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RESEARCH ARTICLE

Canopy gap patterns in Mediterranean forests: a spatio-temporal characterization using airborne LiDAR data

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Abstract
Context In the last century European forests are experiencing tree damage and mortality rise and it is expected to continue due to increased disturbances under global change. Disturbances generally creates canopy gaps, which leads to secondary succession, compositional changes and landscape mosaic transformations. Forest gap characterization has traditionally been performed in light-limited tropical and boreal forests, but no studies have been found on water-limited Mediterranean forests. Characterising canopy gaps and their dynamics in Mediterranean forests will help to better understand their dynamics across landscapes under ongoing global change.
Objectives We aimed to characterize canopy gaps and quantify their dynamics identifying hotspots of openings and closings in Mediterranean forests.
Methods We used low density multitemporal airborne LiDAR data between 2010 and 2016, over a large region (Madrid, Spain, 1732.7 km^2) with forests ranging from monospecific conifer and broadleaved to mixed forests, to delineate canopy gaps. The characterization was made through its Gap Size Frequency Distribution (GSFD) by forest type and year. We analysed canopy gap dynamics and identified statistically significant hotspots of gap openings and closings in each forest type.
Results There were major differences between conifers and broadleaved forest in terms of gap characteristics and GSFD. In general, we found a great dynamism in Mediterranean forests with high rates of forest openings and closings, but a net closing trend. A high spatial heterogeneity was observed finding hotspots of gap openings and closings across the entire study area.
Conclusions We characterised for the first-time large-scale structure and dynamics of canopy gaps in Mediterranean forests. Our results represents the characterisation of the GSFD of Mediterranean forests and could be considered a benchmark for future studies. The provision of up-to-date periodic maps of hotspots of gap opening, closing and net change help to understand landscape mosaic changes as well

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as to prioritise forest management and restoration strategies.

Resumen

Contexto Durante el último siglo, los bosques europeos están experimentando un incremento de la mortalidad y del decaimiento forestal que se espera que siga en aumento debido al cambio global. Estas perturbaciones generalmente crean huecos en el dosel, lo que conduce a sucesiones secundarias, cambios en la composición y transformaciones en el mosaico del paisaje. La caracterización de estos huecos se ha realizado tradicionalmente en los bosques tropicales y boreales, limitados por la luz, pero no se han encontrado estudios en los bosques mediterráneos, limitados por el agua. La caracterización de la dinámica de estos huecos en los bosques mediterráneos ayuda a comprender mejor su dinámica, desde una perspectiva de paisaje, en el contexto actual del cambio global.

Objetivos Caracterizar la estructura y dinámica de los huecos en el dosel identificando puntos calientes de apertura y cierre en los bosques mediterráneos.

Métodos A partir de datos LiDAR de baja densidad del 2010 y 2016 hemos identificado los huecos en el dosel en una extensa área de estudio (Madrid, España, 1732.72 km^2) que presenta bosques mediterráneos de coníferas, frondosas y mixtos. La caracterización de estos huecos la hemos realizado a partir de la distribución de frecuencias de tamaños por tipo de bosque y año. Por último, hemos analizado la dinámica de los huecos identificando zonas estadísticamente significativas de apertura y cierre por tipo de bosque.

Resultados Existen diferencias significativas entre los bosques de coníferas y frondosas tanto en las características de los huecos como en la distribución y frecuencia de los tamaños. Los bosques estudiados presentan un gran dinamismo con relación a los cambios en el dosel con altas tasas de apertura y cierre, observando una ganancia forestal neta. Además, existe una alta heterogeneidad espacial en la dinámica de huecos encontrando puntos calientes de apertura y cierre de bosque en el área de estudio.

Conclusiones Este estudio representa la primera caracterización a gran escala de la estructura y dinámica de huecos en el dosel de bosque Mediterráneo. Nuestros resultados representan la caracterización de la Distribución de Frecuencia de Tamaño de huecos en bosque Mediterráneos lo cual puede usarse como punto de referencia en futuros estudios. La generación de mapas periódicos actualizados de los puntos calientes de apertura, cierre y cambio neto forestal contribuyen a entender los cambios en el mosaico del paisaje, así como a priorizar actuaciones de gestión y restauración forestal.

Keywords Airborne laser scanning · Forest canopy gaps · Hotspots · Forest dynamics · Spatial distribution · Gap size frequency distribution (GSFD) · Gap dynamics

Introduction

Worldwide forests harbour terrestrial biodiversity, regulate the carbon and water cycles and, therefore, are key for climate change mitigation (Sabine et al. 2004; Thompson et al. 2009). During the last century there has been a marked increase in tree damage and mortality due to disturbances in European forests (Schelhaas et al. 2003; Neumann et al. 2017; Astigarraga et al. 2020) which is expected to increase due to climate change and variations in management practices (Schelhaas et al. 2003; Seidl et al. 2014; Jump et al. 2017). Global change is therefore altering tree demographic rates (Lloret et al. 2012; Neumann et al. 2017), which is directly linked to forest structure, composition, and carbon storage (Astigarraga et al. 2020; Ruiz-Benito et al. 2017). As environmental change continues, we need to expand our knowledge on the temporal net balance of tree structure and demography to better predict future forest development (McDowell et al. 2020).

Disturbance directly affects forest dynamics and, therefore, it has been central in ecology (Turner 2010). Disturbances in forests generally create canopy gaps, which leads to secondary succession and species changes due to the differential conditions in light, temperature, moisture or soil properties (Schliemann and Bockheim 2011; Muscolo et al. 2014). Hence, the study of canopy gaps is key to understanding forest structure and dynamics (Jucker 2021). Most of gap dynamics studies have been performed in tropical, temperate and boreal forests, but no study has been previously performed in Mediterranean forests. In tropical and temperate forests light is one of the most limited resource and, therefore, small gaps are one of the main sources of light availability leading to secondary succession (Uriarte et al. 2018). In Mediterranean forests water and nutrients are the most limited resources with human management as a key factor shaping forest structure (Zavala et al. 2000). Therefore, the strong climatic seasonality (Olson et al. 2001) and the disturbances regimes due to climate and human activities (e.g. fires, drought and grazing) leads to Mediterranean forests being more open and less dense than temperate and tropical forests, forming mosaics at landscape level (Pausas 1999). The expected increase of extreme events and water scarcity (Palahi et al. 2008; Senf and Seidl 2021) in the Mediterranean bioclimatic region makes it one of the most vulnerable to global change (Palahi et al. 2008) and, hence, to landscape transformations.

The spatial distribution of canopy gaps affects soil diversity, plant interactions, species diversity and, therefore, forest structure and dynamics (Muscolo et al. 2014; Schliemann and Bockheim 2011). Forest dynamics are strongly driven by gap characteristics, such as gap size and perimeter (Muscolo et al. 2014) that has been related to soil temperature (Muscolo et al. 2007), soil fertility (Muscolo et al. 2007) regeneration and vegetation growth (Coates 2002). In fact, forest gaps have been traditionally characterised through its Gap Size Frequency distribution (GSFD) since the size distribution of gaps is quantitatively related to the disturbance regime and, hence, dependent on the forest characteristics such as forest type, substrates or ecozones (Lobo and Dalling 2013; Goodbody et al. 2020).

Studies of gap dynamics started in the late 70s (Bugmann 2001) using a range of methodologies from transects (Runkle 1982, 1990) to long-term plots (Miura et al. 2001; Woods 2000) and from field-based estimates, hemispherical (Hu and Zhu 2009) and aerial photographs (Fujita et al. 2003; Henbo et al. 2006) to remote sensing technology, including multispectral (Senf and Seidl 2021) and LiDAR (Asner et al. 2013; Goodbody et al. 2020). Field-based methods provide valuable information to understand gap characteristics and formation including species identification, evidence of pests or diseases or signs of anthropogenic impacts. However, the delimitation of the gaps requires a high amount of fieldwork and it is susceptible to shape assumptions -i.e. simplifying the complex shape of a gap to circles, ellipses or polygons—that directly influence gap area and geometry (Schliemann and Bockheim 2011). Despite missing valuable field information to understand gap structure and formation, remote-sensing methods as LiDAR appear as a promising technique for detailed 3D and semiautomatic characterization of gaps shape, covering large areas (landscape-scale) and reducing the amount fieldwork (Wulder et al. 2012). It has been increasingly used to canopy gap detection and dynamics in tropical forests (Asner et al. 2013; Goulamoussène et al. 2017), mangroves (Zhang 2008) and boreal forests (Vepakomma et al. 2008; Goodbody et al. 2020). In Mediterranean forest, although structure has been characterized in several studies with LiDAR technology (Wiggins et al. 2019; Tijerín-Triviño et al. 2022), no studies have been found using this technology to assess gaps dynamics.

Here, we studied gap forest structure and dynamics in a large continental Mediterranean area (1732.72 km^2), ranging from monospecific conifer and broadleaved to mixed forests, and an ample altitudinal gradient (432 to 2102 m a.s.l.); using two airborne LiDAR datasets available for Madrid region. Specifically, we aimed to: (1) identify and characterize forest gaps; and (2) quantify canopy gap dynamics between 2010 and 2016, identifying hotspots of gap openings and closings; analysing differences among forest types. Our results will show for the first time large-scale structure and dynamics of gaps in a variety of Mediterranean forests, allowing to further understand recent gaps dynamics and their spatial distribution, highlighting its consequences for forest management and conservation.

Materials and methods

Study area

We studied the Community of Madrid's forests, occupying 1732.72 km^2 (21.65% of the total area), located in the centre of the Iberian Peninsula (see Appendix S1 in Supporting Information to further information of the study area). To isolate forests, we used the Spanish Forest Map (SFM, 1:25,000) attributes (MITECO 2013). In order to avoid overestimation in forest gaps we masked roads and firebreaks, using the Transport Networks available in the CNIG (IGN, http://www.ign.es) or masking them manually.

Delineation and characterization of canopy gaps

We used LiDAR data from Spanish National Plan for Aerial Orthophoto (PNOA-LiDAR project), distributed in 2×2 km tiles for 2010 and 1×1 km tiles for 2016 (LiDAR-PNOA 2016 CC-BY 4.0 scne.es, Table 1).

For each year, after normalizing the height of the returns, we created 2 m spatial resolution canopy height models (CHMs) from the LiDAR data in FUSION v4.21 (McGaughey 2021). LiDAR tiles were reviewed for overlapping errors at the edges of each tile and corrected if necessary. Gaps were delineated using ForestGapR package (Silva et al. 2019) in R 4.04 (R Core Team 2021) (Fig. 1a). All pixels with a height below 2 m were selected as a potential gap. This threshold of 2 m was applied to avoid returns from understory vegetation, considering mean values of commercial height in Mediterranean forests and according to gap definition given by Brokaw (1982). We used 4m^2 as minimum gap size (i.e., one pixel) to take full advantage of the maximum spatial resolution of the generated CHMs. However, as the minimum gap size and the height threshold can affect the results and there are not previous studies in Mediterranean forests, we evaluated the impact of different minimum gap sizes from 4 to 16 m^2 (i.e. 1, 2, 3 and 4 pixels, respectively, from CHM) and height thresholds (1, 1.5 and 2 m), see Appendix S2.

GSFD is the most common method to characterize canopy gaps in literature (Fisher et al. 2008; Asner et al. 2013; Goodbody et al. 2020). However, this parameter does not explore the spatial arrangement or shape characteristics (Jucker 2021). Therefore, for the forest gaps polygons extracted, we calculated shape metrics per forest type and year (Fig. 1b) and hotspots of change (Fig. 1c). The shape of the gaps was characterized through the area, perimeter and shape index (perimeter / (2·π·area)). The shape index characterizes gap shape complexity (Patton 1975) and it is commonly used in canopy gaps studies (Hu and Zhu 2009; Koukoulas and Blackburn 2004; Goodbody et al. 2020). Shape index minimum value, one, represents a perfect circle and its value increases with complexity with no upper limit. In our case, since our minimum area is a square of 4m^2 (pixel) we cannot get a perfect circled gap, so shape index of 1.128 represents de minimum achievable complexity, i.e., minimum ratio between perimeter and area given by a square.

To assess if there are significant differences in gap's shape metrics, between years and forest types, we used Welch's ANOVA test and Games-Howell post-hoc test since the data were unbalanced, not normally distributed and the homoscedasticity assumption was not met. Generally, violating normality assumptions does not strongly influence classic ANOVA results (Harwell et al. 1992); however, is not a robust test when data show unequal variances and/or unequal sample sizes (Liu 2015; Delacre et al. 2020). In such cases the Welch's test is a robust alternative to classic ANOVA (Quinn and Keough 2002; Delacre et al. 2020). Moreover, the Games-Howell post-hoc test is a good alternative when sample size

Table 1 Specifications of the PNOA-LiDAR data acquisition in 2010 and 2016 in the Community of Madrid used in our study area

Parameter	LiDAR 2010	LiDAR 2016
Number of tiles	2212	8645
Date of acquisition	Aug–Dec 2010	Aug–Sep 2016
Sensor	LEICA ALS50	LEICA ALS70-HP
Mean flying height (m AGL)	3070	3500
Flying speed (km h^{-1})	150	130
Root mean squared error xy (RMSE xy (m))	0.3	0.2
Root mean squared error z (RMSE z (m))	0.4	0.15
Pulse rate (kHz)	91.8; 81.6; 89.9	18.44
Scan rate (Hz)	32.1; 31.6; 31.7	25.4
Max scan angle (°)	50; 38; 48	25–39
Mean return density (returns m^{-2})	0.5	1

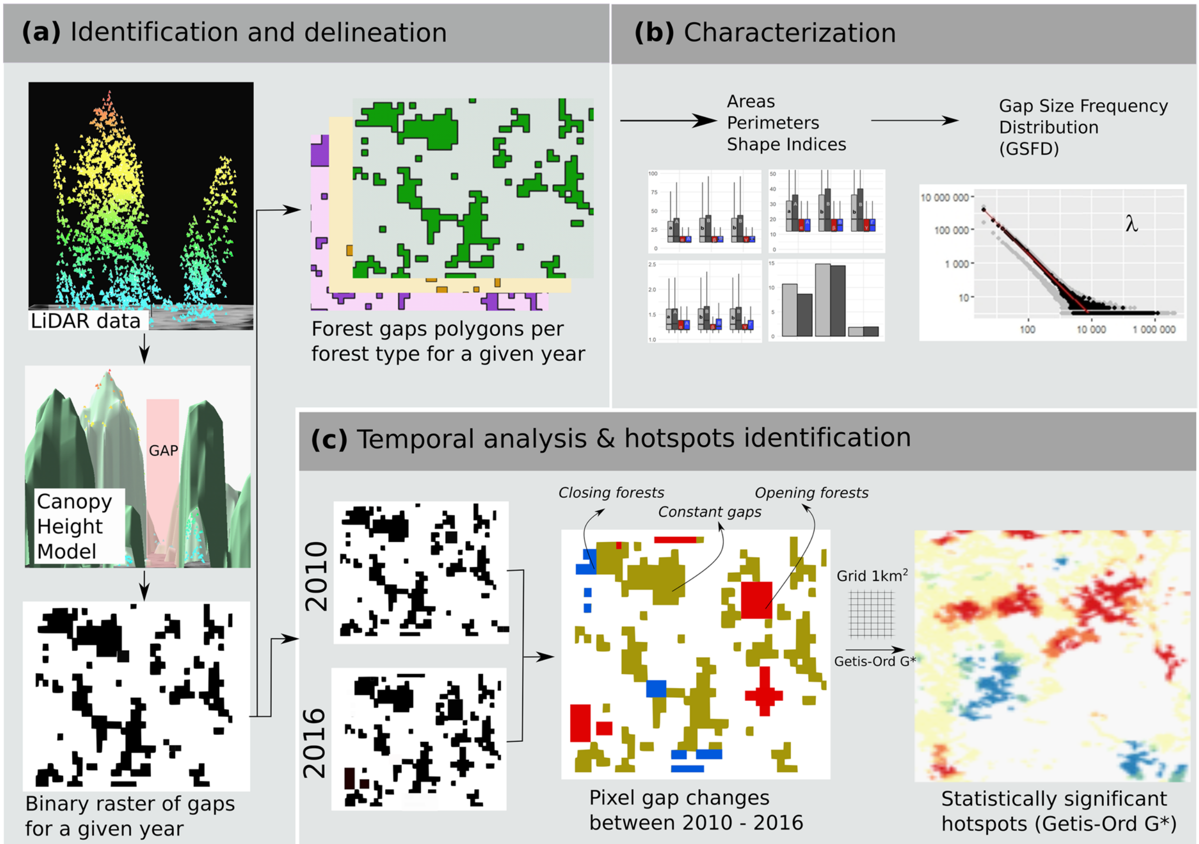

Fig. 1 Flow chart for identification and analysis of canopy gaps from the PNOA-LiDAR. **a** Identification and delineation of forest canopy gaps: from cloud points to binary raster or vector file. **b** Canopy gaps characterization: geometric features (area, perimeters) and GSFD. **c** Temporal analysis and hotspots identification: raster algebra for pixel gaps changes and statistically hotspots according to Getis-Ord G* statistic

is bigger than 50 (in each group) (Lee and Lee 2018). Welch's and Games-Howell post-hoc tests were performed with rstatix-package (Kassambara 2021) in R 4.0.4 (R Core Team 2021).

To model the size-frequency of canopy gaps we calculated GSFD (i.e. the frequency of gaps according to gap size classes) for each forest type and year (Fig. 1b). GSFD were calculated using power-law distribution and fitting its exponents (i.e., scale parameter λ) following Hanel et al. (2017) approach in MATLAB 9.10.0 (MATLAB 2021). The scale parameter (λ) of the power-law distribution may be a good indicator of gap differences among types, substrates, ecozones and forest types (Lobo and Dalling 2013; Goulamoussène et al. 2017; Goodbody et al. 2020). The Kolmogorov–Smirnov goodness of fit test (Ks) was also calculated in order to confirm that the power-law calculated and its exponent λ represent the same distribution function as the data. In order to control the false rejection rate we calculated critical values (Kcrit) through Hanel's "r_plfit_calibrate" and "r_plfit_calibrate_eval" functions in MATLAB 9.10.0 (MATLAB 2021), accepting estimates when Ks < Kcrit (Hanel et al. 2017).

Gap patterns temporal analysis and hotspots identification

To quantify gap dynamics, we combined the 2010 and 2016 binary gaps rasters obtaining for each pixel if a gap closed (i.e. gap present in 2010 and disappeared in 2016), opened (i.e. gap absent in 2010 and present in 2016), or remained constant (i.e. gap present in 2010 and 2016, Fig. 1c). Gap area, perimeter and shape index were calculated for forest closings and openings, and the Welch's ANOVA test was used to assess its differences among forest types.

We identified hotspots of change i.e., clustering in a certain spatial distribution (Chaikaew et al. 2009), through heatmaps of gap openings, closings and net changes (closing-opening) (Fig. 1c). We overlaid a 1 km^2 grid over forest areas and we calculated the percentage of opening, closing and net change pixels for each polygon. To confirm the existence of statistically significant hotspots across our study area, we used the local spatial statistic *Getis-Ord Gi** (Anselin and Rey 2010), with ArcGis Pro 2.8.3 (ESRI Inc., Redlands, CA, USA). *Getis-Ord Gi**, or hotspot analysis, is a method to detect spatial clustering through computing local autocorrelation, i.e. degree to which neighbour cells have similar values (Peeters et al. 2015), that report a Z-score (GiZ-score) and P-value for each grid to measure statistical significance (whether clustering is different from that one expected in a random distribution). We considered as hotspots the statistically significant positive Z-scores (the higher the Z-score the more intense the clustering) and as coldspots the statistically significant negative Z-scores (the lower the value, the less intense the clustering) (Philippe and Karume 2019).

Results

Forest gaps detection and characterization in Mediterranean forests

In 2010 a total of 6.811.409 gaps were identified, 32.5% more than the number of gaps found in 2016 (5.140.235 gaps, Fig. 2; Table 2). In all forest types, the number of gaps and the total area of gaps decreased between 2010 and 2016, but the mean gap area slightly increased (see mean polygon area in Table 2). It can also be seen that smaller gaps predominate for both 2010 and 2016 (median = 4 m^2 and P75 from 12 to 16 m^2).

The mixed and broadleaved forests had the greatest percentage of gaps area in relation to its forest area (59% and 56.8% in 2010), whereas conifer forests had the lowest proportion (38.54% in 2010, Table 2). Maximum gap area (defined as P99.99 to avoid outliers) also differed between conifers and other forest types (Table 2), with maximum gap area increasing in 2016 in conifer while decreasing in the other forest types.

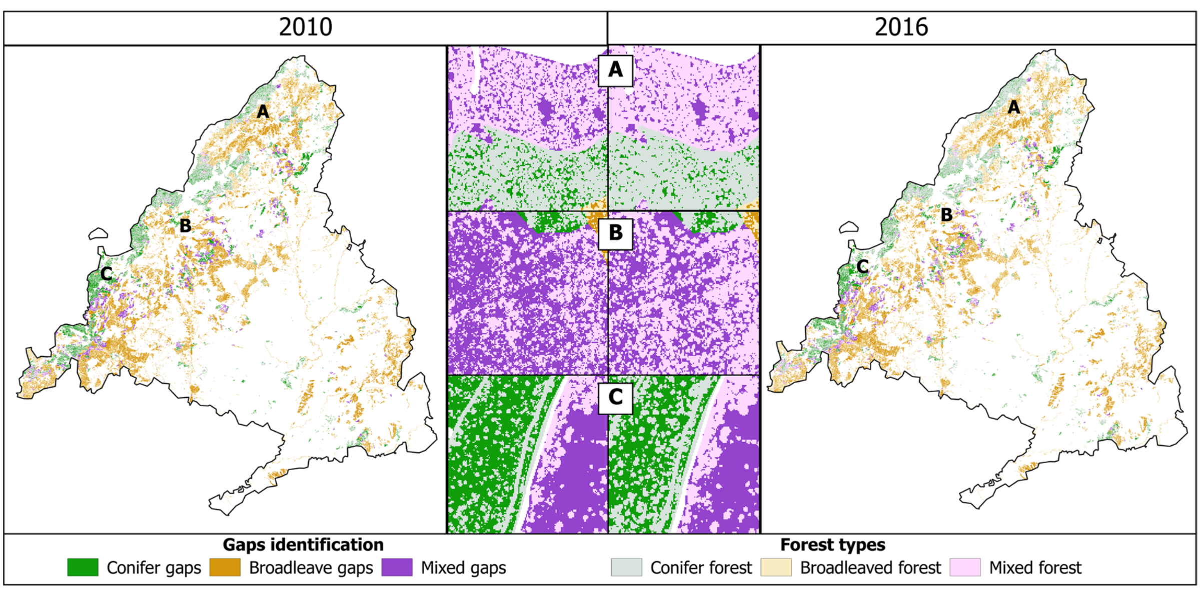

Fig. 2 Canopy gaps delineation (≥ 4 m^2). Gap polygons (dark colours) are shown for each forest type distribution (light colours). *A*, *B*, *C* are insets of three examples of gap delineation areas in 2010 and 2016

Table 2 Forest gaps dynamics statistics by forest type

	Conifer forests (forest area = 49 488.4 ha)					
	2010	2016	Trend	Opening	Closing	Balance
Num. gaps	2,532,471	1,779,094	↓	1,819,977	6,167,079	4,347,102
Total gap area (ha)	19,072.8	15,885.8	↓	1544.73	4731.35	3186.62
Relative gap area (% relative total forest type area)	38.54%	32.1%	↓	3.12%	9.56%	6.44%
Mean polygon area (ha)	75.30	89.28	↑	8.49	7.67	− 0.82
Coef. of variation of polygon area (%)	4221%	3707%	↑	2565%	324%	− 2241%
P75 polygon area	0.0012	0.0016	↑	0.008	0.008	0
P99.99 polygon area (ha)	10.61	11.30	↑	0.11	0.05	− 0.06
	Broadleaved forests (forest area = 109 204.1 ha)					
	2010	2016		Opening	Closing	Balance
Num. gaps	3,828,475	2,971,192	↓	4,665,797	14,654,742	9,988,945
Total gap area (ha)	62,082.5	53,138.7	↓	3381.83	12,333.49	8951.67
Relative gap area (% relative total forest type area)	56.85%	48.66%	↓	3.10%	11.29%	8.20%
Mean polygon area (ha)	162.17	178.84	↑	7.25	8.42	1.17
Coef. of variation of polygon area (%)	4811%	3836%	↑	526%	424%	− 102%
P75 polygon area	0.0012	0.0016	↑	0.008	0.008	0
P99.99 polygon area (ha)	27.26	25.15	↓	0.07	0.06	− 0.01
	Mixed forests (forest area = 14 579.4 ha)					
	2010	2016		Opening	Closing	Balance
Num. gaps	450,463	389,949	↓	669,824	2,051,178	1,381,354
Total gap area (ha)	8603.3	7476.3	↓	474.1	1601.14	1127.04
Relative gap area (% of mixed forest area)	59.01%	51.28%	↓	3.25%	10.98%	7.73%
Mean gap area (ha)	191.00	191.74	↑	7.08	7.81	0.73
Coef. of variation of gap area (%)	3251%	2944%	↓	282%	200%	− 82%
P75 gap area (ha)	0.0012	0.0016	↑	0.004	0.008	0.004
P99.99 gap area (ha)	27.49	23.43	↓	0.05	0.03	− 0.02

Three first columns represent gaps in 2010, gaps in 2016 and trend (arrows). Arrows represent the increase (↑) or decrease (↓) between the 2010 and 2016 value for each statistic. Minimum gap area and median gap area take the same value for all years, opening, closing and forest types and correspond to $4m^2$. Three last columns represent polygons of opening forest, closing forest and balance (closing-opening)

We found significant differences between years in the forest gap shape metrics assessed (i.e., see P-value < 0.001 in area, perimeter and shape index in Fig. 3), except for the area and perimeter of gaps in mixed forests; and among forest types, across time and comparing gap openings and closings (see letters inside the boxes in Fig. 3). Among forest types, significant differences were found between conifer and the other two forest types for both 2010 and 2016 (Fig. 3).

The scale parameter (λ) of the GSFD ranged from 1.729 to 1.905 with a mean value of 1.878 and 1.740 for 2010 and 2016, respectively (Fig. 4). A reduction of the λ parameter between 2010 and 2016 was observed for all forest types, being largest for the broadleaved forest type (9.0%) and smallest for conifers (5.6%, Fig. 4).

Gap dynamics and hotspots identification in Mediterranean forests

A 13.9% of the study area changed from 2010 to 2016 (24 067 ha), with a clear trend towards gap canopy closing in all forest types (Table 2 and Appendix S3). Broadleaved forests had 3.65 more area of closings than openings (3.06 and 3.38 for conifer and mixed forests, see raw values in Table 2). The net balance of canopy gap closing was 16.71% for conifers, 14.41% for broadleaves and 13.09% for mixed forests. In terms of mean gap area, conifer was the only forest

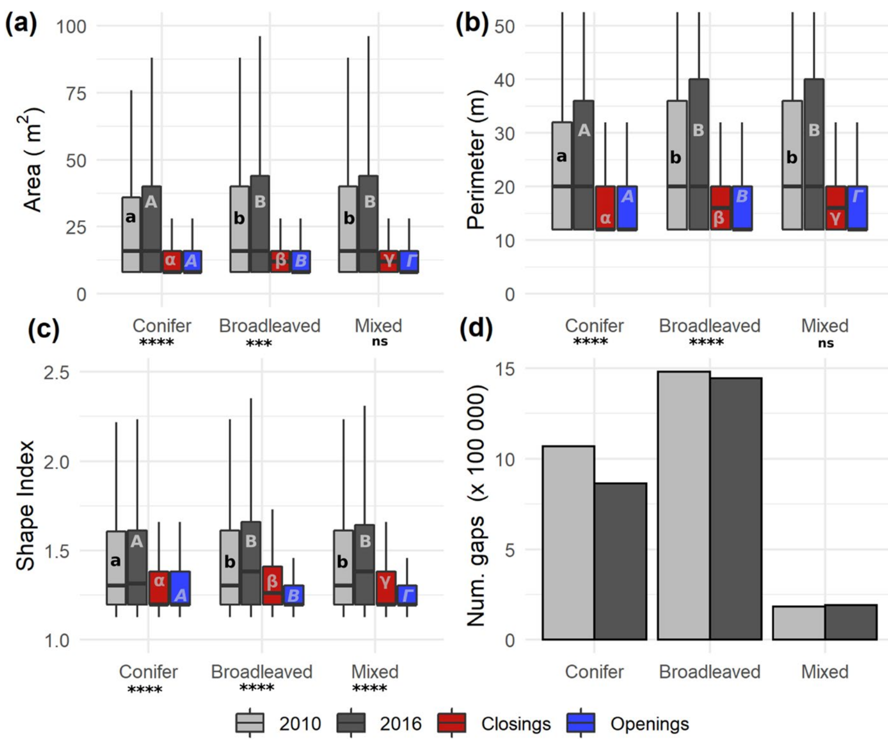

Fig. 3 Plots of gap shape metrics including **a** gap area, **b** gap perimeter, **c** shape index and **d** number of gaps. Outliers are not shown and a minimum threshold of 8 m^2 was chosen for visualization purposes (4, 8, 12, 16m^2 thresholds in Fig. S2.1, Appendix S2). The significance of the differences in the gap shape metrics between years within forest type is shown below each forest type label (Welch's ANOVA results ****P < 0.001; ***P < 0.01; **P < 0.05; *P < 0.1; ns = no significant). Letters inside boxes show significant differences in the comparison (Game-Howell post-hoc test) between forest types within years (Welch's ANOVA results: P < 0.001 for all cases): lowercase Latin letters for 2010, capital Latin letters for 2016, lowercase Greek letters for openings and capital italic Greek letters for closings

type for which the mean area of gap closing polygons is smaller than for gap opening (Table 2). Although there is a clear predominance of closure in all forest types, the maximum area of gap opening was larger than for gap closing, especially in conifers (see P99.99 of opening and closing in Table 2).

Regarding net changes in forest gaps most of the 1 km^2 cells of the study area remains unchanged (65%, Fig. 5). Therefore, 35% of the cells suffered a change between 2010 and 2016 (32% of conifer forests' 1km^2 cells, 37% of broadleaved; 38% of mixed). Forest opening pixels predominated only in 4% of changing cells (Conifers-6%; Broadleaved-4%; Mixed-3%, see Fig. S3-2 and S3-3 for separate figures per forest type in Appendix S3). Statistically significant hotspots of closing were greater than openings across the study area according to Getis-Ord Gi* (see Fig. 5 and Fig. S3-4 for separate figures per forest type in Appendix S3). Forest openings between 2010 and 2016 predominate in the southern half of the study area while forest closings are more common in the north-central part of the community.

Discussion

We have provided the first analysis of canopy gap structure and dynamics of Mediterranean forests through spatially explicit characterization of canopy gap dynamics regionally. The combination of gap geometry and GSFD allowed us to better understand continuous forest gaps dynamics (Jucker 2021), observing a highly dynamic landscape with a trend towards forest closure in a six years' time lapse spatially heterogeneous, with hotspots of gap openings and closings. Forest dynamics and recovering from

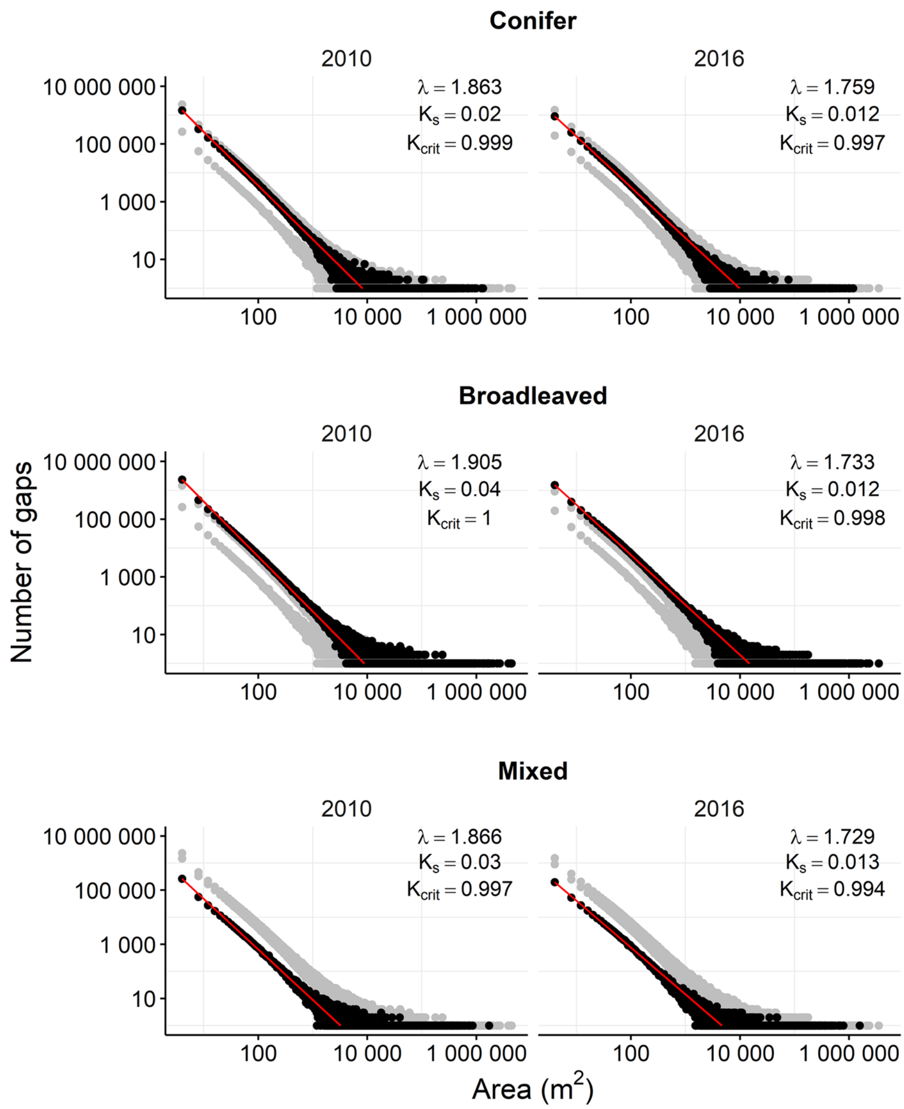

Fig. 4 GSFD by year and forest type. Black dots represent the GSFD for the target forest type, while light grey dots represent GSFD for the other two forest types. The red lines represent the power-law distribution fitted. Axes are logarithmic. λ, Ks (Kolmogorov–Smirnov goodness of fit test) and Kcrit (critical values for Ks) are shown for all years and forest types. Ks < Kcrit for all cases (i.e. the hypothesis that the power-law estimates represent the same distribution function as the data is accepted)

disturbance and periodic maps of hotspots will help to benchmark the effectiveness of forest management and restoration strategies (Muscolo et al. 2014; Philipson et al. 2020).

Forest gaps detection and characterization in Mediterranean forests

We observed a reduction in the number of gaps and forest gap area, but an increased size gap (mean gap area) between 2010 and 2016. This trend could be linked to forest cover increase within the study area. As we are working with fixed forest polygons from the Spanish Forestry Map (MITECO 2013) we did not capture deforestation or forest expansion, but changes of forest cover. We have observed a predominant closure of small gaps, which skewed the gap mean area towards higher values (from 75.3 to 89.3 ha in conifers; from 162.2 to 178.8 ha in broadleaved and from 191.0 to 191.7 ha in mixed forests), in agreement with previous studies that report a densification in the structure in Mediterranean forests (Vayreda et al. 2016; Cervera et al. 2019). Forest closure can be strongly related to rural abandonment and the loss of associated traditional agriculture and livestock activities (Delgado-Artés et al. 2022). Thus, it has been reported high rates of recent land cover changes towards woodlands (Lasanta-Martínez et al. 2005;

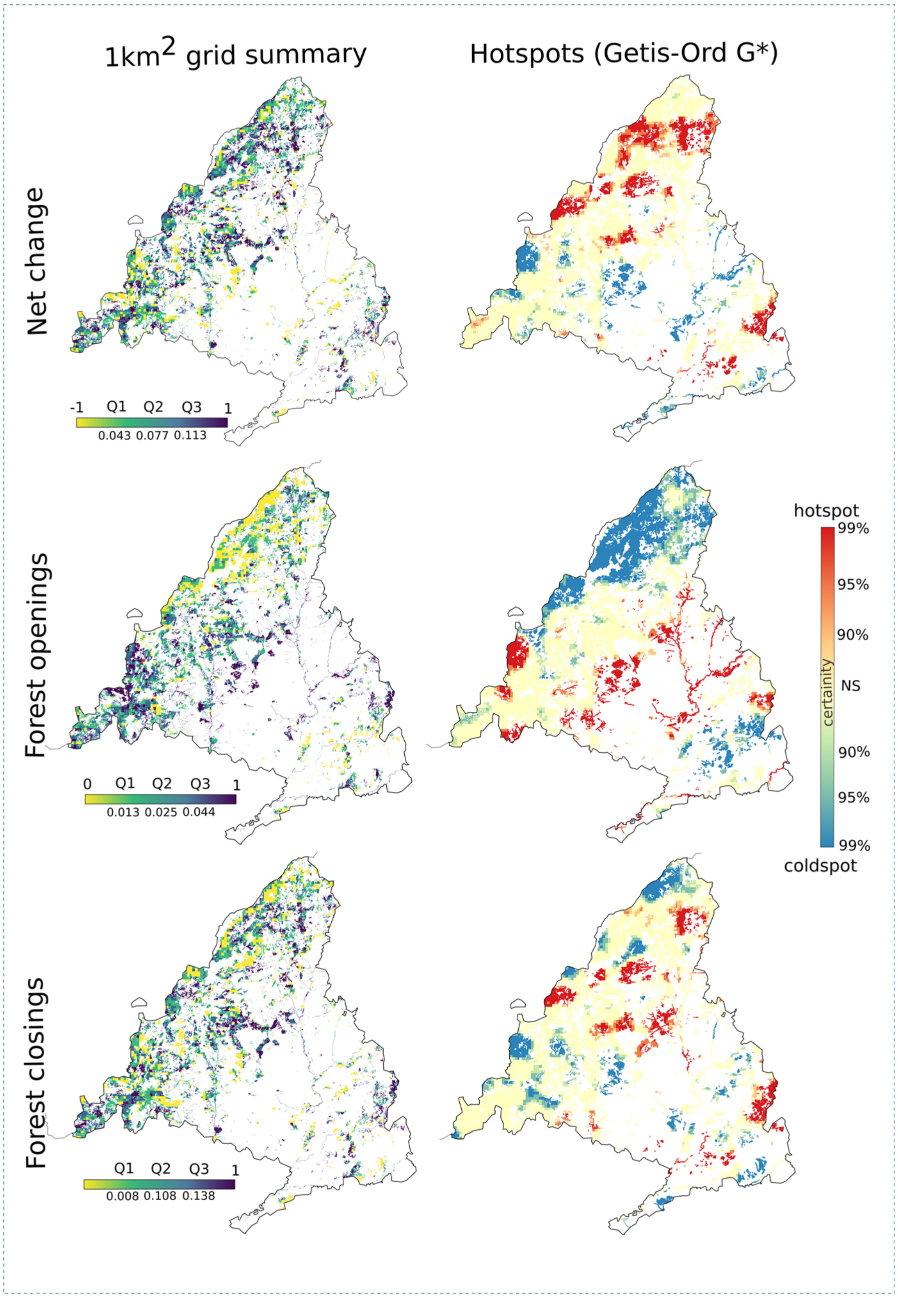

Fig. 5 Forest openings, closings and net balance of gap change. In the first column we used a 1 km^2 grid and classified in quartiles from 0 (0 changed pixels/1 km^2 cell) to 1 (all pixels within the 1 km^2 cell changed between 2010 and 2016). In the second column we calculated statistically significant hotspots according to Getis-Ord G*results

Ruiz-Benito et al. 2010). Moreover, the observed land cover increases could be due to the changes in forest use and management since the twentieth century due to rural depopulation (Palahi et al. 2008).

We found that gap proportion and characteristics depended on forest types, with no significant differences between broadleaved and mixed but with conifer forests. The mixed and broadleaved forests had the greatest gap proportion, mean gap area, maximum gap area, perimeter and shape indices compared to conifers; regardless of the minimum threshold gap area and height threshold chosen (Appendix S2). Similarities between broadleaved and mixed forests gap metrics were expected since there is a high presence of *Quercus* species in the mixed forest type (MITECO 2013), which implies higher similarity in terms of structure and dynamics. Differences between conifer and broadleaved forests may respond to differential morphological characteristics of these contrasting functional groups (Forzieri et al. 2021; Jactel et al. 2009) leading to differences in gap proportion and geometric features (Rodrigues Reis et al. 2021). *Q. ilex* species is the most common species in broadleaved and mixed Mediterranean forests (Appendix S1) and this species has lower stem densities, basal area and volume than *Pinus sylvestris* (main species of the 41.53% of conifer forests in our study area, Appendix S1). In addition, shade-intolerant species (e.g. *Pinus* spp.) tend to better regenerate in larger gaps than shade tolerant species, e.g. *Quercus* spp. (Denslow 1980). Therefore, the observed gaps skew metrics (such as percentage of gap area, mean gap area, perimeter or shape indices) towards higher values can be due to large gaps in broadleaved forests, which can be more difficult to naturally close. This may be amplified by the role of management in abandoned dehesas and field crops. Despite this, we found that the increment of maximum gap area between 2010 and 2016 only appears in conifer forests. This fact, could be attributed to wildfire occurrence since largest gaps are bound to be caused by catastrophic events such as fire or strong windstorms (Franklin et al. 1987) and conifer forests are more intensely and frequently affected by wildfires (Díaz-Delgado et al. 2004). Actually, the largest conifer gap we found in this study (2016) corresponds to a wildfire that took place in Robledo de Chavela (west of the Community of Madrid) in 2012.

The lambda parameter of GSFD (1.729—1.905) for Mediterranean forest are within the range observed in different ecosystems, ranging from 1.1 to 3.1. Regardless of the biome, a common threshold of $\lambda = 2$ has been determined for being an indicator of larger disturbances ($\lambda < 2$) or smaller ones ($\lambda > 2$) (Fisher et al. 2008; Asner et al. 2013; Goodbody et al. 2020); see Appendix S4 for theoretical and observed values of λ. Our values are considerably lower than those found in tropical and boreal forests (Appendix S4) which can be explained, not only in terms of disturbance but also in terms of the structure of Mediterranean forests, which are characterized by more open canopies, lower stem density and smaller trees in terms of height and diameter.

Our values are close to the threshold of $\lambda = 2$, meaning that is an area of moderate disturbances, but it differed among forest types. The lowest λ value in 2010 corresponds to conifer forests and in 2016 to the mixed and broadleaved forests, which could suggest that in terms of GSFD largest disturbances occurred in conifers in 2010 but in broadleaves in 2016. However, if we compare lambda values with different minimum gap area threshold, we can observe that conifer values of lambda are always higher than broadleaved or mixed for all minimum gap thresholds except $4m^2$ in 2010 (see Fig. S2.2, Appendix S2). It is possible that some of the detected gaps of 4 m^2 are due to lower point density in 2010 (0.5 p m^{-2}) compared to 2016 (1 p m^{-2}) (Table 1). It would, therefore, be more correct to state that, in terms of GSFD, larger disturbances are found in broadleaved and mixed in contrast to conifer forests for both years. This is in agreement with Goodbody et al. (2020) results that also calculate λ values separately for conifer (2.21), broadleaved (2.20) and mixed (2.19) getting higher values for conifers in comparison with the other forest types. Similarly, to the values observed for λ, our results of gap metrics showed higher percentage of gap area, mean gap area, maximum gap area and perimeters for broadleaved compared to conifers.

Gap dynamics and hotspots identification in Mediterranean forests

The general reduction in the number of gaps and forest gap area we found in the period studied is not homogeneous for all forest types finding higher closing rates in broadleaved forests (Table 2) compared to conifer. On the contrary, we observed a decrease of λ values between the two years studied, which indicates that all forest types move towards larger disturbances, especially in broadleaved forests. The high rate of forest closure in broadleaved and the decrease in gap proportion is mainly due to the closure of the smallest gaps (Fig. S3-1 Appendix S3). In contrast, this decrease in conifer gaps occurs proportionally in the first size classes which contributes to a smaller decrease of λ.

We have observed a highly dynamic forest (35% of 1 km^2 cells suffered a change between 2010 and 2016) with a net forest gain, finding multiple hotspots of change across the study area. The forest gain detected is in agreement with the increment of forest density reported in the Northern Hemisphere (e.g. McIntyre et al. 2015) and in Mediterranean region

(Vayreda et al. 2016; Cervera et al. 2019; Delgado-Artés et al. 2022). However, we also observed hotspots of gap openings in agreement with the general trend of increasing canopy tree mortality in Europe and in the Mediterranean region due to forest decay caused by drought, pest, diseases and wildfires (Seidl et al. 2014; Senf et al. 2020). The combination of vegetation cover densification and increment in tree mortality and decay due to global change may explain the high dynamisms we found in our study area. Rural abandonment can be driving both forest growth and an increase in the frequency and severity of natural disturbances (Palahi et al. 2008). It generates an increase in amount of forest biomass and in its connectivity, which implies a rising fire risk (Pausas and Fernández-Muñoz 2012; Pausas and Millán, 2019), drought stress mortality because of competition (Vayreda et al. 2012; Jump et al. 2017) and more vulnerability to pest and diseases (Palahi et al. 2008). Rural abandonment, and hence its consequences in terms of forest expansion and vulnerability to disturbances, depends on factors such as soil, topography or socio-economic conditions (Weissteiner et al. 2011) that do not distribute evenly across the territory. Vegetation responses (e.g. recruitment and growth) also depend on factors such as type of disturbance, geographic location and stand age (McDowell et al. 2020). In summary, current vegetation dynamics in Mediterranean forests are affected by land abandonment, disturbance regimen, recruitment or growth, among others, that are spatially heterogeneous. Consequently, it is expected to find areas where forest opening or closing are concentrated, represented by the significant hotspots of change according to Getis-Ord Gi* detected in this study.

Study limitations and considerations

There are some considerations about the data used and the thresholds applied. Regarding the data it is important to consider, firstly, that the time gap between the SFM (2013) and the LiDAR datasets (2010 and 2016) might miss changes in forest cover. Secondly, some of the identified gaps could be the result of forest management practices. Similarly, plantations that become naturalized are considered as natural forest or regeneration. Thirdly, both datasets are low density airborne LiDAR data, which could affect the delineation ability of our approach. This is particularly important for the 2010 dataset which had half the density of the 2016 dataset, which may imply an over-detection of gaps in 2010, especially of the smaller ones. Nevertheless, the raster resolution was selected based on the point density of the 2010 dataset to reduce this effect. Finally, the impact that can be caused by phenological differences between the datasets, particularly in broadleaved and mixed stands as the first coverage acquisition spanned during summer and fall.

Regarding the thresholds applied for gap delineation (minimum gap area and maximum tree height within a gap) it is important to remark that threshold choice may have a significant impact on the results, depending on the structure heterogeneity of the forests under analysis. For this reason, we have tested different thresholds for minimum gap area and tree height within a gap and we have corroborated that the trends in gap characteristics between years and forest types are maintained (Appendix S2). However, considering that Mediterranean forests are very different in terms of dynamics, structure and historical management from tropical and boreal forests, and that this is the first study carried out in canopy gap patterns in this type of forests, more research in this topic should be done in order to test size and height thresholds in different zones of Mediterranean areas. Due to the high diversity within the Mediterranean forests, it should not be specifically tested the thresholds depending on the vegetation type. In addition, the great spatial variability of the structure of Mediterraean forests, might also require not only applying vegetation specific thresholds but also spatially dynamic ones.

Management implications

Characterization of spatial and temporal patterns of forest disturbances, as we do in this study, is an important information for policy-makers and forest managers (Muscolo et al. 2017; Zhu et al. 2019). These have an important influence in species composition and forest dynamics (Koukoulas and Blackburn 2004; Muscolo et al. 2017) and contributes to understand how Mediterranean forests are changing due to global change and to propose successful management measures focus on adaptation and mitigation strategies. Besides, knowing the natural disturbance regime of a given area can help to management decisions aiming recreating natural processes in forests (Schliemann and Bockheim 2011), as gap-cutting silviculture to increase diversity and to improve forest structure (Muscolo et al. 2014, 2017).

Periodic maps of hotspots of openings and closings also provides valuable information for managers as well as for researchers, providing key areas for the study of Mediterranean forest dynamics and the processes underlying these changes. Hotspots of opening are likely to be areas under some type of disturbance that is causing tree decay and, hence, needs special attention. Hotspots of closing are, on the contrary, areas that are getting denser because of tree growth. These areas need to be also monitored since a structural overshoot process could take place (Jump et al. 2017) and some silvicultural treatments may be necessary to decrease drought-related forest dieback risk.

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Author contributions MR, PRB and MG and conceived the ideas and designed methodology; MR and MG collected the data; MR and MG analysed the data; MR, CS and MG developed the scripts for airborne LiDAR data processing; MR led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data availability LiDAR data used: LiDAR-PNOA 2010 and 2016 CC-BY 4.0 Instituto Geográfico Nacional y Comunidad Autónoma de Madrid. Available in: https://centrodedescargas.cnig.es/CentroDescargas/index.jsp.

Declarations

Conflict of interest The authors declare no conflict of interest.

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