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Sentinel-2 time series reveal species-specific responses in temperate conifer dieback

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Highlights

- Anomalies on Times-series of Sentinel-2 data allow to characterise forest decline
- The performance of dieback detections depends on species and vegetation indices used
- Detection performed better in pure than in mixed stands, especially for Norway spruce
- Early warning dieback detection performs better for silver fir

Abstract

Silver fir (Abies alba Mill.), Norway spruce (Picea abies (L.) H. Karst) and Scots pine (Pinus sylvestris L.) are three major conifer species in Europe that are currently experiencing severe dieback. Developing effective monitoring of these species over large areas and at high temporal frequencies is essential to assess their mortality dynamics. Multispectral satellites have demonstrated their effectiveness in identifying mortality patterns for different functional types, but differences among species remain poorly addressed. Using Sentinel-2 time series and ground observations collected between 2018 and 2023 over the French mountains for 742 pure and 949 mixed stands, we investigated the interest of analysing dieback detection at the species

level. We used spectral time series analysis from seven raw bands and eight vegetation indices and integrated spectral anomalies for different periods prior to the ground survey. Results differed significantly among species: the best performance was obtained for silver fir with a fifteen-month period and Inverted Red-Edge Chlorophyll Index (IRECI), for Norway Spruce with a one-month period and Continuum removal of the shortwave-infrared spectrum (CRSWIR), and for Scots pine with a four–month period and red-edge (CRRE). In pure stands, the time series analysis detected Norway spruce dieback better (R^2 = 0.54, OA=77%) than it did Silver fir (R^2 = 0.34, OA=61%) or Scots pine (R^2 = 0.16, OA=64%). Dieback was difficult to detect in its early warning stages and in mixtures mainly for Norway spruce and Scots pine. This study highlights the importance of developing species-specific methods for large-area monitoring of dieback.

Keywords

Time series, Sentinel-2, dieback, Norway spruce, silver fir, Scots pine

Introduction

Forests provide multiple ecosystem services including wood production, hydrological regulation, carbon sequestration and recreational activities (Millennium Ecosystem Assessment, 2005) are being threatened by the recent increase in forest mortality observed in many parts of the world, including Europe (Senf et al., 2020). Dieback is a multifactor phenomenon linked to a general, progressive degradation of tree health, and result in higher than usual tree mortality (Allen, 2009). The factors involved include predisposition (e.g. tree age, soil compaction), external abiotic conditions (e.g. storms, drought, frost) and biotic events (e.g. fungi, insect outbreaks) (Manion, 1981). Climate change is also contributing to the recent

upward shift in mortality trends worldwide through increasingly intense and frequent extreme climatic events (Senf et al., 2020) and biotic threats (Seidl et al., 2017). Historically, the health of forests has been assessed using inventories that express the severity of dieback through various symptoms (Lausch et al., 2017; Taccoen et al., 2019). Among them, foliar loss leading to an increase in canopy transparency, and dead outer and upper branches are the most frequently observed. These can lead in extreme cases to the death of the tree (Pontius & Hallett, 2014). Most forest health inventories rely on a systematic sampling design. They may not always accurately reflect dieback patterns due to the localised nature of some mortality events and to the harvesting of dead trees prior to sampling. Because they are too sparse to map dieback at a fine scale, remote sensing may provide valuable complementary information essential to robust decision-making (Hartmann et al., 2018). Multispectral data are the most widely used for forest dieback assessment (Torres et al., 2021). Currently, operational multispectral missions provide global coverage with a short revisit period, and medium to high spatial resolution. Spectral information over multiple bands makes it possible to distinguish the specific characteristics of forest canopies. Photosynthetically active pigments influence reflectance in the visible domain (VIS, 400-700 nm), leaf structure and canopy structure influence reflectance in the near infrared domain (NIR, 700-1100 nm), and absorption features from plant water content act in the shortwave infrared domain (SWIR, 1100–2400 nm) (Carter & Knapp, 2001; Gitelson & Merzlyak, 1998; Kokaly et al., 2009). Spectral bands can be used alone or in combination with vegetation indices (VIs). The latter approach maximises sensitivity to specific vegetation properties, often associated with a specific part of the electromagnetic spectrum, and minimises sensitivity to other factors (e.g., atmospheric conditions, acquisition geometry) (Jackson & Huete, 1991). VIs have been widely used to assess forest dieback, and perform better than spectral bands (Bárta et al., 2021). Dense satellite-image time series (SITS) are now outperforming single-image-based approaches to forest

dieback monitoring (Torres et al., 2021). SITS are used to model the normal behaviour of spectral indices over time for a given site, then to compare this with current values to identify spectral anomalies. The greater the difference over a period of time, the more important the changes in stand fitness are likely to be. Detecting change with continuous SITS provides an unprecedented opportunity for real-time monitoring (Woodcock et al., 2020). Algorithms have been developed to monitor forest change from Landsat time series, such as LandTrendr, BFAST or CCDC-SMA (Kennedy et al., 2010; Verbesselt et al., 2010; Chen et al., 2021). Their performance depends in part on the availability of cloud-free data, which is necessary to properly characterise the seasonality of the signal. This is particularly important in cloudy humid regions such as mountainous areas (Lastovicka et al., 2020). Comparisons between time series from satellite missions have shown differences in their ability to predict conifer forest dieback. Sentinel-2, which has a high spatial resolution and revisit period, provides in general better results (König et al., 2023). Most existing studies distinguish only a few dieback classes, often only one degraded stage and a contrasting healthy stage (Abdullah et al., 2019a). Studying the shape of the transition between the normal health status and strong dieback symptoms (Trumbore et al., 2015) requires detailed gradients covering all the stages of dieback, especially when visible symptoms are moderate (crown defoliation, presence of dead branches, ...), i.e. the early warning stages, which are often omitted despite their importance for managers (Torres et al., 2021). Few studies have evaluated remote sensing approaches on a detailed dieback gradient with a description of tree dieback status based on ground survey observations (Hawryło et al., 2018). Most remote sensing studies on dieback have focused on one tree genus, such as Pinus or Quercus, or one functional type, as it is quite difficult to distinguish tree species over large areas (Gallardo-Salazar et al., 2023; Drechsel & Forkel, 2025). A few specific studies in contexts with enough pure stands have focused on a single species (Bárta et al., 2021; Marx & Kleinschmit, 2017); this simplifies detection since responses to stress differ among species. For

example, Radeloff et al. (1999) showed that the NIR reflectance of Pinus banksiana was greater than that of other conifer species and that it tended to increase with stress, whereas it decreased in other conifer species (Abdullah et al., 2019b). This suggests that detection performances should be improved by selecting the method and spectral index according to the target species (Ye et al., 2021). Selecting only pure stands is recommended to study single-species responses (Radeloff et al., 1999); however, 70% of the forests in Europe consist of multi-species stands (UNECE & FAO, 2011). Integrating species differences and mixture effects into satellite data analysis is quite challenging and is a limiting factor for current dieback detection algorithms (Bárta et al. 2021). We aimed to investigate how the responses of species belonging to the same functional group differ at different levels of mixture and dieback in time-series dieback monitoring. We focused on silver fir (Abies alba Mill.), Norway spruce (Picea abies (L.) H. Karst) and Scots pine (Pinus sylvestris L.), representative of the three most important conifer genera in Europe (Strona et al., 2016). We used an anomaly detection method and compared different spectral bands and vegetation indices over different time periods to evaluate their performance in predicting dieback gradients for pure stands of each species. The most efficient vegetation index for each species was retained, and its ability to predict dieback gradients was then evaluated for different levels of species mixture.

Materials and methods

Study area

We evaluated silver fir, Norway spruce and Scots pine dieback on plots located throughout the southwestern part of their geographical range, in five mountain ranges (the Vosges, the Jura, the Massif Central, the Alps and the Pyrenees), as well as the surrounding areas, which are all located in France. The elevations in the studied forests range from 80 to 2,100 meters, with an average of about 900 meters. Mean annual precipitation during the study period varied from 650 mm to 2,100 mm, with an average of 1,100 mm. Mean annual temperatures ranged from

2.5 degrees to 15.0 degrees with an average of 8.7 degrees (Piedallu et al., 2016). Four of the mountain ranges (Vosges, Massif Central, Alps and Pyrenees) are composed of crystalline and calcareous rocks, while the Jura is only calcareous. Forests cover approximately 40% of the study area (i.e. 10M ha), of which 26 % is coniferous, 58 % is deciduous, and the remaining 16% is mixed coniferous/deciduous forest (IGN, 2019). Approximately 57% of the forest area is composed of multiple species (Bontemps et al., 2019), and silver fir, Norway spruce and Scots pine make up 83% of the coniferous forest (IGN, 2019).

Data collection

Ground observations

We used a subset of 1,773 French National Forest Inventory (NFI) plots, surveyed from 2018 to 2023, containing at least one dominant or co-dominant tree of our target species (Vidal et al., 2005). They provide circumferences and species names for each tree with a diameter greater than 7.5 cm and ecological information on a circular plot of 15 metres with continuous tree cover (i.e. without discontinuities such as roads). The selected plots showed no signs of management intervention or decline due to extreme events (fire, windthrow…) in the five years prior to the survey. We focused on declining changes such as insect- or drought-induced dieback and therefore excluded plots affected by other extreme events (windthrow, fire, avalanche…) (Fig.1) (Ye et al., 2021). As dieback symptoms are rarely observed in systematic large-area monitoring, we added 191 plots across the area that were specifically surveyed for forest dieback, and provide information on tree species and circumferences (Fig.A.1) (Gilles et

al., 2024). The NFI plots have a surface area of 700 m² and the additional plots ranged from 300 m² to 6300 m² (average 1000 m²).

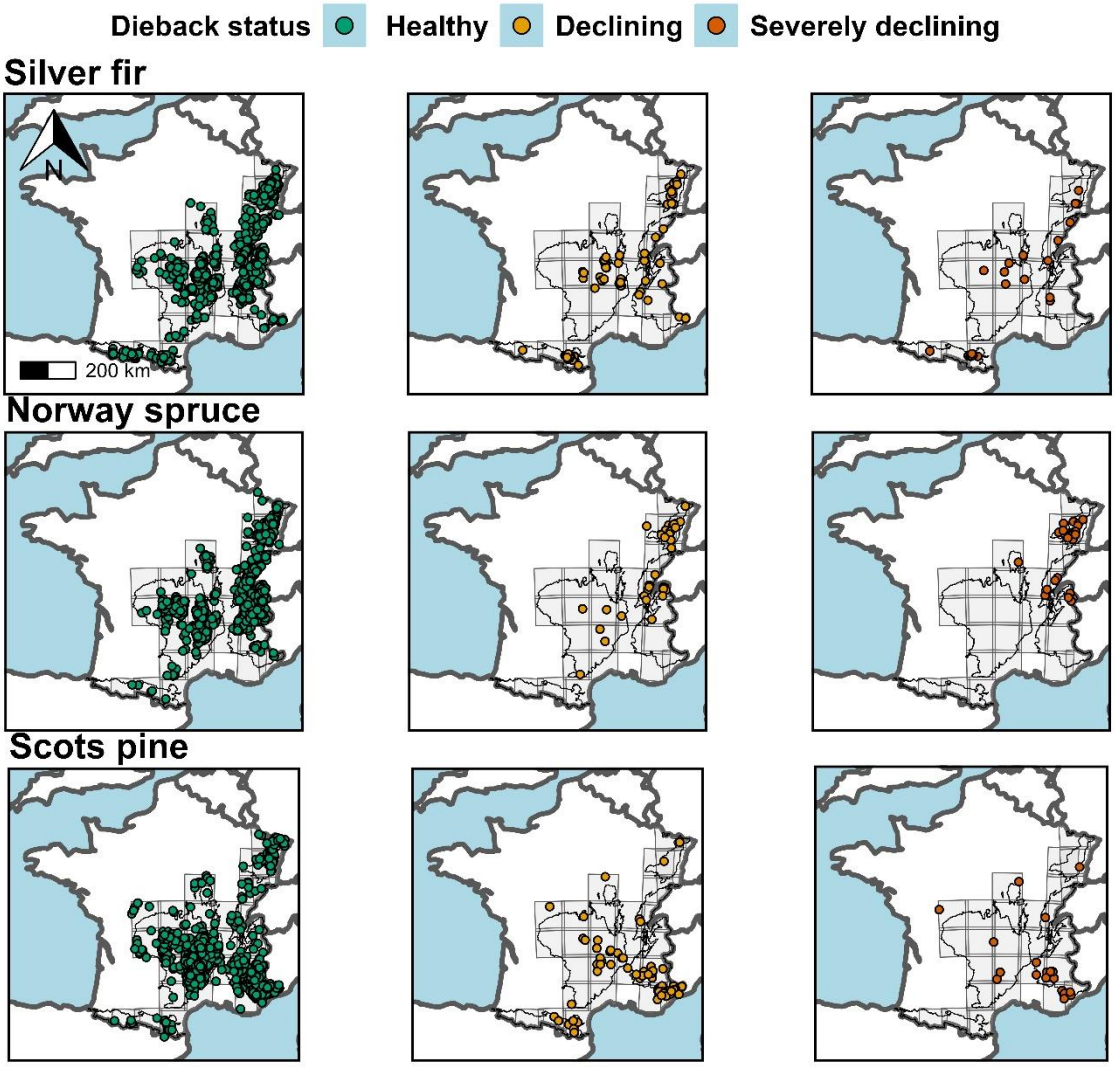

Fig.1: Distribution of the 1,964 study plots located in the selected mountain ranges, by species and dieback status. The location of the selected Sentinel-2 tiles is delineated in grey (each tile contains at least 100 ground observations) (Dieback status categories correspond to [0%-25%],]25% - 50%] and]50% - 100%] for "Healthy", "Declining" and "Severely declining" respectively).

The NFI database provided information on the social status of living trees (whether dominant or co-dominant), but not dead ones. Instead, the ratio of a tree's circumference to the mean circumference of all the trees in the plot was used to identify dominant and co-dominant trees for dead trees. This threshold was calibrated for each species (Tab.A.1). As dieback was not

assessed for the small trees, we eliminated the plots where more than 50% of the trees had a diameter at breast height of less than 22.5 cm.

On 55% of the plots, we used the percentage of dead branches (DB) and leaf defoliation (LD) to determine the degree of dieback for each of the dominant and co-dominant trees (Goudet et al., 2018). As LD was not available, we only used DB for the remaining 45%. A DB value of 100% indicates a dead tree. When both DB and LD were assessed, we calculated the *Idx* index (Eq. 1), as recommended by the French Forest Health Service (DSF): When LD was missing, the *Idx* index took DB alone.

$$Idx = DB + (1 - DB/100) * LD \qquad \text{Eq.1}$$

For the dataset studied, silver fir, Norway spruce and Scots pine had mortality rates of 3.0%, 5.0% and 6.1%, respectively. These rates are higher than those observed in France from 2009 to 2015 (Taccoen, 2019). At the plot level, dieback was calculated for each species by weighting the individual scores of the dominant or co-dominant trees according to the proportion of their species in the total basal area of the plot. To describe the health status of each species in the plot, we attributed a species dieback plot score (*Dps*) ranging from 0 % (healthy) to 100 % (all the trees of the species are dead), as follows:

$$Dps = \sum_{i=1}^{n} Idx * Gi/Gp \qquad \text{Eq. 2}$$

where, for the considered species, *Gi* is individual tree basal area, n total number of trees, and *Gp* plot basal area.

The plots were then divided into two groups: 862 pure stands, in which the species covered 100% of the basal area of the dominant-codominant tree layer of the plot, and 1,102 mixed

stands, in which the target species covered less than 100% of the basal area (Fig.2). In the mixed stands, only the plots with healthy non-target species were retained.

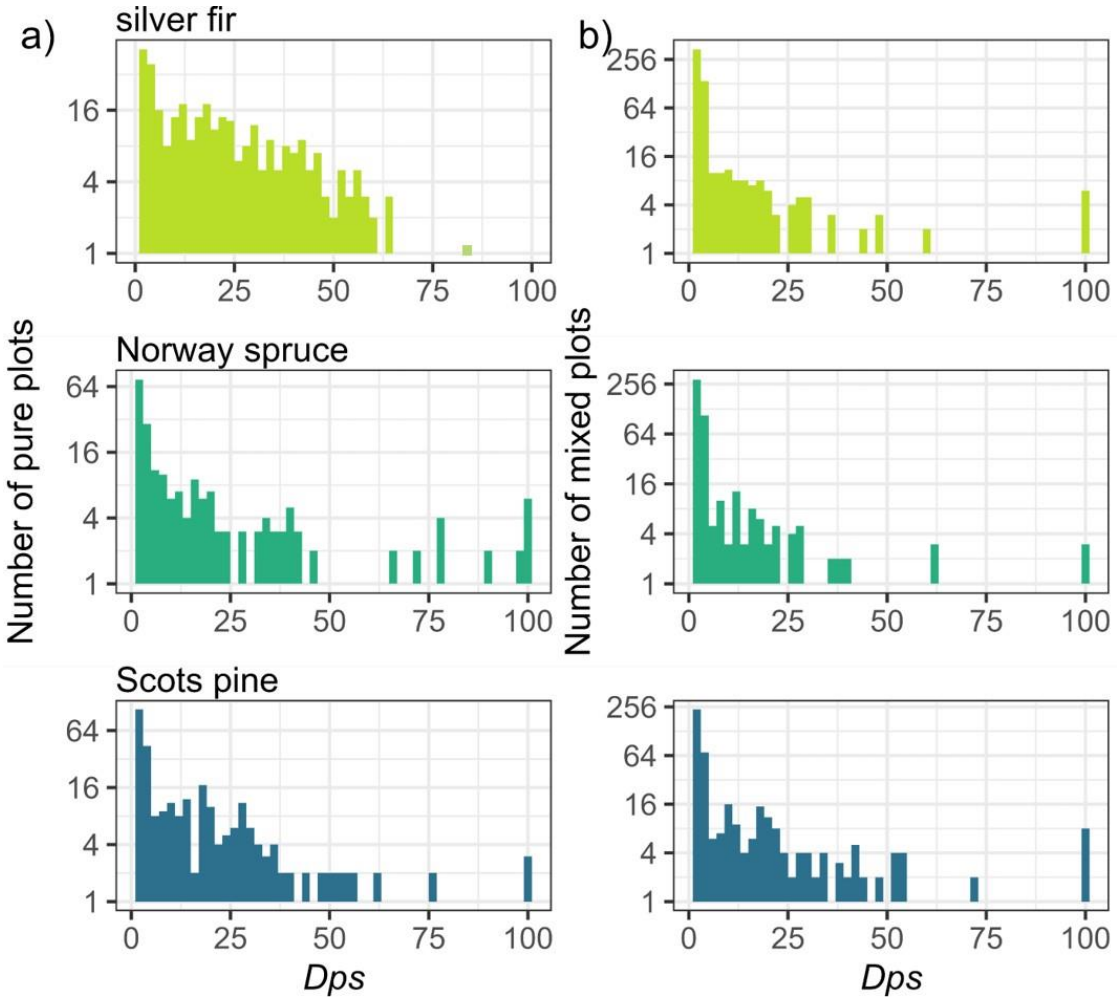

Fig.2: Log2 transformed distribution of the species dieback plot score (Dps) in a) pure (N=862), and b) mixed (N=1,102) stands for each studied species.

Satellite data

We used satellite-image time series (SITS) acquired by Sentinel-2A and 2B which is part of the Copernicus program (Drusch et al., 2012). Revisit time is five days and sensors acquire information in 13 spectral bands, ten of which are available with atmospheric correction. The spectral bands cover the VIS, NIR and SWIR domains. The spectral characteristics (centre wavelength for each band) and spatial resolution are given in Table.A.1.

The Sentinel-2 Level-2A images for the 28 Sentinel-2 tiles covering the study area (Fig.1), pre-processed for atmospheric correction by the MAJA processing chain, were downloaded from the Theia platform1 for the period from January 1, 2016 to December 31, 2023. Acquisitions with more than 30% cloud cover were discarded, resulting in 1,186 images and a revisit time ranging from six to 19 days. Non-valid observations corresponding to unmasked clouds, haze and snow were removed based on a reflectance threshold on band (B2) excluding surface reflectance > 6% out of the physical range (0-1), according to the method developed by Dutrieux et al. (2021). A pixel was attached to a plot if its centroid was included in the plot area resulting in an array from four to 100 pixels per plot (mean = 9 pixels, standard deviation = 3 pixels). The *Dps* defined at the plot level was then applied to each of its pixels. For each image associated with each plot, the plot was retained if the spectral information was valid (no clouds or shadows) in at least 50% of its pixels. We selected eight vegetation indices regularly used in conifer dieback detection studies and weakly intercorrelated (Tab.1, Fig.A.2): CRSWIR, NDWI, NDVI, REP, IRECI, CRRE, NDMI and MCARI (Table.1).

Table 1: Presentation of the selected vegetation indices. λBi and Bi are, respectively, the wavelength and reflectance (nm) of band i (Tab.A.1).

Vegetation index	Formulation	Reference
CR_{SWIR}	B11/ ((B8A + (λ_{B11} - λ_{B8A}) * ((B12-B8A) / (λ_{B12}- λ_{B8A})))	(Dutrieux et al., 2021)
NDWI	(B3-B8)/(B3+B8)	(McFeeters, 1996)
NDVI	(B8-B4)/(B8+B4)	(Tucker, 1979)
REP	700+35*(((B4+B7)/2)-B5)/(B6-B5)	(Gitelson & Merzlyak, 1998)
IRECI	(B7-B4)/(B5/B6)	(Frampton et al., 2013)
CR_{RE}	B5/(B4+(λ_{B5}- λ_{B4})*(B6-B4)/(λ_{B6}- λ_{B4}))	(Huang et al., 2004)
MCARI	((B5-B4)-0.2*(B5-B3))*(B5/B4)	(Daughtry, 2000)

NDMI	(B8A-B11)/(B8A+B11)	(Vogelmann & Rock, 1988)

Time-series analysis

FORDEAD approach

The FORDEAD time-series approach (Dutrieux et al., 2021) is an anomaly detection method applicable to satellite-image time series that operates at the pixel level. FORDEAD assumes that the seasonality of spectral information is stable over time for 'healthy' forest pixels. Spectral information may correspond to a vegetation index or to a spectral band, depending on the vegetation property expected to change with dieback. For each pixel, the seasonality corresponding to the healthy stage is calibrated with a harmonic model fitted over a sufficiently long period and based on a least-squares criterion (Eq.3). Anomalies correspond to a deviation from the harmonic model when extrapolated over time (Fig. 4). The training period defined to fit the harmonic model should be long enough to cover at least one full growing season, with a sufficient number of acquisitions. Here, we used a training period of two years (2016 and 2017) during which very little dieback occurred (Fig.A.3). Two growing seasons during the two-year training period were considered when fitting the harmonic model in order to account for within - and between-season variability (Rautiainen et al., 2018). A minimum of ten Sentinel-2 images with at least one per season during the training period were required to calibrate the model for each pixel, and the plot was only retained if at least 50% of its pixels could be calibrated. The most extreme 5% of the reflectance values for each spectral band (2.5% lowest and 2.5% highest) were eliminated during the training period in order to improve model fit.

$$HM = a1 + b1 * \sin(2\pi t/T) + b2 * \cos(2\pi t/T) + b3 * \sin(4\pi t/T) + b4 * \cos(4\pi t/T) \text{ , Eq. 3}$$

where T=365.25, t = number of days between the Sentinel-2 image and 01/01/2015, and ($a1$,$b1$,$b2$,$b3$,$b4$) are pixel model coefficients.

After the training period, for every Sentinel-2 image available for the period 2018-2023, a spectral anomaly at the plot level was defined as the average difference between the current value of the spectral index and the value predicted by the harmonic model for each pixel (Lastovicka et al. 2020) (blue arrows in Fig.3). The anomalies were then averaged over different time periods, called integration periods (orange arrows in Fig.3).

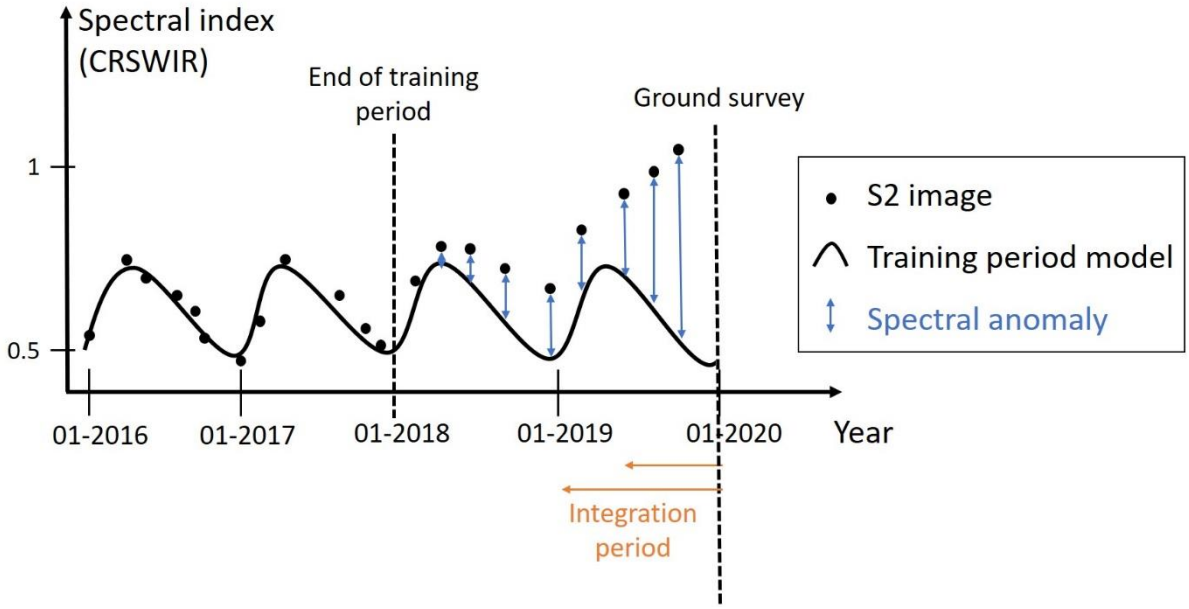

Fig.3: Schematic pixel trajectory analysed with the FORDEAD method.
The figure above shows CRSWIR dynamics for a plot with dieback symptoms observed in 01/2020.

After applying the above filters to the dataset, the 18 spectral indices (eight vegetation indices and ten Sentinel-2 spectral bands) were calculated for 1,691 of the 1,964 plots available. This represented 742 pure stands (289, 166 and 287 for silver fir, Norway spruce and Scots pine, respectively) and 949 mixed stands (438, 339 and 392 with silver fir, Norway spruce and Scots pine, respectively, including possible mixtures with each other).

Capacity of spectral indices and anomaly integration periods to predict dieback

For each of the 18 spectral indices, we used the averaged spectral anomaly as a predictive value for species *Dps* for the pure plots. Several integration periods, from one to 40 months, of the spectral anomaly were tested for each spectral index. We fitted a linear regression model with a quadratic term composed of the average observed anomaly for each spectral index over each anomaly's integration period as the y variable, and the *Dps* as the x variable, then calculated the coefficient of determination (R^2). For each species, we selected the best spectral index and integration period that, in combination, best correlated with the actual measured dieback. We then evaluated its capacity to detect dieback gradients for different degrees of mixture (Tab.A.3). We evaluated the quality of the model by looking at its coefficient of determination (R^2) and root mean square error (RMSE) (Chai & Draxler, 2014; Figueiredo Filho et al., 2011).

In order to compare our results with a more classical approach, contrasting the healthy and degraded condition of the trees, we classified the pure plots into two classes from the 30% *Dps* threshold recommended by the French Forest Health Service. For each species, this binary status was modelled using the best spectral index and integration period with a generalised linear regression model. A Receiver Operating Characteristic (ROC) curve was used to determine when each plot should be considered either healthy or declining (Fielding & Bell, 1997). Standard metrics overall accuracy (OA) and balanced accuracy (BA) (Pedregosa et al., 2011) were calculated (Fig.A.4). OA estimates the percentage of well classified plots and BA is defined as the average between the true positive rate and the true negative rate and is not influenced by an unbalanced dataset. The performance was validated with repeated tenfold stratified cross-validation; 70% of the dataset was used for training and the remaining 30% for testing.

Results

Performance of spectral indices and integration periods varies among conifer species

The performance of the spectral indices in predicting dieback gradients varied greatly among species (Fig.4). The best performing model had an R^2 of 0.54 for Norway spruce, 0.34 for silver fir, and 0.16 for Scots pine (RMSE 24, 22 and 22%, respectively). When considering only healthy and declining plots, OA and BA were 77% and 74% for Norway spruce, 61% and 63% for silver fir, and 64% and 62% for Scots pine (Tab.A.4).

The spectral index with the highest performance differed among species: IRECI for silver fir, CRSWIR for Norway spruce and CRRE for Scots pine. The performances were strongly species-dependent. For example, IRECI, the most efficient spectral index for silver fir, had an R^2 37% lower than CRSWIR for Norway spruce (28% RMSE) and 13% lower than CRRE for Scots pine (22% RMSE). CRSWIR was the best spectral predictor of the dieback gradient in terms of average R^2 regardless of species. However, selecting CRSWIR for all three species would have had a major impact on dieback predictability. The R^2 value for silver fir dieback predictions would have decreased from 0.34 to 0.19 (24% RMSE) and the capacity to predict Scots pine gradient of dieback would have been negligible (22% RMSE).

With the best spectral index applied for each species, optimal anomaly integration periods were 15 months for silver fir, four months for Scots pine and one month for Norway spruce (Fig. 5a). The best integration period in terms of average R^2 was nine months regardless of species. Applying a nine-month integration period for all three species, would have had a slight impact on the predictability of dieback. The R^2 value for silver fir, Norway spruce and Scots pine dieback predictions would have decreased by 6%, 7% and 19%, respectively.

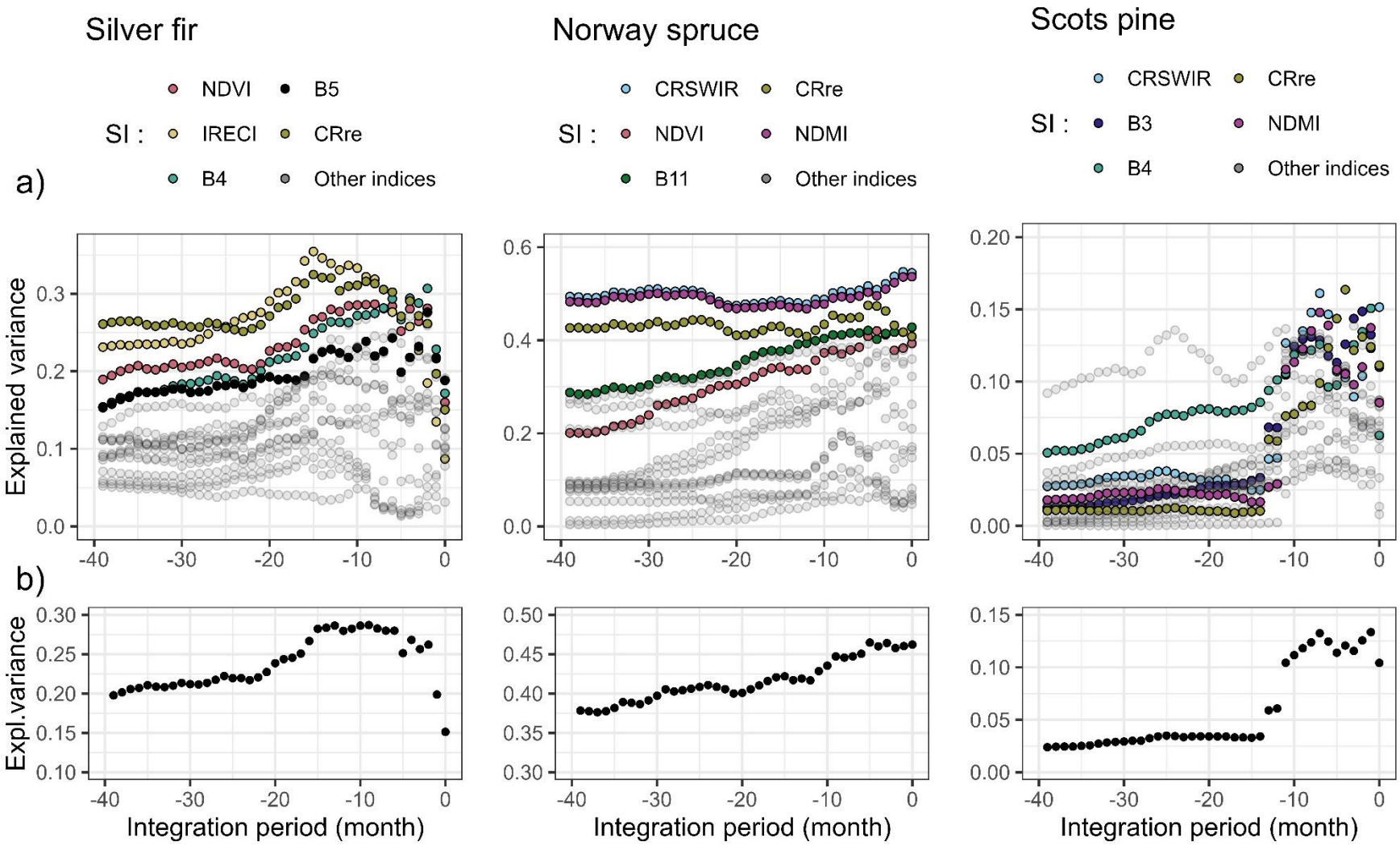

Fig.4: a) Explained variance (R^2) of different spectral index (SI) anomalies in detecting a continuous dieback gradient for silver fir, Norway spruce and Scots pine (n =289,166 and 287, respectively), for a range of integration periods. The five SIs with the highest explained variance is represented in colour. b) R^2 of the five best spectral indices averaged for each period. Each dot represents the R^2 between the Dps and the spectral anomaly for one SF and integration period.

Dieback detection according to dieback intensity and mixture percentage

We selected the spectral index and integration period that best predicted the observed dieback gradients for pure stands and examined its response to varying degrees of mixture. The spectral anomalies differed according to species, dieback intensity and mixture proportion (Fig.5). In pure stands, the spectral anomalies of silver fir showed a linear response to increasing dieback values. For Norway spruce, the response was exponential, while for Scots pine, the regression line was almost horizontal. Differences from healthy stands appeared from a *Dps* of 20-30% for silver fir, in contrast to Scots pine for which a high level of dieback was required to distinguish healthy from declining plots. For Norway spruce, no real distinction was discernible before a 50% *Dps* in pure stands, but beyond that value, the difference became increasingly accentuated.

Dieback detection was more challenging for species in mixed stands. However, the degree of mixing from which dieback can be detected varied among species. Even with the best spectral index, it was difficult to detect dieback for Norway spruce or Scots pine in mixed stands, whereas it was possible for silver fir, particularly when the species exceeded 50 % of the total basal area of the stand. The four next best spectral indices (Fig.4) showed similar patterns.

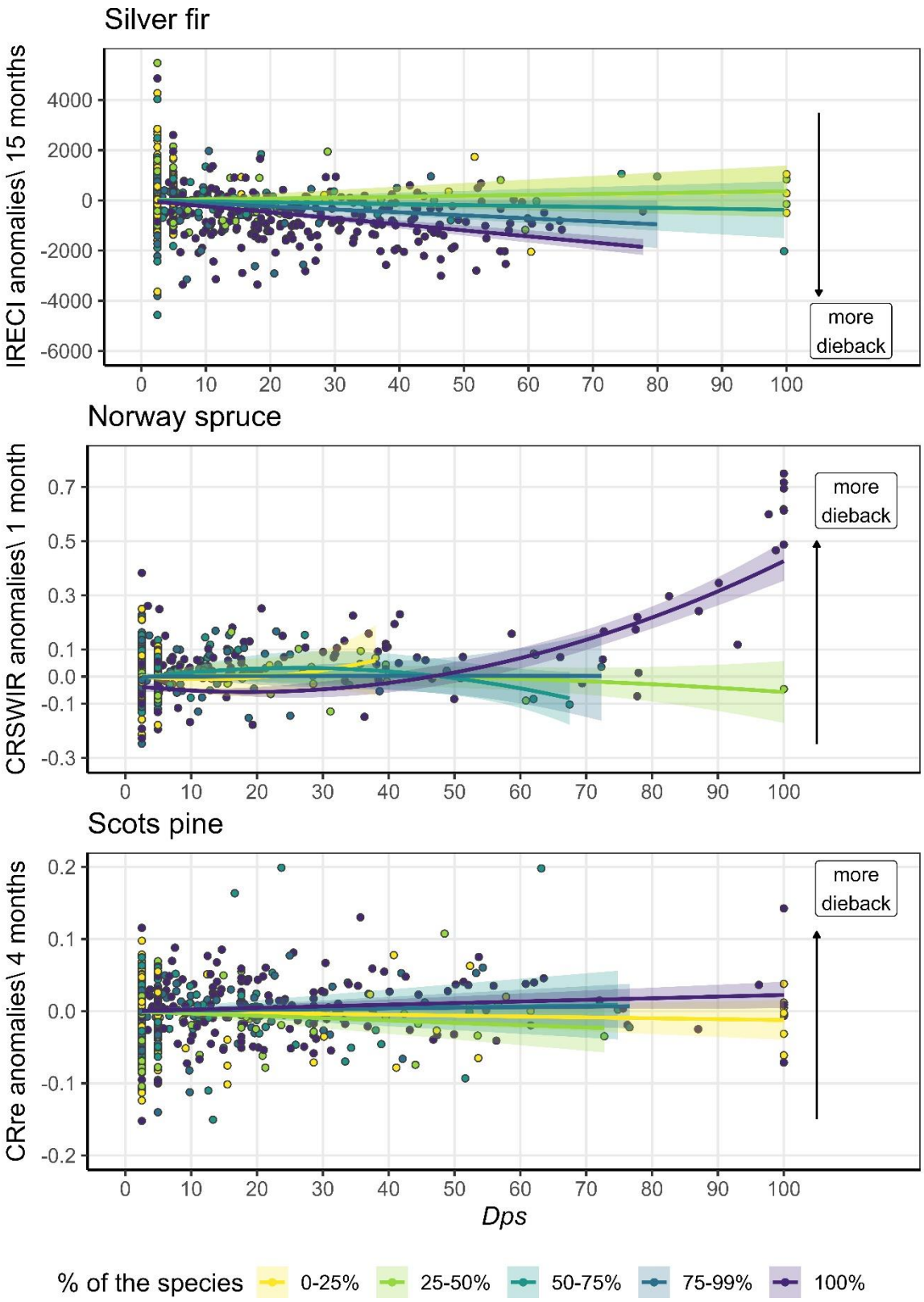

Fig.5: Comparison between spectral index anomalies and dieback gradient (Dps) for pure stands (noted 100 %) and different mixture classes for silver fir, Norway spruce and Scots pine (n=727,505 and 679 respectively). The dots represent each plot's averaged spectral anomalies. The supposed evolution of the spectral index under dieback is indicated by the black arrow. The regression curves are fitted and 95% confidence intervals are represented. R^2 and RMSE values are in Tab.A.5.

Discussion

The most efficient spectral index varied by species

Although a similar method is often used to detect dieback for different species (Lambert et al., 2013; Senf et al., 2018), we found predictions can be improved at the species level. This suggests that species-specific physiological responses are at play (Garrity et al., 2013). The differences among species may also be explained by the factors causing the dieback, which induce different symptoms. Silver fir and Scots pine dieback were most accurately identified with, respectively, IRECI and CRRE. Both indices contain visible and red-edge bands, which appear to be relevant for monitoring dieback in both species (Hawryło et al., 2018). This suggests that the detection of their dieback may depend on changes in photosynthetic activity, particularly chlorophyll content, which is the main factor influencing the reflectance of vegetation in the visible and red-edge regions. For these two species, the factors are more diverse than for Norway spruce but an increasing amount of the dieback reported by the French Forest Health Service is associated with the fungus Sphaeropsis sapinea for Scots pine (Fabre et al., 2011), and with the bark beetle Pitokteines spp. for silver fir (Durand-Gillmann et al., 2014), both of which cause crown discolouration. This is consistent with spectral index related to changes in chlorophyl content performing the best.

Norway spruce dieback was optimally detected with CRSWIR, which takes advantage of NIR and SWIR reflectance (Fig.A.5). This spectral index was developed specifically to detect Norway spruce dieback, and was identified as the most relevant spectral index during the development of the FORDEAD method (Dutrieux et al., 2021). In contrast to silver fir and Scots pine, bark beetles, especially Ips typographus L., are an important factor in Norway spruce dieback. They initially affect the water content of the tree crown by forcing the stomata to close (Abdullah et al., 2019b), thereby reducing their photosynthetic activity (Kautz et al.,

2023). This explains the high performance of CRSWIR, which is correlated with canopy water content and therefore particularly relevant for detecting bark beetle infestations (Abdullah et al., 2019a). Using the same spectral index to predict dieback for all species decreased detection performance, especially for silver fir, thus illustrating the benefit of detecting dieback at the species level. For all species, spectral bands were less effective than vegetation indices, thus confirming the latter's interest (Abdullah et al., 2019a).

Detection accuracy varies among species

Time-series analysis varied in performance among the studied coniferous species, with much better dieback gradient detection for Norway spruce than for silver fir or Scots pine. Differences in dieback detection for species belonging to the same functional group have rarely been investigated but similar observations have already been reported in studies conducted at the local scale with high-resolution unmanned aerial systems (Ecke et al., 2024; Kamińska et al., 2018). These differences may be explained by variations in the spectral characteristics of declining plots for each species, or by local mortality patterns, canopy cover or causes of dieback. The influence of the understory on surface reflectance measured with Sentinel-2 may be particularly important in severely declining plots with limited vegetation cover (Meiforth et al., 2020). Pine forest canopies are less dense than those of spruce or fir forests (Grabska & Socha, 2021); this could explain the lower detection rate for Scots pine dieback. When the influence of the understory is limited, as it is on poor sandy soils, performance can be better (Hawryło et al., 2018). These results highlight the importance of considering species-specific characteristics to improve large-area monitoring. Despite the limited number of studies focusing on dieback gradients at the species level, our performance appears to be in line with other studies. For example, Lambert (2013) reported 31 % of explained variance in detecting

the proportion of stressed silver fir trees using NDVI time series analysis. Crespo-Antia et al., (2024) found a correlation of -0.57 between silver fir stand defoliation and Enhanced Vegetation Index (EVI) time-series. Most existing studies focus on classifying a binary variable representing the presence or absence of dieback, which also showed close performance (Abdullah et al., 2019b; Bárta et al., 2021). For example, Bárta et al., (2021) obtained an OA of 78% for discriminating healthy from declining Norway spruce pure stands through time series analysis in Central Europe. Grabska et al., (2020) obtained an OA of 75% detecting dominated Scots pine forest loss with Sentinel-2 time series in Poland. Our results were obtained even though dead branches and defoliation are more difficult to detect than stand changes in colour or defoliation alone, as is the case in most studies (Abdullah et al., 2019a; Meneghini et al., 2022). We highlighted a non-linear response for Norway spruce with severe symptoms. Meddens et al., (2013), who examined changes in dieback accuracy as a function of red-stage percentage within pixels for Norway spruce, observed a similar result. We did not find the same nonlinearity for silver fir and Scots pine, possibly due to the absence of stands with high levels of dieback in our sample (maximum dieback plot score of 78% in silver fir stands, and only seven plots with a plot dieback score above 70% for Scots pine stands). Collecting a large number of ground observations with equal representation of dieback stages is challenging due to the rarity of declining stands and the frequent harvesting of declining trees. To mitigate this problem, we added plots located in areas of significant dieback to the systematic sampling plots from the NFI. The differences in dieback intensity observed at the plot scale also reflect different patterns among the three species studied. In the declining NFI plots, we observed a higher mortality rate for Norway spruce (39%), which is experiencing more massive dieback, than for Scots pine (26%) and silver fir (23%). These results suggest that the potential for mapping dieback areas is better for Norway spruce than for silver fir or Scots pine.

Shorter integration period for Norway spruce than for Scots pine and silver fir

The optimal integration period for Norway spruce dieback was one month before field observations, while for the other two species, a much longer period must be considered. This is consistent with Bárta et al. (2021), who showed that the trajectories of vegetation indices for red-stage Norway spruce stands deviated from their usual trend one or two months before field observations. For silver fir, on the other hand, Lambert et al. (2013) found the highest performance when considering spectral anomalies one or two years before field observations. The way different species react over time is linked to the cause of the stress. For example, Cailleret et al., (2017) studied tree growth prior to mortality and showed a shorter dieback period when mortality was caused by a biotic agent - particularly bark beetles - compared to a climatic cause. Norway spruce dieback is closely linked to bark beetle infestations, whereas for the other two species, decline is more common due to non-biotic factors and biotic factors are less aggressive (DSF & IGN, 2024). This could explain the earlier detection of anomalies for Norway spruce compared to Scots pine and silver fir.

Detection of the early-warning stage and dieback in mixtures remains challenging

The ability to detect early symptoms of dieback would allow managers to better anticipate crises and adapt forest management planning (Torres et al., 2021). Detecting gradients, including the early-warning stage, is complex, as demonstrated by White et al., (2005) and Meddens et al., (2013), whose results showed low accuracy at early dieback stages in conifer forests. In our study, we did not detect any early signals for Norway spruce dieback in pure stands. However, we did identify early signals for silver fir, and to a lesser extent for Scots pine, despite poorly estimated dieback gradients. These results suggest that early-warning dieback stages cannot be

detected for all species. This could hinder effective management of bark beetle infestations for Norway spruce, for example.

Seventy percent of European forests are mixed (UNECE & FAO, 2011). Even so, most studies assessing forest dieback through satellite detection have focused on pure stands (Marx & Kleinschmit, 2017), or have not considered the influence of species mixture when studying dieback for a given species (Hawryło et al., 2018). As expected, the detection of dieback performed less well in mixtures as the proportion of healthy species increased. At intermediate levels of mixture, we were better able to detect dieback for silver fir than for Scots pine and, especially, Norway spruce, for which dieback detection was efficient only in pure stands. For Scots pine and Norway spruce, the absence of mixed stands with high levels of dieback (plot dieback score > 70%) limited the comparison with pure stands. Mixtures - particularly between deciduous and coniferous trees - clearly increase the complexity of dieback detection (Lee & Lee, 2019). In our study, deciduous species were present in 72% of the mixed stands. With field survey information on species at the pixel scale rather than at the plot scale, the description of plot heterogeneity and the accuracy of dieback monitoring should improve. Precise species distribution maps are needed to adapt time-series analyses to the stand's composition. Some promising novel methods of species identification based on satellite time series or artificial intelligence are in development and may allow researchers to produce updated maps of species distribution over broad areas (Hermosilla et al., 2022; Gilles et al., 2024).

Uncertainties and improvements

The forest plots we studied covered a wide range of environmental conditions across Europe, in terms of altitude, soil, climate and management. Despite the pixel-scale calibration of our time-series analysis, which we expected would account for the local context (forest type, stand

characteristics, elevation), sources of uncertainty remain that can be due to local disturbances caused by changes in vegetation cover or management. We know that tree mortality increased In France after our calibration period (2016-2017) but we cannot be sure that no dieback occurred during the training period (DSF & IGN, 2024). We may therefore have underestimated mortality in some plots. The more time that elapses after the training period, the greater the risk of confounding mortality with changes related to stand dynamics or management. One solution might be to calibrate the model to a moving window (Mouret et al., 2024), but in this case, care should be taken to avoid calibrating the model during a period of higher mortality.

Finally, we considered the dieback plot score to be uniform at the plot scale and this probably limited the model's performance since the actual distribution of declining trees was not uniform throughout the plot, particularly for silver fir and Scots pine. Further analyses should evaluate the interest of integrating tree location inside the plot, for example, by using sensors with higher resolutions (airborne, UAV...) to allow work at the pixel scale and not at the plot scale.

The above-mentioned limitations can be important since they introduce noise into the spectral anomaly signals (Grabska & Socha, 2021). However, these uncertainties would not have affected the differences among the species highlighted in this paper.

Finally, the time series analysis method we used is based on the detection of anomalies with a single index. For all three species, we found different responses related to dieback intensity in almost all the spectral bands, which cannot be represented by a single vegetation index. The method could therefore be further optimised by combining different spectral indices, a technique that has been identified as a vector for improving current satellite-based forest monitoring (Ye et al., 2021). It should be noted, however, that this technique does not systematically improve the accuracy of dieback detection (Mouret et al., 2024).

Conclusion

We reveal important among-species differences in performance, spectral indices, anomaly integration periods, early warning stages and dieback detection. The ability of remote sensing to detect declining stands is related to dieback causes and patterns, which are different depending on the species and are also strongly influenced by mixture. Our results argue in favour of calibrating detection methods at the species level rather than at the functional group level. Our research should be extended to the other major tree species to determine the best parameters to assess and monitor their dieback. Our results also illustrate the interest of analysing Sentinel-2 time series, which could be used to produce high-resolution dieback maps at the species level when accurate and detailed land-use maps are available. This would make it possible to monitor dieback trends over time. Dieback is increasing in many parts of the world and there is an urgent need to develop an efficient monitoring system that provides a periodic picture of forest health and can help to improve forest management planning and policy making over large areas.

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Declaration of interest statement

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

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