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(Article begins on next page)

1 Gap disturbances and regeneration patterns in a Bosnian old-growth forest: A multispectral

2 remote sensing and ground-based approach.

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- 7

8 Abstract

Objectives: We examined canopy gap structure and regeneration patterns at the landscape scale
using a combination of remote sensing and field based surveys.

Methods: The study was carried out in the forest reserve of Lom, an old-growth *Fagus-Abies- Picea* forest located within the Dinaric Alps in the north-western part of Bosnia and
 Herzegovina. A high resolution (1-m Panchromatic and 4-m Multispectral) Kompsat-2 satellite
 image was orthorectified and classified through an unsupervised pixel based classification using
 an artificial neural network method.
 Results: This approach allowed the identification of 650 canopy gaps, ranging in size from 32 to

17 1776 m². Only 20 intermediate to large gaps (> 250 m²) were identified, and they were mainly 18 present near the perimeter of the reserve. The origin of these large openings was associated with 19 past human-caused disturbances or topographic conditions. The species composition of 20 regeneration within large, human-caused gaps differed markedly from small gaps and non-gap 21 sites in the core area of the reserve. Shade-intolerant species dominated the seedling and sapling 22 layers in large openings. The landscape approach employed in this study confirmed the 23 hypothesis that small gaps predominate at Lom, especially within the core area of the reserve.

24

25 Keywords

- 26 Canopy opening; gap-phase; primeval forest; spatial pattern; remote sensing; Balkan peninsula
- 27

28 1. Introduction

29 Forest disturbance and recovery strongly influence ecosystem processes and carbon balance both 30 at regional and global scales. Disturbances influence successional pattern and process due to their 31 extreme variability in size, frequency, and intensity (Turner et al. 1998). In temperate forests 32 where large-scale, catastrophic disturbances are absent or very rare, dynamics are driven by the 33 formation of small to intermediate scale openings in the forest canopy following mortality of 34 canopy trees, often referred to as gap dynamics (Spies et al. 1990). Canopy gaps have a strong 35 influence on forest dynamics because they increased light into the understory and drive tree 36 recruitment to the canopy layer. They also contribute to the spatial heterogeneity of a forest 37 landscape and are influenced by several climatic and physiographic factors that mainly act at the 38 landscape level (Rich et al. 2010). However, little is known about canopy gap patterns and 39 processes at the landscape scale, and only a few studies have addressed gap patterns at this scale 40 (Battles et al. 1995; Hessburg et al. 1999; Smith and Urban 1988).

41 The spatial distribution of forest canopy gaps has important implications for understory light 42 regimes and tree regeneration. Gap size and spatial distribution influence forest regeneration, and 43 in turn, tree species diversity (Lawton and Putz 1988). Another important effect of the spatial 44 distribution of canopy gaps is the creation of a mosaic of structural types within a forested 45 landscape (Frelich and Lorimer 1991). Although spatial distribution is an important descriptor for 46 forest disturbances such as canopy gaps, relatively few studies have investigated the spatial pattern 47 of gap formation (e.g. Frelich and Lorimer 1991; Hessburg et al. 1999; Lawton and Putz 1988; 48 Nuske et al. 2009).

49 A traditional approach to the study of gaps is based on field survey methods (for a complete 50 review, see Schliemann and Bockheim 2011), which are limited in their ability to capture spatial 51 and temporal patterns, and cannot be used extensively because of their financial cost (Vepakomma 52 et al. 2008). An alternative approach is to employ remote sensing together with multiple scale 53 ground surveys (Rich et al. 2010). Multispectral imagery can be a useful tool, but has rarely been 54 used for canopy gap identification (Jackson et al. 2000). High resolution (e.g. < 5 m) spaceborne 55 remote sensing data (e.g. Ikonos, QuickBird, Kompsat-2) provide a detailed view of forest 56 canopies and are potentially useful tools to study canopy gaps at a variety of spatial scales 57 (Jackson et al. 2000; Rich et al. 2010). These aerial and satellite sensors permit automatic data
58 collection enabling the sampling of broader areas and scales in the same period. Moreover, remote
59 sensing analysis can be used to better structure the sampling design at a landscape scale.

60 In this study, we coupled high-spatial resolution Kompsat-2 satellite imagery from a single date 61 with field observations in an old-growth mixed Fagus-Abies-Picea forest in Bosnia and 62 Herzegovina. Such old-growth remnants in eastern and southeastern Europe provide valuable 63 opportunities to evaluate small-scale tree mortality processes. Kompsat-2 digital imagery was 64 chosen for the study because its geometric resolution approaches the scale of individual forest 65 components, such as tree crowns and forest canopy gaps. Our specific objectives were: 1. to 66 propose a classification method to detect complex gaps from satellite images and compare this 67 approach with data collected in the field; 2. to quantify characteristics of canopy gaps, particularly 68 gap spatial pattern, at the landscape scale; and 3. to understand the role of geometric attributes of 69 gaps on forest regeneration.

70

71 **2. Methods**

72 **2.1. Study area**

73 The study was conducted in the Lom forest reserve. The reserve is a 297.8 ha area of old-growth 74 forest (between 44°27' - 44°28' N, and 16°27' - 16°30' E, DATUM WGS84) located in the 75 Dinaric Alps, within the Klecovača region in the north-western part of Bosnia and Herzegovina. 76 The reserve has relatively gentle topography (1223-1503 m a.s.l.), but sinkholes are scattered 77 throughout the area, which are typical features of the karst geology in the region. The climate is 78 transitional continental with a mean annual temperature of 3.5°C and mean annual precipitation of 79 1600 mm, with maximum in December and minimum in July (Drinic climate station, 730 m a.s.l.). 80 The forest reserve of Lom is divided in two zones, a core area of 55.8 ha that consists of well 81 preserved old-growth (Motta et al. 2008; Motta et al. 2011) and a buffer zone that has some evidence of past human activities. Since 1956 all management activities are strictly forbidden in 82 83 the entire reserve. The forest is dominated by silver fir (Abies alba Mill.), Norway spruce (Picea 84 abies (L.) Karsten), and European beech (Fagus sylvatica L.), while sycamore maple (Acer 85 pseudoplatanus L.) and Scots elm (Ulmus glabra Hudson) occur less frequently (Bucalo et al.

86 2007; Motta et al. 2008).

87 2.2. Image pre-processing and classification

88 A high resolution Kompsat-2 (Korea Multi-Purpose SATellite-2) satellite image was acquired on 89 June 11, 2009. The acquired image is a Bundle type, comprising a 1-m GSD (Ground Sample 90 Distance) panchromatic band (0.50-0.90 µm) and four 4-m GSD multispectral bands (Blue, 91 Green, Red, Near Infrared). The sensor acquired the image with a 248.23° azimuth and an 92 incidence angle of 6.44° and clouds were completely absent from the scene. The Kompsat-2 93 multispectral data were initially calibrated into reflectance at-the-ground values using the nominal 94 values of Gain and Offset (Table 1) and applying the Dark Subtraction algorithm for a simplified 95 atmospheric correction. These operations were performed using the ENVI software (ITT 2009). 96 The satellite image was orthoprojected with the Toutin rigorous model for Kompsat-2 data 97 implemented within the Orthoengine module of PCI software (PCIGeomatics 2009). 11 three 98 dimensional Ground Control Points (GCPs), previously surveyed in the field with a Trimble 99 GEOXM GPS, were used in this process. GPS pseudo-range code measurements were post-100 processed using the nearest permanent station (Sarajevo) belonging to the EUREF network. The 101 resulting planimetric accuracy was about 1.5 m, sufficient enough for a 1:10,000 scale map. The 102 digital elevation model used during the orthoprojection was the NASA/METI ASTER Global 103 Terrain Model, with a geometric resolution of 30 m and vertical Root Mean Square Error (RMSE) 104 of about 9 m. Both the panchromatic and the multispectral bands were orthoprojected obtaining a 105 RMSE for the GCPs of 1.35 m.

The 1-m panchromatic band was used as an up to date map of the site to support surveys in the field. The 4-m multispectral image was used to test its suitability for canopy gap detection. A subsample of the area surrounding the forest reserve of 12612 ha was selected for this purpose. To obtain a high degree of automation we adopted an unsupervised pixel-based classification method in place of an object-oriented one. In optical remote sensing, especially when using a pixel-based classification approach, dark shadows cast by larger crowns adjacent to smaller trees or edge canopies into a canopy gap can be a significant problem and hence can make it difficult to reliably quantify gap characteristics (Asner et al. 2003; Leboeuf et al. 2007). Bands ratios such as NDVI (Normalized Difference Vegetation Index) can be used to limit the effect of shadows and illumination differences without losing the physical meaning of the investigated object (canopy). In fact the NDVI is considered relatively insensitive to changes in shadow fraction (Asner et al. 2003). Thus, an NDVI image was generated from the Red and NIR bands and stacked together with the four original bands. Five bands were then used during the classification.

119 The proposed approach tests the ability of an unsupervised pixel-based classification to separate 120 the class 'canopy gap' from the remaining vegetation. The classifier used for this task is based on 121 the Artificial Neural Networks (ANN) philosophy. In particular, we used the Neural Gas algorithm 122 which was specifically developed with IDL (Interactive Data Language) routine. The unsupervised 123 classifier was applied twice successively. First, the image was classified into 16 classes that were 124 subsequently aggregated into 7 classes following the Jeffries-Matusita separability test. Second, 125 two textural occurrence measures (i.e. data range and standard deviation) were generated with a 126 7x7 kernel for each of the original bands. The new 10 band image was first masked to address the 127 operation to the 'gap' class pixels, then clustered through the NG algorithm into 2 clusters. This 128 permitted the separation of the large and homogeneous openings (meadows in our case) from 129 forest canopy gaps. A polygon vector canopy gap map (Fig. 1) was derived from the final 130 classification image in a GIS environment adopting a minimum mapping unit (MMU) of two 131 pixels (32 m²). The class 'canopy gap' comprised those openings in the forest canopy dominated 132 by soil, grasses, and coarse woody debris where the gap-filling process by tree regeneration was in 133 its early phase. From an image processing point of view a "gap" can be considered as a local 134 spectral and textural anomaly within the forest class. The accuracy of the canopy gap map was 135 assessed through two different approaches: field observations of 40 sample gaps were used to 136 evaluate the underestimation of canopy gaps and a visual check of all classified gaps (n = 360) on 137 a false color RGB composite was done to assess the potential overestimation of gaps. One hundred 138 percent of the visited gaps were correctly classified. The visual check revealed that 82 % of gaps 139 were correctly classified, and 8 % were uncertainly classified. Moreover, the spectral signature of 140 the whole 'canopy gap' class was compared to the spectral characteristics of 18 photointerpreted gaps in order to test the ability of the classification to detect real canopy gaps. The spectral statistics for the class 'canopy gap' were very similar to the spectral statistics of the photointerpreted gaps (Fig. 2).

144 2.3. Spatial pattern of canopy gaps

145 Because canopy gaps are objects with finite size and irregular shape and they can be large in 146 comparison to the investigated spatial scales we treated the gaps as patches or polygons avoiding 147 point approximation (Wiegand et al. 2006). Three different categorical raster maps (i.e. the whole 148 reserve, buffer zone, and core area) of 4-m spatial resolution were derived from the canopy gap 149 vector map obtained from the satellite image. The categorical maps were transformed to a matrix 150 with 2 categories (canopy gaps, and forest) and a mask was used to take into account the irregular 151 shape of the study area (space restriction effect). In order to analyse the spatial pattern of gaps we 152 used both Ripley's L-function (Ripley 1976) and the O-ring statistic (Wiegand et al. 1999). This 153 latter was computed as complementary analysis to avoid the misinterpretation of results due to the 154 cumulative effect of Ripley's index that can confound effects at larger distances with effects at 155 shorter distances (Perry et al. 2006). Complete spatial randomness (CSR) was chosen as a null 156 model built by rotating and moving the objects within the raster map. All the spatial analyses were 157 performed using the Programita software (Wiegand and Moloney 2004).

158 **2.4.** Gap geometry and forest regeneration

159 The influence of gap geometry (size, shape, and direction) on regeneration structure and 160 composition was assessed through field surveys. The orthorectified Kompsat-2 image was used to 161 locate larger gaps (> 200 m2) in order to include additional samples to an existing dataset (Bottero 162 et al. 2011) of 56 canopy gaps (ranging from 11 to 708 m2). Data on regeneration structure and 163 composition were collected and georeferenced with a GPS. The density of seedlings (trees < 1 m 164 height), saplings (trees > 1 m tall and with diameter at the breast height < 7.5 cm), and gap fillers 165 (trees > 7.5 dbh and less than 20 m tall) was measured within a 6 m radius circular plot located in 166 the centroid of each canopy gap. Gap size was calculated in a GIS environment using the triangles 167 method based on the mapped position on the ground of the trees bordering the gap. The shape was measured as direction expressed as north-eastness index and elongation of polygons by using theLongest Straight Line extension for ArcView 3.x (Jenness 2007).

170 The relationship between regeneration composition and gap geometry was analyzed through 171 redundancy analysis (RDA) (Rao 1964). This direct gradient analysis is a constrained ordination 172 method that was used to investigate the variability explained by the explanatory variables and their 173 correlation with regeneration composition variation. Two data sets were used in this ordination 174 analysis: (a) regeneration composition (10 species x 60 plots); and (b) geometry of canopy gaps (5 175 variables x 60 plots). The RDA was performed using Canoco® (ter Braak and Smilauer 1998), and 176 the statistical significance of all ordination analyses was tested by the Monte Carlo permutation 177 method based on 10000 runs with randomized data.

178

179 **3. Results**

180 **3.1.** Canopy gaps characteristics

A total of 650 canopy gaps were located by multispectral remote detection within the Lom forest reserve (Table 2). The average size of these gaps was 78.2 m² and the variability observed was high, ranging from 32 to 1776 m². The total gap area was 5.1 ha, resulting in a gap fraction of 1.7 % and the density of canopy gaps within the whole reserve was 2.2 ha⁻¹.

The core area and buffer zone differed in canopy gap density (1.7 and 2.3 ha⁻¹ respectively) and mean size (62.6 and 81.2 ha⁻¹ respectively). The average gap area was strongly influenced by the different size of the largest gap in the two zones (320 m² in the core area and 1776 m² in the buffer zone). Moreover, the variability of gap area was much smaller (50 m² standard deviation) in the core area than in the buffer zone (106.7 m² standard deviation).

190 The frequency distribution of canopy gap size in both the core area and buffer zone (Fig. 3) 191 followed a negative exponential form with smaller gaps more frequent than larger ones. The 192 difference in size distribution between the two zones was not significant (Komolgorov-Smirnov 193 test, p = 0.116). The proportion of gaps smaller than 100 m² differed slightly between the core 194 area (89%) and the buffer zone (80%), and the amount of gaps larger than 300 m² was similar in 195 the two zones (4% core area; 6.6% buffer zone).

196 **3.2. Spatial pattern of canopy gaps**

The spatial distribution of canopy gaps varied in the different parts of the Lom reserve. The univariate Ripley's L-function for the whole reserve showed a deviation from complete spatial randomness starting at a distance of 20 m (Fig. 4e). Spatial patterns between the buffer zone and the core area were different. In the core area the L-function values stay within the confidence envelope (Fig. 4a), indicating a random distribution of the canopy gaps at all scales (0 to 200 m). In the buffer zone the spatial pattern of the gaps was clustered for distances larger than 20 m (Fig. 4c). The results are consistent with the O-ring analysis (Fig. 4b, d, f).

204 **3.3.** Gap geometry and forest regeneration

205 Silver fir was the dominant species in the seedling layer, beech in the sapling one, and Norway 206 spruce, rowan and maple were denser in large and elongated gaps (Table 3). The redundancy 207 analysis revealed that gap geometry was related to regeneration composition (Fig. 5). The first and 208 second axes accounted for 10.4 and 1.6 % of the total variation, respectively (Table 4). Early-209 successional and shade-intolerant species, such as sycamore maple and rowan, were positively 210 associated with large (Area, Perimeter) and elongated (Long) gaps. European beech saplings were 211 not influenced by gap size, but were weakly associated to gap filler basal area. The different 212 pattern observed for rowan seedlings (Sorbus_1) and saplings (Sorbus_2) was probably due to the 213 fact that this species is shade-tolerant only in the first stages of its life.

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215 4. Discussion and conclusion

216 4.1. Gap delineation using high resolution multispectral data

In this study, high-spatial resolution Kompsat-2 satellite imagery was coupled with field data to assess important components of the gap disturbance regime across a temperate mixed forest landscape. Our results indicate that it is possible to measure key components of gaps using spectral and textural features from high-spatial resolution data. The 650 identified gaps were dominated by grasses, forbs, bare soil and coarse woody debris, indicating that the classification method adopted in this study picked out predominately recently formed gaps. This explains the very low gap fraction observed in the study compared to those values (often > 10%) reported in studies of similar forests in Europe (Drösser and von Lüpke 2005; Nagel and Svoboda 2008; Splechtna et al. 2005) and in a companion study (Bottero et al. 2011). Typically, field based surveys of gaps distinguish openings from closed canopy areas by using a height cutoff of gapfilling trees, often around half the height of the main canopy layer. The minimum gap size considered in the present study (32 m²) was larger than the threshold adopted in many field based surveys. Consequently, these studies sample a broad range of gap ages and sizes, resulting in a higher gap fraction.

230 The NDVI was calculated to help in the classification process, but there was a low correlation 231 between the index and the disturbed surfaces. The weak relationship observed was mainly due to 232 the fact that vegetation (e.g. forest regeneration, shrubs, and grasses) was present beneath the 233 forest canopy and within the openings. Forest canopy gaps with dense understory vegetation likely 234 have a similar near infrared response to a closed canopy site, particularly for gaps in the later 235 stages of the gapfilling process with gap fillers reaching the lower canopy layer. Nevertheless, 236 disturbed sites like canopy gaps often have rougher texture and are more heterogeneous than 237 closed canopy areas (Rich et al. 2010). To overcome the limits of spectral data, textural features 238 were subsequently used to improve the automatic classification method. Although the 239 classification method proved to be useful, a substantial improvement for canopy gap detection can 240 be obtained through the use of LiDAR imagery (Gaulton and Malthus 2010; Vepakomma et al. 241 2008). However, the automatic classification on high resolution multispectral data presented in this 242 study proved to be a good estimator of recently formed canopy gaps and it is more cost effective 243 than LiDAR. Another advantage of multispectral satellite imagery is the possibility of performing 244 a diachronic study on a series of historical satellite images.

245 4.2. Spatial pattern of canopy gaps

The spatial pattern observed in our study site seems follow these findings. The gaps within the core area of the Lom reserve were randomly distributed, which is likely due to the relative environmental homogeneity of the area and the lack of recent higher severity disturbance events. Consistently, a large proportion of the gaps in the core area were formed by endogenous mortality of large canopy trees (Bottero et al. 2011). The random spatial distribution of canopy gaps found in Lom's core area is in agreement with other studies in temperate forests (Frelich and Lorimer 1991; Nuske et al. 2009). In contrast, gaps were larger and clustered in the surrounding buffer zone, which is due to topographic and human caused influences. A higher density of gaps was found at higher elevations in close proximity to the ridges of the reserve. This may be partly because these areas are more wind exposed, but also due to several artificial gaps from recent (1992-1995 Bosnian War) illegal logging and former grazing activities. These artificial openings were located in close proximity to manmade trails and dirt roads, which likely contributed to the clumped pattern of gaps.

4.3. Forest regeneration as influenced by canopy gap geometry

260 First, it should be noted that the gap size range observed in Lom (32-1700 m2) was similar to the 261 size distribution of gaps commonly reported for forests where small-scale disturbance events occur 262 (Lawton and Putz 1988; Lertzman and Krebs 1991; Nagel and Svoboda 2008; Spies et al. 1990). 263 Gap size had little influence on regeneration density in Lom, which was also found in a companion 264 study (Bottero et al. 2011). This finding is confirmed by other studies in southeastern European 265 forests, where the presence of a stratum of advance regeneration partially explains the weak 266 relationship between regeneration density and gap size. Other factors such as gap age seem to be 267 related to seedling density more than gap size, probably due to thinning and architectural 268 differences between species over time due to competition (Poulson and Platt 1989; Spies et al. 269 1990).

270 The results from our study area partially confirmed a conceptual gap model that predicts an 271 increase in the relative dominance of shade-intolerant species as size of disturbance increases 272 (Runkle 1985). Gap geometry (size, direction, and shape) had very little influence on the 273 occurrence of shade-tolerant species such as P. abies, F. sylvatica, and A. alba, because they were 274 already present as advance regeneration before gap formation. Thus, it was not surprising to 275 observe that forest canopy gaps were not primary sites of regeneration, but mainly acted in 276 regulating the recruitment of advance regeneration dominated by shade-tolerant species (Busing 277 and White 1997). Less shade-tolerant species, such as A. pseudoplatanus and S. aucuparia were 278 present only in lager gaps and were dominant in only a few artificial openings located in the buffer 279 zone of the reserve. Large canopy gaps are important for the maintenance of shade-intolerant

species that are more competitive in open areas (Whitmore 1989) and occur only in small numbers

281 in closed canopy forests.

282

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394 Tables

395 Table 1. Nominal coefficients used for the calibration to surface reflectance of the Kompsat 2396 image.

	Band	L max	L min	Sun Irradiance	Central wavelength
		(W/(m ² .sr.µm))	(W/(m ² .sr.µm))	(W/(m ² .sr.µm))	(μm)
	1 (Blue)	-1.52	193.00	1929.00	0.485
	2 (Green)	-2.84	365.00	1837.00	0.560
	3 (Red)	-1.17	264.00	1556.00	0.660
	4 (NIR)	-1.51	221.00	1068.00	0.830
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416 Table 2. Landscape metrics and statistics of geometrical attributes of canopy gaps of the Lom old-

417	growth	forest	in	Bosnia	Herzege	ovina.
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Metrics	Unit	Core area	Buffer Zone	Reserve
Total area	ha	55.8	242.0	297.8
Number of gaps	n	102	548	650
Density of gaps	n/ha	1.7	2.3	2.2
Minimum gap area	m^2	32.0	32.0	32.0
Maximum gap area	m^2	320.0	1776.0	1776.0
Mean gap area	m^2	62.6	81.2	78.2
Median gap area	m^2	48.0	48.0	48.0
Stdv. gap area	m^2	50.0	106.7	100.2
Minimun gap perimeter	m	24.0	24.0	24.0
Maximum gap perimeter	m	96.0	368.0	368.0
Mean gap perimeter	m	35.1	40.8	39.9
Stdv. gap perimeter	m	15.1	27.6	26.1
Gap fraction	%	1.08	1.85	1.70

429 Table 3. Gap geometry characteristics and seedlings (1) and saplings (2) species composition

430 (*Abies* = silver fir; *Fagus* = European beech; *Picea* = Norway spruce; *Acer* = sycamore maple;

Sorbus = rowan) divided by 4 classes of canopy gaps' area.

Gap area classes (m ²)	< 50	50-100	100-250	>250	Total		
Number of gaps	21	14	16	7	58		
Gap area mean (m ²)	25.64	74.66	145.47	670.80	139.22		
Gap area standard deviation (m ²)	13.75	14.69	36.42	142.11	196.07		
Gap perimeter (m)	20.79	37.29	54.01	147.75	47.53		
Gap elongation (m)	8.23	14.06	19.41	38.92	16.03		
Gap fillers (m ² /ha)	7.28	7.88	9.75	9.08	8.31		
Regeneration composition (n/ha)							
Picea_1	640	783	619	1120	719.77		
Picea_2	17	227	133	1238	229.58		
Abies_1	4143	4446	3890	3183	4045.58		
Abies_2	152	303	133	2476	428.14		
Fagus_1	1196	1036	1326	1415	1216.15		
Fagus_2	825	884	884	1592	936.94		
Acer_1	337	51	354	589	297.83		
Acer_2	0	25	0	0	6.20		
Sorbus_1	118	0	155	589	148.92		
Sorbus_2	0	0	0	236	24.82		

439 Table 4. Correlation of gap geometry variables with the first four axes of the regeneration 440 composition RDAs. Boldface numbers represent the correlations greater than 0.3 between 441 explanatory variables and the ordination axes. A p value of 0.004 on the significance of all 442 canonical axes is derived from a Monte Carlo test with 10000 permutations.

Axis	RDA-1	RDA-2	RDA-3	RDA-4
% of variance	10.4	1.6	1.2	0.3
Species-environment correlations	0.74	0.39	0.31	0.16
Area (gap area)	0.59	0.17	0.09	-0.04
Perimeter (gap perimeter)	0.52	0.14	0.15	-0.03
Long (gap elongation)	0.59	0.06	0.07	-0.01
NE (gap direction)	0.16	0.03	0.12	0.13
Fillers (gap fillers basal area)	-0.20	0.30	-0.08	0.01

456 Figure captions

- 457 **Fig. 1** Canopy gap map of the Lom forest reserve showing the geographic distribution of canopy
- 458 gaps (minimum mapping unit = 32 m^2) bounded by the core area and the forest reserve borders.
- 459 Example Kompsat-2 subset images reporting the zoom of a single canopy gap as observed on (A)
- 460 the panchromatic (1-m resolution) and (B) the multispectral image are also showed.



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Fig. 2 Comparison between spectral mean values of classified gaps (class 'canopy gap') and 18 photointerpreted gaps from the Kompsat-2 image. Error bars represent standard deviation of spectral features.



Fig. 3 Frequency distribution of canopy gap size in the core area and in the buffer zone of the Lom





473 **Fig. 4** Univariate Ripley's L-functions -L(d)- and O-ring pair-correlation functions -O(r)- of the 474 canopy gaps of the Lom old-growth forest using the polygon-based approach respectively in the 475 core area (a, b), the buffer zone (c, d), and the whole reserve (e, f). Black line: estimated function; 476 dotted lines: upper and lower confidence envelopes under the null hypothesis of complete spatial 477 randomness, computed by Monte Carlo simulation using 1000 replicates.



485 Fig. 5 Redundancy analysis (RDA of 60 plots) of regeneration composition in relation to canopy 486 gap geometry and gap filler basal area. Dashed arrows show the tree species (Abies = silver fir; 487 Fagus = European beech; Picea = Norway spruce; Acer = Sycamore maple; Sorbus = Rowan) 488 divided by seedlings (1) and saplings (2). Solid line arrows represent the "biplot scores of canopy 489 gaps geometry" (Perimeter = gap perimeter; Area = gap area; Long = longest straight line across 490 the interior of a gap; NE = north-eastness index of gap direction) and gap filler basal area (Fillers). 491 A p value of 0.004 on the significance of all canonical axes is derived from a Monte Carlo test 492

- 1.0 Fillers Area Perimeter Sorbus 2 Abies 1 Fagus Long NE Acer_1 Abies 2 Picea_2 ▶ Picea Fagus 1 Sorbus 1 -0.6 -0.6 1.0

with 10000 permutations.

