# Can land surface phenology from Sentinel-2 time-series be used as an indicator of Macaronesian ecosystem dynamics?

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**A B S T R A C T**

Land surface phenology (LSP), the study of phenological patterns of vegetation using vegetation index (VI) time-series derived from multi-spectral satellite imagery, has helped to improve the understanding of the seasonal dynamics of terrestrial ecosystems from local to global scale. High spatial resolution satellite observations have emerged as a new possibility for monitoring the seasonal dynamics of heterogeneous ecosystems. Under-studied Macaronesian ecosystems have specific characteristics that make LSP estimation a complex task (e. g., frequent cloud cover, frequent presence of atmospheric aerosols, different degrees of vegetation density, diversity of plant species, landscape heterogeneity). Thus, this study aims to analyse the potential of LSP based on Sentinel-2 data to monitor the phenological dynamics of vegetation in the Macaronesian ecosystems of Canary Islands (Spain). NDVI time-series were generated using Sentinel-2 data from January 2018 to December 2021. NDVI time-series were smoothed using double logistic function. Three phenometrics, such as the start of the growing season (SOS), the end of the growing season (EOS) and the length of the growing season (LOS), were extracted using a threshold-based method (20%) only for pixels where the mean NDVI value of the smoothed four-year time-series was higher than 0.2. Growing season of the major of Macaronesian vegetation started between late summer and late autumn (start of the wet season) and ended between early spring and early summer (end of the wet season). The most representative Macaronesian tree species had a clear and marked seasonality, except for the laurel forest species. SOS of *Juniperus phoenicea* subsp. *turbinata* was slightly later than for *Olea europaea* var. *sylvestris* and *Pinus canariensis*, while the mean EOS was slightly later for *Olea europaea* var. *sylvestris*. The intra-specific variability of SOS and EOS in the laurel forests was very high. LSP derived from Sentinel-2 data contributed to understand the seasonal dynamics of the main Macaronesian ecosystems. However, the heterogeneity of laurel forests made it difficult the LSP estimation in laurel forests. Thus, complementary phenological approaches are suggested to improve the knowledge of the seasonal dynamics of this Macaronesian ecosystem.

## 1. Introduction

Vegetation phenology is defined as the scientific study of seasonal dynamics of the different biological phases (i.e., phenophases) that occur during the life cycle of plants (Lieth, 1974). The dates of plant phenophases, such as the emergence of leaves, flowering, change of leaf colour or leaf fall, were traditionally observed directly in the field at individual organism level (Menzel et al., 2006). This phenological information is characterised by the length of the time-series, with records available since the early 18th century (Holopainen et al., 2013; Sparks et al., 2009). However, the spatial distribution of observation stations is still very unequal at global level, with most of them concentrated in a few countries (e.g., United States, China, Germany, Austria and United Kingdom) (Berra and Gaulton, 2021). Thus, the traditional ground-based phenological observations have focused particularly on plant species in the temperate forests of the Northern Hemisphere, being unusual in tropical or subtropical ecosystems or in arid or semi-arid ecosystems (Richardson et al., 2013).

Land surface phenology (LSP) can be defined as the study of seasonal vegetation dynamics using multi-spectral satellite observations. (De Beurs and Henebry, 2004). LSP has played an essential role in monitoring the phenological patterns of plants in terrestrial ecosystems (Adole et al., 2016; Caparros-Santiago et al., 2021). LSP is generally based on the study of phenological metrics (hereinafter phenometrics) extracted from functional analysis of vegetation index (VI) time-series (Caparros-Santiago and Rodríguez-Galiano, 2020; Li et al., 2010;

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Rodriguez-Galiano et al., 2015). These phenometrics may be related to spring and autumn plant phenophases. The start of the growing season (SOS) may be related to leaf unfolding or flowering (spring phenophases), and the end of the growing season (EOS) may be associated to the autumnal colouring of leaves or leaf fall (autumn phenophases) (Caparros-Santiago et al., 2021). Near-surface remote sensing, based on multi-spectral radiometric sensors or image sensors on board near-surface platforms, has contributed to monitor the seasonal patterns of plants at an intermediate scale between traditional in-situ human observations (i.e., individual organism scale) and LSP (i.e., landscape scale) (Browning et al., 2017; Richardson et al., 2009).

LSP provides an aggregated view of the seasonal dynamics of vegetation at pixel level. Therefore, phenometrics may be influenced by both the biological cycles of different species and spectral information on non-vegetated covers (e.g., urban elements and waterbodies) (Helman, 2018). Satellite observations at a coarse spatial resolution (i.e., from 250 m to 8 km) have been used extensively to monitor LSP dynamics in terrestrial ecosystems (Rodriguez-Galiano et al., 2015; Wang et al., 2017). However, the applicability of coarse spatial resolutions in heterogeneous landscapes is limited (Melaas et al., 2013). Thus, the recent launch of satellite missions based on high-resolution spatial sensors may offer new possibilities for describing the seasonal vegetation patterns of heterogeneous ecosystems (Elmore et al., 2012; Vrieling et al., 2018). Satellite imagery at a more detailed spatial resolution (i.e., ≤ 30 m) have been used to analyse the phenological dynamics of evergreen, deciduous and mixed temperate forests in the mid- and high latitudes of the Northern Hemisphere. However, tropical or subtropical ecosystems have received less attention, despite their ecological importance at global level (Caparros-Santiago et al., 2021).

Seasonality in ecosystems of tropical and subtropical regions is mainly driven by rainfall patterns (Allen et al., 2017; Chamaille-Jammes et al., 2006), unlike the temperate and boreal forest ecosystems of the mid- and high-latitudes of the Northern Hemisphere, where seasonality is mainly driven by temperature (Jeong et al., 2011). Tropical and subtropical ecosystems where rainfall has strong seasonal variation (i.e., alternating between a wet season and a dry season) have been the most studied (e.g., tropical and subtropical dry forests or savannahs) (Caparros-Santiago et al., 2021). However, some of those ecosystems, such as the Macaronesian ecosystems (e.g., laurel forests, thermo-sclerophyllous woodlands), have received less attention, despite their singular natural characteristics (Kier et al., 2009).

Macaronesian region is a biogeographic region located off the western coasts of the Iberian Peninsula and the northern African continent in a latitudinal range from 14° N to 40° N (i.e., a transition zone between temperate and tropical environments). The five volcanic archipelagos in this biogeographic region (i.e., the Azores, Madeira, Savage Islands, Cape Verde Islands and Canary Islands) are important biodiversity hotspots with a large variety of endemic plant species (Hobohm, 2000; Myers et al., 2000). Despite the biological richness of the Macaronesian ecosystems and the important variety of the ecosystem services they provide (Hobohm, 2000; Vergílio et al., 2017), few studies have analysed the seasonal behaviour of vegetation in this biogeographic region (Izquierdo et al., 2011; Medina-Alonso et al., 2020; Rumeu et al., 2009). Most of these studies focused on the analysis of the temporal and/or spatial dynamics of certain phenophases (e.g., flowering, fruiting) using traditional human phenological observations (Arévalo et al., 2007; Medina-Alonso et al., 2020; Rumeu et al., 2009). Complementarily, Izquierdo et al. (2011) studied the seasonal behaviour of Macaronesian ecosystems by observing the phenological trajectory (VI curve) of vegetation derived from satellite data at a coarse spatial resolution (250 m). Izquierdo et al. (2011) reported the existence of moderate seasonality in the phenological trajectory of vegetation in laurel forests and recommended the use of VI time series to monitor vegetation dynamics in these ecosystems.

Macaronesian ecosystems range from arid or semi-arid deserts with sparse (or non-existent) vegetation to dense evergreen broadleaf forests

(Fernández-Palacios and Whittaker, 2008). The high density and wide diversity of plant species in some Macaronesian evergreen broadleaf forests (e.g., laurel forests) can make the detection of vegetation seasonality a difficult task (Ganguly et al., 2010). Conversely, some Macaronesian forest ecosystems (e.g., thermo-sclerophyllous woodlands) are characterised by low or moderate density of tree species and a significant presence of herbaceous and shrub vegetation. Thus, the phenological trajectory of these open forests may include a mix of the biological cycles of different functional vegetation types (i.e., herbaceous, shrub and tree vegetation) and the effects of bare soil, making LSP estimation challenging (Higgins et al., 2011; Jeong et al., 2011). Phenological trajectory can also be influenced by soil effects in non-forest ecosystems where vegetation is sparse. Also, frequent cloudiness and/or the significant presence of atmospheric aerosols (e.g., desert dust, biogenic atmospheric aerosols, marine aerosols) in certain Macaronesian ecosystems may affect the capture of good-quality optical satellite images (Ganguly et al., 2010). Therefore, the availability of a high number of satellite observations (i.e., high temporal resolution) at high spatial resolution should be able to improve LSP modelling in these ecosystems. At species level, LSP has focused on tree species in extensive, dense (closed forests) and very homogeneous forest stands of temperate ecosystems in the mid-latitudes of the northern hemisphere (Aragones et al., 2019; Duchemin et al., 1999; Gómez et al., 2020). Macaronesian forest ecosystems are defined by a high diversity and heterogeneity of plant species. Thus, a higher spatial resolution of satellite images (e.g., ≤ 10 m) could favour LSP estimation at species level of Macaronesian tree species in both dense (i.e., closed forests) and sparse forest stands (i.e., open forests).

This study aims to analyse LSP patterns as indicators of the dynamics of Macaronesian vegetation using Sentinel-2 optical data at a high spatial resolution. This requires answering the following scientific questions: i) do Macaronesian ecosystems show a marked seasonality in the phenological trajectory from Sentinel-2 spatial and temporal resolution? and ii) do Macaronesian forest ecosystems have suitable structure (e.g., density, coverage, homogeneity) to be studied using a LSP approach?

## 2. Materials and methods

### 2.1. Study area

Canary Islands (Spain) are located off the north-western coast of the African continent in the subtropical Northeast Atlantic region (27° 35′ N-29° 25′ N; 13° 20′ W-18° 10′ W) (Fig. 1). This volcanic archipelago, the largest in the Macaronesian biogeographic region, hosts its most representative ecosystems, ranging from arid or semi-arid ecosystems with sparse shrub or herbaceous vegetation to dense evergreen needle-leaf and broadleaf forests (Fig. 2). Thus, Canary Islands are an excellent natural laboratory for monitoring LSP patterns as an indicator of the dynamics of Macaronesian ecosystems. Lanzarote and Fuerteventura were not included in this study. These islands are characterised by the predominance of open spaces with little or no vegetation. Therefore, the phenological information was limited to a very small area.

The characteristic forest ecosystems in the Canary Islands are the laurel forests, thermo-sclerophyllous woodlands and pine forests (Fernández-Palacios and Whittaker, 2008). Laurel forests are subtropical forests generally located on the windward slopes of mountain regions (300–1500 m). This ecosystem is characterised by an annual rainfall regime between 500 and 1200 mm, frequent fog, limited insolation and moderate mean annual temperatures (13–18 °C). Laurel forests are characterised by the predominance of broadleaf tree species, which form a dense canopy that can be 30 to 40 m high. The low light that penetrates through the treetops hinders the development of vegetation in the understory, where ferns are frequent (i.e., umbrophilic species). Some representative tree species of this forest are *Laurus novocanariensis*, *Laurus azorica*, *Erica arborea* and *Myrica faya* (del Arco Aguilar and
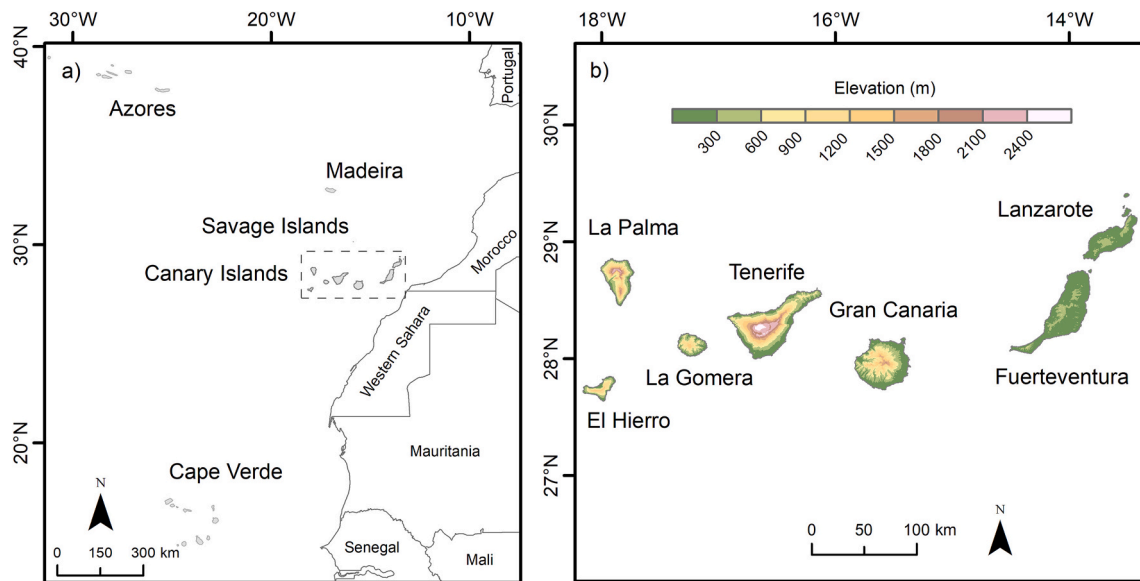
**Fig. 1.** Geographic location of the Canary Islands in the context of the Macaronesian biogeographic region (a) and spatial distribution and elevation of the Canary Islands (b).

Rodríguez Delgado, 2018). Thermo-sclerophyllous woodlands are Mediterranean-like ecosystems in the Canary Islands, located in areas with high insolation, higher mean annual temperature (15–19 °C), low precipitation (300–400 mm) and sporadic sea fogs. These forests are characterised by the presence of different tree species adapted to summer drought conditions (e.g., *Juniperus phoenicea, Olea europaea, Pistacia atlantica, Phoenix canariensis*). These tree species usually form a low-moderate canopy density, which allows the development of a significant understory where different xerophilous shrub species grow (e.g., *Bosea yerbamora, Jasminum odoratissimum, Retama rhodorhizoides, Rhamnus crenulata*) (del Arco Aguilar and Rodríguez Delgado, 2018; Fernández-Palacios et al., 2008). *Pinus canariensis* is the main tree species in the pine forests. These forests, generally located in areas with a highly variable elevational range (700–2300 m), are characterised by a mean annual temperature of 11–15 °C and an annual precipitation regime of 450–600 mm (Arévalo et al., 2011; del Arco Aguilar and Rodríguez Delgado, 2018).

Shrublands are also very common ecosystems in the Canary archipelago, which can be identified both near the coast and in high mountain areas. Coastal shrublands are sub-arid ecosystems located in areas of relatively low elevation (i.e., from sea level to 400 m). This coastal ecosystem is characterised by high mean temperature and low precipitation (100–200 mm). Summit shrublands are less arid ecosystems than those mentioned above, with an annual precipitation regime of 400–500 mm. They are in regions with an elevation above 2000 m, where low temperature (< 10 °C), frequent frosts and wind intensity hinder the development of arboreal vegetation (del Arco Aguilar and Rodríguez Delgado, 2018).

### 2.2. Datasets

Two data sources were used in this research: i) time-series of Sentinel-2 A/B MultiSpectral Instrument (MSI) images; and ii) field data on the most representative tree species of the main forest ecosystems in the Canary Islands.

292 Sentinel-2 surface reflectance satellite images were obtained for the period between January 2018 and December 2021 (i.e.,73 images per year with a temporal resolution of 5 days) from the Google Earth Engine platform. These satellite images were atmospherically corrected. These were filtered using SCL (Scene Classification Layer) quality band, removing saturated or defective pixels, dark area pixels, cloud shadows,

water areas, and clouds and cirrus. The tiles corresponding to the study area are 27RYL, 28RBS, 28RCS, 28RDR, 28RDS, 28RES, 28RFS, 28RFT. The study area is covered by three overlapping orbits. Maximum value was chosen as representative of 5-day period in the overlapping area between tiles. NDVI time-series were subsequently generated at a spatial resolution of 10 m using the red band (0.65 μm–0.68 μm) and the near-infrared band (0.78 μm–0.90 μm).

The identification of the representative species of Macaronesian ecosystems and their location was done by means of sampling based on a pre-existing forest inventory (IFN3) and the Forest Map of Spain at 1:25,000 scale (MFE25). IFN3 (1997–2007) provides information about the characteristics of the tree and shrub species (e.g., spatial distribution, diversity, stand age structure, origin) of >96,000 forest plots. MFE25 contains updated information about different characteristics of Spanish forest ecosystems (e.g., spatial distribution of main tree species, plant cover). These data allowed to stratify the phenological analysis based on the most common tree species of the Macaronesian forest ecosystems (i.e., laurel forests, thermo-sclerophyllous woodlands, pine forests (Fernández-Palacios and Whittaker, 2008)).

Sampling points were selected using photo-interpretation of high-resolution orthophotographs derived from Spain's National Aerial Orthophotography Plan (PNOA; https://pnoa.ign.es/). Previous studies based on LSP monitoring at species level generally focused on large, dense (i.e., closed forests) and very homogeneous (i.e., mono-specific, or nearly mono-specific) forest stands (Aragones et al., 2019; Duchemin et al., 1999). In this sense, only forest stands of *Pinus canariensis* presented characteristics considered by those studies. Laurel forests were characterised by their high forest stand density. Despite this, the wide variety and mixture of tree species made it difficult to identify homogeneous forest stands in an area of 100 m$^2$ (i.e., spatial resolution of the Sentinel-2 pixel). Therefore, the forest stands dominated mainly by *Myrica Faya* and *Erica arborea* were selected as representative of this Macaronesian forest ecosystem. The spatial distribution of the thermo-sclerophyllous species is quite variable. Moderate canopies of multiple thermo-sclerophyllous tree species (i.e., heterogeneous forest stands) could be identified in different areas of the islands. However, open thermo-sclerophyllous woodlands (i.e., low canopy density) are predominant, where small mono-specific (or nearly mono-specific) tree forests (about 100 m$^2$) could be identified in the various forest plots. Thus, *Olea europaea* var. *sylvestris* and *Juniperus phoenicea* subsp. *turbinata* were the only two tree species selected as representative of the
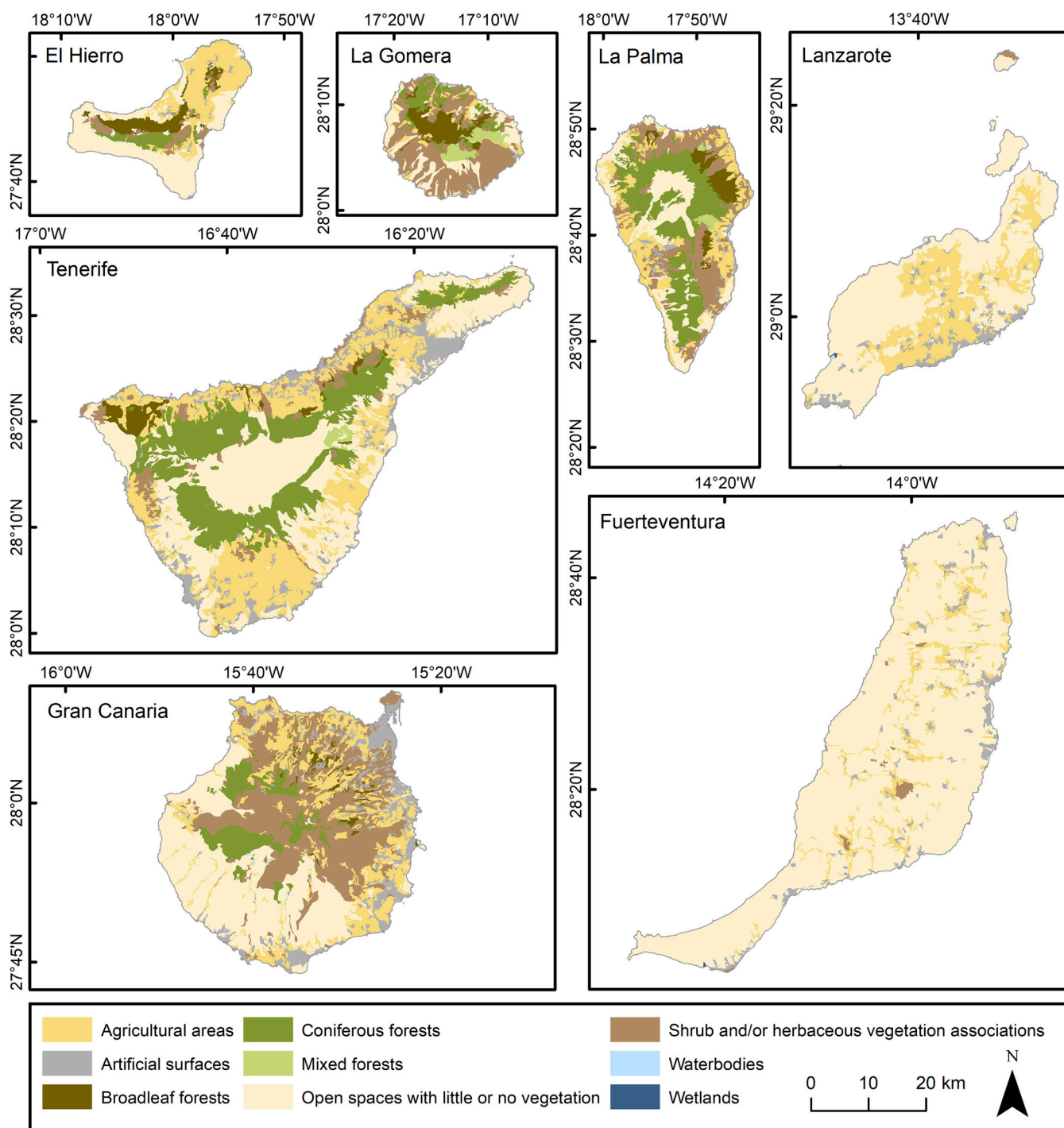
**Fig. 2.** Spatial distribution of the main land cover categories of the Canary Islands. This map is based on data obtained by the CORINE Land Cover project (2018) (https://land.copernicus.eu/pan-european/corine-land-cover).

thermo-sclerophyllous woodlands.

The selected sampling points coincided with those pixels where the forest stand met two specific criteria: i) the forest stand should be mono-specific (or nearly mono-specific) or dominated by *Myrica Faya* and *Erica arborea* in laurel forests; and ii) the forest stand should be representative of at least 60% of the pixel. Thus, 340 sampling points were selected (Fig. 3).

*2.3. LSP estimation*

The estimation of LSP from the smoothed NDVI time-series was based on two steps: i) data smoothing and ii) extraction of phenometrics. NDVI time-series was smoothed using the double logistic function implemented in the TIMESAT software (Jönsson and Eklundh, 2004). The areas where the mean NDVI value of the smoothed four-year time-series was low ($\leq 0.2$) were not considered in this study, as these areas may be associated to open spaces with little or no vegetation (Jeong et al., 2011; Zhou et al., 2001).

Three phenometrics were extracted using a threshold-based method: i) SOS, defined as the moment (day of year; DOY) when the smoothed NDVI value reached 20% of the curve's amplitude before the maximum; ii) EOS, defined as the moment (DOY) when the value of the smoothed
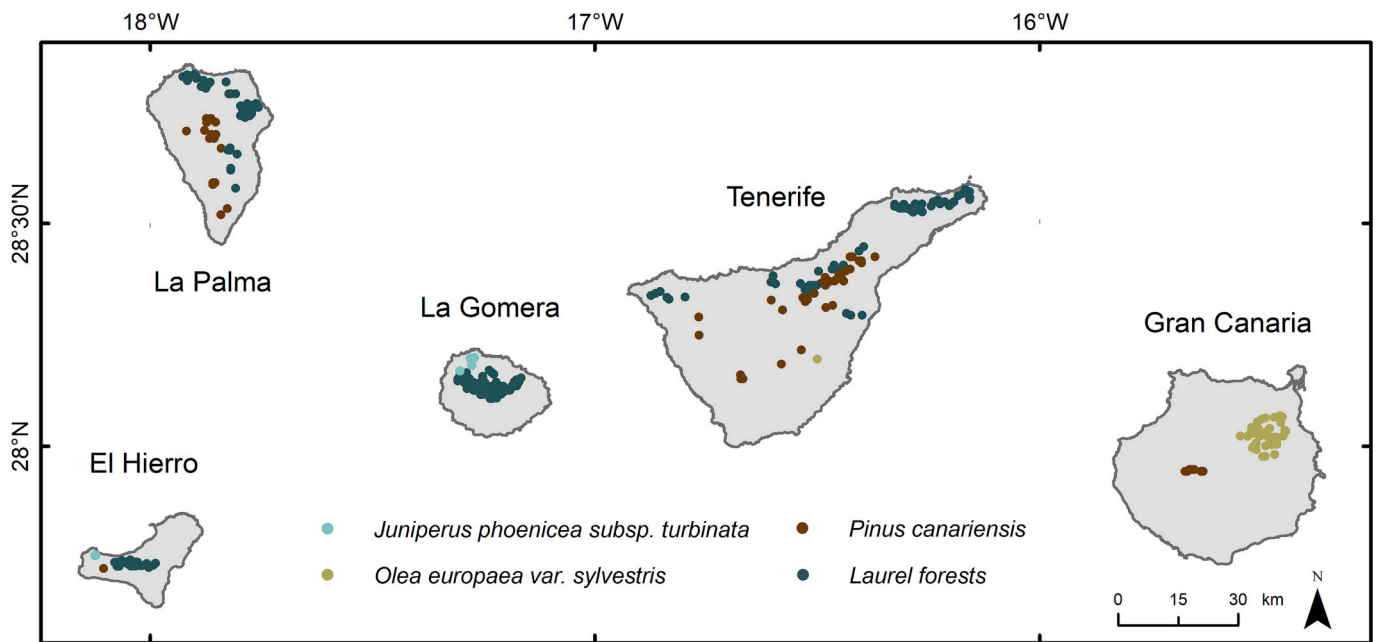
**Fig. 3.** Spatial distribution of samples of the tree species selected as representative of the forest ecosystems in the Canary Islands: *Pinus canariensis* (61), *Olea europaea* var. *sylvestris* (38), *Juniperus phoenicea* subsp. *turbinata* (34) and laurel forest (207).

NDVI curve fell to 20% of the amplitude after the maximum; and iii) LOS, defined as the difference between EOS and SOS (number of days). Growing seasons of >365 days were excluded. The phenometrics of the second growing season were excluded in this study, as few pixels had bimodal seasons (<3% of the pixels). SOS and EOS dates were rescaled between 1 and 365 to facilitate interpretation of the results.

### 2.4. Statistical test

Welch's *t*-test was used to quantitatively analyse the influence of the number of cloud-free observations on the detection of SOS and EOS in each of the tree species considered in this study. Welch's test is based on the calculation of the t-statistic (Welch, 1938), which was used as a measure of the difference in means between phenometrics and number of cloud-free observations with the variability within each group. This test considers that the variances are unequal, adjusting the degrees of freedom. Therefore, the result is a more accurate estimate of the standard error of the mean difference.

### 3. Results

#### 3.1. Spatial patterns of phenometrics in the Macaronesian ecosystems

Fig. 4 and Table 1 shows the spatial variability of spring and autumn phenometrics (i.e., SOS and EOS) of the vegetation in the Canary Islands for the period 2018–2021. Tenerife, Gran Canaria, La Gomera, El Hierro and La Palma showed a general phenological pattern, in which a significant part of the vegetation started the growing season between September and December and ended it between March and June. This seasonal pattern was generally observed in conifer forests throughout the archipelago, where forests of *Pinus canariensis* are dominant. However, the broadleaf forests did not have a common phenological pattern between islands. The southern area of all these islands is dominated by open spaces with little or no vegetation. Phenological information was thus limited to: i) areas where the natural vegetation had a more significant presence (e.g., herbaceous vegetation and shrublands); and ii) cultivated areas. LOS of vegetation in the Canary Islands is indicated in Fig. 5. The shortest growing seasons (<6 months) were generally associated to agricultural areas and areas of herbaceous vegetation. The

growing season of the conifer forests was approximately 8–9 months. Broadleaf forests were the forest ecosystems with the longest growing seasons.

Despite the existence of certain similarities in the phenological dynamics of these islands, the spatial variability of LSP showed substantial differences.

#### 3.1.1. Tenerife

The sparse (or non-existent) vegetation in the highest area of Tenerife was the reason for the lack of a marked seasonality and, therefore, phenological information (area 1). The area bordering that zone (area 2) is dominated by conifer forests, where SOS occurred between September (DOY 256, 25th percentile) and October (DOY 297, 75th percentile) and EOS between April (DOY 94, 25th percentile) and June (DOY 167, 75th percentile). The latest SOS dates over the 4-year period were in 2019 (October, mean DOY 277) in this coniferous area. In contrast, both SOS and EOS occurred earlier in 2021: the mean growing season for coniferous forests started in September (DOY 256) and ended in April (DOY 107). The northern valley of Tenerife (area 3) is dominated by different cultivation types, such as banana plantations, vineyards and citrus orchards (Pestana et al., 2016). This diversity of crops may explain the lack of a common phenological pattern in this area. These croplands had the highest spatial variability in SOS and EOS dates for the whole island and the study period (>75 days). Shrublands and herbaceous vegetation, characteristic of the area closest to the eastern coast of Tenerife (area 4), had the SOS between October (DOY 288, 25th percentile) and November (DOY 312, 75th percentile). EOS was between May (DOY 140, 25th percentile) and June (DOY 177, 25th percentile). The phenological interest of the southern zone of the island, where there is little or no vegetation, lies in the few cultivated areas. The largest area of cultivation, located on the south-west coast (area 5) (i.e., area dominated by banana plantations (Pestana et al., 2016)), had the SOS between October (DOY 285, 25th percentile) and November (DOY 311, 75th percentile) and the EOS between May (DOY 133, 25th percentile) and June (DOY 176, 75th percentile). The earliest SOS dates and the latest EOS dates were observed for areas 4 and 5 in 2020, leading to longer growing seasons.
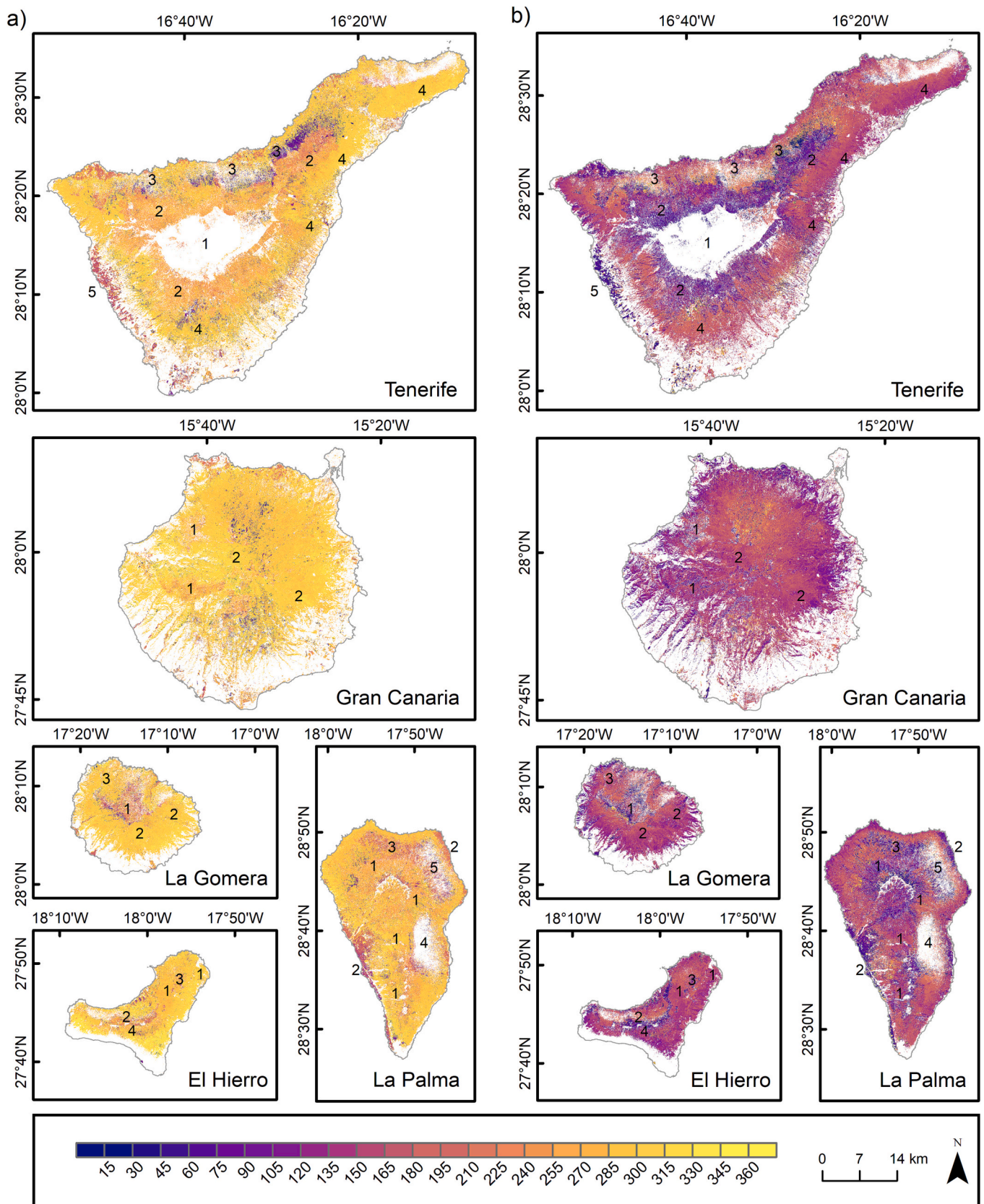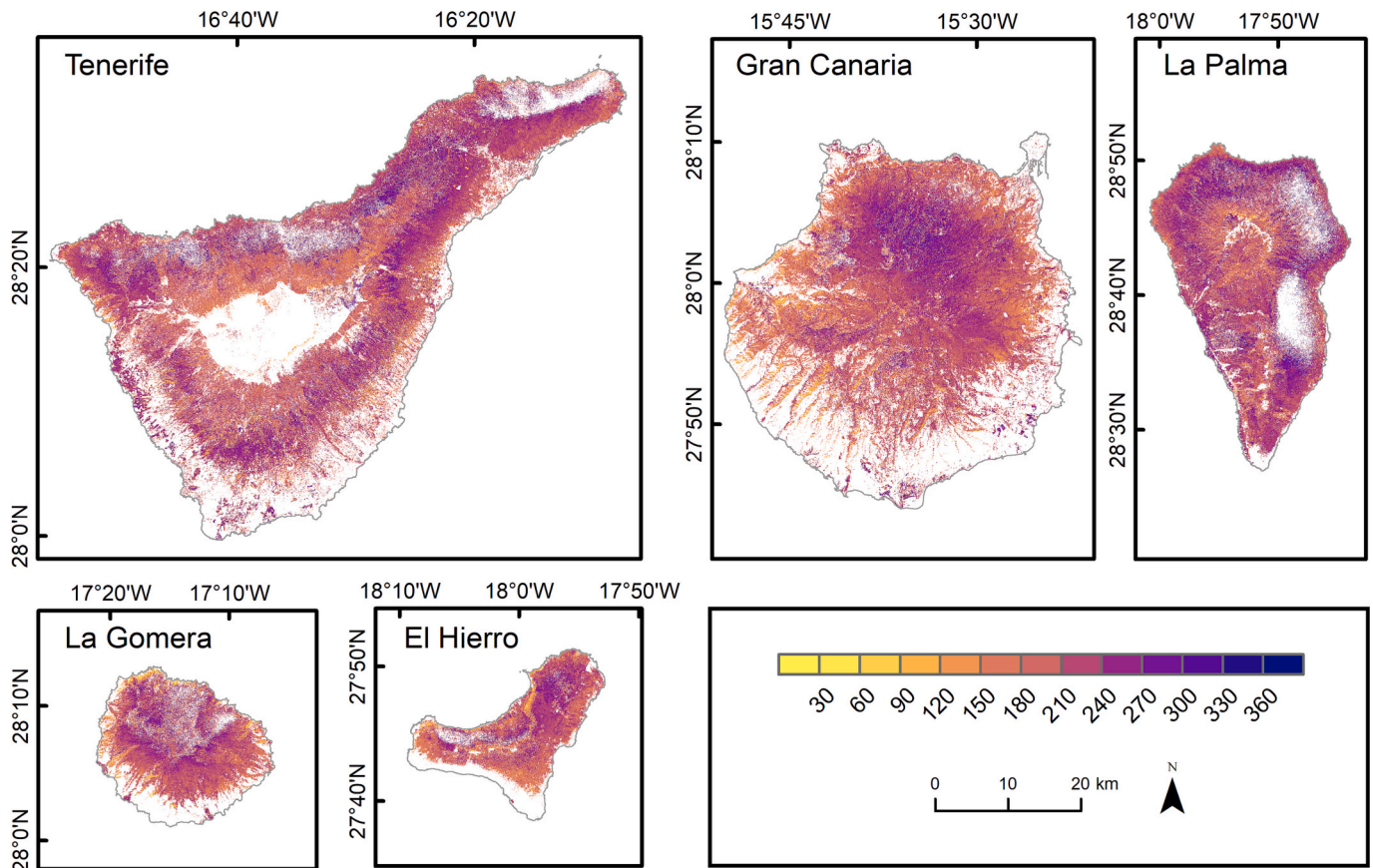
**Fig. 4.** Spatial distribution of the median phenometrics for the period 2018–2021: a) median SOS and b) median EOS. The numbers in the islands indicate areas of special phenological relevance. The white pixels show areas with little or no vegetation (areas where the NDVI values of the phenological trajectory are low) or areas where the vegetation did not have clear seasonality.

**Table 1**
Spatial averages (x̄) of SOS and EOS dates and differences (σ) for the identified areas for each island. * No data (areas with a low percentage of LSP data were excluded).

| ISLANDS | AREAS | 2018 | | | | 2019 | | | | 2020 | | | | 2021 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SOS (x̄) | SOS (σ) | EOS (x̄) | EOS (σ) | SOS (x̄) | SOS (σ) | EOS (x̄) | EOS (σ) | SOS (x̄) | SOS (σ) | EOS (x̄) | EOS (σ) | SOS (x̄) | SOS (σ) | EOS (x̄) | EOS (σ) |
| EL HIERRO | 1 | 290 | 22 | 163 | 33 | 305 | 34 | 156 | 54 | 314 | 52 | 112 | 59 | 290 | 21 | 139 | 30 |
| | 2 | 264 | 44 | 129 | 60 | 273 | 63 | 121 | 77 | 240 | 130 | 172 | 90 | 250 | 60 | 143 | 70 |
| | 3 | 256 | 77 | 164 | 70 | 225 | 124 | 168 | 88 | 268 | 99 | 156 | 97 | 238 | 77 | 175 | 78 |
| | 4 | 280 | 35 | 128 | 49 | 271 | 58 | 129 | 44 | 241 | 97 | 124 | 51 | 276 | 53 | 118 | 47 |
| LA PALMA | 1 | 274 | 37 | 141 | 50 | 266 | 42 | 134 | 52 | 270 | 41 | 131 | 53 | 279 | 41 | 132 | 62 |
| | 2 | 211 | 67 | 119 | 73 | 198 | 73 | 107 | 83 | 263 | 61 | 123 | 64 | 239 | 62 | 117 | 75 |
| | 3 | 247 | 53 | 146 | 58 | 269 | 52 | 149 | 58 | 267 | 74 | 160 | 62 | 263 | 43 | 142 | 53 |
| | 4 | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| | 5 | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| LA GOMERA | 1 | 244 | 69 | 127 | 68 | 264 | 70 | 133 | 78 | 261 | 101 | 163 | 64 | 229 | 52 | 99 | 51 |
| | 2 | 295 | 16 | 168 | 29 | 302 | 16 | 166 | 28 | 304 | 30 | 159 | 42 | 296 | 16 | 130 | 34 |
| | 3 | 270 | 52 | 148 | 78 | 296 | 64 | 184 | 62 | 294 | 59 | 132 | 59 | 276 | 55 | 131 | 52 |
| TENERIFE | 1 | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| | 2 | 275 | 51 | 122 | 59 | 277 | 55 | 125 | 59 | 267 | 65 | 131 | 63 | 256 | 70 | 107 | 64 |
| | 3 | 238 | 85 | 142 | 76 | 241 | 91 | 144 | 84 | 269 | 81 | 160 | 77 | 247 | 81 | 128 | 77 |
| | 4 | 297 | 27 | 154 | 37 | 292 | 41 | 134 | 45 | 292 | 84 | 174 | 42 | 295 | 36 | 142 | 35 |
| | 5 | 288 | 45 | 151 | 43 | 284 | 53 | 133 | 51 | 281 | 92 | 169 | 49 | 287 | 52 | 139 | 43 |
| GRAN CANARIA | 1 | 270 | 54 | 150 | 48 | 296 | 48 | 174 | 64 | 276 | 76 | 132 | 50 | 264 | 44 | 122 | 45 |
| | 2 | 282 | 56 | 161 | 41 | 305 | 51 | 155 | 42 | 291 | 92 | 145 | 55 | 278 | 58 | 135 | 42 |



**Fig. 5.** Spatial distribution of the median LOS for the period 2018–2021. This phenometric is expressed in number of days. The white pixels show areas with little or no vegetation (areas where the NDVI values of the phenological trajectory are low) or areas where the vegetation did not have clear seasonality.

### 3.1.2. Gran Canaria

Vegetation generally showed two main phenological behaviours on Gran Canaria. The tree vegetation of the area dominated by conifer forests (area 1) had the SOS between the late summer and early autumn (i.e., between September (DOY 269, 25th percentile) and October (DOY 303, 75th percentile) and its growing season lasted until the spring months (i.e., from April (DOY 118, 25th percentile) to June (DOY 172, 75th percentile)). Vegetation in area 2, characterised by a notable heterogeneity of land covers (i.e., broadleaf forests, shrubland and agricultural areas), generally started the growing season between October (DOY 290, 25th percentile) and November (DOY 313, 75th percentile) and ended it between May (DOY 127, 25th percentile) and June (DOY

178, 75th percentile). The earliest SOS and EOS dates were observed in 2021 in both areas: the growing season started between September and October (DOY 264 (area 1) - DOY 278 (area 2)) and ended in May (DOY 122 (area 1) - DOY 135 (area 2)). The latest SOS dates were observed for both areas in 2019. The latest EOS was also observed in that year for coniferous forests (area 1) (June, DOY 174). However, the latest EOS was for area 2 in 2018 (June, DOY 161).

### 3.1.3. La Gomera

The central area of La Gomera (area 1) was characterised by the lack of a defined phenological pattern in SOS and EOS. Broadleaf forests are the dominant vegetation type in this area, where the presence of different plant communities characteristic of laurel forests is very common (Izquierdo et al., 2011). These forests had a very high spatial variability in SOS and EOS dates for the whole study period (between 50 and 100 days). A clearer phenological pattern could be discerned in the area located immediately south of this central region (area 2). Mixed forests are the dominant vegetation type in this area. They generally had the SOS between October (DOY 290, 25th percentile) and November (DOY 306, 75th percentile) and the EOS between May (DOY 146, 25th percentile) and June (DOY 175, 75th percentile). Mixed forests had the earliest SOS and EOS dates in 2021: the growing season started in October (mean DOY 296) and ended in May (mean DOY 130). The latest SOS was in 2020 (November, mean DOY 304), while the latest EOS occurred in 2018 (June; mean DOY 168) for these forests. The vegetation of the conifer forests in the north-western area of the island (area 3) had a similar phenological pattern, in which the SOS occurred between October (DOY 283, 25th percentile) and November (DOY 311, 75th percentile) and the EOS between May (DOY 131, 25th percentile) and July (DOY 188, 25th percentile). Conifer forests had the latest SOS and EOS dates in 2019: the growing season started in October (mean DOY 296) and ended in July (mean DOY 184). The earliest SOS was in 2018 (September, mean DOY 270), while the earliest EOS occurred in 2021 (May; mean DOY 131) for these forests.

### 3.1.4. El Hierro

The north-eastern sector of the island of El Hierro (area 1) is dominated by agricultural areas with a general phenological pattern, with SOS occurring between October (DOY 287, 25th percentile) and November (DOY 312, 75th percentile) and EOS between May (DOY 142, 25th percentile) and June (DOY 175, 75th percentile). The region of El Hierro dominated by evergreen broadleaf forest (e.g., laurel forests) and shrublands (areas 2 and 3) showed a very high phenological variability. Thus, no phenological pattern could be observed in these areas. The growing season of the conifer forests (area 4) started between September (DOY 262, 25th percentile) and November (DOY 310, 75th percentile) and ended between April (DOY 106, 25th percentile) and June (DOY 160, 75th percentile). The latest SOS in this area was observed in 2018 (October; mean DOY 280) and the earliest in 2020 (August; mean DOY 241). The latest EOS was in 2019 (May; mean DOY 129) and the earliest in 2021 (April; mean DOY 118).

### 3.1.5. La Palma

SOS and EOS dates showed a high spatial variability on the island of La Palma. The SOS date was between September (DOY 261, 25th percentile) and October (DOY 297, 75th percentile) and the EOS date between April (DOY 104, 25th percentile) and June (DOY 177, 75th percentile) in the vegetation of the conifer forests (area 1). Conifer forests had the earliest SOS in 2019 (September; mean DOY 266) and the latest SOS in 2021 (October; mean DOY 279). The earliest EOS was in 2020 (May, mean DOY 131), while the latest EOS occurred in 2018 (May; mean DOY 141).

Agricultural areas of the northeast and southwest coasts of La Palma (area 2), dominated by banana plantations (Pestana et al., 2016), showed similar phenological patterns. However, SOS and EOS dates were earlier in the southwest area: the growing season started between

June (DOY 170, 25th percentile) and October (DOY 290, 75th percentile) and ended between March (DOY 60, 25th percentile) and June (DOY 174, 75th percentile) the southwest area, while SOS was between August (DOY 213, 25th percentile) and October (DOY 277, 75th percentile) and the EOS between March (DOY 60, 25th percentile) and June (DOY 174, 75th percentile) in the northeast area. Shrublands located in north-western La Palma (area 3) started their growing season between September (DOY 247, 25th percentile) and October (DOY 289, 75th percentile) and ended it between April (DOY 95, 25th percentile) and July (DOY 189, 25th percentile). North-western shrublands had the earliest SOS in 2018 (September; mean DOY 247) and the latest SOS in 2019 (September; mean DOY 269). The earliest EOS was in 2021 (May, mean DOY 142), while the latest EOS occurred in 2020 (June; mean DOY 160). The shrublands associated to herbaceous vegetation, where the presence of broadleaf forests is very common, dominated the areas 4 and 5. LSP phenological information is limited in these areas due to an unclear seasonality.

### 3.2. Interannual variability of phenometrics in the Macaronesian ecosystems

Fig. 6 shows the interannual variability of SOS and EOS over the 4-year period from median absolute deviation (MAD) values. EOS generally presented higher MAD values than SOS. The most substantial differences in the interannual variability of SOS and EOS were determined by the different land covers at local scale. Broadleaf forests, which include a wide variety of tree species belonging to the laurel forests and thermo-sclerophyllous woodlands, generally had the highest mean interannual variability in both SOS (40–50 days) and EOS (50–70 days). However, this forest ecosystem presented the lowest interannual variability for both SOS (<20 days) and EOS (<30 days) in Gran Canaria, where the tree species of thermo-sclerophyllous woodlands are dominant (Fernández-Palacios et al., 2008; Fernández-Palacios and Whittaker, 2008). Mixed forests showed the lowest interannual variation of SOS (10–25 days) and EOS (20–35 days) in La Gomera and Tenerife, islands with the largest surface area of this type of forest ecosystem. Areas dominated by coniferous forests showed a mean interannual variation of than 25 days for SOS and 40 days for EOS.

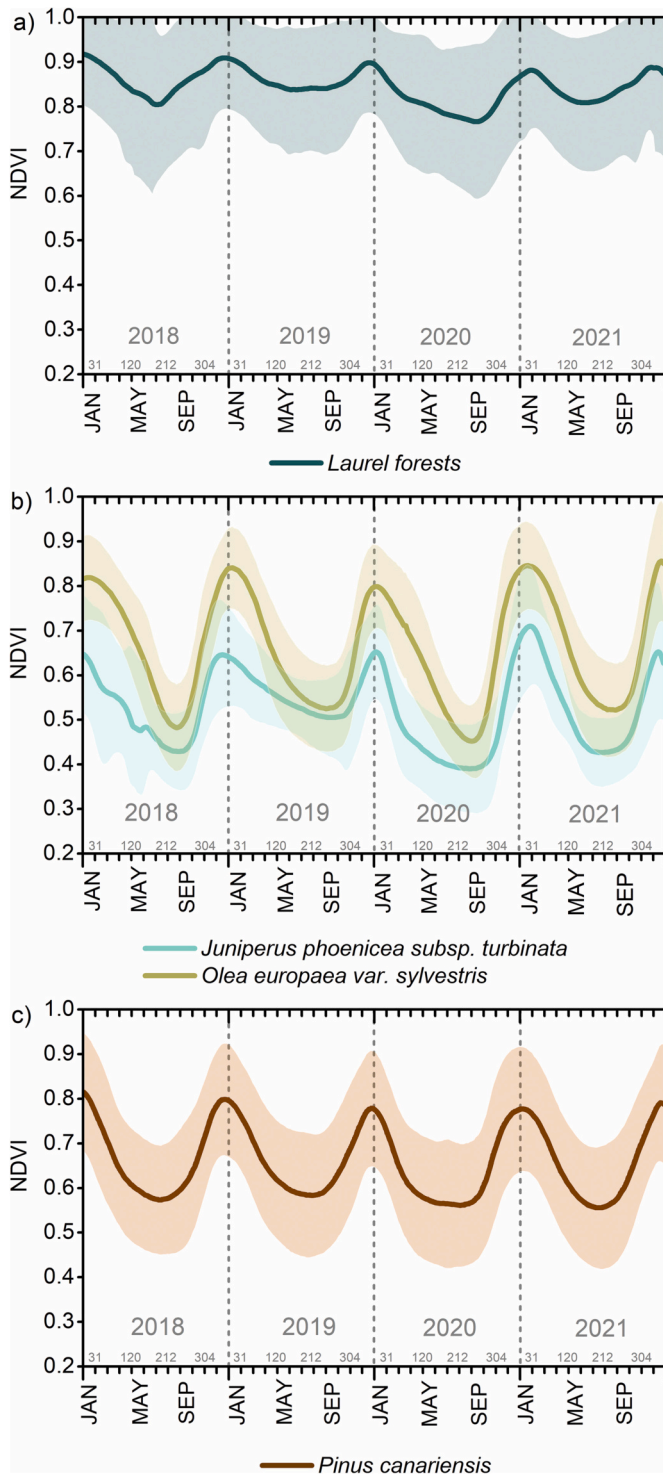### 3.3. Inter and intra-specific variations of the phenometrics in Macaronesian tree species

NDVI phenological trajectory of the tree species in forest ecosystems of the Canary Islands is shown in Fig. 7. *Olea europaea* var. *sylvestris, Juniperus phoenicea* subsp. *turbinata* and *Pinus canariensis* showed a marked and strong seasonality. The seasonal patterns of *Olea europaea* var. *sylvestris* and *Juniperus phoenicea* subsp. *turbinata* were similar, with a minimum value (base level) between late August and early September. *Pinus canariensis* showed the minimum values of NDVI in July. The maximum values of these three tree species were reached between mid-December and late January. Laurel forests, dominated by *Myrica Faya* and *Erica arborea*, had a weak seasonal pattern, showing the lowest annual NDVI amplitude (<0.1). The maximum NDVI values of the laurel forests were between December and January (i.e., dates like those shown by the maximum values of thermo-sclerophyllous woodlands and pine forests), and the minimum values were found between June and September.

Growing season of the Macaronesian species generally started between late summer and late autumn (SOS date) and ended between early spring and early summer (EOS date). However, Macaronesian tree species showed phenological patterns with certain differences, which can be seen in Fig. 8. Laurel forest had the SOS between July (DOY 210, 25th percentile) and October (DOY 290, 75th percentile) and the growing season ended between March (DOY 64, 25th percentile) and July (DOY 184, 75th percentile). LOS was between 195 (25th percentile) and 266 days (75th percentile) in this forest ecosystem. The growing season of
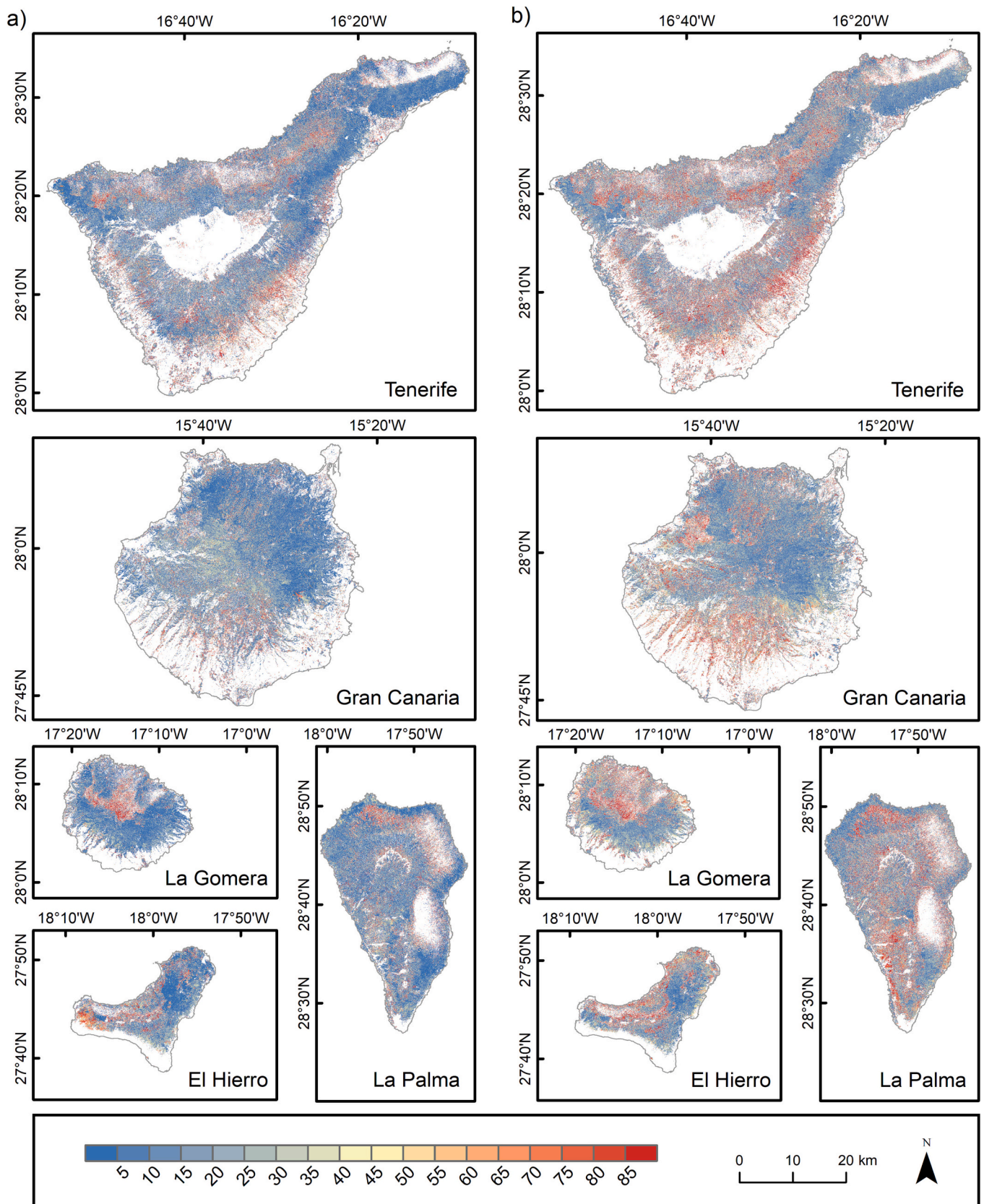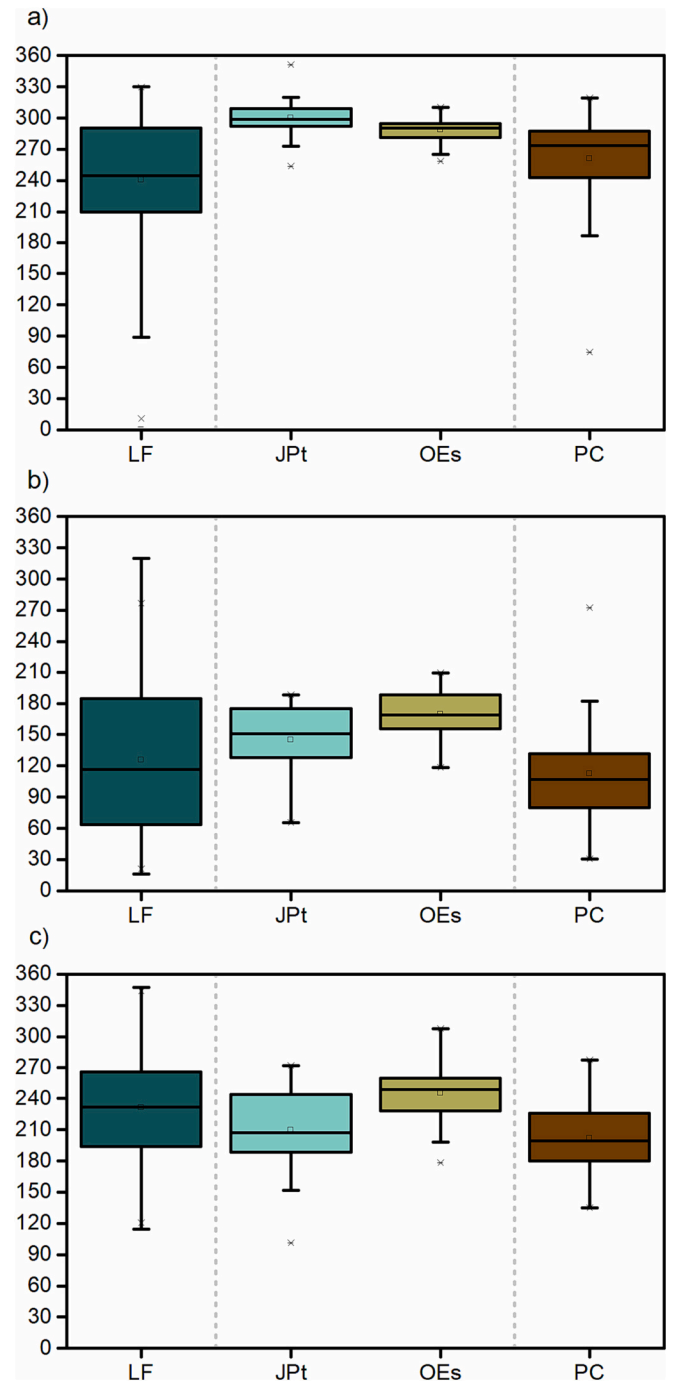
**Fig. 6.** Spatial distribution of the median absolute deviation (MAD) of the (a) SOS and (b) EOS for the period 2018–2021. This measure is expressed in number of days. The white pixels show areas with little or no vegetation (areas where the NDVI values of the phenological trajectory are low) or areas where the vegetation did not have clear seasonality.

**Fig. 7.** Mean phenological trajectory of the NDVI of tree species in forest ecosystems of the Canary Islands: a) laurel forests; b) thermo-sclerophyllous woodlands (*Olea europaea* var. *sylvestris* and *Juniperus phoenicea* subsp. *turbinata*); c) pine forests (*Pinus canariensis*). Shaded areas represent the standard deviation of the mean NDVI phenological trajectories for each Macaronesian tree species. Months and DOYs are represented on the x-axis.



**Fig. 8.** Boxplot of the SOS (a) EOS (b) and LOS (c) of representative tree species of Macaronesian forest ecosystems: i) laurel forests (LF); ii) thermo-sclerophyllous woodlands (*Olea europaea* var. *sylvestris* (OEs) and *Juniperus phoenicea* subsp. *turbinata* (JPt)); and iii) pine forests (*Pinus canariensis* (PC)). The horizontal line and the square symbol inside each box represent the median and the mean, respectively. The limits of each box are the 25th and 75th percentiles (i.e., interquartile range) and the upper and lower ends of the vertical lines are a prolongation of 1.5 times the interquartile range. The maximum and minimum outliers are represented with a dash, and the 1st and 99th percentile with an x.

*Juniperus phoenicea* subsp. *turbinata* started between October (DOY 292, 25th percentile) and November (DOY 309, 75th percentile) and ended between May (DOY 129, 25th percentile) and June (DOY 175, 75th percentile). *Olea europaea* var. *sylvestris* had the SOS in October (between DOYS 282 (25th percentile) and 295 (75th percentile)) and the

EOS between June (DOY 156, 25th percentile) and July (DOY 188, 75th percentile). LOS of *Olea europaea* var. *sylvestris* was between 228 (25th percentile) and 260 days (75th percentile), while the growing season of *Juniperus phoenicea* subsp. *turbinata* extended between 196 (25th percentile) and 245 days (75th percentile). SOS of *Pinus canariensis* was

between September (DOY 244, 25th percentile) and October (DOY 287, 75th percentile), while the EOS occurred between March (DOY 82, 25th percentile) and May (DOY 131, 75th percentile). LOS was between 179 (25th percentile) and 223 days (75th percentile) in *Pinus canariensis* forests.

The intra-specific variation of the Macaronesian tree species can be seen in Fig. 8. Laurel forest generally showed the highest variability in both SOS (>80 days) and EOS (>120 days), which may be related to the landscape characteristics of this ecosystem (i.e., species heterogeneity). Most individuals of *Pinus canariensis* presented a spatial variation of 30–40 days in SOS. This intra-specific variability was higher in EOS (50 days). Both *Juniperus phoenicea* subsp. *turbinata* and *Olea europaea* var. *sylvestris* had the lowest variation in SOS. The variation of the SOS date of most of the individuals of these species was <20 days. However, EOS variation was higher (30–50 days).

The interannual variability of SOS and EOS for Macaronesian species is shown in terms of MAD (Fig. 9). Generally, SOS had lower MAD values

than EOS. Laurel forests generally had the highest mean interannual variability in both SOS (average MAD value of 53 days) and EOS (average MAD value of 58 days). *Olea europaea* var. *sylvestris* showed the lowest interannual variation of SOS (average MAD of 15 days) and EOS (average MAD of 21 days). *Juniperus phoenicea* subsp. *turbinata* and *Pinus canariensis* had a mean interannual variation similar (average MAD of 27 days). However, the MAD values of EOS were higher in *Pinus canariensis* (46 days vs 38 days of average MAD).

## 4. Discussion

This study was based on the estimation of spring and autumn phenometrics of Macaronesian vegetation using NDVI time-series generated from Sentinel-2 data. These data provided an overview of the seasonal dynamics of Macaronesian vegetation in the Canary Islands at both landscape and species scales.

### 4.1. Seasonal NDVI trajectory of Macaronesian tree species

NDVI time-series generated from Sentinel-2 high spatial resolution data provided a description of the phenological trajectory of the main tree species of Macaronesian forest ecosystems. *Olea europaea* var. *sylvestris*, *Juniperus phoenicea* subsp. *turbinata* and *Pinus canariensis* showed a clear and marked seasonality. NDVI seasonality in these stand forests was less pronounced than in deciduous forests due to the permanent presence of leaves (Klimavičius et al., 2023). Therefore, the marked seasonality of NDVI in these Macaronesian forests may be related to environmental factors (e.g., temperature, precipitation) (Ghebrezgabher et al., 2020; Schultz and Halpert, 1993; Wang et al., 2001). Several studies, which focused on subtropical evergreen forests with similar structural characteristics to these Macaronesian ecosystems, indicated that the marked seasonality of NDVI was closely related to the precipitation regime. Thus, NDVI values may be directly proportional to precipitation values. Therefore, as precipitation increased, the NDVI value also tended to increase, and vice versa. This suggested that the increase in precipitation favoured vegetation growth and development (i.e., higher NDVI values), while the decrease in precipitation contributed to vegetation decay (i.e., lower NDVI values) (Jiao et al., 2021; Wang et al., 2001; Wang et al., 2003).
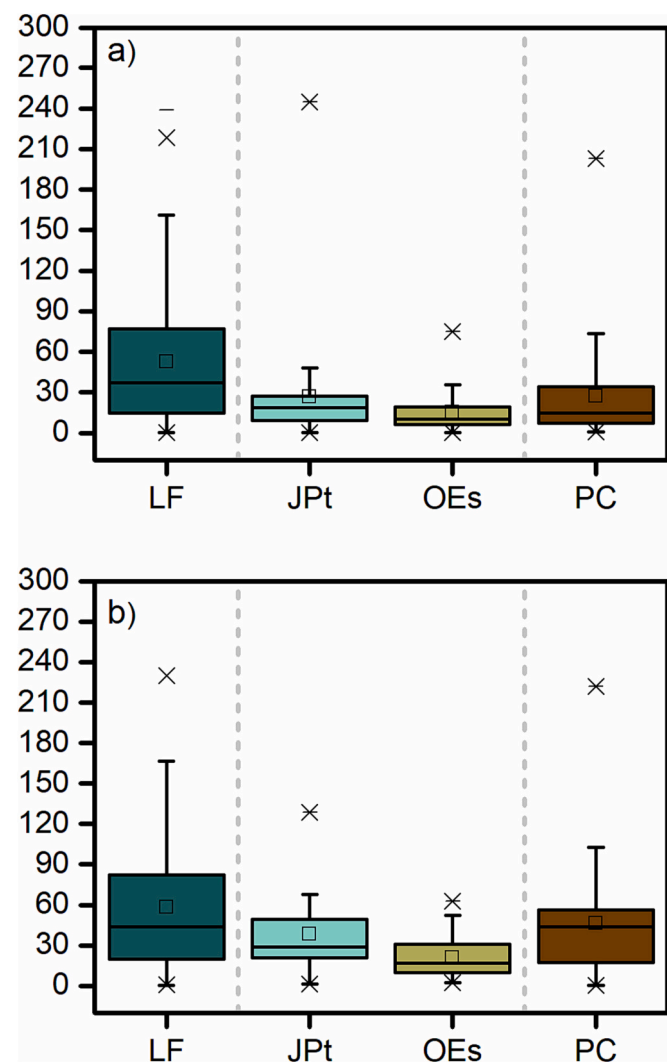
The seasonality in *Olea europaea* var. *sylvestris*, *Juniperus phoenicea* subsp. *turbinata* and *Pinus canariensis* was similar to that of various Mediterranean tree species (e. g., *Pinus halepensis*, *Pinus pinea* and *Pinus pinaster*). These Mediterranean species also showed a marked seasonal pattern, with a maximum in December–January and a minimum in August (Aragones et al., 2019). Therefore, the characteristics of these Macaronesian tree species (i.e., moderate density, medium (thermo-sclerophyllous woodlands) and high (pine forests) tree cover and the existence of homogeneous mono-specific (or nearly mono-specific) forest stands) were suitable for being studied using LSP from Sentinel-2 data. On the other hand, a weak or unclear seasonality was detected in laurel forests, which may be related to persistent cloud cover and/or the presence of dense canopies of various broadleaf evergreen tree species.

The presence of cloud cover is frequent in laurel forests (Table 2),

**Fig. 9.** Boxplots showing the MAD of SOS and EOS for representative tree species of Macaronesian forest ecosystems: i) laurel forests (LF); ii) thermo-sclerophyllous woodlands (*Olea europaea* var. *sylvestris* (OEs) and *Juniperus phoenicea* subsp. *turbinata* (JPt)); and iii) pine forests (*Pinus canariensis* (PC)). The horizontal line and the square symbol inside each box represent the median and the mean, respectively. The limits of each box are the 25th and 75th percentiles (i.e., interquartile range) and the upper and lower ends of the vertical lines are a prolongation of 1.5 times the interquartile range. The maximum and minimum outliers are represented with a dash, and the 1st and 99th percentile with an x.

**Table 2**
Mean percentage of cloud cover through 2018–2021 on forest stands of tree species representative of Macaronesian forest ecosystems: i) laurel forest (LF); ii) thermo-sclerophyllous forests (*Olea europaea* var. *sylvestris* (OEs) and *Juniperus phoenicea* subsp. *turbinata* (JPt)); and iii) pine forests (*Pinus canariensis* (PC)).

|  | LF | OEs | JPt | PC |
|---|---|---|---|---|
| El Hierro | 55.5 | – | 46.2 | 31.8 |
| La Palma | 56.8 | – | – | 32.9 |
| La Gomera | 52 | – | 49 | – |
| Tenerife | 59.9 | 41.1 | – | 34.2 |
| Gran Canaria | – | 44.9 | – | 20.2 |

which may affect the availability of cloud-free satellite data (Ganguly et al., 2010). The performance of the smoothing algorithms thus may not accurately represent the phenological trajectory of this type of forest ecosystem. Fig. 10 shows the influence of the number of cloud-free satellite observations on the generation of the phenological trajectory of the laurel forests compared to the trajectories described for *Juniperus phoenicea* subsp. *turbinata*, *Olea europaea* var. *sylvestris* and *Pinus canariensis*. Unlike the species of thermo-sclerophyllous woodlands and pine forests, the mean phenological trajectories of the laurel forests did not show a clear seasonality, regardless of the number of cloud-free observations used. The phenological trajectory of laurel forests derived from the mean of the smoothed NDVI time-series with the highest number of observations (i.e., 95th percentile) (Fig. 10c) was generated based on an average of 193 observations (i.e., approximately 66.1% of the 292 observations provided by Sentinel-2A/B MSI for the 2018–2021 period). This mean number of observations was higher than that of *Olea europaea* var. *sylvestris* (181 observations) (Fig. 10i) and lower than that of *Juniperus phoenicea* subsp. *turbinata* (233 observations) (Fig. 10f). The

seasonal trajectory of laurel forests derived from the mean of the NDVI time-series included in 5th percentile (Fig. 10a) was based on an average of only 85 observations (i.e., 29.1% of the total observations available for the study period). This mean number of observations was lower than that of the tree species of *Olea europaea* var. *sylvestris* (130 observations) (Fig. 10g) and *Juniperus phoenicea* subsp. *turbinata* (140 observations) (Fig. 10d). The mean phenological trajectory of laurel forests with the median number ± 0.5 median absolute deviations of observations of NDVI was based on the lowest number of cloud-free observations (129 observations;). *Juniperus phoenicea* subsp. *turbinata* and *Olea europaea* var. *sylvestris* had very similar mean number of observations (150 and 164 observations, respectively). Laurel forests are located on the windward slopes of mountain systems in the Canary Islands. Thus, these subtropical ecosystems are very exposed to the humid northeast trade winds, which cause the effect known as the 'sea of clouds' (see Figs. 1, 2 and 11) (del Arco Aguilar and Rodríguez Delgado, 2018; Marzol-Jaén, 2011). The forest stands of *Olea europaea* var. *sylvestris* were also situated on windward slopes of the mountain systems. However, these forest
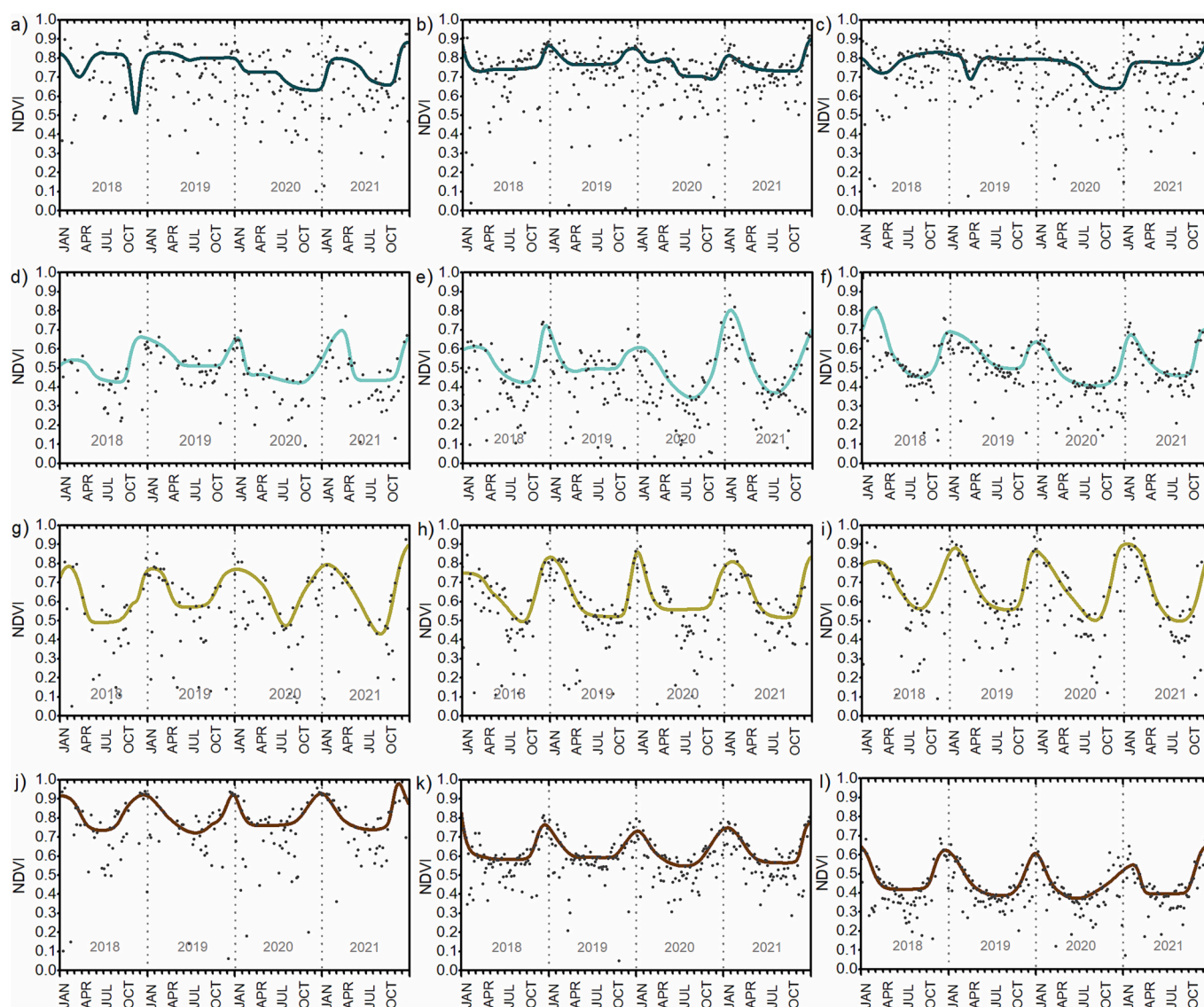


**Fig. 10.** Mean seasonal trajectory of NDVI (solid lines) of representative species of Macaronesian forest ecosystems (laurel forests (a, b, c); *Juniperus phoenicea* subsp. *turbinata* (d, e, f); *Olea europaea* var. *sylvestris* (g, h, i) and *Pinus canariensis* (j, k, l)) in relation to the number of non-smoothed NDVI observations (dots). The first column of the set of graphs (a, d, g, j) represents the average of the four-year NDVI time-series of the pixels with the lowest non-smoothed NDVI observations (5th percentile). The second column of graphs (b, e, h, k) represents the average of the four-year NDVI time-series of the pixels with the median number of non-smoothed NDVI observations ±0.5 median absolute deviations. The third column of graphs (c, f, i, l) represents the average of the four-year NDVI time-series of the pixels with the highest number of non-smoothed NDVI observations (95th percentile).
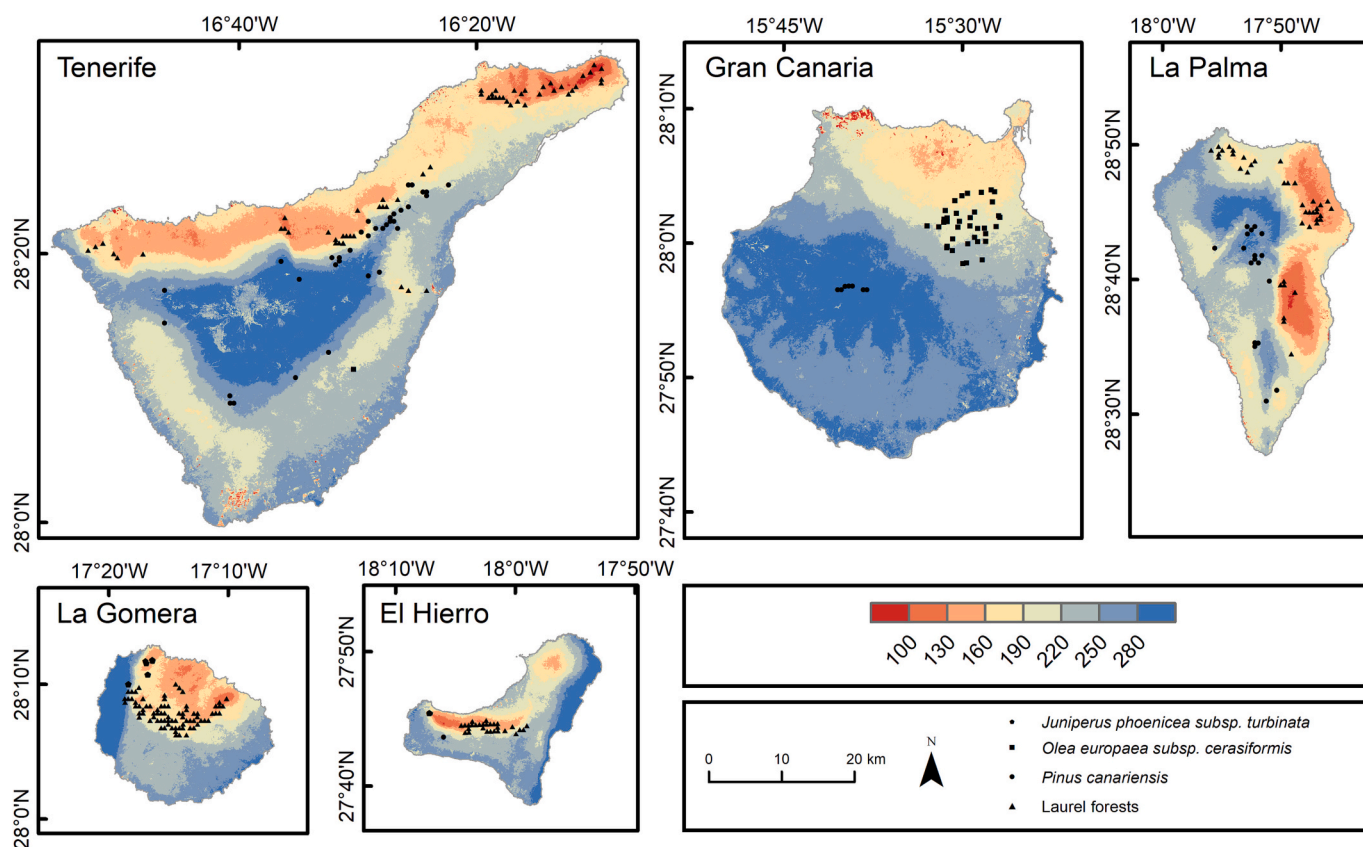
**Fig. 11.** Number of cloud-free observations available for the period between January 2018 and December 2021.

stands were found in areas close to the coast and at a lower elevation. The forest stands of *Juniperus phoenicea* subsp. *turbinata* were in areas of ravines close to the coast. The species from thermo-sclerophyllous woodlands may therefore be influenced by both cloud cover and the sporadic presence of sea mist (see Figs. 1, 2 and 11). Despite all this, the satellite observations provided by Sentinel-2 could capture the marked seasonality of these thermophile tree species. Conversely, the highest number of cloud-free observations (199 observations (median ± 0.5 median absolute deviations); 237 observations (95th percentile) (Fig. 10l); 140 observations (5th percentile) (Fig. 10j) were obtained for *Pinus canariensis* (Table 2). This may be because the extensive conifer forests of *Pinus canariensis* were generally located on leeward slopes, whereby the presence of clouds is less frequent (see Figs. 1, 2 and 11) (Arévalo et al., 2011; del Arco Aguilar and Rodríguez Delgado, 2018).

Overall, the laurel forests did not have a clear phenological trajectory. Despite this, <5% of the pixels from the sample of laurel forests considered in this study showed a marked seasonality (Fig. 12). This low percentage of pixel of laurel forest was based on a number of cloud-free observations ranging from 110 to 175. Therefore, although the number of cloud-free observations is a factor that may affect the generation of the NDVI phenological trajectory in laurel forests, other factors, such as the compositional and structural characteristics of this Macaronesian forest ecosystem, may have a more important influence. The laurel forests selected in this study constitute a dense forest stand, where *Myrica faya* and *Erica arborea* were the dominant tree species. Therefore, NDVI phenological trajectory may generally be influenced by the mix of both species' phenological cycles and those of other secondary evergreen species (del Arco Aguilar and Rodríguez Delgado, 2018). Thus, the marked seasonality in the laurel forests may be related to higher homogeneity of the forest canopy, where species diversity may also be lower. The spatial resolution of Sentinel-2 therefore might not reliably capture the phenological trajectory of most of the heterogeneous forest stands in this Macaronesian ecosystem.

### 4.2. Seasonal dynamics of phenometrics in ecosystems of the Macaronesian biogeographic region

The spring and autumn phenometrics provided a description of the LSP dynamics of Macaronesian ecosystems in the Canary Islands. The phenological dynamics of the Macaronesian vegetation showed a general seasonal pattern in the Canary archipelago, except Lanzarote and Fuerteventura. Generally, the dates of the spring and autumn phenometrics of thermo-sclerophyllous woodlands, pine forests and shrublands coincided with the beginning of the wet season (September–December) and the start of the dry season (March–June), respectively (Cropper and Hanna, 2014; Sánchez-Benítez et al., 2017). Tree species in the thermo-sclerophyllous woodlands showed this general phenological pattern, although the SOS generally was earlier and the EOS later in *Olea europaea* var. *sylvestris.* Median SOS in *Pinus canariensis* was like different Mediterranean pine species (*Pinus nigra*, *Pinus pinaster*, *Pinus halepensis* and *Pinus pinea*). The mean growing season of the Macaronesian pines nevertheless ended at an earlier date: EOS occurred 1–2 months earlier in the forests of *Pinus canariensis* (Aragones et al., 2019).

Spring and autumn phenometrics of laurel forests showed the highest variability of the Macaronesian tree species. This may indicate a higher phenotypic variation in the tree species of this Macaronesian forests. However, the lack of marked seasonality in the phenological trajectory of laurel forests may suggest that the estimation of SOS and EOS may be less robust in laurel forests than in tree species of thermo-sclerophyllous forests and pine forests. NDVI phenological trajectory in the laurel forests may be influenced by the significant presence of cloud cover and/or the presence of dense canopies of various broadleaf evergreen tree species. Table 3 shows the influence of the number of cloud-free observations on the detection of both SOS and EOS. Generally, the phenometrics obtained from the lowest number of observations showed a higher MAD value. However, this study does not show sufficient
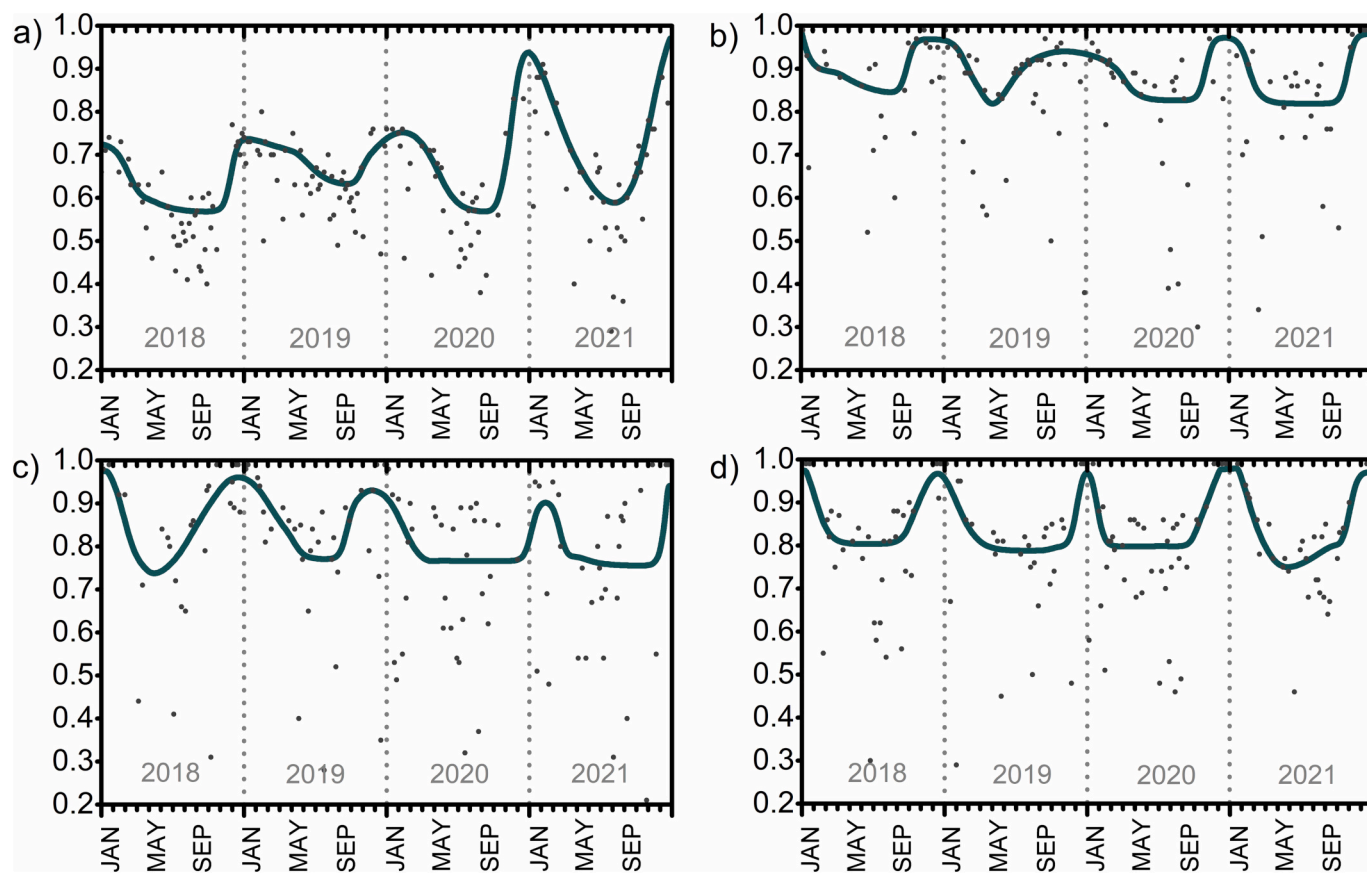
**Fig. 12.** NDVI phenological trajectory in some locations of the laurel forests. The dots represent the non-smoothed NDVI time-series, and the solid lines represent the smoothed NDVI time-series using the double logistic function.

**Table 3**

Results of Welch's t-test (*p*-value) comparing SOS and EOS for each forest ecosystem derived from NDVI time-series generated using the highest (+) and lowest (−) mean number of non-smoothed NDVI satellite observations (N). Mean SOS, EOS and MAD also are represented. The mean number of observations was calculated using two years, because the phenological cycles of Macaronesian species usually extend over two calendar years.

| | TWO-YEAR PERIOD (−) | | | | | TWO-YEAR PERIOD (+) | | | | | p-value (SOS) | p-value (EOS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | SOS | MAD | EOS | MAD | N | SOS | MAD | EOS | MAD | | |
| *Olea europaea* var. *sylvestris* | 224 | 309 | 87 | 171 | 63 | 231 | 303 | 14.75 | 173 | 36.8 | 0.67 | 0.87 |
| *Juniperus phoenicea* subsp. *turbinata* | 217 | 312 | 87 | 189 | 95 | 226 | 311 | 21.33 | 129 | 36.3 | 0.94 | 0.04* |
| *Pinus canariensis* | 244 | 291 | 75 | 215 | 128 | 248 | 274 | 22.8 | 288 | 87.5 | 0.19 | 0.08 |
| Laurel forests | 191 | 282 | 45 | 261 | 138 | 192 | 292 | 43.71 | 187 | 124.3 | 0.19 | 0.0002* |

evidence to claim that the number of observations is the most determinant factor in the detection of phenometrics. The data derived from Welch's *t*-test were not conclusive. Therefore, the compositional and structural characteristics of the laurel forest may make it difficult the extraction of SOS and EOS dates from Sentinel-2 spatial resolution. Thus, the absence of a clear and marked seasonality made it difficult the identification of the phenological cycles. Therefore, the spring and autumn phenometrics extracted from these phenological cycles may not accurately represent the phenological dynamics of this Macaronesian forest ecosystem.

Direct human field observations can provided information on plant phenophases at individual organism level (Menzel et al., 2006), while near-surface measurements (e.g., phenological cameras, sensors on board unmanned aerial vehicles (UAVs)) can provide phenological data at both individual organism and plant community level (Berra et al., 2019; Liang et al., 2020; Richardson, 2019). These phenological approaches based on a more detailed scale could therefore improve the understanding of the phenological behaviour of species in these heterogeneous subtropical forests.

## 5. Conclusions

Sentinel-2 NDVI time-series played an important role in monitoring the LSP spatial patterns in ecosystems of the Macaronesian biogeographic region. LSP dynamics were analysed in mono-specific (or nearly mono-specific) forest stands of the main tree species of two of the main Macaronesian forest ecosystems: thermo-sclerophyllous woodlands (*Olea europaea* var. *sylvestris* and *Juniperus phoenicea* subsp. *turbinata*) and pine forests (*Pinus canariensis*). The heterogeneity of the landscape in the laurel forests made it difficult to identify mono-specific forest stands in an area with Sentinel-2-pixel size (100 m²). Therefore, LSP was analysed in the representative plant community of laurel forests where two tree species are dominant (i.e., *Myrica faya* and *Erica arborea*). *Olea europaea* var. *sylvestris, Juniperus phoenicea* subsp. *turbinata* and *Pinus canariensis* showed a clear and marked seasonal dynamics. However, laurel forests showed an unclear seasonality. The number of cloud-free satellite observations may have a certain influence on the NDVI phenological trajectory in laurel forests. This study nevertheless suggests that the absence of a clear seasonality in laurel forests may be more

related to the compositional and structural characteristics of this forest ecosystem.

Some of the most representative Macaronesian ecosystems of the Canary Islands (i.e., thermo-sclerophyllous woodlands, pine forests and shrublands) generally showed a similar pattern in spring and autumn phenometrics. The dates of phenometrics may be associated to precipitation regime: the growing season of vegetation in these ecosystems generally extended from the autumn months (i.e., start of the wet season) to the spring months (i.e., end of the wet season). However, laurel forests did not show a common phenological pattern. SOS and EOS dates in this forest ecosystem had a very high variability. Thus, the phenometrics may not accurately show the LSP dynamics in laurel forests. In this regard, the use of complementary phenological approaches, such as human field observations at individual organism level, phenological cameras or UAV-borne sensors, could improve the understanding of the vegetation phenology of this Macaronesian forest ecosystem.

## Credit authorship contribution statement

All authors conceived the idea, proposed the methodology and processed the satellite data. Jose A. Caparros-Santiago analysed the data, produced the figures, and drafted the manuscript. Lorenzo C. Quesada-Ruiz and Victor Rodriguez-Galiano contributed substantially to the drafting of the manuscript.

## Declaration of Competing Interest

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

## Data availability

Phenological data is available from https://doi.org/10.5281/zenodo.8184679

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