Assessing effects of drought on tree mortality and productivity in European forests across two decades: a conceptual framework and preliminary results

Jan-Peter George¹, Mathias Neumann², Jürgen Vogt³, Carmelo Cammalleri³, Mait Lang⁴

¹ Tartu Observatory, University of Tartu, Observatooriumi 1, Tõravere, Estonia
² Institute of Silviculture, University of Natural Resources and Life Sciences Vienna, Peter- Jordan-Str. 82, Vienna, Austria
³ Joint Research Centre (JRC), European Commission, Ispra, Italy

E-mail: jan.peter.george@ut.ee  https://orcid.org/0000-0003-4285-746X

Abstract. Forests are currently experiencing an unprecedented period of progressively drier growing conditions around the globe, which is threatening many forest ecosystem functions. Trees as long-living organisms are able to withstand drought periods. Our understanding on critical drought severity resulting in substantial decline in net primary productivity and/or eventually tree mortality is underdeveloped. A wide range of remote sensing products and ground observations, including information on productivity, tree vitality, climate, and soil moisture with high temporal and spatial resolution are now available. Linking these data sources could improve our understanding of the complex relationship between forest growth and drought. We introduce here a conceptual framework using satellite remotely sensed net primary productivity (MOD17A3 and MODIS EURO), ground observations of tree mortality (ICP level I survey data), soil moisture anomaly (Copernicus European Drought Observatory), and spatially-downscaled daily climate data for entire Europe. This unique analysis will enable us to test the influence of biotic and abiotic covariates such as tree age, stand history, and drought legacy using historic droughts for model development. This conceptual framework, as evident from the preliminary results shown here, can help anticipating the effects of future droughts and optimize global climate models considering drought effects.

1. Introduction
European forests cover a total area of 174 million hectares and constitute the most important carbon sink among all ecosystems in Europe with an average carbon (C) density of 71t C per hectare [1,2]. As a rule of thumb, carbon that is stored in European forests accounts for 10% of the total EU-27 fossil-fuel emissions [3]. As such, these forest ecosystems play an important role for climate regulation, economy, welfare, and society by providing resources, income, clean water, and protection against natural hazards [4]. However, recent studies have demonstrated that European forests are currently experiencing a drastic change in disturbance-driven mortality and productivity [5,6]. One of the keystone drivers of this unprecedented tree decline and associated productivity decrease has been identified as the exposure to progressively drier growing conditions, which have led, for instance, to massive canopy mortality in 2018 after a devastating and prolonged drought that affected large areas of Europe [7]. Droughts such...
as the one in 2018 have the potential to turn forest ecosystems into large sources of carbon and could reverse the effects of preceding and successful carbon sequestration efforts under periods of stable growth conditions [8]. Unfortunately, the relationships between forest productivity, tree mortality and drought occurrence are poorly understood and thus limit our ability to properly project growth response into the future. In particular, studies assessing the adverse effects of drought intensity and duration on growth and mortality at a larger geographical scale and with high spatial resolution have not been yet compiled and analysed together. Nevertheless, there is increasing availability of consistent remotely sensed and modelled datasets on growth, mortality and forest structure with high temporal and spatial resolution [2, 9, 10], that have so far not been analysed jointly in order to explore the effects of drought on productivity and mortality. A joint analysis of growth and mortality data from already existing datasets such as MODIS will be a valuable contribution to this research field given the latest forecasts for future drought occurrence under climate change [11, 12].

Instead of reviewing the physiological and biological consequences of drought stress for trees in general (this is reviewed elsewhere such as in [13, 14], and many others) we want to underpin the necessity for our study by demonstrating the devastating effects of a recent drought period on European forests. The drought in 2018 was a unique phenomenon among the last 500 years [7] with unprecedented dry climatic conditions in the Boreal North [15]. Approximately 140,000 km² coniferous forest as well as 20,000 km² deciduous forests in Europe significantly suffered from the 2018 drought and many regions in Europe experienced forest productivity losses of around 40% [15]. Even after this drought had terminated, tree mortality remained (and still remains) at a high level in subsequent years due to so-called carry-over effects (i.e. drought effects that are carried-over across years due to a “legacy” of the drought) [15]. Recent simulations showed that temperature and rainfall conditions such as in 2018 could become a common occurrence as early as 2043 under high-end emission climate scenario projections in Europe [7]. This demonstrates that large-scale analysis approaches such as the one proposed here are timely and will have the potential to provide the scientific basis for future projections of drought-induced growth responses and mortality of trees under climate change in order to assist adaptive forest and hazard management at high spatial resolution.

In this project we will build upon previous collaborations and studies which produced and made accessible datasets for tree mortality and productivity at European scale and with very high spatial resolution (see Methods). This will save time and allows us to focus on novel aspects. We are presenting models that are capable to predict tree mortality, growth decline and recovery time of European forest ecosystems as a function of the intensity and duration of droughts over the last two decades. Within this period, several prominent extreme droughts (e.g. 2003 and 2018) had occurred over Europe and it will thus advance our understanding on future trajectories of European forest ecosystems in a drier world under climate change. We will combine observational data from long-term monitoring (tree mortality assessed at ICP level 1 plots) with satellite remotely sensed net primary productivity (NPP) covering entire Europe (MOD17A3 and MODIS EURO) [9,16].

2. Materials and methods

2.1. General concept

Our study aims at quantifying the effect of drought on forest productivity, recovery of productivity, and single-tree mortality. We emphasize to predict these three quantities (hereafter called response indices) as a function of the severity and the duration of a drought. We aim to answer the following research questions:
i) Is drought response (as expressed by the three response indices) equal among forest types and geographical regions in Europe?
ii) Which combination of drought intensity and duration has the strongest effect on productivity and mortality and can we distinguish spatial clusters showing similar response patterns?
iii) How much of the spatiotemporal variation in drought response can be explained by using drought intensity and duration as predictors?
iv) What is the effect of biological and climate covariates (e.g. tree age, pre-drought productivity and climate conditions prior to drought) for productivity and mortality?

v) How are productivity and mortality related to each other in the context of increased forest background mortality?

Questions i) and ii) arise from findings of recent studies unravelling genecological differences in drought adaptation which demonstrated that boreal forest populations are significantly more vulnerable to drought compared to populations from the South or Central parts [17, 18].

Question iii) is a keystone question for future research, since it will determine the capability of such a dataset for producing vulnerability and prediction maps under different climate change scenarios projected into the near and far future [13].

Question iv) is motivated from previous studies, that have shown that drought response in trees is often confounded by biological covariates as well as by carry-over effects from preceding years. For instance, tree age [19,20], pre-drought productivity [5], and climate-driven growth potential [21] are among the most important parameters influencing drought response. Since the effects of those covariates are sometimes oppositional depending on whether productivity or survival is addressed, we want to explore their general relationship with the three response indices rather than stating explicit hypotheses in advance.

Question v) will quantify the relationship between both response types in order to clarify whether productivity patterns under drought and prior to drought can be used to explain mortality patterns after a drought event (i.e. background mortality). While mortality can directly occur in a year with extreme dry climatic conditions (e.g. due to hydraulic failure), it can also be triggered by depleted tree carbon pools as a result of reduced photosynthetic activity [22]. The latter process often lasts for several years. We hypothesize that increased background mortality during the last 20 years (that is: mortality in non-drought years) can be explained by decreases in net primary productivity.

The above-mentioned response indices comprise two measures of relative productivity and recovery: i) annual NPP in a drought year compared to average NPP of three preceding non-drought years (hereafter called forest ecosystem resilience (FERS) and ii) the time that is needed to reach pre-drought productivity levels after a drought has occurred, hereafter called forest ecosystem recovery period (FERC). FERS will be given as a ratio of NPP [kg C m⁻² yr⁻¹] and FERC [years]. For single-tree mortality we will use tree mortality observations from a European-wide survey (see section 2.3.2).

2.2. Study area
The study area comprises all the EU-27 member states and surrounding countries, including Norway, the United Kingdom, Switzerland, Serbia, Bosnia and Hercegovina, Albania, North Macedonia, Montenegro, and Turkey.

2.3. Datasets for forest productivity, mortality, and drought occurrence
2.3.1. Forest productivity. Forest productivity can nowadays be assessed at high temporal and spatial resolution by using freely available remotely sensed data [23]. In particular, MODIS (MODerate resolution Imaging Spectroradiometer) onboard the Terra and Aqua satellites is a standard data source for various research applications [24]. For estimating drought effects on forest productivity we rely on the MODIS EURO dataset [9]. MODIS EURO was created based upon the MOD17 net primary productivity (NPP) algorithm with regional high-resolution climate data at 1-km and validated against 196,434 national forest inventory plots in Europe. It was shown to be superior compared to the global MODIS NPP in estimating NPP comparing with forest inventory data over Europe [9]. We complement MODIS EURO until 2019 by using the global MOD17 A3 product [25] providing annual NPP at global scale and with the same spatial resolution as MODIS EURO. The complete analysis workflow and an overview of the conceptual framework is shown in figure 1.
2.3.2. Tree mortality. We quantify tree mortality using the already compiled dataset from [20]. This dataset contains repeated observations for a total of 235,895 trees between 2000 and 2012 across Europe and is based upon ICP Forests Level 1 forest damage surveys [26]. Within this pan-European framework, tree vigor and defoliation status are visually assessed at sample plots on a 16x16 km grid (13,630 plots) each year since 1995. A tree is assessed as being dead when its defoliation status has reached 100% and when the tree is not any longer included in the consecutive years survey. Since this dataset covers the period 2000-2012, we expand the mortality data until 2019 to include recent and extreme drought events that occurred over Europe (e.g. 2018). Complementary data covering the period from 2013 onwards were obtained from the ICP Program Co-Ordinating Centre (PCC) in Eberswalde (Germany) and are accessible upon formal request [27]. Figure 2 shows the available data for crown defoliation and tree mortality.

2.3.3. Drought indices. We employ a drought index that is capable of assessing onset, end, duration, and intensity of droughts in a spatially and temporarily explicit manner. We utilize the SPEI index (Standardized Precipitation Evapotranspiration Index [28]) as it has been shown to be superior in detecting meteorological drought conditions which are relevant for forest vegetation compared to other indices [5, 29]. SPEI is based on a climatic water balance (that is the difference between incoming precipitation and outgoing evapotranspiration) and returns a monthly water surplus/deficit. These surpluses/deficits are aggregated over desired integration times (1-12 months) and expressed as standard deviations relative to the reference integration time 1950-2020. Increasing negative SPEI values indicate an increasing water deficit and drier climatic conditions. No 1-km gridded SPEI dataset is currently available for Europe. We create this dataset on our own based on freely available high-resolution daily climate data for Europe [17] that has been recently updated and expanded. We employ the SPEI package in the programming language R [30] and use the Thornthwaite method [31] for calculating potential evapotranspiration for every 1x1 km grid cell. The result is a monthly pan-European SPEI dataset (hereafter called SPEI\textsubscript{EURO}) at 1x1 km spatial resolution covering the period from 2000 onwards.

We plan to cross-validate SPEI\textsubscript{EURO} against a reasonable number of SPEI observations from available databases such as the global SPEI database with 0.5° resolution [32]. We will use integration times of
1, 3, 6, and 12 months in order to capture different hydrological stages that might be relevant for trees and make SPEI\textsubscript{EURO} publicly available. We define onset and end of drought in a similar way as described in [5], that is, a drought begins when SPEI ≤ -1 for at least one month and ends when SPEI > -1. As drought duration we define the number of consecutive months with SPEI ≤ -1 and drought intensity as maximum intensity (i.e. most negative SPEI value) that was reached during this time. The defined thresholds are in concordance with the general classification scheme of standardized drought indices [28] and permit us to compare our results to studies using the same definitions [e.g. 5]. While we are able to link productivity and drought for every 1x1 km pixel, for the mortality we link about the 14,000 ICP Forests observation plots to the nearest 1x1 km pixels from the produced SPEI dataset.

We further utilize soil moisture anomaly [33] as a second indicator of drought occurrence. In contrast to SPEI the SMA was originally developed for detection of agricultural droughts and is calculated for 10-day periods. Briefly, we calculate soil moisture on a daily basis according to a hydrological rainfall-runoff model [34]. Subsequently, SMA is calculated as:

\[
SMA = \frac{\bar{SMI}_t - \bar{SMI}}{\delta_{SMI}}
\]

with SMI\textsubscript{t} being the 10-day average soil moisture index for the period \(t\) of the current year, \(\bar{SMI}\) being the long-term average and \(\delta_{SMI}\) the standard deviation calculated over the period from 1995 to the last available full year. Consequently, and similar to SPEI, SMA is solely expressed in standard deviations and intensity/duration will be used in analogy to SPEI.

2.4. Statistical analysis
We apply two different types of statistical analyses that take into account the special nature of both datatypes (productivity and mortality). First, we use the random forest algorithm [35, 36] in order to unravel the effect of drought intensity, duration, and intensity x duration interaction on the two response indices FERS and FERC (figure 1). We include all grid cells that showed at least one unravelled drought event using SPEI\textsubscript{EURO} (according to our definition above) during the period 2000-2019. We include explanatory covariates such as stand age and pre-drought growth conditions (average SPEI of the three preceding growing seasons) in order to assess their relative influence on drought response. Variable importance is determined by calculating importance scores for each variable. Important explanatory covariates should intuitively display one of the following features in the response function: i) visible tipping points, ii) well-defined minima and maxima, or iii) a significant slope [36]. We infer clusters showing similar drought response in space by performing a principal component analysis of the drought response predicted by the random forest algorithm and visualize clusters by employing the clara package in R.

Second, we apply Cox proportional hazard models [37] to mortality observations in order to unravel climatological and ecological drivers of tree mortality. Cox models are capable of including a set of explanatory covariates (fast and slow) and are specifically designed for right-censored data such as mortality observations. We use the same procedure as described in [20] with the only difference that our fast explanatory variables will be drought intensity and duration (+interaction), respectively. Since tree mortality is also a multi-year phenomenon that integrates abiotic conditions prior to the mortality event [38], we also include SPEI values three years prior to the mortality event (aggregated over the growing season from Apr-Aug). Tree age is used as slow explanatory covariate in the Cox model (figure 1). Finally, we use the satellite derived NPP prior to mortality as well as in the year mortality occurred as fast predictor in order to unravel whether a steady decrease in tree vigor may lead to increased background mortality. All analyses are carried out in the R environment [30] by using the survival and glmulti packages.
3. Results and discussion

We show here data coverage and selected preliminary results, focusing on tree mortality, soil moisture anomalies and response on net primary production. We focus on research questions i) and v) outlined in the introduction.

3.1. Available data and spatiotemporal coverage

The compiled datasets are covering the entirety of Europe across a timespan of more than two decades and permit us to include a large variety of prominent drought events with significant impact for forest growth and tree vitality. For instance, the three large-scale droughts in 2003, 2015, and 2018 are well covered by our dataset and can be used to shed light into the complex relationship between extreme drought occurrence and tree growth and mortality (figure 1). Our framework considers both climatic drivers of tree mortality as well as predisposing factors like tree age and drought legacies. Remote sensed net primary production allows us to quantify the impact of droughts on productivity, while ground observations provide robust tree mortality rates [39].

In total, 3.7 million observations on crown defoliation assessment are available between 1987 and 2020 (plots x trees x years) and 24,493 trees have died within this period. Our data suggest that about 0.7% of observed trees died during the study period (33 years). These observations span the entire study region, including parts of Russia and Turkey (figure 2). The observation density is associated with forest cover and is the highest in North Europe. The British Isles have poor coverage with crown defoliation assessment. For some Baltic countries, parts of Germany and the Balkan we have also little data. Here we excluded European ash (Fraxinus excelsior L.) and narrow-leafed ash (Fraxinus angustifolia Vahl) from analysis, to avoid biases due to non-climatically driven mortality. Observed mortality for these two species are presumably mostly attributable to biotic reasons rather than drought [40, 41].

Figure 2. Data coverage for MODIS NPP and soil moisture availability (black) and ICP forest monitoring data on crown defoliation (green dots).

3.2. Annual tree mortality and effects of droughts

We observed a significant positive trend in annual mortality rate (AMR, standardized using standard deviations and the long-term mean) across the last two decades from 1995 to 2020. We excluded the data prior 1995 due to inconsistent coverage across the study region. Dry years such as 2003 and 2018
have clearly caused excess mortality, compared to years with average climate conditions. Mortality peaks occurred two years after the extremely dry year 2003 or directly in the drought year 2018 (figure 3). The majority of death events were attributable to the conifers *Picea abies* (L.) H. Karst. (Norway spruce) and *Pinus sylvestris* L. (Scots pine) and to a lesser extent to the broadleaves *Quercus robur* L. (pedunculate oak), *Quercus petraea* (Matt.) Liebl. (sessile oak) and *Fagus sylvatica* L. (European beech).

Since 2012, AMR has constantly been positive (i.e., higher tree mortality than long-term average), strongly suggesting that the positive trend is caused by climate-induced changes in water regime (comparing figures 3 and 4). We can speculate, that the 2003 drought combined with heatwave (the hottest summer on record in Europe) has predisposed European trees to following droughts and/or secondary pathogens [42]. The next years (2021-2023) may see a decrease of tree mortality, if the drought in 2018 had similar response on trees than the drought 2003, where mortality dropped to pre-drought levels about 3-4 years after the drought. We need continued consistent measurements of the ICP Forests monitoring plots to verify this. Our current results, however, give already some evidence, that consistent links exist between mortality, productivity and climate conditions (research question v) and that drought response varies, presumably caused by differences drought intensity and/or duration [13, 43]. SPEI [28] will help to better characterize the features of drought events.

![Figure 3](image_url)

**Figure 3.** Standardized mortality rate calculated over all tree species since 1995. The red line shows mean over all monitoring plots and the blue shaded area shows standard deviation across all monitoring plots. Vertical grey dashed lines mark drought years 2003 and 2018, respectively.
3.3. Response of soil moisture anomaly and drought years on primary production

MODIS NPP visually showed high to moderate correlation with soil moisture anomaly (figure 4). This is confirmed by correlation coefficients in the range 0.4-0.6, suggesting that lower soil moisture anomaly triggers net primary productivity decline and vice versa higher soil moisture is associated with productivity increases. In this preliminary analysis, we selected six locations across the study region, spanning latitudinal and longitudinal gradients. The locations in Western Europe showed decrease in net primary productivity in the drought years 2003 and 2018. The selected location in Finland is typical for boreal forests on peat bogs and here we observed an inverse correlation in 2018 (see Finnish site in figure 4). A potential explanation is that these forests have commonly a soil water surplus, which may impair root growth and nutrient mobilization [44]. A year with negative soil water anomaly could drain the soil and allow mineralization of soil organic matter and facilitate tree growth [45]. Our results suggest that the response to drought varies across European regions (research question i), but our understanding of drivers is still underdeveloped. More detailed analysis of the entire dataset incorporating soil data into multivariate models may help provide conclusive answers.

Our results also suggest that the extent of the 2003 drought was different from the 2018 drought based on soil moisture anomaly (SMA). In 2003, all six sites showed negative SMAs of varying intensity (figure 3). On the other hand, in 2018 there were strong negative SMAs in the Finnish, the German and Italian site, but modest or even positive SMAs. In particular, the French site had an exceptional large positive SMA in 2018. This suggests that broad-brush interpretations of drought impacts are problematic and that detailed analysis, for instance using gridded data as proposed here, is needed to quantify the actual impacts of droughts.

This preliminary analysis points toward important characteristics of response of European forests to droughts. The full soil moisture anomaly dataset contains a total of 9,881,404 retrievals between 1995

Figure 4. Illustrative example (six selected locations across Europe) for the correlation between MODIS NPP (left Y-axis, solid lines) and soil moisture anomaly (right Y-axis, vertical bars). Exceptional drought years (2003, 2018) are marked with a red dashed line.
and 2020 (for the vegetation period spanning April to August) and may provide insight into processes not visible in this study. While we here pooled all data across tree species, managed and conserved forests, bioregions and soil conditions, further analysis will look into these effects. A continental study for instance suggested that response primary production varies between managed and conserved forests and that southern European forests have a less pronounced production response to conservation [46]. This may be associated to dominant tree species and species composition and/or stand age. Analysis of the response of selected forest types or dominant species may help disentangle the results of this study.

4. Conclusion
We present here a conceptual framework for studying responses of forest stands and single trees to drought at large geographical scale and with high spatiotemporal resolution. Preliminary results from this ongoing work summarized here point towards important facets that require more detailed analysis. For instance, our dataset will allow testing the effects of biotic and abiotic drivers for tree mortality and productivity response, such as stand age, forest type or tree species. Compiling such a dataset is only possible through open data-sharing policy, requires a transdisciplinary project team, including foresters, ecologists, data scientists and remote sensing experts, and is time demanding. On the other hand, the anticipated impact can be significant. Robust statistically significant quantitative relationships between forest growth/mortality, climatic conditions and drought will be pertinent for future vegetation models that attempt to consider the effects of contrasting climate change scenarios.

Acknowledgements
This study is carried out with the support of the European Regional Development Fund and the programme Mobilitas Pluss (Project ID: MOBJD588). The GIS and Remote Sensing for Sustainable Forestry and Ecology (SUFOGIS) project has been funded with support from the EU ERASMUS+ program. The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

References
[1] EUSTAFOR 2010 European Forestry in the Face of Climate Change EUSTAFOR Guidelines (European State Forest Association, EFI)
[2] Moreno A, Neumann M and Hasenauer H 2017 Forest structures across Europe Geosci. Data J. 4 17–28
[3] Ciais Pet al. 2008 Nat. Geosci. 1 425–9
[4] Brecka A F J, Shahi C and Chen H Y H 2018 For. Policy Econ. 92 11–21
[5] Schwalm C R et al. 2017 Nature 548 202–5
[6] Senf C, Pflugmacher D, Zhiqiang Y, Sebald J, Knorn J, Neumann M, Hostert P and Seidl R 2018 Nat. Commun. 9 4978
[7] Toreti Aet al. 2019 Earth’s Futur 7 652–63
[8] Ciais Pet al. 2005 Nature 437 529–33
[9] Neumann Met al. 2016 Remote Sens. 8 1–18
[10] Seidl R, Klonner G, Rammer W, Essl F, Moreno A, Neumann M and Dullinger S 2018 Nat. Commun. 9 1626
[11] Burke E J, Brown S J and Christidis N 2006 J. Hydrometeorol. 7 1113–25
[12] Stagge J H, Kingston D G, Tallaksen L M and Hannah D M 2017 Sci. Rep. 7 1–10
[13] Greenwood S et al. 2017 Ecol. Lett. 20 539–53
[14] Williams A P et al. 2012 Nat. Clim. Chang. 3 292–7
[15] Buras A, Rammig A and Zang C S 2020 Biogeosciences 17 1655–72
[16] Moreno A and Hasenauer H 2016 Int. J. Climatol. 36 1444–58
[17] Isaac-Renton M, Montwé D, Hamann A, Spiecker H, Cherubini P and Treydte K 2018 Nat. Commun. 9 5254
[18] George J P, Grabner M, Campelo F, Karanitsch-Ackerl S, Mayer K, Klumpp R T and Schüler S 2019 Sci. Total Environ. 660 631–43
[19] Zang C, Hartl-Meier C, Dittmar C, Rothe A and Menzel A 2014 Glob. Chang. Biol. 20 3767–79
[20] Neumann M, Mues V, Moreno A, Hasenauer H and Seidl R 2017 Glob. Chang. Biol. 23 4788-97
[21] Moreno A, Neumann M, Moreno A, Neumann M and Hasenauer H 2018 Glob. Planet. Change 169 168–78
[22] McDowell N et al. 2008 New Phytol. 178 719–39
[23] Lausch A, Erasmi S, King D J, Magdon P and Heurich M 2016 Remote Sens. 8 1–44
[24] Barnes W L, Xiong X and Salomonson V V 2002 IEEE International Geoscience and Remote Sensing Symposium vol 2 (IEEE) pp 970–2
[25] Zhao M and Running S W 2010 Science 329 940–3
[26] Eichhorn J et al. 2016 Visual Assessment of Crown Condition and Damaging Agents. Manual Part IV. In: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests (UNECE ICP Forests Programme Coordinating Centre, Hamburg)
[27] ICP Forests 2016 Strategy of ICP Forests 2016 – 2023 (ICP Forests)
[28] Vicente-Serrano S M, Begueria S and López-Moreno J I 2010 J. Clim. 23 1696–718
[29] George J P, Grabner M, Karanitsch-Ackerl S, Mayer K, Weißenbacher L and Schueler S 2017 Tree Physiol. 37 33–46
[30] R Development Core Team 2021 R: A language and environment for statistical computing R Found. Stat. Comput. Vienna, Austria.
[31] Thornthwaite C W 1948 Geogr. Rev. 38 55
[32] Begueria S, Vicente-Serrano S M, Reig F and Latorre B 2014 Int. J. Climatol. 34 3001–23
[33] European and Global Drought Observatories 2021 EDO Soil Moisture Anomaly (SMA) (version 2.1.0).
[34] De Roo A P J, Wesseling C G and Van Deursen W P A 2000 Hydrol. Process. 14 1981–92
[35] Breiman L 2001 Mach. Learn. 45 5–32
[36] Liaw A and Wiener M 2002 J. R. Stat. Soc. 34 187–220
[37] Cox D R 1972 J. R. Stat. Soc. 34 187–220
[38] Bigler C, Bräker O U, Bugmann H, Dobbertin M and Rigling A 2006 Ecosystems 9 330–43
[39] Anderegg W R L, Anderegg L D L, Kerr K L and TrugmanA T 2019 Glob. Chang. Biol. 25 3793–802
[40] Skovsgaard J P et al. 2017 Forestry 90 455–72
[41] Kowalski T and Holdénrieder O 2009 For. Pathol. 39 304–8
[42] Schuldt B et al. 2020 Basic Appl. Ecol. 45 86–103
[43] Blackman C J et al. 2019 Tree Physiol. 39 910–24
[44] DeLuca T H and Boisvenue C 2012 Forestry 85 161–84
[45] Finér L and Laine J 1998 Plant Soil 201 27–36
[46] Moreno A, Neumann M, Mohebianl PM, Thurnheer C and Hasenauer H 2019 Remote Sens. 11 87