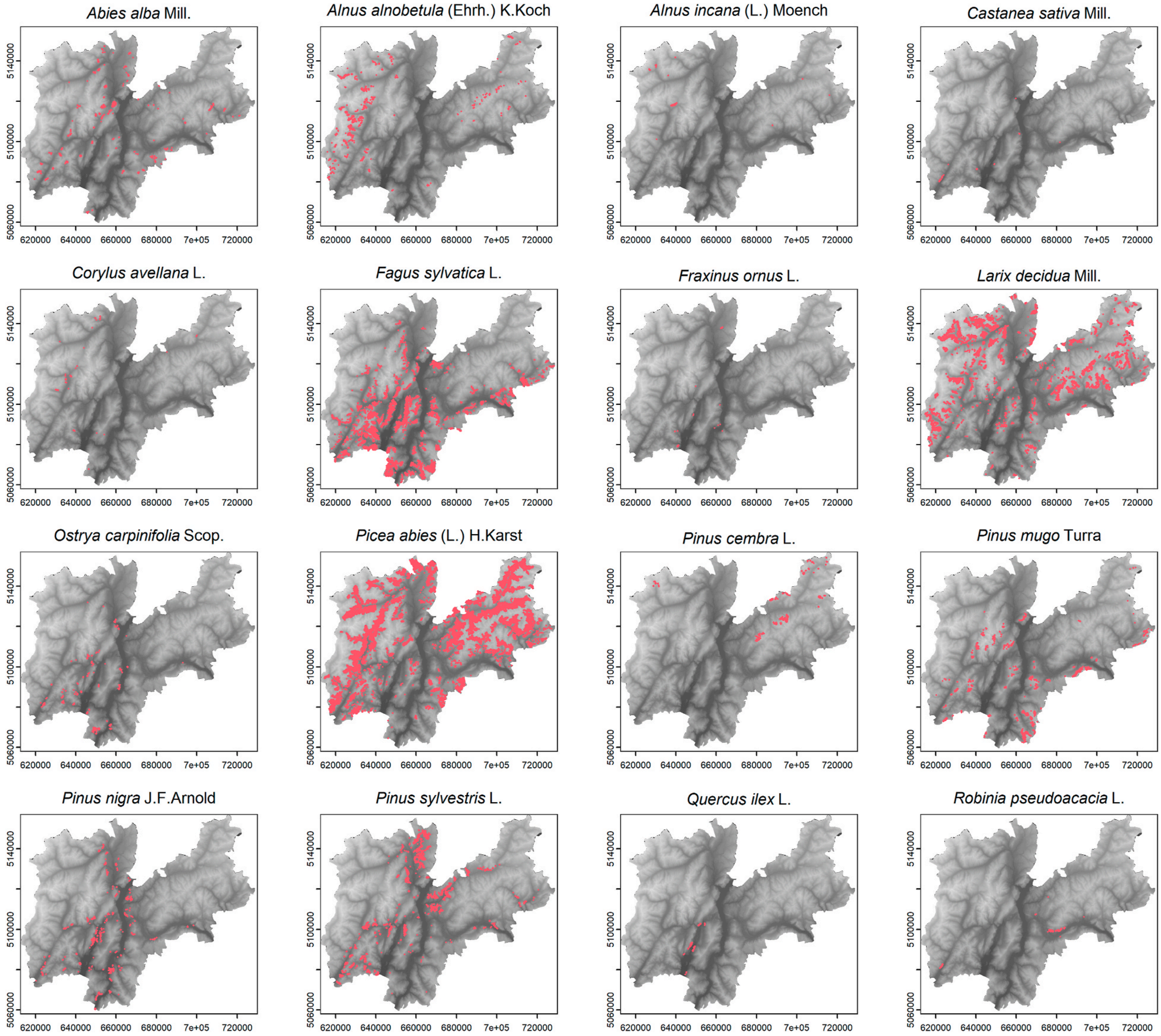

Fig. 2. A: The distribution of the sampling points by species over the study area. The background image is the digital terrain model of the area.

using the method of Gu et al. (2009).

2.5. Weather station data

Daily average temperature in °C and daily precipitation amount in millimetres were retrieved from 108 MeteoTrentino meteorological stations (96 stations for the precipitations) distributed over the entire study area (Fig. 2). The mean daily temperature data underwent spatial interpolation through linear kriging, factoring in both location and digital terrain model values. Similarly, total daily precipitation data was subjected to linear kriging interpolation, taking only location into account. Root means square error was computed using the leave-one-out-cross-validation strategy over the 108 weather stations. Our linear kriging approach resulted in an RMSE of 0.83 °C for mean daily temperature and 2.0 mm for daily precipitation, which are within the range reported by previous studies (e.g., Stahl et al., 2006; Wu and Li, 2013; Xu et al., 2013)

2.6. Statistical analysis

To assess any positive or negative shifts in NDVI values, temperatures, and cumulative precipitation compared to the average over the period of Sentinel-2 imagery availability (2018–2024), we used the non-parametric Mann-Whitney-Wilcoxon test. This test was applied by comparing the values of each year to the 2018–2024 time series in 7-day intervals, starting from March 1st and ending on November 30th. For example, the NDVI values from March 1st to 7th, 2022, were compared to the corresponding values from the same period across all years (2018–2024), to determine if the 2022 values were significantly higher or lower than the average for that time period at a 95 % confidence level.

To analyse the relationship between the significance of the Mann-Whitney-Wilcoxon test and the topographical characteristics of the study area, we used a Generalized Additive Model (GAM) with a binomial family. The significance of the test was treated as a binary response variable (1 for a statistically significant result, 0 otherwise). We used this model to predict the probability of a significant test result as a function of the following topographical variables: elevation, slope, and aspect. The aspect, a circular variable, was decomposed into its sinusoidal and cosinusoidal components to account for its cyclical nature. A penalized smoothing spline was fitted for each predictor variable to allow for non-linear relationships. All statistical analyses were conducted using the *mgcv* package in

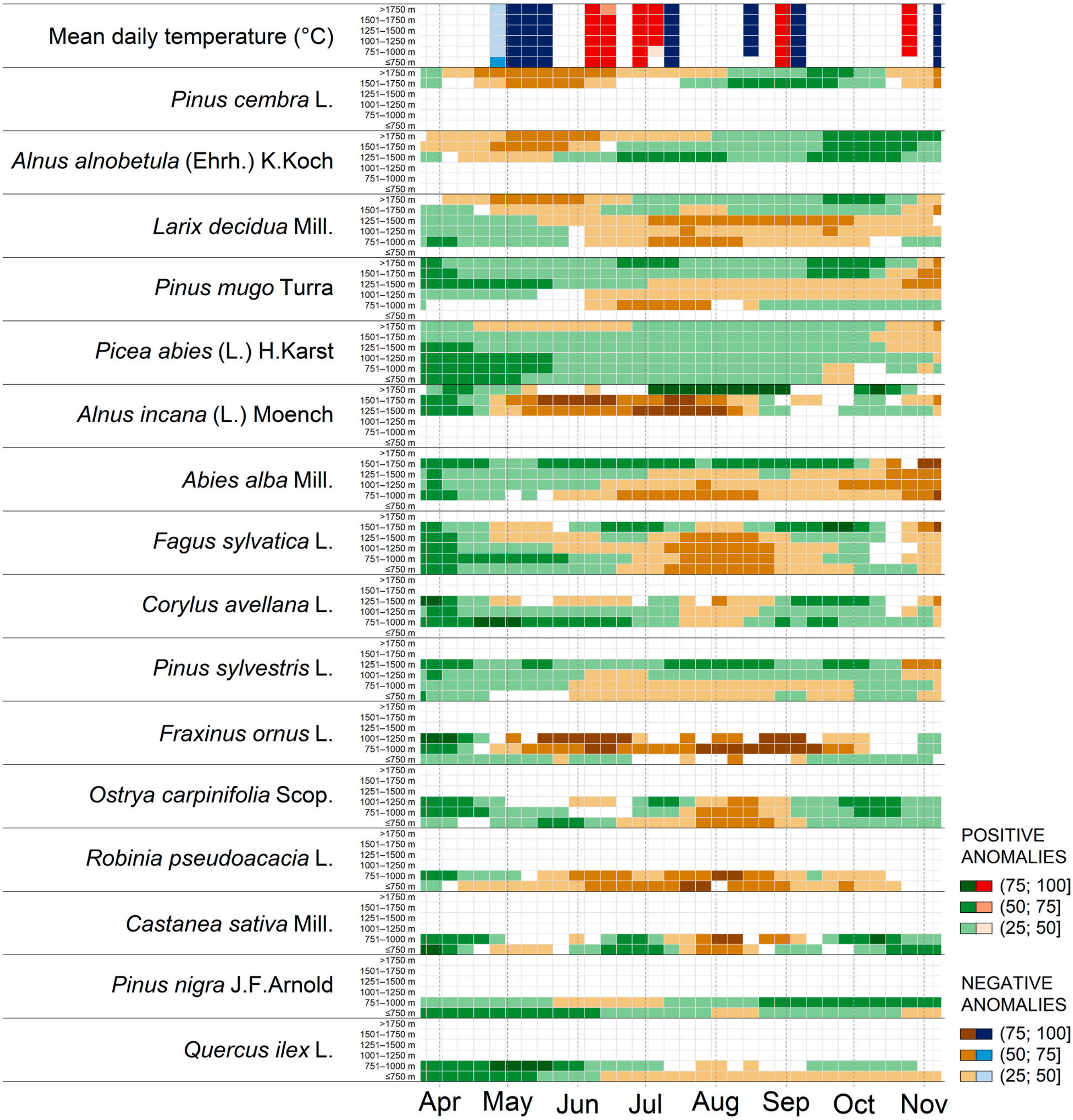

Fig. 3. NDVI and mean daily temperature anomalies in 2019 compared to the 2018–2024 period divided by species and elevation ranges. Colours indicate the percentage of sampling points with values that are significantly higher (green for NDVI/red for mean daily temperature) or lower (brown for NDVI/blue for mean daily temperature) than the reference period, based on the Mann–Wilcoxon test. The species order is based on median elevation of the sampling points from higher to lower.

R.

Phenological variables were evaluated using a mixed-effects model considering *Year* as a fixed effect, *Elevation class* as categorical variable and the point identifier (*ID*) as random effect. *Year* can have the values “2019”, for the subset of phenological metrics for the year 2019, and “2018–24” (this range contains all the values for the years from 2018 to 2024 including also 2019). Elevation classes were defined as “<750 m”, “750–1000 m”, “1000–1250 m”, ”1250–1500 m” and “>1500 m” above sea level.

3. Results

3.1. Canopy spectral response to late spring frost across tree species and elevations in temperate forests

During three to four weeks in late April–May 2019, temperatures at the sampling points were significantly below the 2018–2024 average, as indicated by the blue bars in the mean daily temperature panels of Fig. 3. This cold spell had variable impacts depending on phenological stage and elevation, coincided with early vegetative development for many species. In general, the impact was limited to trees located in a specific altitudinal range (1000–1500 m a.s.l.) and in particular on deciduous species. The frost event delayed the green-up phase in *Pinus cembra* and *Alnus alnobetula* across all elevations, while *Picea abies* was notably affected only above 1750 m (Fig. 3). *Larix decidua* exhibited a delayed green-up phase above 1500 m. For *Larix decidua* at mid-elevations (1250–1500 m), the combined effects of frost and the hot drought in June 2019 resulted in persistently below-average NDVI values throughout the season. *Pinus mugo* was impacted below 1250 m, whereas *Alnus incana* showed below average NDVI values primarily between 1250 and 1750 m, with extended periods of reduced NDVI due to the compounded stress of frost and hot drought. *Abies alba* was affected between 750 and 1000 m, while *Fagus sylvatica* displayed lower NDVI values above 1250 m but recovered by late June. At mid-elevations (1000–1250 m), the green-up peak was diminished, with NDVI values remaining below average for much of the year. Additionally, *Corylus avellana* exhibited below average NDVI values in May above 1250 m, and both *Fraxinus ornus* and *Robinia pseudoacacia* were affected above 750 m, showing persistently low NDVI values likely exacerbated by hot drought stress of June. *Ostrya carpinifolia* experienced NDVI declines above 1000 m, while *Castanea sativa* showed a below-average NDVI values. *Pinus nigra* was affected above 750 m at some locations but later recovered, whereas *Quercus ilex* and *Pinus sylvestris* did not exhibit any significant effects.

An example of the frost impact on *Fagus sylvatica* is illustrated in Fig. 4 for a single sampling point located at ~1100 m a.s.l. The mean daily temperature dropped below 5° for several days from May 5, 2019, stopping leaf development and damaging the already developed buds. Full NDVI recovery did not occur until July.

The GAM interpolated NDVI time series are shown in Fig. 5. These graphs confirm the considerations derived from Fig. 3. Indeed, *Fagus sylvatica* NDVI was above average at the beginning of the season and then the late spring frost moved the NDVI curve in line with the average. Looking in detail the phenology metrics extracted from *Fagus sylvatica* points (Fig. 6) we could note that the start of the season in 2019 was earlier below 1500 m a.s.l. and delayed above 1500 m a.s.l. On the contrary, the end of the green-up phase above 750 m a.s.l. was delayed in 2019 respect to the period 2018–24. The delay was particularly marked between 1000 and 1500 m a.s.l. This difference emerges clearly when considering the length of the green-up phase where we have that between 750 and 1500 m a.s.l. in 2019 it was much longer than the reference period 2018–24. The length of the season between 1000 and 1500 m a.s.l. was again much shorter in 2019 than in the reference period.

The analysis using a Generalized Additive Model on the points of *Fagus sylvatica* revealed significant non-linear relationships

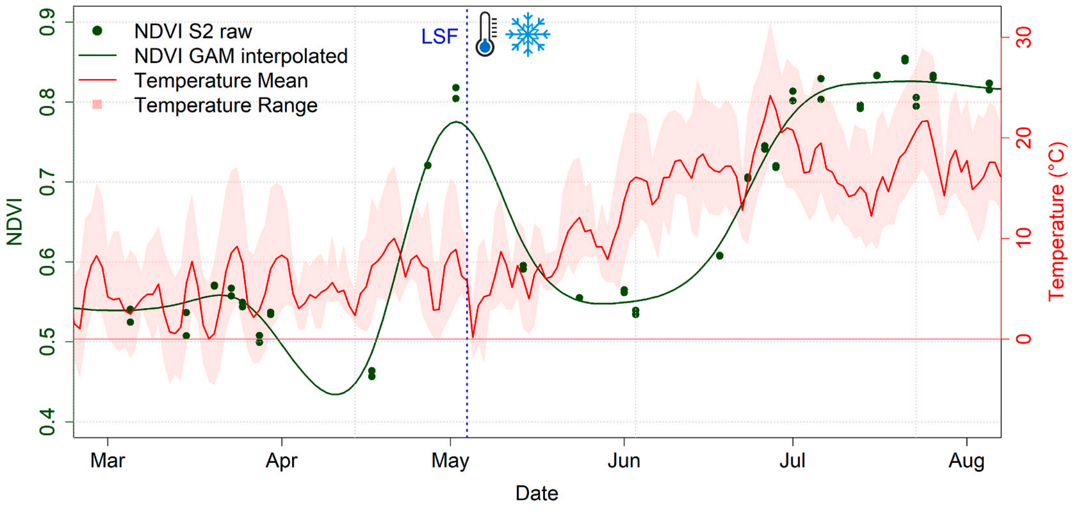

Fig. 4. NDVI values of a point of *Fagus sylvatica* in 2019 and predicted temperature for the same point in 2019. The green dots represent raw NDVI values from Sentinel-2 (NDVI S2 raw), while the black line shows interpolated NDVI trend, generated by Generalized Additive Modelling (GAM). The red line indicates the mean temperature, and the shaded red area represents the temperature range. The vertical blue dashed line marks the first day of the Late Spring Frost event.

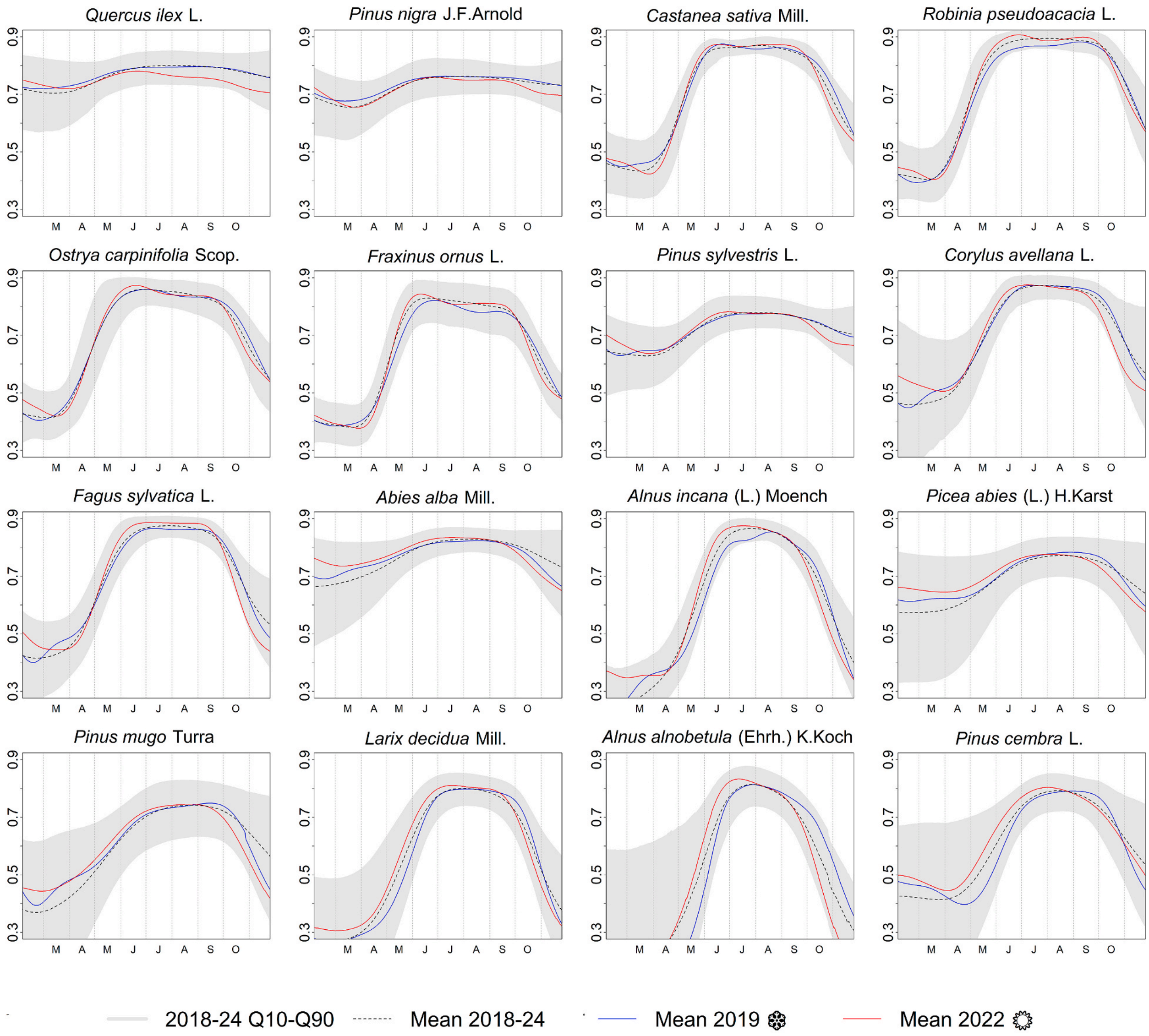

Fig. 5. NDVI time series for each species, interpolated using the GAM function and ordered by mean elevation. The grey band shows the 10th–90th percentile range (2018–24), the dashed line represents the period mean (2018–24), the blue line the 2019 mean, and the red line the 2022 mean. The letters on the x-axis indicates the months from April to October.

between the probability of a point having a significantly lower NDVI and the topographical variables (Fig. 7). The effect of elevation was highly dependent on the week considered as emerged previously. In early May, the probability of lower NDVI was highest at mid and high elevations above 1000 m), in early June at mid elevation (~1200 m) while in July the probability was low at all elevations. Slope consistently showed a negative relationship, with a higher probability of lower NDVI on flatter terrain. Again, this effect was most pronounced in May and June and was absent in early July. The aspect plots revealed that the probability of significantly lower NDVI was not changing varying the aspect.

3.2. Canopy spectral response to a hot drought event across tree species and elevations in temperate forests

Fig. 8 describes the effects of the 2022 hot drought on NDVI across species and elevations alongside with mean daily yemperature anomalies. The pronounced temperature spikes in July, represented by the red bars at the top of the figure, coincided with noticeable shifts in NDVI for several species. In general, it could be seen that we have two different behaviours for species and trees located at a median altitude above 1000 m a.s.l. and species below. Above 1000 m a.s.l. in general the effect of the hot drought was positive while below was generally negative. Overall, *Pinus cembra*, *Alnus alnobetula*, *Pinus mugo*, *Alnus incana*, *Abies alba*, and *Fagus sylvatica* exhibited above-average NDVI throughout much of the season, suggesting a positive impact. *Picea abies* remained well above average

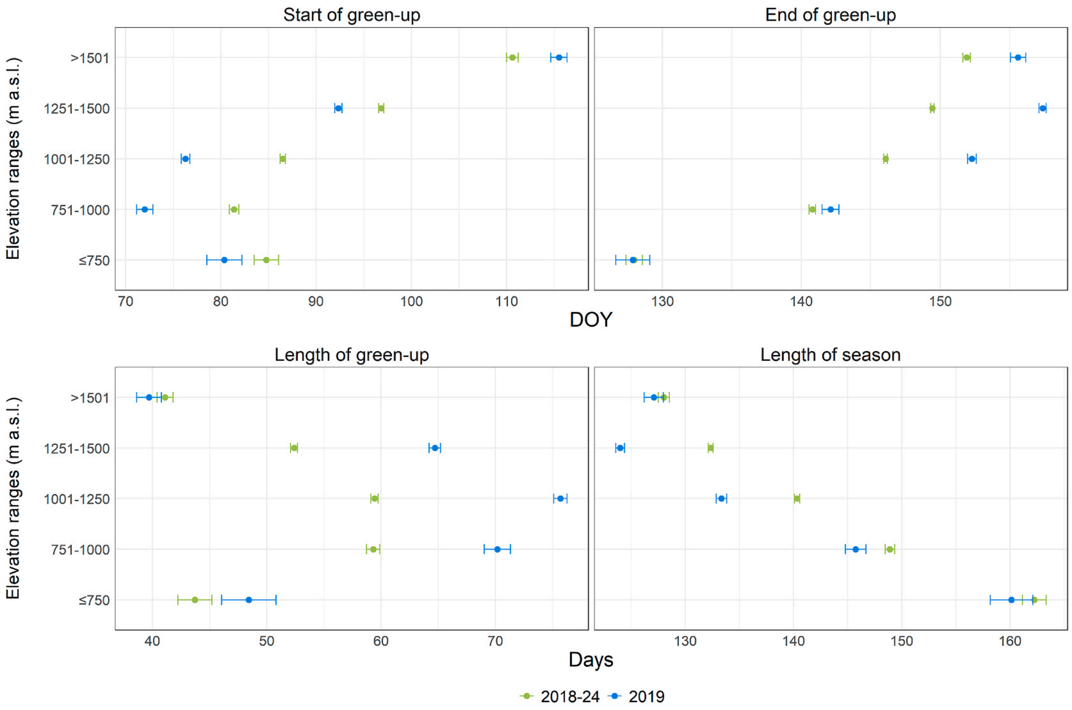

Fig. 6. Phenology metrics for *Fagus sylvatica* points (elevation-class averages) calculated as the average of 6 years and a year with spring frost (2019).

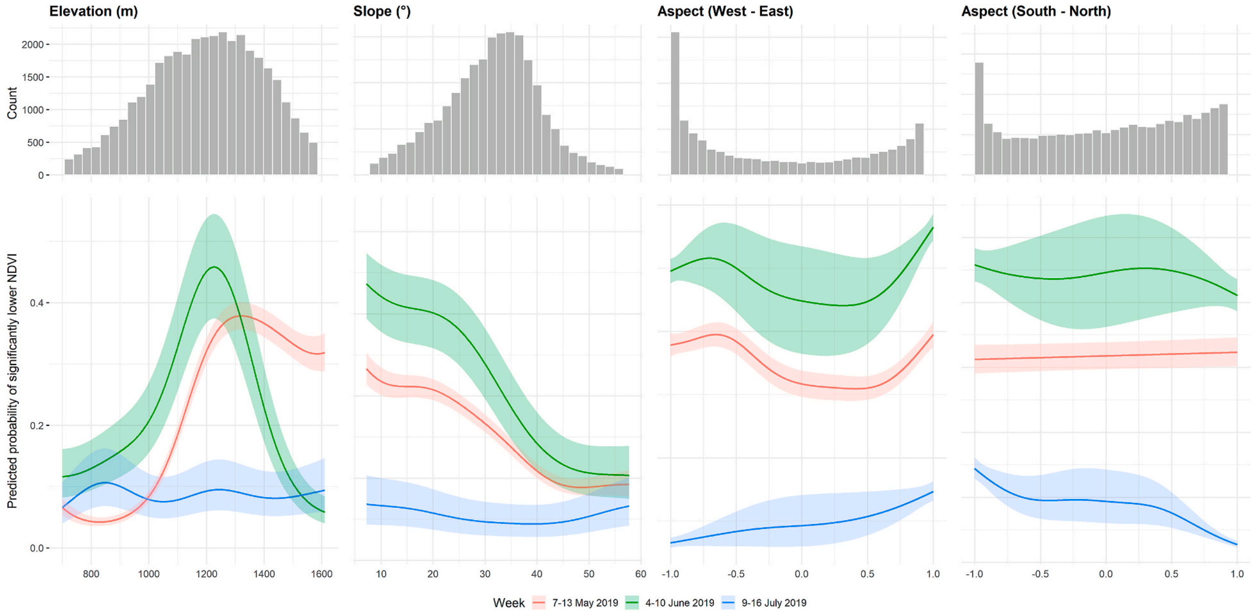

Fig. 7. Predicted probability of *Fagus sylvatica* points having a significantly lower NDVI as a function of elevation, slope, and aspect. The plots were generated from a GAM with a binomial family, and the shaded areas represent the 95 % confidence intervals. The lines are coloured by the week of observation during the 2019 growing season. The histograms at the top of each plot show the distribution of the topographical variables across the *Fagus sylvatica* points.

from July onward at elevations above 750 m, while *Corylus avellana* maintained elevated NDVI until July before experiencing a decrease in NDVI. By contrast, *Pinus sylvestris* displayed below-average NDVI in August, following with the peak of the July heat wave. *Fraxinus ornus* also experienced below-average values in July across all elevations, with more pronounced effects below 750 m

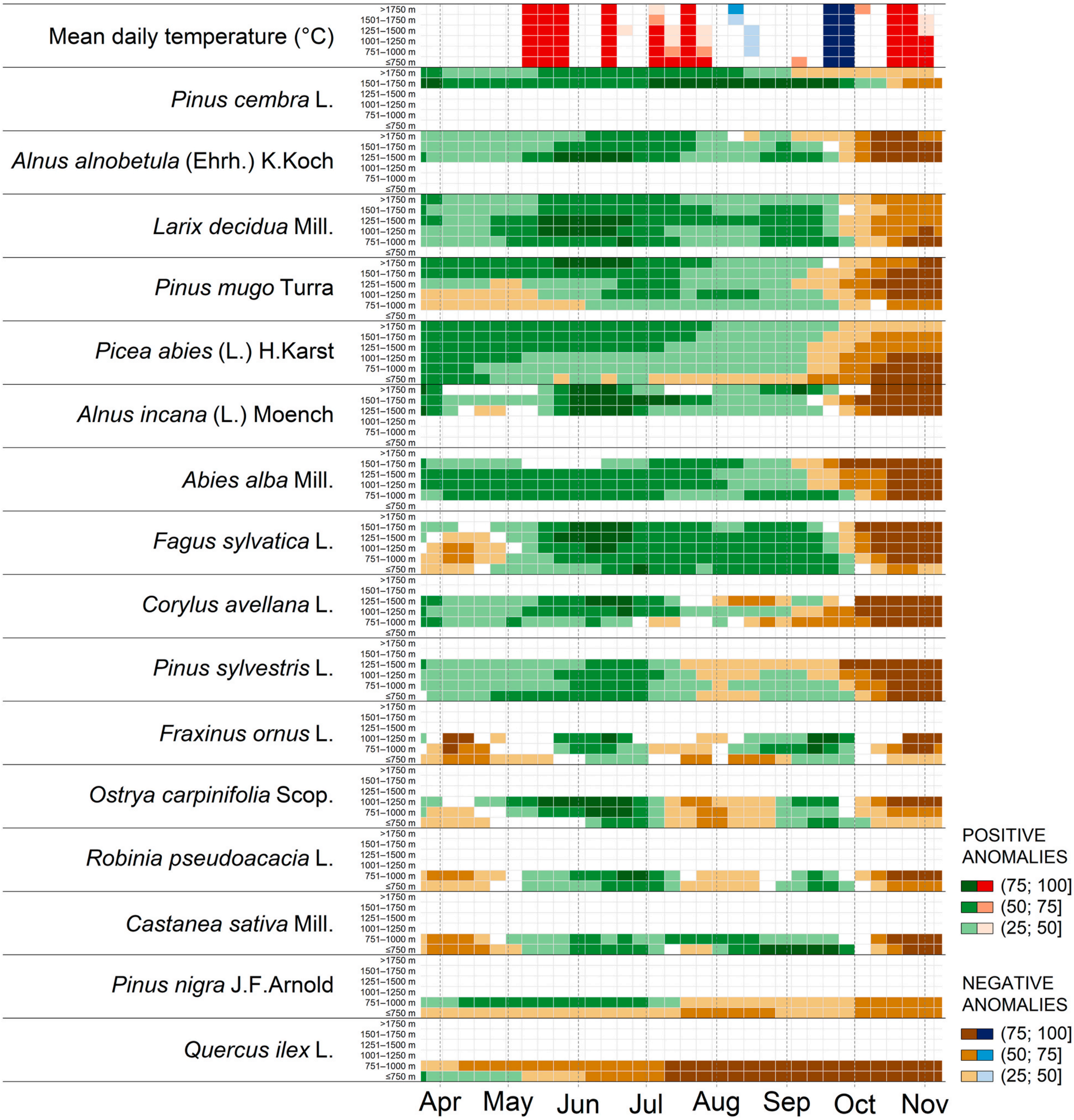

Fig. 8. NDVI and mean daily temperature anomalies in 2022 compared to the 2018–2024 period divided by species and elevation. The colours represent the percentage of points significantly higher (green/red) or lower (brown/blue) than the reference period, according to the Mann-Wilcoxon test. The species order is based on median elevation of the sampling points from higher to lower.

extending into August. Similarly, *Ostrya carpinifolia* and *Robinia pseudoacacia* both showed below-average NDVI during July and August, indicating a stronger drought-induced stress response, whereas *Castanea sativa* had only a minor NDVI decline in July below 750 m. *Pinus nigra* recorded below-average values throughout the season at lower elevations and from July onward at higher elevations. Finally, *Quercus ilex* was notably affected across all elevation bands for the entire year, reflecting the most persistent negative impact.

Looking more in details the case of *Quercus ilex* (Fig. 9), NDVI dropped notably one week after the heat wave began in July. Looking at all *Quercus ilex* points (Fig. 10) we could see that on average in 2022 there was a clear NDVI drop during and after the heat wave of July. The NDVI values remained below average for the entire 2022, but interestingly in 2023 there was a complete recovery in terms of spectral response.

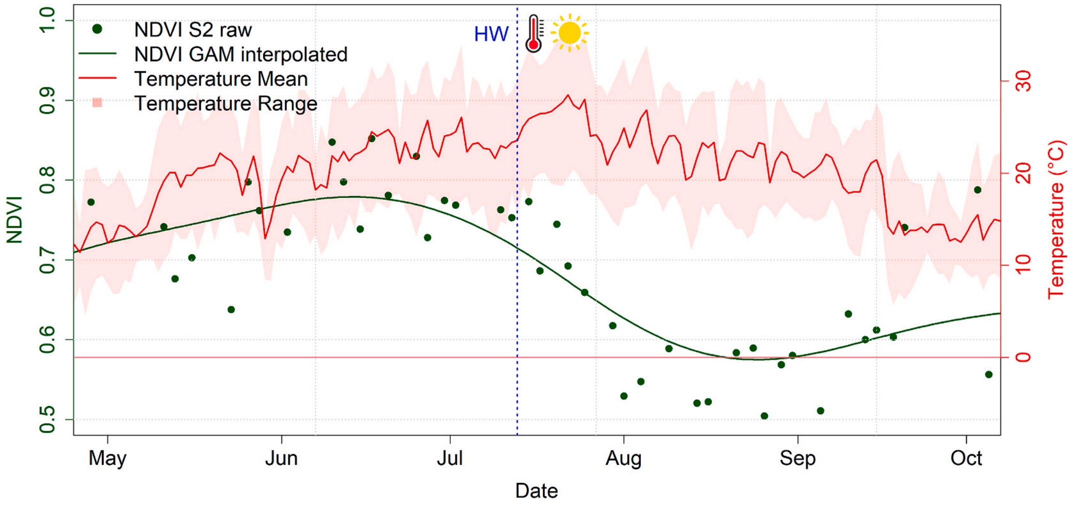

Fig. 9. NDVI values of a point of *Quercus ilex* in 2022 and predicted temperature for the same point in 2022. The green dots represent raw NDVI values from Sentinel-2 (NDVI S2 raw), while the black line shows the Generalized Additive Model (GAM) interpolated NDVI trend. The red line indicates the mean temperature, and the shaded red area represents the temperature range. The vertical blue dashed line marks the first day of the Heat Wave (HW) event.

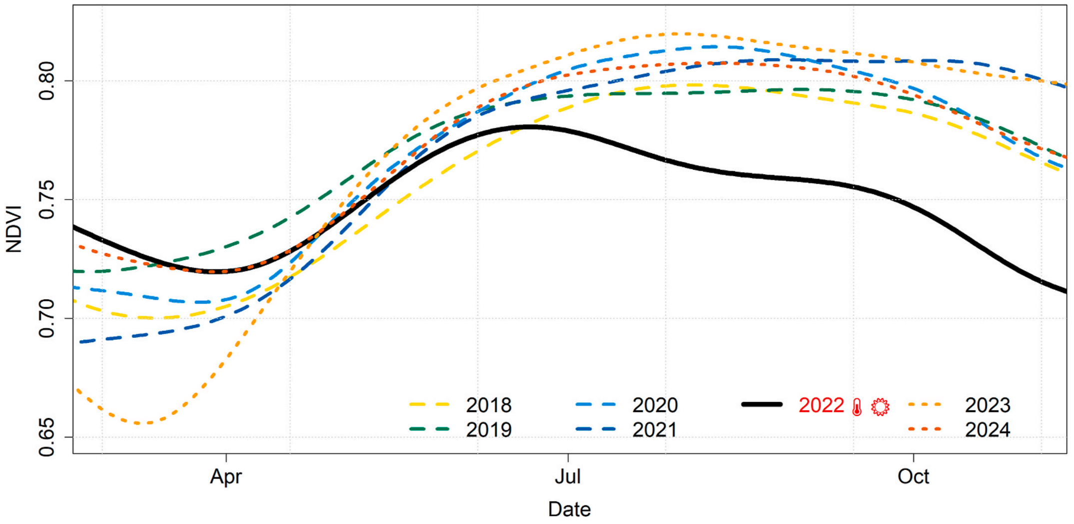

Fig. 10. Average GAM interpolated NDVI for the Quercus ilex points in the seven years analysed. NDVI values in 2023 and 2024 closely match the baseline levels observed from 2018 to 2021, demonstrating the species' resilience to the extreme hot drought experienced in 2022.

Figs. 5 and 8 indicate that all species across all elevation classes experienced much lower NDVI values in October 2022, probably in response to the colder-than-average two-weeks at the end of September 2022. However, it remains unclear whether the faster senescence is a result of the preceding summer heatwave, the subsequent September cold spell, or a combination of both phenomena.

4. Discussion

Extreme climatic events such as late spring frost and hot drought can significantly impact forest ecosystems by disrupting phenological patterns and altering vegetation dynamics. This study examined the canopy responses of different tree species to these ECEs across elevation gradients. The main findings of this study are that these two events differently impacted different tree species, and the same species varying the altitudinal gradient.

4.1. How does the canopy spectral response to late spring frost varies across tree species and elevations in temperate forests?

The impact of the late spring frost event was very differentiated along altitudinal gradients: the highest impact was at mid elevations (750–1250 m) where LSF impacted trees with an early leaf development resulting in a delayed end of the green-up phase. Indeed, in this altitudinal range there were already some leaves unfolded that were heavily damaged by the temperatures that dropped below zero (Fig. 1, 3 and 4). As highlighted in the introduction, this is a very well-known event that is largely discussed in the literature and represents also a challenge in relation to climate change (Lhotka and Brönnimann, 2020; Lamichhane, 2021). Warmer winters will generate an advance of the spring phenology increasing the risk of late spring frost damages. At higher elevation LSF resulted mainly in a delay in the start of the green-up phase but had almost no effect on the end of the green-up phase. Elevation-dependent response of leafing phenology to the negative spring temperature anomaly was particular evident for the European beech (*Fagus sylvatica* L.), a widespread species in temperate forests, which is present across a wide elevational gradient in the study area. Our results are very similar to the ones found by (Rubio-Cuadrado et al., 2021): the frost impact depended on prior climate conditions, since warmer days prior to frost occurrence predisposed to frost damage. Rubio-Cuadrado et al. (2021) analysing autumn NDVI data showed also delayed leaf senescence in spring-frost years and subsequent years as compared with pre-frost years.

Similar studies have been carried out in Italy, particularly in the Apennine mountain chain, where European beech forms extensive forest stands. Allevato et al. (2019) investigated the 2016 LSF event and, consistent with our findings, reported that damage severity was strongly site-dependent and determined by both freezing temperatures and the phenological stage of trees. They also observed that mid-elevations were more severely affected than higher altitudes. Bascietto et al. (2018) analysed the same event using MODIS-derived enhanced vegetation index (EVI) data and Net Ecosystem Exchange (NEE) estimates. Their results showed that low-elevation beech forests, which experienced earlier greening, suffered substantial frost damage, leading to markedly reduced productivity compared with the preceding 15 years. In contrast, high-elevation beech forests escaped frost impacts due to their later leaf unfolding. The effects of freezing stress in frost-damaged pixels persisted for about two months, until the end of June, as confirmed by NEE measurements. A similar study from Greco et al. (2018) examined the 2016 frost event in southern Italy using again MODIS and Sentinel-2 data. They reported extensive crown dieback in the 1400–1600 m elevational belt; however, beech forests showed efficient recovery, likely supported by the storage of photosynthetic products in roots and latent buds. Looking at the connection between topography and LSF damages, Nolè et al. (2018) conducted a study on the 2016 event using NDVI time series from Landsat-8 focusing on the influence of local geomorphic factors (aspect, elevation, and slope) on forest NDVI dynamics. Their results revealed that NDVI values were significantly higher on north-facing slopes than on south-facing ones. The most severe canopy damage occurred between 1250 and 1500 m a.s.l., which represented the elevational band most affected by frost disturbance. Full NDVI recovery was measured within approximately three months after the event.

4.2. How does the canopy spectral response to hot drought varies across tree species and elevations in temperate forests?

Similarly to the late spring frost event, the impact of 2022 hot drought varied according to the elevation. Indeed, a few species at low elevation were severely impacted by the hot drought, but species at high elevation had a positive response to the increased temperatures. This is strongly correlated with temperatures and precipitations in 2022 for different elevation ranges as showed in Fig. 1. Above a certain elevation temperatures were not limiting for vegetation and moreover precipitations, that below a certain elevation were lower than average, above 1500 were even higher than average.

Our results confirm and consolidate the findings of Jolly et al. (2005), that analysed the effect of the heat wave of summer 2003. They also found a pattern of growth enhancement for high elevation trees while growth suppression for low elevation trees in the heat wave year. Additionally, they found that growing season lengths were shorter in 2003 by an average of 9 % and 5 % for hill and montane areas respectively and were 2 %, 12 % and 64 % longer for subalpine, alpine and nival areas respectively. In our study we found that the growing season of 2022 was in average 7 % shorter varying from 0.9 % longer to 8.2 % shorter depending on the elevation. Differently, Rita et al. (2020) analysing the summer heat wave of 2017 showed a decreased of NDVI also at high elevations.

Quercus ilex was the species most affected by the hot drought according to our findings. *Quercus ilex* plants in the study region are located on steep, low elevation, south facing slopes on very shallow soils. In areas where *Quercus ilex* trees are located mean daily temperatures were above 25 °C for many days in July, and the cumulative precipitations of 2022 were way below average. Also, in this case previous studies highlighted that heat waves could affect various physiological processes of such trees. Sancho-Knapik et al. (2018) showed that intense droughts and heat stress can reduce photosynthetic capacity in *Quercus ilex* by altering chlorophyll fluorescence parameters. Ogaya and Peñuelas (2007) using ultrasonic acoustic emissions found that xylem tension induced by heat and drought leads to cavitation and decreased leaf water potential, potentially limiting growth and survival in drier climates of *Quercus ilex*. Looking at phenology Misson et al. (2011) analysed the experimental response of *Quercus ilex* trees exposed to autumn and spring drought: they found that autumn rainfall exclusion did not significantly affect leaf, flowers or fruit development, while spring rainfall exclusion resulted in larger and more sustained depression of leaf water potential during the key phases of foliar and floral development.

Despite its adaptation to warm and dry environments, *Quercus ilex* experienced significant negative effects during the hot drought of 2022. As no specifically designed field campaign was performed in the areas interested by the event, we do not know if the strong decrease in NDVI in 2022 was either only a browning of the leaves or a defoliation. The most probable effect is a browning and desiccation of the leaves at the top of the canopy. Similarly, we cannot state that there was a full recovery of the *Quercus ilex* trees as the full recovery of the NDVI could be due also to the fact that only the upper and outer leaves of the crown were affected by drought and temperatures and thus the increased of the NDVI value is due to the inner leaves, or in subsequent years, the NDVI may be connected to the contribution of ground vegetation.

In the literature many studies exist that analysed the behaviour of *Quercus ilex* during drought periods in the Mediterranean areas both in Italy and in other Mediterranean regions. Many studies exist that analysed the behaviour of *Quercus ilex* to drought from a physiology point of view, with and without the use of remote sensing. Indeed, may studies used MODIS remote sensing data, in particular in areas with widespread *Quercus ilex* forest. This is very different from the *Quercus ilex* formations that we are dealing with in this study. As an example, Moreno-de-las-Heras et al. (2023) analysed enhanced vegetation index (EVI) extracted from MODIS satellite images to study the effect of drought on *Quercus ilex* in Spain. They concluded that *Quercus ilex* forest response to drought is ruled by climate aridity and forest structure and drought intensity and both pre- and post-drought conditions affect drought responses. *Quercus ilex* forests in semi-arid areas showed a low resistance and a poor resilience to drought and drought vulnerability is particularly high for dense semi-arid *Quercus ilex* forest stands. Ogaya et al. (2020) used NDVI and EVI extracted from MODIS data to study *Quercus ilex* mortality due to drought concluding they there are good predictors of *Quercus ilex* mortality, and moreover they noticed that *Quercus ilex* is more susceptible to mortality due to drought than other co-occurring species.

Studies (Pasquini et al., 2023; Alderotti and Verdiani, 2023; Alderotti et al., 2023, 2025) show that embolism-induced hydraulic dysfunction and carbon limitation are central to drought-induced decline in *Quercus ilex*, particularly when drought intensity and duration exceed typical Mediterranean variability. Case studies in central Italy confirm that stand-level dieback and reduced radial growth follow severe drought episodes, with recovery depending heavily on site conditions, stand structure, and genetic predisposition (Pasquini et al., 2023; Alderotti et al., 2023; Italiano et al., 2024). Indeed, decline severity is often linked to prior stress history and local water availability. *Quercus ilex* populations in water-limited or drought-prone sites appear particularly susceptible to carry-over effects, including growth reductions and heightened mortality risk in subsequent dry seasons (Pasquini et al., 2023; Alderotti et al., 2023; Italiano et al., 2024).

Taken together, the literature suggests that while *Quercus ilex* has evolved effective drought-avoidance and tolerance strategies—such as stomatal regulation, deep rooting, and storage of carbon reserves—these adaptations may not suffice under the increasingly extreme droughts forecast under Mediterranean climate change scenarios. Recovery following drought is possible, especially when rehydration occurs early and non-structural carbohydrate reserves are mobilized, but persistent hydraulic dysfunction and carbon deficits can produce lasting declines in tree vigor, growth, and survival. These findings emphasize the need to consider legacy effects and drought frequency when predicting the future resilience of holm oak forests in Italy.

Differently, *Fagus sylvatica* that we expected to be a species that could have potentially been more strongly affected by the hot drought (Leuschner, 2020), had a contrasting behaviour. In 2022 we clearly observed that the increase in temperatures was even beneficial (higher NDVI peak values) to beech forests above certain altitudes, even if then as expected an earlier senesce occurred compared to previous years. Looking at temperatures and precipitations in the different elevation ranges it is clearly understandable that the main point is that the areas mainly dominated by *Fagus sylvatica* did not suffer a hot drought as temperatures increased but not over a problematic thresholds and precipitations above 1500 m were even similar or above the historical average.

4.3. Limitations of this study

Having high temporal frequency and high spatial resolution remote sensing data such as Sentinel-2 images was a game changer in earth observation studies. A study like this one would have been impossible before the advent of Sentinel-2. This also represent the main limitation of this study, as S2 data are available only since less than a decade (the first satellite was launched in June 2015 and the second in March 2017) and thus it is impossible to have long-time series of reference data. While higher spatial and temporal resolution imagery, such as Dove Planet data, does not solve this issue—since it has also been available only since 2017—it could offer a significant advantage for finer temporal resolution canopy response analysis and more accurate tree species classification, due to its daily revisit time and 3-m resolution.

This study is limited to a specific area of the Alps, which constrains the generalizability of our conclusions. However, the study area is representative of diverse species distributions and elevational gradients, ranging from mediterranean to boreal vegetations. Expanding the study to the entire Alpine region would be valuable, but unfortunately not possible, since single species abundance data are not uniformly collected by regional agencies in the Alps. On the contrary, we leveraged the uniformly collected dataset of the Province of Trento to identify species occurrence with high spatial accuracy. It must be noted, however, that we classified parcels dominated by at least 70 % of a single species as pure stands, but small mixed-species stands or non-forest vegetation patches may exist and may have partially influenced the observed canopy response, especially in forest types where the canopy cover is intrinsically low (e.g., *Pinus cembra* forests, *Larix decidua* forests).

Another limitation of our data analysis lies in the extraction of phenological metrics. In this study, we used *phenofit*, a widely adopted R package that implements various methods for fitting Sentinel-2 NDVI values and extracting phenological variables. However, during preliminary analyses, we observed that different cloud score thresholds and fitting methods within *phenofit* sometimes yielded notably different phenological metrics. Therefore, throughout our paper, we consistently emphasized the comparative differences in phenological metrics between years, rather than focusing on specific calendar dates.

This work is based on a species distribution map that is not available everywhere. Indeed, the specific dataset may only be available in the Province of Trento (Italy), but similar types of data, as an example in the form of forest types, can be found in other regions/ countries, or species maps at coarse resolution at regional level (like the main tree species maps available over Europe (European Commission. Joint Research Centre, 2023)) enabling comparable studies in other parts of the world.

5. Conclusions

In this study, we provided valuable insights into the differences in the canopy and phenology response to ECE across species and elevations. Our findings revealed that trees above 1000 m were the most affected by late spring frost, regardless of species, with a particularly pronounced impact between 1000 and 1250 m a.s.l. At these elevations, early leaf development followed by freezing temperatures resulted in significant damage and delayed phenological recovery. European beech (*Fagus sylvatica*) exemplified this pattern, showing vulnerability when warmer pre-frost periods triggered early leaf development. This confirms the increasing risk posed by climate change, as warming winters may advance spring phenology while maintaining the risk of damaging frost events.

In contrast, hot drought primarily affected low-elevation species, especially *Quercus ilex*. Meanwhile, higher-elevation species exhibited increased NDVI values during the hot drought year compared to previous years, despite experiencing an earlier onset and end of senescence. This pattern aligns with previous research on heat waves.

These findings contribute to our understanding of forest ecosystem responses to extreme climatic events and underscore the importance of considering elevation gradients and species-specific characteristics when predicting future forest dynamics under climate change. This has an impact also on future forests management: as an example an increase in ECE and a change in the climatic conditions and thus of the potential habitats of species will pose the question on which species to use for reforestations after fires or windthrows.

CRediT authorship contribution statement

Michele Dalponte: Conceptualization, Data Curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Davide Andreatta:** Writing – review & editing, Methodology. **David A. Coomes:** Writing – review & editing, Conceptualization. **Luca Belelli Marchesini:** Writing – review & editing, Conceptualization. **Daniele Marinelli:** Writing – review & editing, Data curation, Conceptualization. **Loris Vescovo:** Writing – review & editing, Conceptualization. **Damiano Gianelle:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readbility. After using this tool/ service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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