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Review

Tree crown defoliation in forest monitoring: concepts, findings, and new perspectives for a physiological approach in the face of climate change

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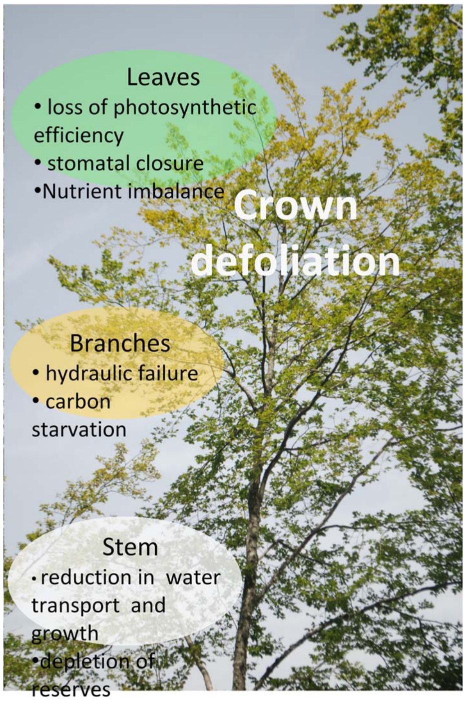
Recurrent climate-driven disturbances impact on the health of European forests that reacted with increased tree dieback and mortality over the course of the last four decades. There is therefore large interest in predicting and understanding the fate and survival of forests under climate change. Forest conditions are monitored within the pan-European ICP Forests programme (UN-ECE International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) since the 1980s, with tree crown defoliation being the most widely used parameter. Defoliation is not a cause-specific indicator of tree health and vitality, and there is a need to connect defoliation levels with the physiological functioning of trees. The physiological responses connected to tree crown defoliation are species-specific and concern, among others, water relations, photosynthesis and carbon metabolism, growth, and mineral nutrients of leaves. The indicators to measure physiological variables in forest monitoring programs must be easy to apply in the field with current state-of-the-art technologies, be replicable, inexpensive, time efficient and regulated by *ad hoc* protocols. The ultimate purpose is to provide data to feed process-based models to predict mortality and threats in forests due to climate change. This study reviews the problems and perspectives connected to the realization of a systematic assessment of physiological variables and proposes a set of indicators suitable for future application in forest monitoring programs.

Graphical Abstract



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Introduction

In the context of climate change, where extreme climatic events are expected to become more frequent and harsher (Spinoni et al. 2018, Hari et al. 2020, Moravec et al. 2021), the future condition and fate of forests are of growing importance. In recent years, the increased recurrence and severity of climate-driven disturbances have been impacting European forests (Forzieri et al. 2021, Romeiro et al. 2022, Patacca et al. 2023). The impact of climate on defoliation, crown dieback and tree mortality has been discussed previously (Allen et al. 2010, Anderegg et al. 2013, 2015). Taking the uncertainty related to the magnitude and character of climate change as context, several papers addressed tree vitality on country, regional and European level in recent years (Neumann et al. 2017, Gazol and Camarero 2022, George et al. 2022, Jaime et al. 2022), with many basing their analysis on the ICP Forests dataset.

The systematic assessment of the condition of European forests was launched in the 1980s within the ICP Forests programme (Sanders et al. 2016) (UN-ECE International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, https://unece.org/environmental-policy/air/forests; Supplementary Information—SI1). Within this framework, several parameters are monitored. The most widely used parameter is tree crown defoliation. Defoliation is defined in the ICP Forests Manual—Part IV (Visual assessment of crown condition and damaging agents), as needle or leaf loss in the crown as compared to a reference tree (Eichhorn and Roskams 2014, Eichhorn et al. 2020). Defoliation is an unspecific indicator, integrating the intrinsic genetic constitution of trees and site effects (soil fertility, climatic features, structure, and composition of the forest stand), and can be considered indicative of the equilibrium of a tree in its own environment, representing the result of accumulated impacts of stressful environmental conditions. External fluctuating pressures, such as abiotic and biotic factors, can cause year-to-year variations of defoliation. In addition to defoliation, other parameters concerning damage symptoms on different parts of the tree (leaves, branches, trunk) are assessed. The term ‘tree condition’, therefore, refers to the overall appearance of a tree, encompassing defoliation and damage symptoms. Concurrently, the term ‘tree health’, as defined by Innes (1993), refers to the incidence of both abiotic and biotic factors affecting trees within a forest. The vitality of a tree concerns ‘the capacity to assimilate carbon, to resist stress, to adapt to changing environmental conditions and to reproduce’ (Brang 1998). The concept of ‘tree vitality’ has been reviewed by Dobbertin (2005), who concluded that physiological indicators may best reflect the reaction of trees to environmental stressors. Unfortunately, many such indicators are difficult to measure in the field.

Because of the complex interactions of external and internal factors influencing defoliation and tree vitality, evidence concerning the relationships between levels of defoliation and physiological status of trees were often considered elusive and contradictory (Innes 1988a), although recent studies (reviewed in this paper) filled this gap at least partially. In current and future scenarios of climate change, the fate of forests is strictly connected to the physiological impacts and responses (acclimatization, recovery, decline) of trees. It is, therefore, of crucial importance to connect ‘condition’ (defoliation and damage symptoms) and ‘vitality’ of trees by means of physiological indicators.

In this paper, we undertake a comprehensive review of the concepts and key findings associated with defoliation, drawing on over 30 years of monitoring activities within the ICP Forests programme. We explore the role of main factors as determinants for defoliation and subsequently investigate the physiological aspects connected to this phenomenon. The aims of this review are: (i) to analyse the physiological implications of defoliation in the light of the currently available literature, (ii) to outline a strategy for the assessment of the physiological condition of trees in the field; (iii) to identify a set of indicators suitable for assessing the physiological condition of trees in the field. The methods for the selection of literature are reported in Supplementary Information 2 (SI2).

Assessment of defoliation and quality assurance in the ICP Forests programme

Defoliation is assessed visually regardless of the cause of foliage loss, and it is scored in 5% steps, starting from 0% (no defoliation) up to 100% defoliation (indicating a dead tree). Defoliation has been criticized because it is assessed visually and may be affected by the subjectivity of field surveyors and serious errors can occur (Innes 1988a, 1988b, 1990, Innes et al. 1993, Ghosh et al. 1995, Ghosh and Innes 1995, Redfern and Boswell 2004). To assess and reduce the subjectivity of field crews, a lot of effort was invested within ICP Forests into the development and implementation of Quality Assurance (QA) protocols (Ferretti et al. 2009, 2021a, Ferretti and König 2013). The QA activities included the production of a field manual (latest version: Eichhorn et al. 2020), photo-guides for the most important tree species and environmental conditions (Innes 1990, Müller and Stierlin 1990, Ferretti 1994), photo-exercises and international and national training/intercalibration/intercomparison courses for the personnel involved in field assessments. Results demonstrated that the QA objectives can be reached with mean deviation of defoliation (with respect to the crown assessment ‘reference’ team) within the ±10% interval for single sample trees and ±5% per plot (Ferretti et al. 1999, Solberg and Strand 1999, Bussotti et al. 2009, Eickenscheidt and Wellbrock 2014, Meining et al. 2016). These achievements make defoliation data quite reliable in a time series, but differences between countries persist because of differences in the methodological approaches (Klap et al. 2000). Defoliation levels and patterns at European level are analyzed in ICP Forests Technical reports annually (http://icp-forests.net/page/icp-forests-technical-report), revealing a general trend of increasing defoliation over time, with species-specific patterns (Potočić et al. 2021, Timmermann et al. 2022).

Site factors and environmental stress as the driving factors for defoliation

Analyses of ICP Forests data reveal that site factors (physical like elevation, climate, and soil conditions, and vegetational like forest structure and composition) are of fundamental importance in explaining the levels of defoliation, with defoliation being higher in higher elevation and dryer sites (Klap et al. 2000, Seidling 2001, Seidling and Mues 2005). In a study carried out in Bavarian Alps (Germany), Ewald (2005) found that defoliation is influenced by soil chemistry, increasing towards shallow calcareous soils.

Forest age, structure, and tree species composition

Crown defoliation was found to increase with stand age in several studies (Table 1, Solberg 1999a, Eichhorn et al. 2005, Pokorný and Stojnič 2012, Eickenscheidt et al. 2019); however, exceptions have been observed (Iacopetti et al. 2019). Basal area, leaf area index,

Table 1. Papers dealing with the relationships of defoliation with forest age and structure, on the ICP Forests monitoring plots.

Authors	Country/Region	Species	Main findings
Solberg (1999b)	Norway (country)	*Picea abies*	Highly significant correlations were found between crown density and age on *P. abies*
Ewald (2005)	Germany (Bavarian Alps)	*P. abies*	Defoliation was controlled by soil chemistry (defoliation increased towards shallow calcareous soils) and stand age.
Eichhorn et al. (2005)	Germany (country)	*Fagus sylvatica*, *Quercus* sp.pl.	Defoliation shows clear relations with age, relative crown spacing, composition, and fruit bearing.
Pokorný and Stojnič (2012)	Czech Republic	*P. abies*	Defoliation increases with Leaf Area Index reduction in oldest forests
Vitale et al. (2014)	South Europe	*F. sylvatica*, *P. abies*	Tree crown defoliation was mainly related to age in *P. abies* and in *F. sylvatica*.
Ferretti et al. (2014a)	France (country)	Several species	Defoliation correlates with tree density and frequency of trees with reported health problems.
Pollastrini et al. (2016)	Italy (Tuscany)	Broadleaved species	The shape of the crowns and their area (LAI) affected forest defoliation.
Eickenscheidt et al. (2019)	Germany (country)	Several species	Stand age is the most relevant factor explaining defoliation in German forests.
Ugarkovic et al. (2021)	Croatia (country)	*Abies alba*	Decline of *A. alba* trees was slower in mixed stands, and tree mortality was higher in pure stands.

and tree density are also predictors for defoliation, but their relative role changes according to the species and site characteristics (Ferretti et al. 2014b, 2015, Pollastrini et al. 2016a). Basal area and leaf area index were negatively correlated to defoliation in a regional survey in Central Italy (Pollastrini et al. 2016a), with species-specific effects. Ferretti et al. (2014b), in a study on French forests, have shown that the direction of the effect of tree density may be different according to the species and the site. In a successive study, Ferretti et al. (2015) found that tree density was negatively correlated to defoliation in Central European forests. Higher tree density may increase defoliation in drought-sensitive forests (Carnicer et al. 2011, Toïgo et al. 2020) because of the competition among trees for water resources in the soil. The effects of the combination of these variables may be complex, depending also on the ecological requirements of species (sun loving trees/Heliophytes vs. shade loving trees/Sciophytes; early successional vs. late successional). The role of species composition on defoliation was explored by the studies listed in Table 2. The variation in defoliation in beech was found to mostly depend on the basic tree and stand variables such as age, relative crown spacing, stand composition and fruiting (Eichhorn et al. 2005). High basal area and leaf area index in a forest stand can be achieved with few large dominant trees, which correspond to low density and low tree–tree competition, or with a greater number of small trees (with high density and high competition among trees). Ugarkovic et al. (2021) also found that the decline of *Abies alba* Mill. trees was slower in mixed stands, and that tree mortality was higher in pure stands. Tree diversity was proven to increase the resilience of forests under increasing stress conditions, as observed by Sousa-Silva et al. (2018) in Belgian forests, Bussotti et al. (2018a) and Iacopetti et al. (2019) in Italy.

Atmospheric deposition and air pollutants

The ICP Forests monitoring programme was launched as a reaction to the concerns about the alleged impacts of air pollution on forests. In the 1980s, acidifying atmospheric depositions of sulfur (S) and nitrogen (N) were singled out as causal agent of the so-called ‘forest decline’ (*Waldsterben*, in the German literature) in Central Europe and North America (Schütt and Cowling 1985, Schulze 1989), although this interpretation was questioned by Skelly and Innes (1994) and Kandler and Innes (1995). For example, atmospheric nitrogen depositions are nowadays known to both act as acidifying factor, but also as fertilizer that positively affects tree growth (Etzold et al. 2020). The latter effect is expected to alleviate defoliation (De Marco et al. 2014). Sulfur and nitrogen inputs to the ecosystems have been decreasing since the beginning of the 21st century (Waldner et al. 2014, Schmitz et al. 2019) whereas increasing attention was devoted to tropospheric ozone concentrations (O_3), that is now the most widespread air pollutant impacting the forests in some parts of Europe (Gerosa et al. 2007). In a Europe wide analysis, De Vries et al. (2014) concluded that subtle effects on defoliation of long-term nitrogen inputs and high tropospheric ozone levels, can be masked by other stronger influences, such as climate and site factors. It is hence difficult to clearly discern the effects of air pollution on defoliation from other site and stress factors.

Statistical analyses of the data from the ICP Forests monitoring network tried to discern the role of pollutants as contributing factors for tree crown defoliation at national and transnational levels, with contrasting results summarized in Table 3. Of the 14 papers listed, connection between air pollution and atmospheric deposition with defoliation were found by 8 of them (Rehfuess 1991, Innes 1992, Nelleman and Frogner 1994, Hendricks et al. 1997, Augustaitis et al. 2007, Thimonier et al. 2010, Vitale et al. 2014, Ferretti et al. 2014a), whereas 6 (Andersson 1990, Innes and Whittaker 1993, Solberg and Tørseth 1997, Aamlid et al. 2000, Ferretti et al. 2015, Jakovljević et al. 2019) found contradictory results or no relationships. The results, however, depend on the statistical analysis method, the species assessed (most papers deal with conifers, especially *Picea abies* (L.) Karst. And *Pinus sylvestris* L.), the air pollution metrics and the geographical range considered.

In Table 4, 16 papers discussing the role of ozone as contributing factor to defoliation are listed. A negative impact of the environmental levels of ozone was recognized in 10 papers (Sanz et al. 2000, Ferretti et al. 2003, Ferretti et al. 2007, Augustaitis and Bytnerowicz 2008, Sicard and Dalstein-Richier 2015, Diaz-de-Quijano et al. 2016, Sicard et al. 2016, De Marco et al. 2017, Araminiene et al. 2019, Sicard et al. 2020). Only one paper deals with fluxes (Zierl 2002) and 5 papers found no effect

Table 2. Papers dealing with the relationships of defoliation with stand composition and tree diversity, on the ICP Forests monitoring plots.

Authors	Country/Region	Species	Main findings
Eichhorn et al. (2005)	Germany (country)	*Fagus sylvatica*, *Quercus* sp.pl.	Tree diversity is an explicative variable for defoliation in *Fagus* but not in *Quercus*.
Pollastrini et al. (2016)	Italy (Tuscany)	Broadleaved species	Tree diversity reduced defoliation in *Castanea sativa* affected by *Drycosmus kuriphilus*
Sousa-Silva et al. (2018)	Belgium (country)	*F. sylvatica*, *Quercus* sp.pl.	Higher species diversity reduces the impacts of severe drought stress.
Bussotti et al. (2018)	Italy (North)	*Picea abies*	Defoliation of *P. abies* is higher in ecotonic zones with high diversity.
Iacopetti et al. (2019)	Italy (country)	Several species	A beneficial role of diversity has been observed in *Quercus ilex* and *P. abies* after dry periods.
Ugarkovic et al. (2021)	Croatia (country)	*Abies alba*	Different effects of tree diversity are explicated with the structure of forests.

Table 3. Papers dealing with the relationships of defoliation with primary air pollutants (Nitrogen and Sulfur) and acidic deposition.

Authors	Country/Region	Species	Main findings
Andersson (1990)	Sweden	Conifers	The defoliation of conifers does not have a linear relationship with the pollution gradient.
Rehfuess (1991)	Germany	*Picea abies*	The significance of pollutants and acidic deposition has been identified only for the high elevation sites.
Innes (1992)	UK (country)	Several species	Surveys of tree condition have provided no indication that forest trees in the UK are being adversely affected by air pollution.
Innes and Whittaker (1993)	UK (country)	*P. abies*	Relationships with pollution variables were identified with *Picea sitkensis* and *P. abies*.
Nelleman and Frogner (1994)	Norway (country)	*P. abies*	Defoliation was connected to stand acidification
Hendricks et al. (1997)	The Netherland (country)	*P. abies*	Defoliation was connected to stand acidification
Solberg and Tørseth (1997)	Norway (country)	*P. abies*	No evident support for the hypothesized negative effect on crown condition from sulfur and nitrogen deposition.
Aamlid et al. (2000)	Norway (country)	*P. abies*	The actual effect of the air pollution is difficult to estimatebut its importance is not discounted.
Augustaitis et al. (2007)	Lithuania (country)	*Pinus sylvestris*	Significant impact of SO_2 on *P. sylvestris* defoliation
Thimonier et al. (2010)	Switzerland (country)	Conifers	Crown defoliation tended to be negatively correlated with nitrogen concentrations in the needles.
Vitale et al. (2014)	South Europe	*Quercus ilex*	Tree crown defoliation was related to air pollution predictors in *Q. ilex*.
Ferretti et al. (2014a)	Europe	Several species	Variables related to nitrogen deposition improve defoliation models for European forests
Ferretti et al. (2014a)	Italy (country)	Several species	No impact on crown condition attributed to nitrogen depositions in permanent monitoring plots in Italy.
Jakovljević et al. (2019)	Croatia (country)	Several species	No relevant differences in mean defoliation between the plots were observed in relation to air pollutants.

(Bussotti and Ferretti 2009, Ciriani and Dalstein 2018, Gottardini et al. 2018, Paoletti et al. 2019, Jakovljević et al. 2021). Responsive tree species were *Pinus* sp.pl. and to a lesser extent, *Fagus sylvatica* L.

Climatic factors

The main findings concerning the relationships between tree crown defoliation and climatic factors are summarized in Table 5. Baseline levels of defoliation are expected to be higher in dry and warm sites (Popa et al. 2017). Correlations between climatic factors and defoliation (positive for temperature, negative for precipitation) were found by Popa et al. (2017) in Romania, although with species-specific and site-specific effects (high altitude species favor increasing temperatures). Fluctuating seasonal drought conditions explain year-to-year changes in defoliation (de la Cruz et al. 2014, Ferretti et al. 2014b, Sánchez-Cuesta et al. 2021). Several studies indicate that defoliation can be delayed with respect to the drought event (Solberg 2004, Zierl 2004, Seidling 2007, Ferretti et al. 2014b, Ognjenović et al. 2022). For example, Solberg (2004) specified that in the 1990s Southern Norway was repeatedly affected by summer drought inducing increased needle-fall in *P. abies*, in the autumns after dry summers.

Drought and climatic factors interact with biotic factors in determining defoliation and tree death (Anderegg et al. 2015). *P. abies* and other conifers are threatened by mass outbreaks of the bark beetle *Ips typographus* L. promoted by heat, wind throw and drought (Netherer et al. 2015, 2019, 2021). Infective diseases can also be promoted by drought stress. This is the case for oomycetes in the genus *Phytophthora*, involved in the decline of several *Quercus* species affected by drought stress in Central and Mediterranean Europe (Jung et al. 1999, 2000, Jung 2009, Colangelo et al. 2018), with similar effects recorded also in *F. sylvatica* (Jung 2009). Environmental stress factors may trigger shifts from latent to pathogenic stages in endophytes such as *Biscognauxia*

Table 4. Papers dealing with the relationships of defoliation with tropospheric ozone.

Authors	Country/Region	Species	Main findings
Sanz et al. (2000)	Spain (country)	*Pinus halepensis*	In *P. halepensis* ozone injury affects needle retention and increases defoliation
Zierl (2002)	Switzerland (country)	Several species	A hydrological model connected crown conditions with stomatal ozone uptake in Swiss forests.
Ferretti et al. (2003)	Italy (country)	*Fagus sylvatica, Picea abies*	Defoliation increases with ozone levels in *F. sylvatica* but not in *P. abies*.
Ferretti et al. (2007)	Italy (country—selected plots)	*F. sylvatica*	Ozone levels are significant predictor for defoliation in *F. sylvatica*.
Augustaitis and Bytnerowicz (2008)	Lithuania (country)	*Pinus sylvestris*	Peak of ambient O_3 have a negative impact on *P. sylvestris* crown defoliation and stem growth reduction.
Bussotti and Ferretti (2009)	Italy (country—selected plots)	*F. sylvatica*	Ozone is a predictor of crown transparency in *F. sylvatica*, but the variance explained amounts to less than 10%.
Sicard and Dalstein-Richier (2015)	SE France	*Pinus cembra, P. halepensis*	On *P. cembra* and *P. halepensis*, ozone caused yellow spots and then the older needles dropped off, causing a defoliated canopy.
Diaz-de-Quijano et al. (2016)	Spain (Pyrenée)	*Pinus uncinata*	Ozone contributed to the crown defoliation and tree mortality in *P. uncinata*.
Sicard et al. (2016)	SE France—NW Italy	*Pinus* sp.pl. and various broadleves	Ozone levels significantly correlated with crown discoloration and crown defoliation in conifers (*Pinus*) and broadleaves
De Marco et al. (2017)	Romania (country)	Several species	Ozone concentration and levels were the most important predictors of defoliation. Ozone uptake was not related to defoliation.
Ciriani and Dalstein (2018)	France (country)	Several species	No relation was found between ozone levels and defoliation.
Gottardini et al. (2018)	Italy (Trentino)	*P. abies*	Tree defoliation and growth are not in relationship with ozone exposure.
Araminiene et al. (2019)	Lithuania (country)	*P. sylvestris*	Ozone levels was correlated with crown defoliation and doses with visible foliar injury
Paoletti et al. (2019)	Italy, France, Romania	Several species	Defoliation is not related to ozone.
Sicard et al. (2020)	Italy, France, Romania	Several species	Ozone levels was correlated with crown defoliation in a transnational assessment.
Jakovljević et al. (2021)	Croatia—Mediterranean forests	*Quercus pubescens, Pinus nigra, Pinus halpensis*	Defoliation was significantly correlated with soil water content at various depths, but not with ozone

(=*Hypoxylon*) *mediterranea* (De Not.) Kuntze, *Biscognauxia nummularia* (Bull.) Kuntze and *Sphaeropsis sapinea* (Fr.) Dyko & B. Sutton (Vannini and Valentini 1995, Desprez-Loustau et al. 2006, Capretti and Battisti 2007).

The impact of biotic stressors on tree defoliation and mortality has also been explored on data from the ICP Forests network (Table 6). Jaime et al. (2022) observed that the combined influence of drought events and bark beetle attacks can threaten the persistence of European coniferous forests. Extensive decline and mortality in alpine coniferous forests was also detected on the Italian Level I plots (Bussotti et al. 2022) as a consequence of bark beetle attacks following severe windstorms and a sequence of dry years. The increased occurrence of infectious diseases favored by climatic conditions was observed by Sánchez-Cuesta et al. (2021) in Southern Spain (*Phytophthora* sp.pl.) and Bussotti et al. (2023a, 2023b) in central Italy (*Biscognauxia* sp.pl.). Toïgo et al. (2020), in a French survey, also confirmed that year-to-year fluctuations of defoliation depend mainly on climatic factors, biotic agents and their interactions.

Defoliation and mortality of trees under climate change

Under a sudden and severe stress event, such as a drought and heat wave, defoliation increases sharply (Fig. 1). After that, different pathways are possible: (i) the level of defoliation goes back to the optimal condition (*resilience*, Lloret et al. 2011); (ii) defoliation increases with respect to the pre-event levels (*suboptimal condition*); (iii) successive stress events can increase decline and lead to death (*rupture*).

The shifting of climatic conditions, with a progressive increase in temperature across Europe (IPCC 2021), and the recurrence of drought and heat waves are the new challenges for the forests. Recently, widespread defoliation, premature leaf senescence, crown dieback and tree mortality in different European countries and bio-climatic zones (Bréda et al. 2006, Pollastrini et al. 2019, Rohner et al. 2021, Brun et al. 2020) were attributed to extreme heat and drought events that are recurring in Central and Southern Europe from the beginning of the 21st century (Rebetez et al. 2006, Rita et al. 2019, Schuldt et al. 2020).

Table 5. Papers dealing with the relationships of defoliation with basic climatic factors (year-to-year fluctuations of temperature and seasonal drought) on the ICP Forests monitoring plots

Authors	Country/Region	Species	Main findings
Katzensteiner et al. (1992)	Austria (Bohemian forest)	*Picea abies*	Drought periods and nutritional imbalances enhance needle loss.
Zierl (2004)	Switzerland (country)	Several species	Significant impacts of drought were detected for deciduous tree species. Weak correlations were found for conifers.
Solberg (2004)	Norway	*P. abies*	Defoliation in *P. abies* resulted from increased needle-fall in the autumn after dry summers.
Potočić et al. (2005)	Croatia (country)	*Abies alba*	The combined influence of drought and acid soils affects especially *A. alba* trees of higher defoliation.
Seidling (2007)	Germany (country)	*Pinus sylvestris, P. abies, Fagus sylvatica*	The responses of *P. sylvestris*, *P. abies* and *F. sylvatica* after 2003 hot and dry summer responded 1-year late
Ferretti et al. (2014b)	France (country)	Several species	Defoliation correlates precipitation-related variables of the current and previous years.
de la Cruz et al. (2014)	Spain (country)	Several species	Significant factors related to defoliation were the thermal-related factors and oscillation of both the current year and the previous year.
Popa et al. (2017)	Romania (country)	Several species	The influence of temperature on defoliation was lower than precipitation.
Eickenscheidt et al. (2019)	Germany (country)	Several species	Fluctuations in defoliation were related to weather conditions. South-Western Germany was the region with the highest defoliation since the drought year 2003.
Ognjenović et al. (2020)	Croatia (country)	*F. sylvatica*	High temperatures during spring and summer months of current and previous year induce the increase of defoliation.
Sánchez-Cuesta et al. (2021)	Spain (Andalusia)	*Quercus* sp.pl.	The annual defoliation and mortality were correlated with the mean annual temperature, drought and soil organic matter content.

Table 6. Papers dealing with the relationships of defoliation with biotic interactions on the ICP Forests monitoring plots.

Authors	Country/Region	Species	Main findings
Toïgo et al. (2020)	France (country)	*Fagus sylvatica*, *Quercus* sp.pl.	Crown defoliation was generally higher in the event of insect attack and under drought.
Sánchez-Cuesta et al. (2021)	Spain (Andalusia)	*Quercus* sp.pl.	Mortality is connected to *Phytophthora* interactions.
Bussotti et al. (2021)	Italy (Alps)	*Picea abies*	High defoliation and mortality in Alpine regions connected to bark beetle attacks following a severe windstorm.
Bussotti et al. (2022)	Italy (Tuscany)	*Quercus* sp.pl., *F. sylvatica*	Death is induced by endophytes (*Biscognauxia* sp.pl.) in declining *F. sylvatica* and *Quercus* sp.pl. tree species
Jaime et al. (2022)	Europe	Conifers	The joint influence of drought events and bark beetle disturbance will threaten the persistence of European coniferous forests.

Drought and heat events and their effects on defoliation are discussed in the papers listed in Table 7. Trends of increasing crown defoliation and tree mortality in relation to recurrent severe droughts, and defoliation peaks in dry years, have been recorded in Southern Europe (Carnicer et al. 2011), Italy (Bussotti et al. 2021, 2023a, 2023b), Switzerland (Rohner et al. 2021); Serbia (Češljar et al. 2022) and Southern Spain (Navarro et al. 2022). Recent heat and drought waves were characterized, alongside a strong water deficit in the soil, by high temperatures and increased vapor pressure deficit (VPD) and were found partially responsible for increasing tree mortality in Europe (Gazol and Camarero 2022).

Defoliation and physiological processes

Water relations and transport

With drought being one of the most important drivers for defoliation, water relations play a central role in the dynamic leaf loss and in the vitality of a tree. Drought stress can be induced both by low levels of water in the soil and by high VPD (Schönbeck et al. 2022). VPD regulates xylem cavitation and recovery processes (Grossiord et al. 2020).

Trees subjected to drought stress reduce the density of the crown (reduction of the number and size of leaves) to regulate the transpiration rates. Drought during the time of bud formation, on

Table 7. Papers dealing with the patterns of defoliation of trees under severe climate change and heat and drought waves, on the ICP Forests monitoring plots.

Authors	Country/Region	Species	Main findings
Carnicer et al. (2011)	Spain (country)	Several species	Defoliation trends are paralleled by significant increases in tree mortality rates in drier areas that are related to tree density and temperature effects.
Bussotti et al. (2021)	Italy (country)	Different species	Deciduous species suffer the loss of leaves in during the 2017 drought and heat wave. Extremely defoliated and dead trees increased over time.
Rohner et al. (2021)	Switzerland	*Fagus sylvatica*	The 2018 summer drought induced severe crown transparency, leaf browning and growth reduction in Swiss *F. sylvatica* forests.
Češljar et al. (2022)	Serbia (country)	Different species	High defoliation and mortality were observed in the dry 2014–2018 period.
Navarro et al. (2022)	Spain (Andalusia)	*Abies pinsapo*	Increasing defoliation and mortality in the 2001–2017 period.
Gazol and Camarero (2022)	Europe	Several species	Increasing mortality in the European Level I network is connected to 'composite' drought events (with high VPD)
Bussotti et al. (2023a)	Italy (Tuscany)	Broadleaved species	Severe dieback of evergreen Mediterranean vegetation and extensive foliar abscission in deciduous species happened during the severe heat and drought 2017–2022.
George et al. (2022)	Europe	Several species	An increasing trend in mortality rates was found, accompanied by decreasing soil moisture. Drought was the most important driver of mortality patterns in conifers.

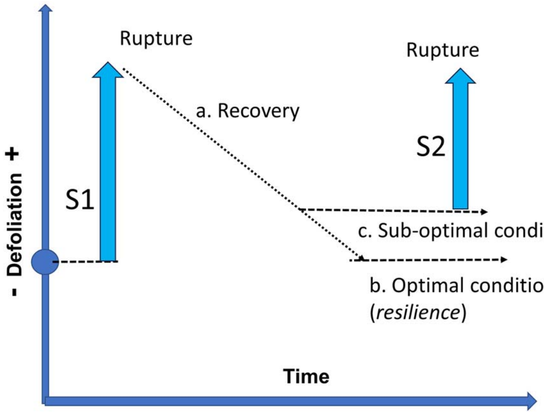

Figure 1. Events following the impact of a severe stress event (S1) that provokes an increase of defoliation. The tree can undergo death or decline (i.e. rupture), or go toward a recovery process (a). Recovery can lead to defoliation levels of the previous optimal condition (*resilience*, b) or to defoliation levels of sub-optimal conditions with higher defoliation with respect to the pre-event state (c). Successive impacts can provoke the rupture of the system (S2).

the other hand, influences both the number of new leaves and leaf surface area in the following year (Bréda et al. 2006), resulting in a delayed effect on crown defoliation. Moreover, current-year level of crown defoliation and preceding-year atmospheric drought conditions were observed to influence leaf traits in beech such as leaf mass (LM) or leaf mass per area (LMA), while needle mass and length in spruce were influenced by the current year spring climate (Zhu et al. 2022). Leaf rolling is also a consequence of drought (Terzi 2007, Kadiouglua et al. 2012).

Walthert et al. (2021) evidenced that defoliation in *F. sylvatica* trees, under drought stress, is induced by cavitation in the xylem vessels (hydraulic failure), that may have consequences on tree water transport also in the following years (Braun et al. 2021). Under extreme drought, hydraulic failure is one of the most likely causes of leaf shedding, branch desiccation and death of trees (Garcia-Forner et al. 2019, Limousin et al. 2022). Therefore, leaf and twig abscission can be viewed as a final adaptation strategy to reduce evapotranspiration (McDowell et al. 2008).

In case of deflation induced by insect herbivory, the alterations of the structure of the overall vascular transport (xylem and phloem) may increase tree vulnerability to drought (Foster 2017, Hillabrand et al. 2019). Hydraulic conductivity measurements showed that defoliated trees had both increased vulnerability to embolism and decreased water transport efficiency. Phloem sieve tube diameter was reduced in the stems of defoliated trees, suggesting reduced transport capability (Hillabrand et al. 2019).

During leaf shedding, the remaining leaves of affected trees increase their stomatal conductance to maintain the overall crown transpiration at the level of non-defoliated trees (Pataki et al. 1998, Hart et al. 2000, Quentin et al. 2012, Eyles et al. 2013). Highly defoliated trees are more likely impacted from subsequent drought and heat waves (Camarero et al. 2015, Guada et al. 2016). Therefore, recurrent droughts have more severe impact on tree defoliation and mortality, compared to a progressive shift of meteorological parameters (Jentsch et al. 2007). According to Salmon et al. 2015, defoliated trees tend to have lower water potentials and smaller hydraulic safety margins, while non-defoliated trees show a typical response to drought for anisohydric species. These responses put defoliated trees at higher risk of branch and stem hydraulic failure and help explain the interaction between carbon starvation and hydraulic failure in dying trees. After the defoliation event, the stabilization of all water status parameters occurs as acclimatization process (Bouzidi et al. 2019).

Photosynthesis and carbon metabolism (growth and defense)

Photosynthesis

Photosynthesis is a key process for tree vitality, since it is the primary source of carbohydrates, that are essential products for growth (cellulose and other structural carbohydrates) and defense (starch and soluble sugars, non-structural carbohydrates—NSCs). The intrinsic factors that affect the rates of photosynthesis at the tree level are the foliar surface, the chlorophyll content, and the efficiency of the photosynthetic apparatus. The first effect of defoliation is therefore the decrease of photosynthesis at the tree level, followed by the increase of photosynthetic rates at the leaf level, as a compensatory mechanism since the remaining leaves have better access to the environmental resources as water, nutrients, and light (Briske 1986, Turnbull et al. 2007, Quentin et al. 2012, Eyles et al. 2013). Plants subjected to severe or moderate defoliation may display higher content of chlorophyll, RuBisCO and soluble proteins in the residual leaves than not defoliated plants (Ovaska et al. 1993). Opposite results were found by Turnbull et al. (2007), who reported that increased photosynthetic rates immediately following partial defoliation were primarily a result of increased activity, rather than amount, of the photosynthetic machinery. Partial defoliation allows a better exploitation of sunlight energy but, at the same time, induces photoinhibition processes of the photosystem II (PSII), with the reduction of the maximum quantum yield of primary photochemistry (expressed by the parameter F_v/F_m) (Gottardini et al. 2016, 2020). A rise of the electron transport rate beyond the photosystem I (PSI) compensates for this reduction of F_v/F_m, with species-specific patterns, as shown by Pollastrini et al. (2017).

Tree growth

Growth is considered an integrative indicator of tree vitality (Dobbertin 2005), and new research underlines the importance of long-term monitoring of defoliation and growth as main tree health indicators (Table 8). Neycken et al. (2022) and Peters et al. (2020) found that climatic events and insect outbreaks can lead to higher defoliation and narrow tree rings in the year of the impact. Negative relations between defoliation and stem growth were found on *P. abies* in Norway (Solberg 1999b, Solberg and Tveite 2000) and *Quercus robur* L. in Southern Sweden (Drobishev et al. 2007). Ferretti et al. (2021b), analyzing tree rings of the Alpine belt conifer species in Northern Italy (*P. abies, Larix decidua* Mill.*, A. alba, Pinus cembra* L.*, P. sylvestris*) found that the relationship between defoliation and growth becomes stronger when data were aggregated over longer time scales, integrating different growth dynamics and delayed impacts. Ferretti et al. (2021c) used the mean periodical defoliation (averaged over 10 years) and the 10-year cumulated growth to determine possible negative effects of defoliation on tree growth, concluding that basal area increment (BAI) is consistently negatively and significantly related to mean defoliation, across functional groups and for most of the tree species considered, at a rate of 0.9% per unit increase of defoliation. The difference in BAI becomes significant at 15% (overall) and 15%–30% (individual species) defoliation levels. Tallieu et al. (2020) also observed significant effects of soil water on the growth of *F. sylvatica* when the difference of defoliation was more than 20% with respect to the previous year.

An asynchrony between defoliation and tree ring width series was registered by several authors. Seidling et al. (2012), Ferretti et al. (2014b) and Tallieu et al. (2020), analyzing annual tree growth, observed that the sprouting of new leaves and the length of branchlets depend on the climate conditions of the previous year, whereas the radial tree growth depends on the water availability in the soil in the current year (Navarro-Cerrillo et al. 2020). Finally, in terms of sensitivity of tree health indicators, Tallieu et al. (2020) found that radial growth presents a strong common signal among trees, while the response of defoliation was more distinct at the individual tree level, resulting in defoliation capturing fewer pointer years than radial growth. However, in view of the significant negative relation of radial growth to defoliation, Ferretti et al. (2021b) support the use of defoliation as a rapid indicator of forest health and vitality.

Non-structural carbohydrates (NSCs)

Reduced production of photosynthates and higher physiological demand for protection under stress conditions provoke the depletion of NSCs as one of the main effects of the defoliation stress induced by drought or insect attacks (for review see Hartmann and Trumbore 2016, Piper and Paula 2020, Wang et al. 2021, El Omari 2022). NSCs are essential for resource transport, energy metabolism and cell osmoregulation, and allow the synthesis of defense compounds playing a crucial role in tree physiological defense systems against environmental and biotic stress and for restoring their growth and post-stress recovery (Furze et al. 2019, Piper and Paula 2020). *L. decidua* trees defoliated by outbreaks of the larch budmoth (*Zeiraphera diniana* Guenée) every 9 years, have been shown to use NSC reserves to rebuild the crown (second flush), but growth stops earlier than during normal years causing narrower tree-rings (Peters et al. 2020).

NSCs storage buffers the asynchrony of supply and demand on daily and seasonal scales and across plant organs (Hartmann and Trumbore 2016). Low levels of NSCs constitute a condition of carbon starvation, and tree mortality is likely to occur if the amount of these compounds falls below certain species-specific thresholds (Barker Plotkin et al. 2021). NSCs are also involved in the protection against hydraulic failure. Tomasella et al. (2017) suggest that, after drought stress, *P. abies* trees repair xylem embolism thanks to the NSCs stored in xylem parenchyma. This process implies dependency on sapwood NSCs reserves for survival, especially if frequent drought spells occur.

The metabolism of carbon in drought-defoliated trees affects both growth and storage of NSCs, with different dynamics. Some studies carried out on defoliated coniferous (*Pinus pinaster* Ait., Puri et al. 2015) and broadleaved (*Quercus velutina* Lam., Wiley et al. 2013) trees evidenced the reduction of growth but not of the NSCs reserves. In an experiment on *Abies balsamea* (L.) Mill., Deslauriers et al. (2015) rejected the hypothesis of a trade-off between growth and NSCs storage, since almost all the related variables decreased in defoliated trees. The reduction of NSCs happens first in the fine roots (Kosola et al. 2001), due to their prevailing action as carbon sinks (e.g. root growth for soil water exploration), as shown by Aguadé et al. (2015). Wang et al. (2021) suggest a shift in the C allocation towards shoots over roots, and in post-defoliation years growth happens at the expense of NSCs reserves that are diverted from defense to growth.

The recovery of NSCs pools after defoliation can take several years: observations in Mediterranean evergreen forests (López Bernat et al. 2009, Galiano et al. 2012) show that 10 years after a drought event, starch stocks in *Quercus ilex* L. trees have only recovered to half of their former amount. Severely defoliated trees after an extreme event can restore their NSCs reserves and full physiological functionality when defoliation periodicity varies from 15 to 60 years (Medvigy et al. 2012), depending on species, climatic regions, and environmental conditions. When the periodicity of extreme events is more frequent, substantial changes may occur in the ecosystems (Saura-Mas et al. 2015) and the co-occurrence of stresses may lead to more severe episodes of decline and tree mortality (De Grandpré et al. 2018). Recovery of carbon reserves and growth is more rapid and complete in trees growing in resource rich environments (Erbilgin et al. 2014).

Nutritional factors

Loss of nutrients from the system, disruption of nutrient cycling and uptake, or imbalances in nutrient status can be associated with declines in forest productivity and stability

Table 8. Papers dealing with the relationships of defoliation with tree growth on the ICP Forests monitoring plots.

Authors	Country/Region	Species	Main findings
Solberg (1999a)	Norway	*Picea abies*	Crown condition and growth were correlated in *P. abies*, although with moderate strength.
Solberg and Tveite (2000)	Norway	*P. abies*	Approximately 1% change in crown density corresponded to 1% change in growth in *P. abies*.
Drobishev et al. (2007)	Sweden	*Quercus robur*	Differences in tree-ring increment between *Q. robur* trees with healthy crowns and trees with heavily declining crowns were pronounced.
Seidling et al. (2012)	Germany	*Fagus sylvatica*, *P. abies*	In *F. sylvatica* and *Pinus sylvestris* current year's crown defoliation was negatively correlated with stem increment.
Tallieu et al. (2020)	French (country)	*F. sylvatica*	No relationship occurs with tree-rings in cases of slight or moderate defoliation.
Navarro-Cerrillo et al. (2020)	Sothern Spain	*Abies pinsapo*	A positive association was found between stand defoliation and relative growth.
Ferretti et al. (2021c)	France (country)	Several species	Basal Area Increment resulted negatively and significantly related to defoliation, with a significant reduction detected already at slight (15%) defoliation level in conifers and a less clear trend in broadleaves.
Ferretti et al. (2021b)	North Italy (Trentino)	Conifers	Negative correlation between defoliation and annual or periodical stem diameter growth in conifers.

(Nilsson et al. 1995, Jonard et al. 2015). Katzensteiner et al. (1992) correlated poor nutrition of *P. abies* stands with excessive needle shedding. Potočić et al. (2005) found that drought caused low needle Ca concentrations in *A. alba* trees of all defoliation classes but affected especially trees in higher defoliation classes growing on acidic soils. After conducting a fertilization experiment in young *A. balsamea* stands, Ouimet and Moore (2015) observed that an increase in K concentration in needles results in a decrease in defoliation.

Many investigations focused on the relationship of defoliation and nutritional status of *F. sylvatica*. A study in Northern Spain recorded higher P concentrations in more defoliated *F. sylvatica* trees (Amores et al. 2006). Jonard et al. (2010) report that higher defoliation values are associated with lower Ca and Mg concentrations in a liming and P/K fertilization experiment in *F. sylvatica* stands in the Belgian Ardennes. Ferretti et al. (2015) found that the share of *F. sylvatica* trees with defoliation over 25% increase with increasing foliar N/Ca and N/K ratios, indicating that defoliation is related to imbalance in foliar nutrients. On the other hand, Ognjenović et al. (2020, 2023) were not able to establish direct relationships but found that both defoliation and foliar nutrient composition reacted to temperature variables. Ewald (2005) states heterogeneous environmental conditions as the reason for the lack of significant relationships between nutrient concentrations and *P. abies* defoliation status in Bavaria, Germany. An alteration of the chemical composition of declining *P. sylvestris* needles was found by Tzvetkova and Hadjiivanova (2006), with K deficiency and an increase of peroxidase activity. The consequences of defoliation on the chemical composition of *P. sylvestris* needles depend on the intensity and timing of defoliation, where the source–sink position of damaged needles play a relevant role (Lyytikainen-Saarenmaa 1999). Overall, the interaction of nutrition and defoliation, as well as the relation of these two vitality indicators with climate conditions is not well understood and demands more research efforts.

Assessing tree vitality with physiological indicators

Towards a system for a physiological assessment of tree vitality

In a new generation of concepts and practices for forest condition monitoring, it will be desirable to combine the traditional visual system described in the current manual (Eichhorn et al. 2020) with new physiologically based indices (Niinemets 2010, Bussotti and Pollastrini 2015, Bussotti and Pollastrini 2017a, 2017b, Bussotti and Pollastrini 2021), effective to describe the vitality of trees. Such indices must be easy to apply in the field, measurable with current *state-of-the-art* technologies and replicable; moreover, they should be inexpensive and time efficient (Bussotti and Pollastrini 2021, Munné-Bosch and Villadangos 2023). The assessment of all the physiological indicators must be regulated with common *ad hoc* protocols elaborated and validated with direct experience in the field.

Different sets of field indicators for the assessment of the physiological condition of trees are proposed in the literature, with different levels of difficulty for sampling, measurement, and analysis. Each set of parameters is indicative of different physiological processes. The combination of different parameters with the visual assessment of tree crowns (defoliation and damage symptoms) will give a holistic picture on the impacts and processes of decline or recovery. In the following paragraphs we briefly discuss their potential and limitations.

Physiological indicators of tree vitality

Tree ring analysis

Taking tree cores is simple and inexpensive. Tree ring measurement (dendrochronology) is a very informative approach for the analysis of past events (Cherubini et al. 2021). The cores, moreover, can be subjected to chemical analysis to detect stable isotopes and elements of exogenic origin (Ferretti et al. 2002), thereby allowing a comprehensive reconstruction of the history of the tree in its environment. Tree coring also offers the possibility to analyze the xylem traits (Carrer et al. 2015, Pandey et al. 2018, Borghetti et al. 2020, Lens et al. 2022) in relation to drought stress, e.g. the relative amount of earlywood and latewood, vessel diameter, conduit area, xylem conductivity, etc. Although considered sometime a practice potentially detrimental for tree vitality, Portier et al. (2023) found no statistical evidence that tree coring reduces tree growth and mortality.

Foliar analysis

Leaves from the top of the crowns are sampled in the Level II plots for the analysis of the mineral nutrition (Rautio et al. 2020). The collection of leaves from tall trees being an expensive operation, the costs can be optimized with the measurement of different physiological variables on the same foliar sample (Bussotti and Pollastrini 2015). The analyses proposed below don't require special permanent equipment within the plots.

Functional leaf traits, such Leaf Area (LA), Specific Leaf Area (SLA), Leaf Mass per Area (LMA), Relative Water Content (RWC) and so on, are easily assessable on detached leaves (Cornelissen et al. 2003, Pérez-Harguindeguy et al. 2013, Bussotti and Pollastrini 2017b, Zhu et al. 2022). These parameters give information about the resource acquisition strategies and acclimatization processes to persistent and fluctuating environmental stress.

Relevant information on the photosynthetic efficiency and tree vitality can be obtained by the analysis of chlorophyll fluorescence and content. These physiological variables can be assessed with optical non-destructive methods, that enable us to make a great number of measurements in a relatively short time (Strasser et al. 2000, 2004, Uchino et al. 2013). Chlorophyll fluorescence methods are currently applied to assess the vitality of trees in forests, plant nurseries, and urban green infrastructures (Pollastrini et al. 2016a, 2016b, Bussotti et al. 2020, Swoczyna et al. 2022), and can be applied directly in the field on freshly taken samples.

Biochemical status of pigments, antioxidants, and secondary metabolites (Tausz et al. 2003, Couture et al. 2016, Munné-Bosch and Villadangos 2023), as well as leaf anatomy (Vollenweider et al., 2016), can also provide a wealth of information about the relation of trees with their environment, but such analyses incorporate a number of difficulties regarding sampling time and treatment prior to the delivery to laboratory.

Stable isotopes

Stable isotope analysis is a very powerful tool to investigate the relationship of plants with their environment (Siegwolf et al. 2022, Snyder et al. 2022), and is applicable to stored desiccated leaves and tree rings. Francey and Farquahar (1982) demonstrated that carbon isotope (δ^{13}C) variations are physiologically strongly controlled by gas exchange in leaves and can reflect the intrinsic water use efficiency of a plant; oxygen isotopes (δ^{18}O) are a time-integrated proxy for stomatal conductance (Barbour 2007) and relative humidity (Helliker and Ehleringer 2002); hydrogen isotopes (δ^{2}H) may function as a metabolic proxy helping to infer on changes in biochemistry and gas-exchange (Cormier et al. 2018, Lehmann et al. 2022), leaf nitrogen isotope (δ^{15}N) composition is determined by the interaction between the external N source and the physiological mechanisms of nitrogen allocation within the plant, and can be used to assess the impact of N deposition on trees (Guerrieri et al. 2009).

Water relations

Water relations in a tree include transpiration, stomatal conductance, hydraulic conductance, water storage and capacitance (Landsberg and Waring 2017). They are of great importance when investigating the role of drought in the worsening of tree condition. The methods currently applied include the application of sap-flow sensors and point dendrometers (Vandegehuchte and Steppe 2013, Dietrich et al. 2018). These measurements require an initial investment for the instruments, that must be installed permanently on the plot (with risk of theft and vandalism), power supply and frequent visits for maintenance and data download. Therefore, this can be done only on intensively monitored plots (Level II). New technologies (Zweifel et al. 2021, 2023) allow automatic download and transmission of data, thereby reducing field work considerably.

Non-structural carbohydrates

There is growing interest in the storage and seasonal changes of non-structural carbohydrates (starch and soluble sugars, NSCs), as key players in the process of the response of trees to extreme drought and heat (Martínez-Vilalta et al. 2016). Because of the high intra-annual dynamics of NSCs, however, it is not easy to develop a harmonized system for comparable sampling and analysis (Landhäusser et al. 2018). In addition to the aspects related to the laboratory work, the main problems concern the sampling strategy (part of the plant, timing) and variations in the ecological and vegetational characteristics of sites. At the current state-of-the-art it is unlikely that large-scale surveys on NSCs will become common soon, but NSC analyses are nevertheless a useful tool to investigate specific forest health-related events.

Monitoring tree vitality: weaknesses and future needs

Ongoing climate change and repeated extreme climatic events pose new threats to European forests and spur a renewed interest in forest monitoring (Ferretti 2021). There is still a lack of knowledge about the distinct and combined roles of drought, VPD, and temperature (Sánchez-Salguero et al. 2017, Breshears et al. 2021), and their interactions with opportunistic insects and pathogens, as well as with past impacts on forest trees (i.e. the legacy effect of cumulative past stress events, e.g. Ruck et al. 2023). The impact of increasing temperatures and extreme weather events (droughts, storms, and temperature and precipitation extremes) on the vitality of forest trees is often difficult to separate from the impact of nitrogen deposition, tropospheric ozone, or heavy metals, as they can exhibit synergistic effects (Potočić 2023). The relative intensity and duration of each stress factor and their interactions can trigger different physiological processes with variable symptomatology even on the same tree species. Loss of leaves during a drought event, for example, may be caused by an active acclimatization process to reduced water availability, or early senescence, or, finally, a collapse of the water transport system due to embolism.

To respond to these new challenges, current field activities of forest monitoring should be combined with additional physiological measurements. Defoliation and growth patterns are considered useful proxies for the likelihood of tree mortality (Dobbertin and Brang 2001, Hülsmann et al. 2017, Cailleret et al. 2019). Ecophysiological data can improve process-based models to separate out the different mechanisms associated with mortality (Camarero 2021, Cochard et al. 2021, Petit et al. 2021) and complement regular ICP Forests damage assessments. To achieve this goal, it is necessary to collect field data from plots representing an array of ecological conditions and tree species. In principle, the ICP Forests Level II plots are suitable for the assessment of physiological indicators, since they are more intensively surveyed, but also selected Level I plots can be upgraded when appropriate, or new *ad hoc* plots can be installed for physiological measurements.

In terms of new monitoring initiatives, *TreeNet* in Switzerland (Zweifel et al. 2021, 2023), demonstrates a perspective for an integrated monitoring network. *TreeNet* collects data from point dendrometers and air and soil sensors using an automated system. Data are collected continuously, and are being automatically transmitted, processed, and stored in a central server, to provide near real-time indicators of forest growth performance and drought stress. Valentini et al. (2019) propose the so-called '*TreeTalker*©', a multi-sensor device that continuously measures and transmits various variables, including: water transport, radial growth, multispectral signature of light transmitted through the canopy, and meteorological variables in real time.

The current ICP Forests monitoring network is an invaluable infrastructure whose importance is now universally recognized in a time of increasing environmental disturbance. To enhance its informative potential, for an even better estimation of the impacts and for the prevision of the development of forest ecosystems, we hope for a closer relationship between ICP Forests and other observational activities (remote sensing, forest inventories) and *ad hoc* cause-effect experiments (Hartmann et al. 2015, 2018, Bussotti et al. 2018b, Bontemps et al. 2022, Trugman 2022). We believe that the introduction of physiological indicators in field surveys can substantially improve the understanding of cause-effect relationships of trees with their environment and contribute to models describing the future condition of forests in Europe. An *ad hoc* working group on physiological indicators has been formed under ICP Forests Expert Panel on Crown Condition and Damage Causes to explore the possibility of adapting the above proposed physiological indicators and concepts in the field.

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Author contributions

F.B. wrote the first draft of the paper. All the authors contributed with critical reading and proposals. All the authors read and approved the final version of the paper.

Supplementary data

Supplementary data are available at *Forestry* online.

Conflict of interest

None declared.

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Data availability

No data available.

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