

Wood Quality and Climatic drivers of Chestnut Tree Growth (*Castanea sativa* Mill.) and Canopy Stress in Central Italian Coppices

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Abstract

Chestnut (*Castanea sativa* Mill.) coppices are increasingly exposed to interacting biotic and climatic stressors that may affect stand health and timber quality. This study assessed the occurrence and the possible technological impact on wood quality in basal logs in a 37-year-old coppice stand in central Italy by integrating field surveys, sawmill assessments, dendrochronological analyses, phenological observations and multitemporal satellite imagery. Dark-brown wood discoloration and localized basal decay were detected in coppice shoots. The mean length of the discarded basal log in the sawmill was 0.87 m, with a total of 0.91 m³, corresponding to 2.4% of the processed stem volume. Tree-ring series showed limited common variability among trees but revealed minimum growth during exceptionally warm and dry years. Radial growth was positively correlated with August precipitation and the Standardized Precipitation–Evapotranspiration Index, indicating sensitivity to late- summer water availability. Satellite imagery did not reveal unequivocal evidence of widespread canopy decline but provided a baseline for continued monitoring. Although old and established stools and root systems may buffer short-term stress, prolonged drought, pathogens and over-aged coppice rotations may increase stand vulnerability. Timely silvicultural interventions and integrated monitoring are therefore recommended to maintain forest health and timber quality.

Introduction

The European chestnut (*Castanea sativa* Mill.) is well known and interesting species widely studied in Europe from different point of view (Manetti et al. 2022, Marini et al. 2021). This species is a prime example of multifunctionality, as it provides multiple ecosystem services while playing a fundamental role in shaping the landscapes and ecological identity of the regions where it is distributed (Marini et al. 2021). However, it is frequently targeted by a range of biotic agents that continuously threaten its regeneration and long-term survival. Among the most important invasive pathogens introduced through the global trade of wood and non-wood products, it can be included *Phytophthora* spp., chestnut blight caused by *Cryphonectria parasitica* (Murr.) Barr, and, more recently the Asian chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Álvarez-Álvarez et al. 2025, Conedera et al. 2016, Keleş et al. 2024, Marcolin et al. 2021, Vannini et al. 2018). Most research on chestnut diseases has focused on fruit-producing orchards, as the impacts on local economies and production systems are more immediate to be assessed and readily apparent. In contrast, relatively less studies have addressed diseases affecting forest chestnut stands and timber production, where the consequences generally become evident only over longer time periods. Nevertheless, these threats require careful monitoring because several pathogens occurring in chestnut forests can seriously compromise not only forest health but also chestnut wood forest productivity and wood quality. For example, *Phytophthora cinnamomi* has been associated with severe forest dieback in several tree species, demonstrating its capacity to cause significant decline at the ecosystem level (Anderson et al. 2010). Consequently, the potential impact of *Phytophthora* spp. on chestnut forests should not be underestimated. Indeed, it has been showed as the interactions among different pathogens may exacerbate tree decline, as many are also involved in trunk diseases characterized not only by foliar yellowing, canopy dieback, but with a concomitant occurrence

of wood necrosis, black vascular streaking, and discoloration of woody tissues (Mohammadi et al. 2015).

The potential role of biotic pathogens in causing wood decay and, more generally, in reducing the technological quality of chestnut timber deserves particular attention in *C. sativa* stands. Among the most important diseases, chestnut blight caused by *C. parasitica* represents a threat to tree vitality but it can also affect timber production (Keleş et al. 2024).

Beyond this well-known diseases, recent observations have revealed internal stem defects characterized by wood discoloration and other chromatic alterations, which are likely associated with the ingress and colonization of wood-inhabiting pathogens (Tamantini et al. 2022). In several cases, pathogen entry appeared to be associated with stem injuries resulting from harvesting operations, although other infections were related to cambial wounds of unknown origin. Similar symptoms have also been reported in Spain, where they were attributed to the colonization of stems by the wood-decaying basidiomycete *Fistulina hepatica* (Meijer et al. 2024, Yurkewich et al. 2017). This fungus is known to cause brown rot, leading to a progressive deterioration of the wood and a consequent reduction in timber quality and commercial value.

These manifestations can have a significant impact on the economic resilience of rural territories that rely on wood resources in accordance with the principles of the bioeconomy (Marini et al. 2021). Although the occurrence of these forms of degradation may represent an isolated and temporary phenomenon, it is essential to understand their underlying causes, promptly monitor the emergence of potential issues, and, where appropriate, implement management measures. It should be recognized that the effects of such actions may not become evident immediately but rather require the long timeframes typical of forest ecosystems before the outcomes of management decisions can be properly assessed.

The most immediate phenotypic indicator of plant stress and the potential onset of dieback is the condition of the tree crown (Romagnoli et al. 2018). In forest chestnut stands, crown condition has also proven to be a reliable indicator of pathogen attacks that should be carefully monitored (Vannini et al. 2018). When dealing with vegetation distributed over large areas, in addition to detailed knowledge of local site characteristics and pedoclimatic conditions, new satellite-based digital technologies, can substantially improve the early detection of plant stress signals (Mouret et al. 2024, Savinelli et al. 2024). Such information can support the timely identification of areas at risk and provide a sound basis for planning targeted field inspections and appropriate management interventions.

Another fundamental prerequisite for designing an effective monitoring program is a thorough understanding of the species' ecological requirements and its sensitivity to climatic drivers. This should take into account the synergistic interactions among meteorological conditions, soil characteristics, and microbial communities, which are recognized as key drivers of tree decline (Singh et al. 2019) and facilitate the establishment and progression of wood decay (Jung 2009).

The objectives of this study are to determine whether the occurrence of wood decay observed at a site in central Italy, where it was predominantly associated with standards (Tamantini et al. 2022), is also present at other sites within the same geographical area, looking with particular attention to coppice shoots. Where wood decay is detected, the study aims to assess its longitudinal extent from the base of the stump along the length of the stem in order to evaluate its economic impact on timber quality and value. A further objective is to establish a monitoring program focused on xylem development and to identify the factors influencing wood formation through dendrochronological analyses in order to detect the climatic drivers of wood growth and the possible climatic factors threatening wood health. In addition, a remote sensing–based monitoring approach using satellite imagery will be initiated to detect potential indicators of canopy stress that may be associated with tree suffering. The study focuses on a site located in the Municipality of Lariano (Central Italy), where forest harvesting operations were carried out during the 2025–2026 harvesting season.

Methods

Study area

The study was conducted on compartment 16, Colle della Noce, since it was harvested in December 2025 (Fig. 1a). It is a chestnut (*Castanea sativa* Mill.) coppice-with-standards stand (Fig. 1b) with a surface area of 24.95 ha, located at an altitude of 500 m a.s.l., characterized by a slope varying between 30 and 60% and southern exposure. The presence of hypovirulent cortical cancer is reported. Generally speaking, at the Lariano and Castelli Romani site, the most adopted rotation (T) is equal to 24 years and the standards left standing have an age equal to 2T (48 years). Chestnut stands in the area are generally thinned to about $2/3$ T (14–15 years).

At the end of the rotation, the total number of coppice shoots per hectare is between 1,100 and 1,200, with an average trunk diameter at breast height of 40.9 cm (30.8 cm for the coppice shoots and 44.6 cm for the standards). The estimated production is 230 m³/ha, for a total of 5,739 m³ from the management plan.

The climate data considered come from the Velletri meteorological station (352 m a.s.l.; 41°41' N, 0°20' E), which in the period 2004–2025 has an average annual precipitation of 1193 mm and an average annual temperature of 15.7°C with a maximum of 21.4°C and a minimum 10.6°C (Fig. 1c).

Climate analysis

Climatic conditions can exacerbate tree physiological stress and influence their capacity to respond to environmental disturbances. Therefore, climate extremes were assessed following the methodology described by (Tamantini et al. 2025). The indices were calculated according to the definitions established by the Expert Team on Climate Change Detection and Indices (ETCDDI) of the World Meteorological Organization (WMO) of the United Nations (UN), reported below in Table 1.

Furthermore, a screening of the daily data for 2026 has begun, also in order to set up an analysis for the study of the phenological stages of the forest stand.

Table 1
Selected climate indices used in the analysis. Precipitation is denoted by P, daily minimum temperature by Tmin and daily maximum temperature by Tmax.

Index	Definition
R0	Days without rain ($P < 1 \text{ mm}$)
R1	Wet days ($P \geq 1 \text{ mm}$)
R10	Days with $P \geq 10 \text{ mm}$
R20	Days with $P \geq 20 \text{ mm}$
CDD	Maximum number of consecutive days with $P < 1 \text{ mm}$
CWD	Maximum number of consecutive days with $P \geq 1 \text{ mm}$
FD0	Frost days ($T_{\min} < 0^{\circ}\text{C}$)
SU30	Hot days ($T_{\max} \geq 30^{\circ}\text{C}$)
TR20	Tropical nights ($T_{\min} > 20^{\circ}\text{C}$)

Basal wood rot analysis

Field investigations began in 2025 in a chestnut coppice compartment scheduled for clear-cutting during the 2025–2026 forestry season. Before harvesting, three circular sample plots (SPs), each with a radius of 20 m and an area of 1256 m², were established to characterize stand structure and assess the occurrence of root and butt rot caused by *F. hepatica* (Schaeff.) With.

Each stem was classified according to its silvicultural category as either a coppice shoot or a standard. Basal diameter, diameter at breast height (DBH, measured at 1.30 m above ground level), stem diameter at crown insertion and total tree height were recorded for each stem after tree cutting.

The health status of each stool and standard was assessed through visual inspection. Particular attention was paid to symptoms and signs potentially associated with root and butt rot, including the occurrence of epicormic shoots as an indicator of physiological stress, together with other features such as fungal fruiting bodies, basal cavities, collar lesions or visible wood decay. Based on these observations, stools and standards were classified as either symptomatic or asymptomatic. Samples collected from symptomatic individuals were subsequently examined under laboratory conditions, confirming the presence of *F. hepatica* as the causal fungal agent. The frequency of symptomatic individuals was then compared among the three SPs and between coppice shoots and standards.

The geographical position of each stool was recorded using a Trimble Geo 7X handheld GNSS receiver (Trimble Inc., Westminster, CO, USA). For stools comprising multiple coppice shoots, a single coordinate was assigned to the stool rather than to each individual shoot. The resulting spatially explicit dataset was used to map the distribution of symptomatic and asymptomatic stools and standards within the three sample plots and to support subsequent assessments conducted during and after harvesting.

Dendrochronological analysis

Ring-width measurement and dendrochronological synchronisation were performed using the TSAP-WIN™ software package (v. 4.89, Rinntech-Metriwerk GmbH & Co. KG®, Heidelberg, Germany). Ring widths were measured along two radii for each disc with a precision of 1/100 mm. Descriptive statistics, such as the mean ring width and its standard deviation, were calculated. Each radial measurement was compared with its corresponding twin on the same disc and cross-checked with ring series from other samples. Both statistical and visual cross-dating were carried out following standard methodologies to ensure solid synchronisation. The mean curve was constructed by identifying dendro-groups through visual and statistical cross-dating. The primary statistical parameters used for synchronisation were Gleichläufigkeit (GLK) (Eckstein & Bauch 1969), t-value Baillie–Pilcher (TVBP) (Baillie & Pilcher 1973), and t-value Hollstein (TVH) (Hollstein 1974).

All individual tree-ring series and the mean chronology were standardized to remove age-related growth trends and other low-frequency, non-climatic variations while preserving the interannual variability potentially associated with climate. Standardization and climate correlation were performed in R through RStudio v. 2026.07.1 Build 147 (Posit Software, PBC, Boston, MA, USA).

The standardized tree-ring series were compared with monthly climatic variables over a 12-month window extending from October of the year preceding ring formation ($t - 1$) to September of the year of ring formation (t). This interval was selected to account for the potential influence of climatic conditions occurring both before and during the current growing season. Climate–growth relationships were assessed using Pearson’s correlation coefficients. To control for multiple comparisons, the resulting P-values were adjusted using the false discovery rate (FDR) procedure. Correlations were considered statistically significant based on the FDR-adjusted P-values.

Phenological development of standing plants

Chestnut phenology was assessed through direct field observations conducted between February and June 2026, encompassing the transition from winter dormancy to full leaf development. Selected trees within the study area were monitored, and their phenological stages were classified according to the BBCH scale (Table 2). During each survey, apical twigs were collected to evaluate bud and leaf development, while increment cores were extracted from the same individuals using a Pressler increment borer to assess xylem formation. Phenological observations were then compared with wood

development to investigate the temporal relationship between above-ground vegetative development and cambial activity. This preliminary monitoring also aimed to establish a methodological framework for relating phenological and xylogenetic dynamics to climatic variables at a daily temporal resolution.

Table 2

Phenological growth stages considered in this study according to the BBCH scale adapted to chestnut by Larue et al. (2021).

Principal stage	BBCH code	Phenological state	Description
Stage 0	00	Dormant buds	Buds closed and protected by bud scales, with no visible openings or green tissues; the plant is in winter dormancy.
	07	Beginning of bud break	Buds open, with the first green leaf tips beginning to emerge.
	09	Green leaf tips visible: first green leaf tips just visible	The first leaves have emerged from the buds, and their blades have begun to unfold.
Stage 1	11	First leaves unfolded	Several leaves are open and expanded but remain young and have not yet reached their final size.
	15	More leaves unfolded, not yet at full size	All leaves are fully unfolded and have reached their final size; no male catkins or female inflorescences are visible.
	19	All leaves unfolded and fully expanded	Buds closed and protected by bud scales, with no visible openings or green tissues; the plant is in winter dormancy.

Aerial analysis with satellite images

A screening of the vegetative state of chestnut stands has been started through the use of satellite images. Therefore, an initial monitoring was set up using satellite images, using both the images available on Google Earth for a diachronic qualitative analysis, and WorldView multispectral images with high spatial resolution (50 cm), provided by Planetek Italia S.r.l. (Bari, Italy).

For the diachronic comparison, two acquisitions carried out during the vegetative season were selected, respectively on 17 June 2024 and 1 June 2025. The images were chosen based on the limited cloud cover and radiometric quality, favoring the period of greatest vegetative development of the chestnut tree, considered the most suitable for highlighting any variations in the spectral response attributable to the physiological state of the stand.

The processing was carried out using QGIS software (version 3.44). The images were preliminarily subjected to the radiometric and atmospheric corrections necessary to guarantee the comparability of the acquisitions in space and time. Subsequently, false color compositions were created, assigning near

infrared (NIR), red and green to the bands, in order to obtain a qualitative representation of the state of the vegetation and identify any changes in the forest cover, such as silvicultural interventions, areas with reduced vegetation cover or differences in phenological development.

The interpretation of the images was carried out by visual comparison between the two acquisitions, considering both the entire municipal territory and the sample plots monitored in the field. The information derived from remote sensing was integrated with phenological, dendrometric and phytosanitary surveys, as well as with observations on the development of xylem tissues, in order to support the interpretation of the observed differences and verify the potential correlation between spectral response, phenological state and physiological conditions of the plants.

Results

Climate analysis

The climatic data considered were obtained from the Velletri meteorological station (Fig. 1c), which, over the 2004–2025 period, recorded a mean annual precipitation of 1193 mm and a mean annual temperature of 15.7°C (mean maximum: 21.4°C; mean minimum: 10.6°C). Analysis of the temperature time series reveals a weakly increasing trend in maximum temperatures, with notable fluctuations throughout the study period and a renewed increase between 2021 and 2025 (Fig. 2b).

Figure 2c, 2d and 2e presents the climate extreme indices related to temperature. Overall, the graphs indicate medium periods variation with a worsening of thermal stress conditions beginning around 2007, with an increasing trend in both the SU30 index (number of days with maximum temperatures above 30°C) and the TR20 index (tropical nights with minimum temperatures above 20°C). A persistent increase in periods characterized by high nighttime mean temperatures is evident from 2016 onward, reaching a peak in 2024. During the most recent period (2021–2025), both the TR20 and SU30 indices consistently exceeded their long-term average values and a remarkable maximum in CWD must also be considered in 2017 and 2020, 2022 and 2024.

Regarding precipitation extremes, no clear long-term trends are apparent, with alternating years of high and low values. However, particular attention should be given to the record maximum number of consecutive dry days (R0) observed in 2021. Together with the previously described increase in temperatures, this finding highlights a progressive deterioration of environmental conditions, after 2020–2021 making them increasingly less favorable for plant growth and development. Particular events worthy of note include punctual signals such as the droughts of 2017 and 2023, the latter characterized by exceptionally high minimum temperatures. In 2024, the highest number of days with temperatures above 30°C was recorded.

Basal wood rot analysis

Following the harvesting operations in the selected zone the post-harvest inspection of the cut stumps (Fig. 3) made it possible to identify and map stumps free from degradation as well as those exhibiting varying degrees of wood decay (Fig. 3). Several stumps across all three sampled portions in the selected stand were found to be affected by butt rot, Among the affected trees of a butt rot 19 trees were investigated in the sawmill to look for the extension of wood degradation (Table 3).

Among the 14 trees analysed in the sawmill, 36% showed basal decay requiring the removal of basal logs between 0.5 and 3.0 m in length, the latter strong value occurs in only one individual. The cumulative volume of discarded butt logs during the initial processing stage was 0.91 m³, representing 2.4% of the total 14 harvested volume of 37.3 m³.

In five trees, the removed basal log, extends for 1 m or more, however the removal of the basal log is not always associated with wood decay but, in some cases, it is related to ring shake, including traumatic ring shake. Generally speaking, the length of the logs discarded during sawmill processing does not exceed the average length commonly observed during the standard practice in the sawmill, due to ring shake, curvature of the basal part of the tree stem due to the coppice management.

Table 3

Descriptive statistics for basal sections discarded during sawmill processing and for the processed stems. Values are means ± standard deviations where applicable.

Parameter	Mean/Total	Minimum	Maximum
Discarded basal length (m)	0.87 ± 0.36	0.5	3.0
Processed stem length (m)	9.2 ± 0.88	7.1	11.0
Stem taper (cm/m)	1.05 ± 0.42	0.48	1.77
Total volume discarded because of decay or ring shake (m³)	0.91	0.03	0.30

Figure 4. Schematic model stem showing the mean processed length and mean discarded basal section for the analysed stems.

Dendrochronological analysis

The ring curves show as usual in coppice stands a characteristic behaviour because, the first growth rings are characterised by very large widths and a strongly decreasing trend (Marini et al., 2019), growth pattern of medium frequency and point years signals can be extrapolated from the curves. Visual inspection of the growth trajectories revealed clear signs of growth decline in only one tree (13), and it cannot be ruled out that the internal degradation observed at the root collar in that tree, may have, to some extent, also affected ring growth. Some individuals, such as trees 13, 14, and 3, show a further decrease in growth after 2010–2011. This phenomenon may have been influenced by the infestation of the chestnut gall wasp which appeared at 2005 in Piedmont and at 2008 it has been detected in Rome and Castelli Romani, with infestation reaching its peak in 2014 (Vannini et al., 2028). Some individuals

exhibited a marked increase in radial growth, starting from the 2015–2018 period. This pattern may be interpreted as the effect of the release and subsequent establishment of the parasitoid *Torymus sinensis* as a biological control agent may have contributed to reducing pest pressure. The enhanced growth observed after 2014 could therefore reflect a recovery in tree vigor associated with the progressive reduction of gall wasp infestation, although a reduced competition among established shoots affecting a positive radial growth cannot be excluded because of an increase in the crown size.. The descriptive statistics related to each tree is reported in supplementary material, ring width is quite large as it is expected because chestnut is on the the most fast-growth species of the area. Trees 22, 7, and 14 exhibit reduced growth after 2020, while other individuals show a substantial decrease in ring widths after 2023. The most relevant discrete signals are the growth minima recorded in 2017 and 2023, already cited as very stressful climatic years.

The poor ability of chestnut ring curves to obtain mean chronologies that are more representative of the site is due to the short length of the ring-width series and the considerable influence of the agamic regeneration expressed by resprouting from the stumps (Marini et al., 2019). However, the tree series synchronization allowed the construction of a mean curve based on nine tree-ring series, which better represents the influence of climate on tree growth.

As it can be observed by Fig. 6, the correlation between tree ring widths and climatic data and the SPEI index does not yield particularly significant results. However, the standardized curves show a positive correlation with August precipitation and SPEI index, indicating that lower drought stress is associated with greater growth. A negative, albeit non-significant, correlation was also observed with temperatures in November of the previous year ($t - 1$) and in February, especially T_{min} .

Phenological development of standing plants

The earliest anatomical evidence of radial growth was observed on 10 April 2026, when the first row of large earlywood vessels characteristic of chestnut ring-porous wood was already forming (Fig. 7a). At this stage, the plants were classified as BBCH 09, with green leaf tips emerging from the buds but without fully unfolded leaves. This finding indicates that xylem differentiation had begun before complete leaf expansion.

By 8 May 2026, xylem development was more advanced, with two to three rows of earlywood vessels visible in the developing annual ring (Fig. 7b). This anatomical progression occurred concurrently with more advanced canopy development: the leaves had emerged from the buds and were progressively unfolding, corresponding to BBCH stages 11–15. On 26 June 2026, xylem formation had accelerated markedly, and a substantial proportion of the latewood was already visible (Fig. 7c). By this date, the leaves were fully unfolded and had reached their final size, corresponding to BBCH 19.

The onset of radial growth coincided with the increase in air temperature recorded at the Velletri meteorological station (Fig. 8). Mean air temperature was 10.3°C in March 2026 and increased to 13.1°C during the first two weeks of April, when the first row of earlywood vessels was observed. Although

these preliminary observations do not demonstrate a causal relationship, they suggest that cambial reactivation and earlywood-vessel differentiation occurred as temperatures increased in early spring. Overall, the results indicate a partial temporal decoupling between xylem formation and canopy development: wood formation had already begun while the buds were opening, whereas the progressive formation of additional vessel rows accompanied leaf unfolding and subsequent canopy expansion.

Aerial analysis with satellite images

The analysis of the aerial photographs acquired in June 2024 and June 2025 does not currently reveal any signals that can be unequivocally attributed to widespread canopy decline, either when comparing the area of Lariano as a whole (Fig. 9a) or when focusing on the detail of compartment 16. The pictures at this stage mainly provide a baseline for establishing continuous monitoring using aerial imaging systems, with the aim of detecting any deterioration in the health status of the woodland over time.

A difference worth noting concerns the acquisition dates: the 2024 imagery was acquired on 17 June, whereas the imagery available for 2025 was acquired slightly earlier, on 1 June. The most evident difference between the two datasets is the presence of lighter-coloured spots, which are associated with the phenological state of plant flowering.

Nevertheless, the prolonged effects of heat and drought should not be underestimated. Indeed, the Google Earth images (S1) show that several standing dead trees can be identified in the 2022 imagery. Their mortality is likely attributable to the effects of severe drought, such as the one at 2017, and the weakening of the trees following the attack by the chestnut gall wasp. In this respect, the age of the coppice stand may also have played a role, as it has now reached the stage of an over-aged coppice. In this respect, the age of the coppice stand may also have a significant influence, as it has now reached the stage of an over-aged coppice.

Discussion

In the study site, signs of wood deterioration in the inner part were observed; however, under the current conditions, their impact on processing yield appears to be relatively limited. The volume of basal logs which is rejected did not differ substantially from the volume normally discarded during sawmill processing due to other defects, particularly ring shake and basal curvature of coppice shoots.

Compared with the findings reported by Tamantini et al. (2022) in the same area, the actual investigation indicates that signs of wood alteration and deterioration occur in coppice shoots, they are not restricted to tree standards, in which logging damage was found to play the major role. However it should be noted that, in some cases, wood from coppice shoots exhibited marked discoloration without clear evidence of degradation of the cell walls or loss of tissue integrity. Such dark-brown discoloration may simply reflect the accumulation of tannins as response associated with infection by primary pathogens such as *C. parasitica*. Chestnut blight is present by long time not only in the study area (Keleş et al. 2024), but also throughout the Lazio Region. In those cases where pronounced degradation of woody tissues required

the rejection of the basal log during processing in the sawmill, the type and spatial pattern of the observed alteration were consistent with symptoms typically associated with root rot. In particular, the distribution of degraded wood suggests that the decay process may have originated in the root system or at the stem base and developed during the juvenile stages of tree growth.

Decline phenomena in trees are often identified through the analysis of dendrochronological series (Romagnoli et al. 2018), while root rot is frequently associated with visible symptoms of crown decline or reduced crown vitality (Garbelotto & Gonthier 2013, Hansen & Delatour 1999, Sinclair & Lyon 2005). In the present study, however, clear evidence of decline in tree-ring growth patterns was generally lacking, with the exception of a single coppice shoot (13) among those examined (see Fig. 5).

More generally, tree-ring series of sweet chestnut do not appear to be particularly sensitive to environmental variability (Romagnoli et al. 2018, Romagnoli et al. 2004, Vlachou et al. 2024). Moreover, in the specific coppice management, the short tree-ring series show the first growth rings as dominated by vigorous radial increments because they are supported by the nutrient and carbohydrate reserves stored in the root system and stools. This strong initial growth response may partly mask signals related to environmental stress or progressive decline. However, tree ring series show triggers that are closely to be associated with discrete events such as the marked reduction in ring width observed in the very dry and warm 2017, while it is more difficult to extrapolate medium frequency fluctuations.

The correlation analysis with climatic variables revealed a positive response to water availability in August. From a climatic perspective, August plays a crucial role, as it is the month in which the cumulative effects of climatic extremes, particularly high temperatures and prolonged drought, impose further physiological constraints on trees already strongly stressed by previous climatic extremes of July. The results derived from the climate–growth relationships indicate that, although the species' resilience may be partly saved by the reserves in the stumps typical of coppice management, prolonged periods of high temperatures and severe drought increase the sensitivity of chestnut vegetative activity to climatic extremes.

The results obtained in this study can, to some extent, be compared with those reported by Marini et al. (2019) for chestnut coppice stands on Monte Amiata. In that study, chestnut tree-ring growth was again found to be only weakly influenced by climatic variability (Marini et al. 2019). However, the Monte Amiata site was characterized by considerably more favorable environmental conditions, particularly in terms of elevation and water balance. Moreover, the dendrochronological series were even shorter than those examined in the Castelli Romani, potentially making growth patterns less responsive to interannual climatic variability.

A distinctive finding of the Monte Amiata study was not only the relatively weak and asynchronous growth response to climatic variability, but also the important role played by silvicultural management. In particular, differences in stand density, expressed as the number of stools per hectare, which ranged from 4 to 9.1, were shown to affect stand-level water-use efficiency for a reduced or increased stand

competition. This suggests that coppice management can modulate the availability and use of water resources and, consequently, influence the sensitivity of chestnut growth to climatic variability.

Nevertheless, some common patterns emerge from the climate–growth correlations that, although generally weak and not always statistically significant, may reflect species-specific responses. For instance, minimum temperatures in March and April were negatively correlated with tree-ring width (TRW) both at Monte Amiata (Marini et al. 2019) and at Lariano, although at the latter site the relationship was relatively weak (Fig. 6). Lariano is located at a lower elevation than the sites investigated on Monte Amiata. At comparable elevations, chestnut has been reported to initiate cambial activity during the first ten days of April and to cease it during the second ten days of October, with mean temperatures of approximately 10.3°C at the onset of cambial activity and 13.1°C at its cessation (Castellani 1978–1979, Ciampi 1951).

At Lariano, the formation of the first row of large earlywood vessels is already evident during the first two weeks of April. During the same period, temperatures recorded at the Velletri meteorological station are already well above 10°C. In Lariano, the first row of earlywood vessels is formed before the resumption of photosynthetic activity, confirming the temporal decoupling between the onset of xylem formation and leaf development observed in chestnut (Čufar et al. 2011, Romagnoli et al. 2011).

The dynamics of tree-ring development, particularly the formation of the first row of earlywood vessels, are also consistent with the physiological mechanisms described by Fonti et al. (2007). Temperatures in February and March may affect cambial sensitivity to auxin, thereby preconditioning the tree's response later in the growing season. April temperatures, in turn, are associated with tree reactivation, when renewed hormone production promotes vessel differentiation and expansion (Fonti et al. 2007). These processes suggest that climatic conditions during late winter and early spring may influence the subsequent development of the annual ring even before the full resumption of canopy photosynthetic activity.

Another weak but consistent pattern emerging from the comparison with the analyses conducted at Monte Amiata is the positive response of tree-ring growth to August precipitation. At Monte Amiata, however, this relationship is considerably weaker, likely because the area is not currently affected by substantial water stress.

At the crown level, no clear signs of stress are currently evident from the analysis of aerial images, the result provides some grounds for optimism regarding the species' potential resilience. In this respect, sweet chestnut appears to have considerable adaptive potential. Indeed, Mediterranean provenances have been shown to possess genetic traits associated with greater resilience to heat stress, which may enhance their capacity to cope with and adapt to ongoing climate change (Castedo-Dorado et al. 2023). However recent studies have showed the strong impact of drought on chestnut distribution and the effect needs to be monitored (Weise et al. 2025).

A general consideration of chestnut health in that specific area of Castelli Romani, is rather complex, as several interacting factors may act simultaneously, and their combined effects are difficult to predict and they are not readily detected through satellite-based monitoring. For example, the infestation of the Asian chestnut gall wasp has been shown to induce both qualitative and quantitative changes in chestnut ecosystems, resulting in an overall reduction in ecosystem resilience, as well as changes in the population dynamics and growth of some microorganisms, such as *Gnomoniopsis castaneae*, and alterations in the biological and disease cycles of major pathogens such as *C. parasitica* (Vannini et al. 2018). The impact of alien species and pathogens should therefore not be assessed solely in terms of the direct damage caused to their primary host. Interactions between the invader and other components of the biome, together with the potential for unexpected synergistic effects, should be equally considered and investigated (Vannini et al. 2018). Noteworthy In our study, a recovery in radial growth was observed approximately 1–2 years after the release of the biological control agent *Torymus sinensis* Kamijo of chestnut gall wasp, in agreement with the findings reported by (Marcolin et al. 2021), despite worsening climatic conditions. However, it remains unclear whether, and to what extent, changes may occur in the soil and root-associated fungal microbiome following infestation and subsequent recovery. This aspect may be particularly relevant in relation to root-rot fungi, which could affect tree vitality and potentially influence wood quality. Thus, the apparent recovery of radial growth does not necessarily imply the complete restoration of ecosystem functioning, particularly belowground, where persistent or delayed effects on fungal communities and pathogen dynamics may occur.

Finally, as also highlighted by studies conducted at Monte Amiata, silvicultural management is likely to play a key role in determining stand resilience. In the present study, the coppice shoots were older than the rotation age traditionally adopted in the area, the shoots are 37 years old while the normal rotation is approximately 24–25 years. The prolonged rotation may be associated with reduced shoot and stool vitality and, consequently, with greater susceptibility to pathogen infection and to the effects of adverse climatic conditions. Coppice age and management should therefore be considered alongside climatic stressors and biotic disturbances when assessing the current condition and future resilience of chestnut stands.

Conclusion

At present, the occurrence of discoloration and/or degradation symptoms in the inner wood tissue of chestnut shoots is confirmed in the area because detected in the new investigated plot. However, during the initial stages of sawmill processing, the basal portion of the log that needs to be removed is generally limited, typically less than 1 m, and is broadly comparable to the length routinely discarded to eliminate the basal timber portion affected by defects such as ring shake, stem curvature, or other abnormalities.

The analysis of satellite imagery revealed no clear signs of crown decline. Nevertheless, a number of standing dead trees were recorded within the study area, with mortality apparently increased after the exceptionally stressful conditions experienced in 2017.

Assessing the effects of climatic conditions and biotic disturbances on tree health remains particularly challenging, at least when tree-ring series are used as a proxy. Sweet chestnut can rely on carbohydrate reserves stored in the stool and root system, thereby exhibiting a relatively high degree of resilience to external stressors. This capacity may buffer or delay the effects of environmental stress on radial growth which is also characterized by few rings in the tree-width curves. However even if the are short, tree-ring series appear to capture the negative effects of chestnut gall wasp infestation from approximately 2008 onwards, followed by a period of growth recovery after 2014, plausibly associated with the release and subsequent establishment of its biological control agent. Conversely, no clear medium frequency decline in radial growth attributable to the worsening climatic conditions observed since 2020–2021 could be detected in the tree-ring chronologies.

A potential signal of increasing vulnerability to environmental stress is, however, provided by the positive relationship between radial growth and August precipitation, which showed a statistically meaningful association. This finding suggests that water availability during the later part of the growing season may play an important role in sustaining tree physiological activity and growth, highlighting a potential sensitivity of these stands to prolonged heat waves and summer water deficits.

Integrating dendrochronological analyses with phenological observations could provide further insight into tree susceptibility to environmental conditions and, consequently, support the identification of silvicultural strategies aimed at mitigating climate-related stress. Such strategies could include reducing competition among individuals through thinning interventions and selecting or promoting genotypes characterized by greater resistance or resilience to climatic stress.

From this point of view it should be considered that, within the investigated plot, shoots had reached an age of approximately 37 years, exceeding the rotation age commonly adopted for this area and management system. This condition likely represents an additional source of vulnerability, as increasing shoot age may reduce the capacity of individual stems to respond to and recover from biotic and abiotic stress. Overall, these findings suggest that extended rotations without a sufficient forest management of sweet chestnut coppice stands may contribute to a progressive deterioration in both stand health and the technological quality of the timber produced.

Declarations

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Conflict of interest statement

The authors declare no conflict of interests.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figures

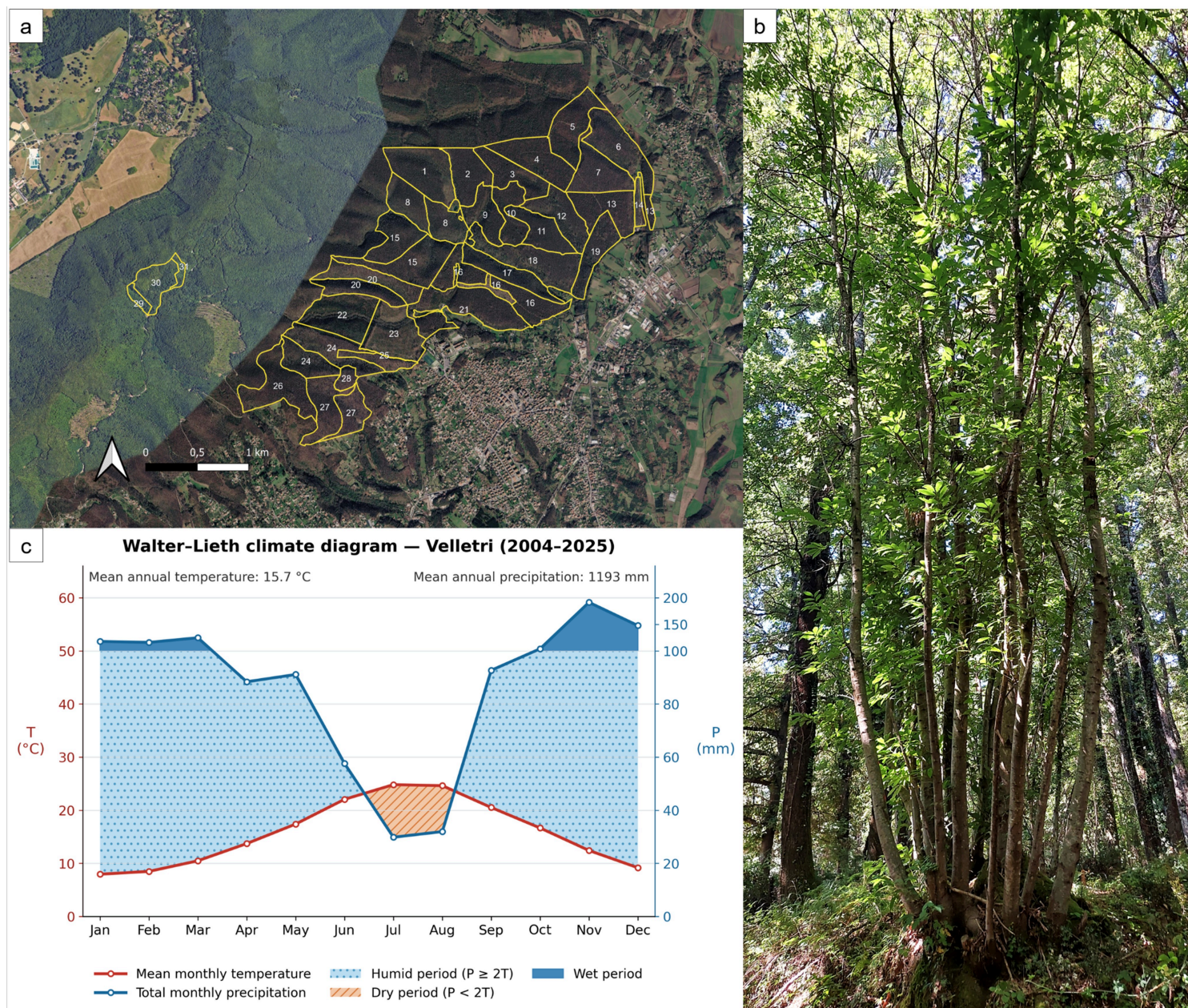


Figure 1

Overview of the study area and climate. (a) Satellite image showing forest-compartment boundaries and numbering. (b) Representative view of the chestnut coppice. (c) Walter–Lieth climate diagram for the Velletri meteorological station over 2004–2025; precipitation values above 100 mm are plotted on a compressed scale.

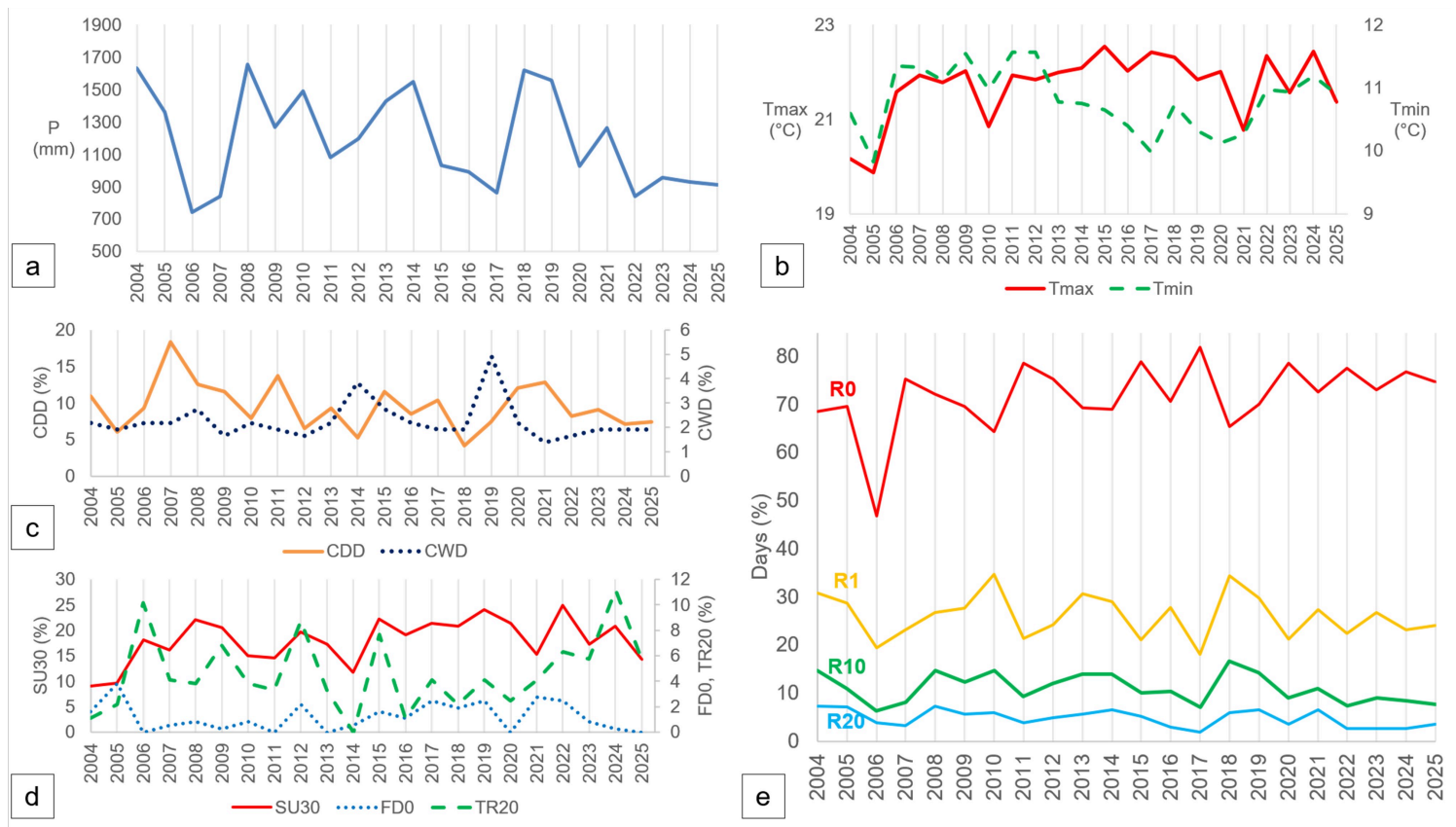


Figure 2

Climate series and extreme indices at Velletri during 2004–2025: (a) annual precipitation; (b) mean maximum and minimum temperatures; (c) consecutive dry and wet days; (d) SU30, FD0 and TR20 temperature indices; and (e) frequencies of R0, R1, R10 and R20 precipitation classes

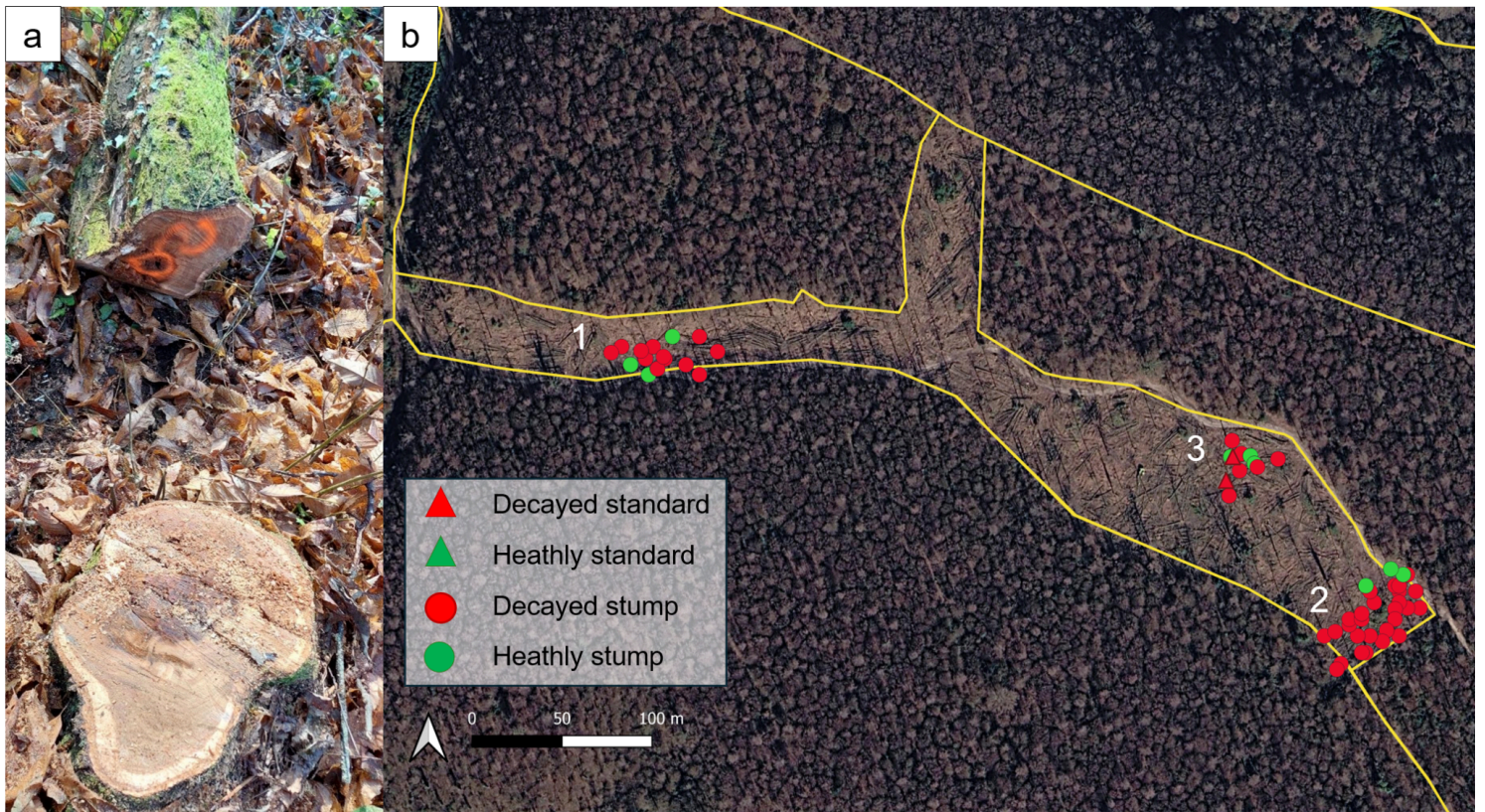


Figure 3

Spatial distribution of basal wood decay. (a) Example of a coppice shoot with visible discoloration and decay. (b) Health status and silvicultural category of surveyed stools and standards in the three sample plots.

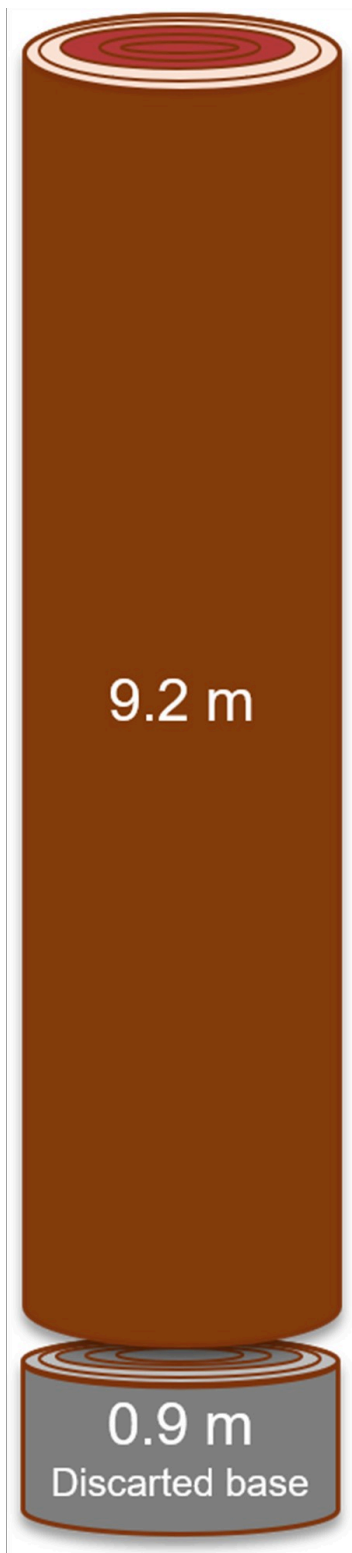


Figure 4

Schematic model stem showing the mean processed length and mean discarded basal section for the analysed stems.

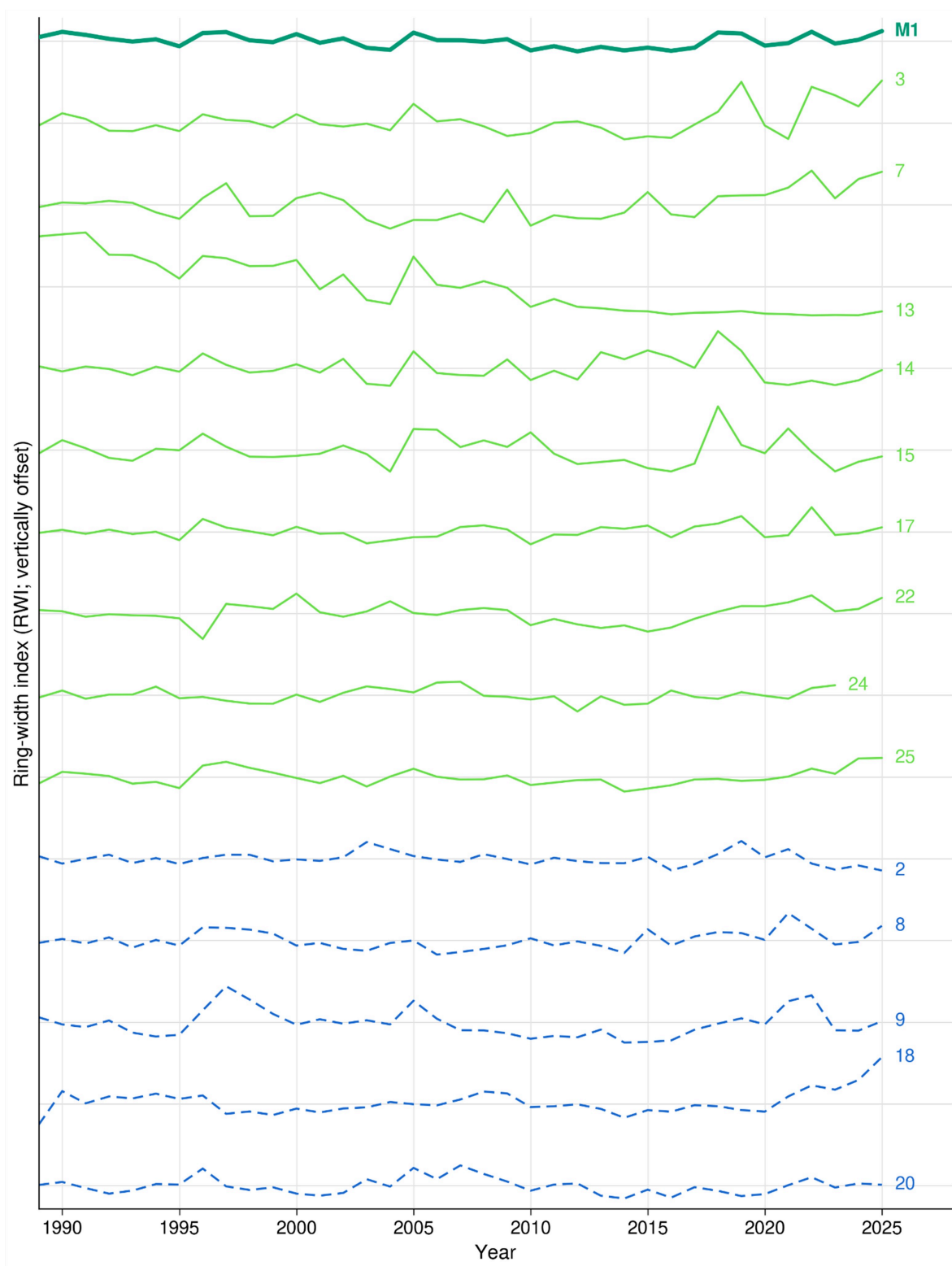


Figure 5

Standardized ring-width index chronologies for sampled chestnut trees, 1989–2025. The thick dark-green line is the mean chronology (M1). Series synchronized with M1 are solid light-green lines; series excluded from M1 are dashed blue lines. Curves are vertically offset for clarity, so their positions do not indicate absolute RWI differences.

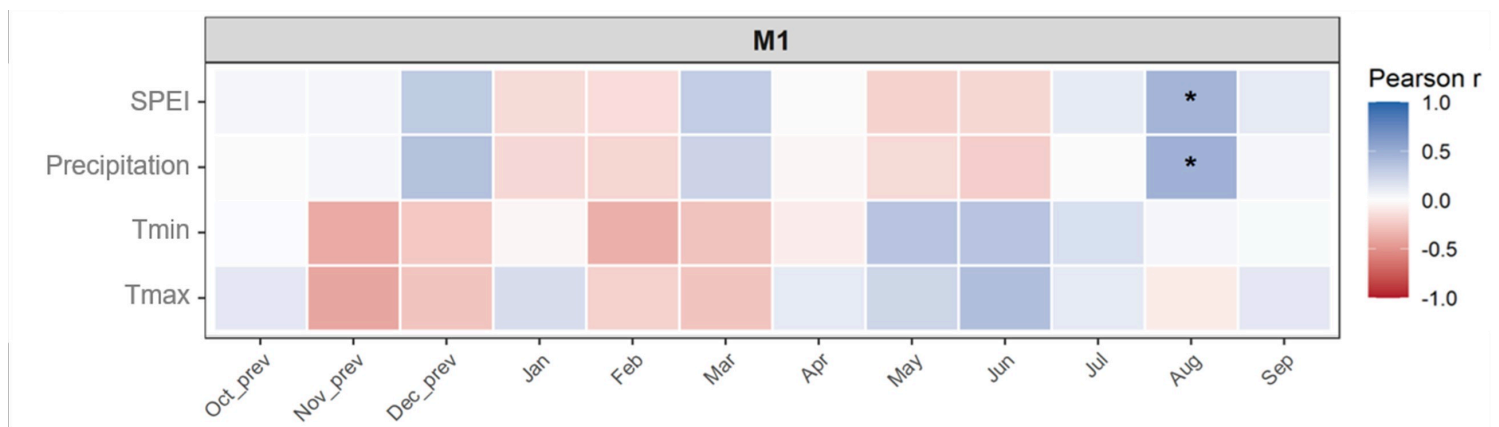


Figure 6

Pearson correlations between the standardized mean chronology (M1) and monthly climate variables from October of the preceding year to September of the growth year. Blue indicates positive and red negative correlations. Asterisks indicate significance after false discovery rate adjustment.

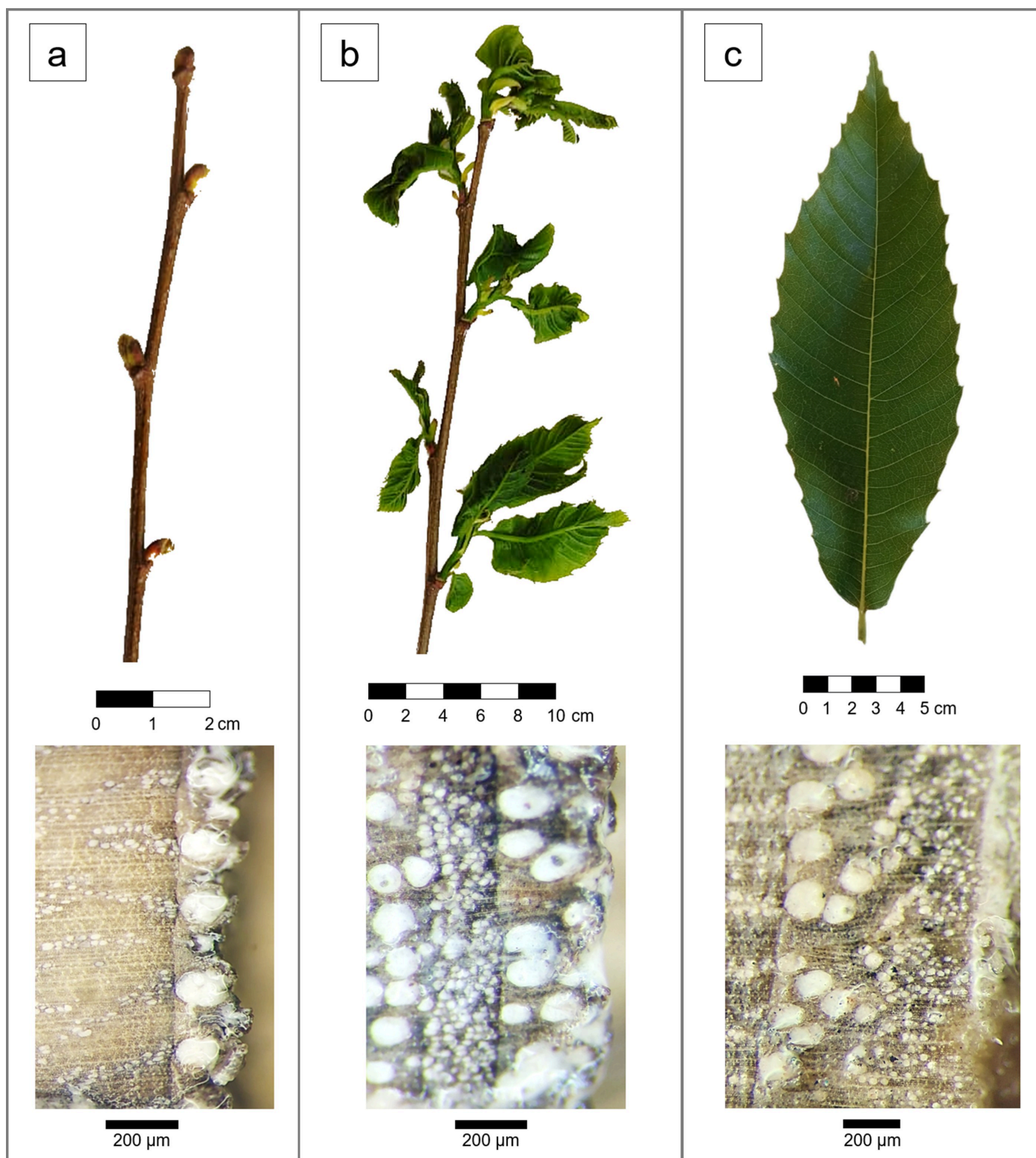


Figure 7

Phenological and xylem development of chestnut in 2026. (a) BBCH 09 on 10 April and the first row of earlywood vessels; (b) BBCH 11–15 on 8 May and two to three rows of earlywood vessels; (c) BBCH 19 on 26 June and advanced xylem formation.

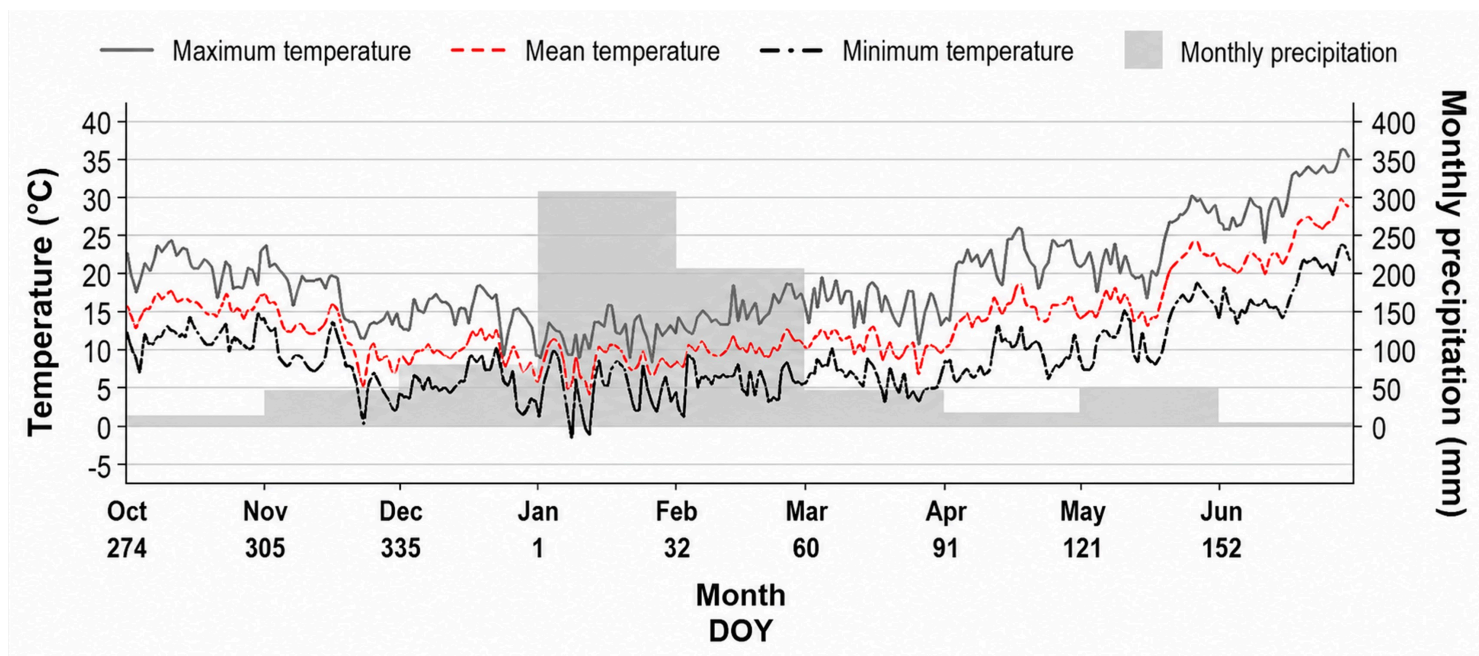


Figure 8

Daily maximum, mean and minimum temperatures and monthly precipitation at Velletri from October 2025 to June 2026. DOY, day of year.

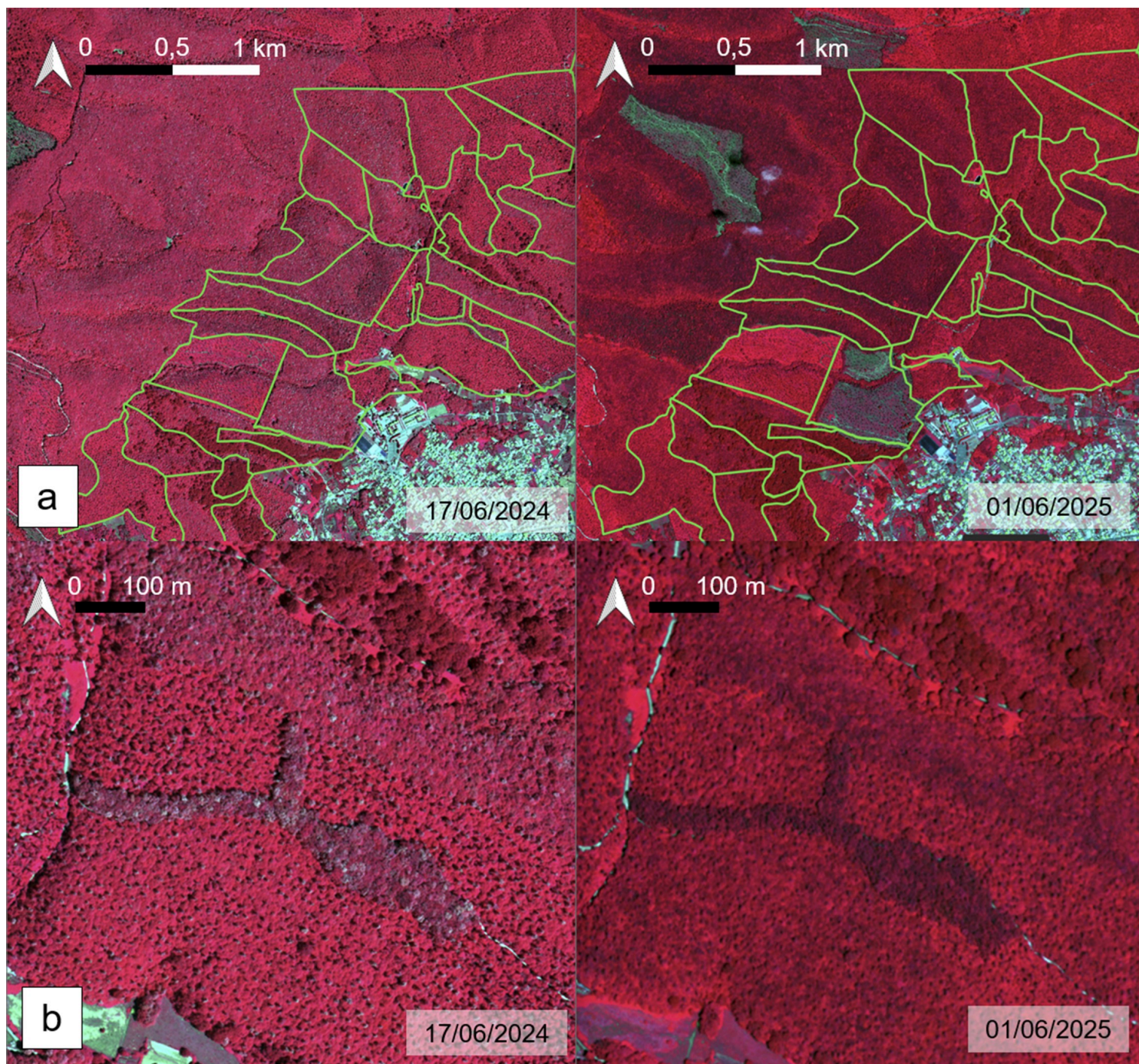


Figure 9

False-colour WorldView composites acquired on 17 June 2024 (left) and 1 June 2025 (right): (a) overview of the forest compartments and (b) detail of compartment 16. Differences may reflect acquisition date, canopy development and phenological stage.