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Gap disturbances and regeneration patterns in a Bosnian old-growth forest: a multispectral remote sensing and ground-based approach

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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.**

3

4 Matteo Garbarino & Enrico Borgogno Mondino & Emanuele Lingua & Thomas A. Nagel &
5 Vojislav Dukić & Zoran Govedar & Renzo Motta

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7

8 **Abstract**

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

11 • **Methods:** The study was carried out in the forest reserve of Lom, an old-growth *Fagus-Abies-*
12 *Picea* forest located within the Dinaric Alps in the north-western part of Bosnia and
13 Herzegovina. A high resolution (1-m Panchromatic and 4-m Multispectral) Kompsat-2 satellite
14 image was orthorectified and classified through an unsupervised pixel based classification using
15 an artificial neural network method.

16 • **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
82 evidence of past human activities. Since 1956 all management activities are strictly forbidden in
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.

106 The 1-m panchromatic band was used as an up to date map of the site to support surveys in the
107 field. The 4-m multispectral image was used to test its suitability for canopy gap detection. A sub-
108 sample of the area surrounding the forest reserve of 12612 ha was selected for this purpose. To
109 obtain a high degree of automation we adopted an unsupervised pixel-based classification method
110 in place of an object-oriented one. In optical remote sensing, especially when using a pixel-based
111 classification approach, dark shadows cast by larger crowns adjacent to smaller trees or edge
112 canopies into a canopy gap can be a significant problem and hence can make it difficult to reliably

113 quantify gap characteristics (Asner et al. 2003; Leboeuf et al. 2007). Bands ratios such as NDVI
114 (Normalized Difference Vegetation Index) can be used to limit the effect of shadows and
115 illumination differences without losing the physical meaning of the investigated object (canopy).
116 In fact the NDVI is considered relatively insensitive to changes in shadow fraction (Asner et al.
117 2003). Thus, an NDVI image was generated from the Red and NIR bands and stacked together
118 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

141 gaps in order to test the ability of the classification to detect real canopy gaps. The spectral
142 statistics for the class ‘canopy gap’ were very similar to the spectral statistics of the
143 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

168 measured as direction expressed as north-eastness index and elongation of polygons by using the
169 Longest 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**

181 A total of 650 canopy gaps were located by multispectral remote detection within the Lom forest
182 reserve (Table 2). The average size of these gaps was 78.2 m² and the variability observed was
183 high, ranging from 32 to 1776 m². The total gap area was 5.1 ha, resulting in a gap fraction of 1.7
184 % and the density of canopy gaps within the whole reserve was 2.2 ha⁻¹.

185 The core area and buffer zone differed in canopy gap density (1.7 and 2.3 ha⁻¹ respectively) and
186 mean size (62.6 and 81.2 ha⁻¹ respectively). The average gap area was strongly influenced by the
187 different size of the largest gap in the two zones (320 m² in the core area and 1776 m² in the buffer
188 zone). Moreover, the variability of gap area was much smaller (50 m² standard deviation) in the
189 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**

197 The spatial distribution of canopy gaps varied in the different parts of the Lom reserve. The
198 univariate Ripley's L-function for the whole reserve showed a deviation from complete spatial
199 randomness starting at a distance of 20 m (Fig. 4e). Spatial patterns between the buffer zone and
200 the core area were different. In the core area the L-function values stay within the confidence
201 envelope (Fig. 4a), indicating a random distribution of the canopy gaps at all scales (0 to 200 m).
202 In the buffer zone the spatial pattern of the gaps was clustered for distances larger than 20 m (Fig.
203 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.

214

215 **4. Discussion and conclusion**

216 **4.1. Gap delineation using high resolution multispectral data**

217 In this study, high-spatial resolution Kompsat-2 satellite imagery was coupled with field data to
218 assess important components of the gap disturbance regime across a temperate mixed forest
219 landscape. Our results indicate that it is possible to measure key components of gaps using spectral
220 and textural features from high-spatial resolution data. The 650 identified gaps were dominated by
221 grasses, forbs, bare soil and coarse woody debris, indicating that the classification method adopted
222 in this study picked out predominately recently formed gaps. This explains the very low gap
223 fraction observed in the study compared to those values (often > 10%) reported in studies of

224 similar forests in Europe (Drösser and von Lüpke 2005; Nagel and Svoboda 2008; Splechtna et al.
225 2005) and in a companion study (Bottero et al. 2011). Typically, field based surveys of gaps
226 distinguish openings from closed canopy areas by using a height cutoff of gapfilling trees, often
227 around half the height of the main canopy layer. The minimum gap size considered in the present
228 study (32 m²) was larger than the threshold adopted in many field based surveys. Consequently,
229 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**

246 The spatial pattern observed in our study site seems follow these findings. The gaps within the
247 core area of the Lom reserve were randomly distributed, which is likely due to the relative
248 environmental homogeneity of the area and the lack of recent higher severity disturbance events.
249 Consistently, a large proportion of the gaps in the core area were formed by endogenous mortality
250 of large canopy trees (Bottero et al. 2011). The random spatial distribution of canopy gaps found
251 in Lom's core area is in agreement with other studies in temperate forests (Frelich and Lorimer

252 1991; Nuske et al. 2009). In contrast, gaps were larger and clustered in the surrounding buffer
253 zone, which is due to topographic and human caused influences. A higher density of gaps was
254 found at higher elevations in close proximity to the ridges of the reserve. This may be partly
255 because these areas are more wind exposed, but also due to several artificial gaps from recent
256 (1992-1995 Bosnian War) illegal logging and former grazing activities. These artificial openings
257 were located in close proximity to manmade trails and dirt roads, which likely contributed to the
258 clumped pattern of gaps.

259 **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 larger 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

280 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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290

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394 **Tables**

395 Table 1. Nominal coefficients used for the calibration to surface reflectance of the Kompsat 2

396 image.

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Band	L max (W/(m ² .sr.μm))	L min (W/(m ² .sr.μm))	Sun Irradiance (W/(m ² .sr.μm))	Central wavelength (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 Herzegovina.

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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
Minimum 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

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

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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)					
<i>Picea</i> _1	640	783	619	1120	719.77
<i>Picea</i> _2	17	227	133	1238	229.58
<i>Abies</i> _1	4143	4446	3890	3183	4045.58
<i>Abies</i> _2	152	303	133	2476	428.14
<i>Fagus</i> _1	1196	1036	1326	1415	1216.15
<i>Fagus</i> _2	825	884	884	1592	936.94
<i>Acer</i> _1	337	51	354	589	297.83
<i>Acer</i> _2	0	25	0	0	6.20
<i>Sorbus</i> _1	118	0	155	589	148.92
<i>Sorbus</i> _2	0	0	0	236	24.82

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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.

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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

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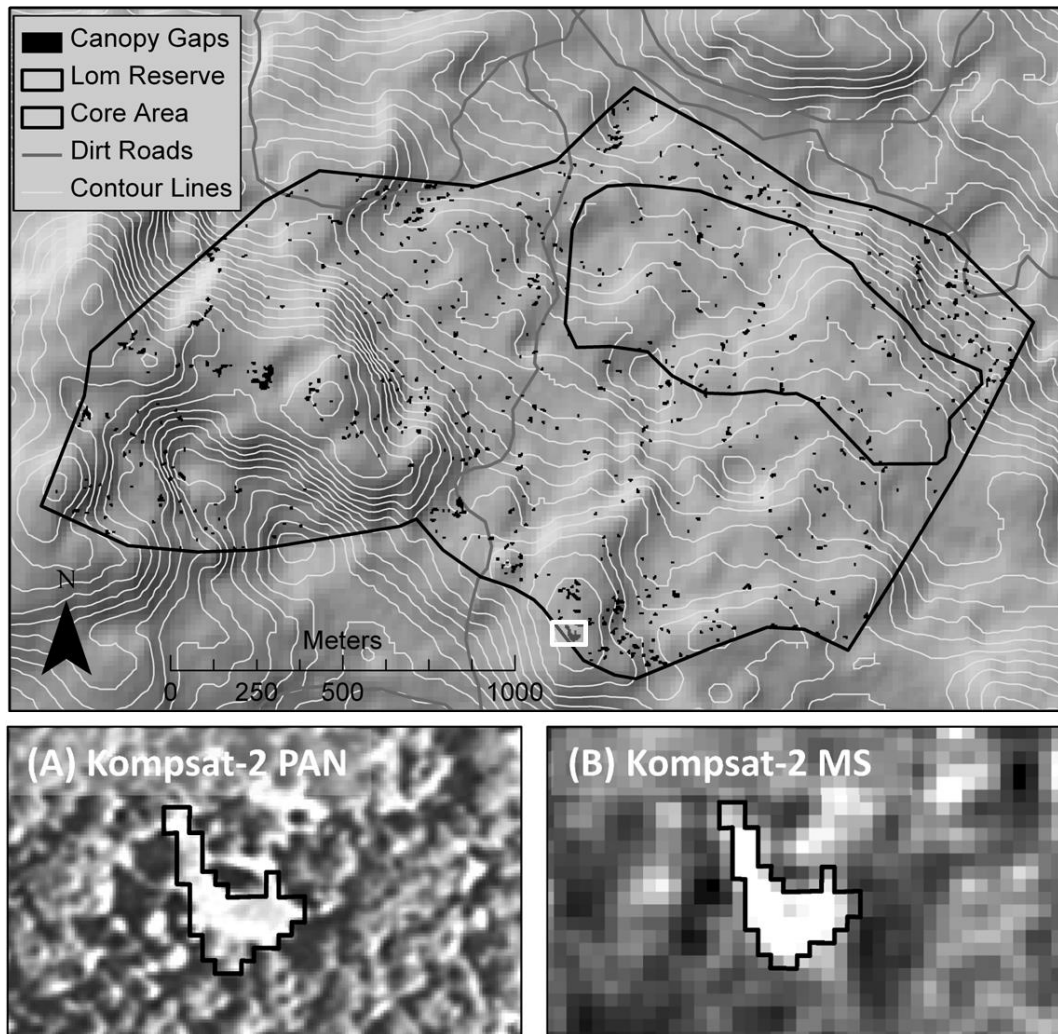
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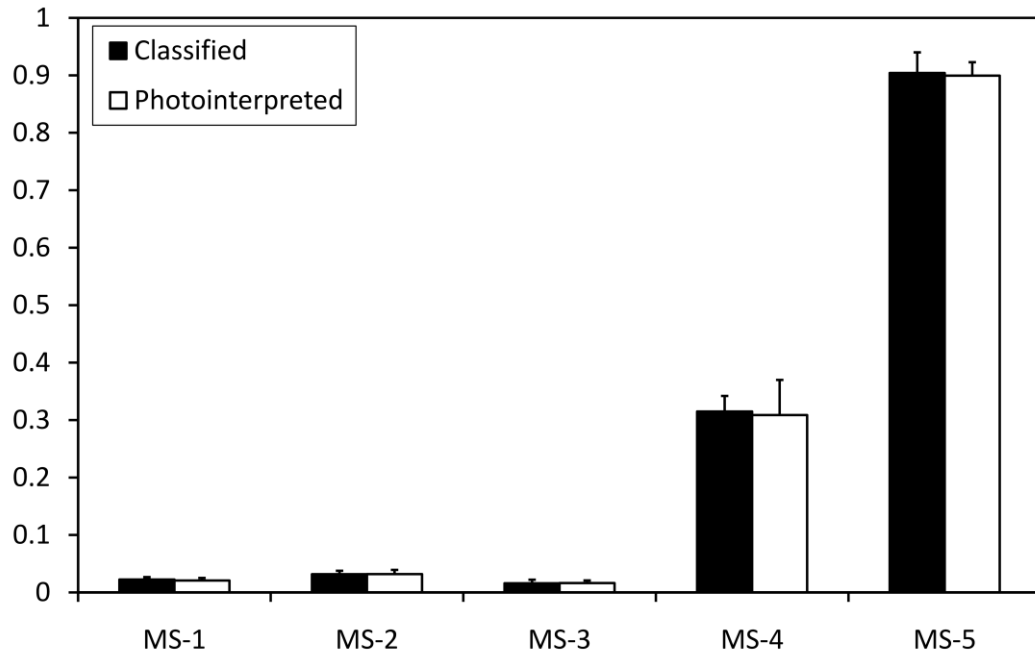
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456 **Figure captions**

457 **Fig. 1** Canopy gap map of the Lom forest reserve showing the geographic distribution of canopy
458 gaps (minimum mapping unit = 32 m²) 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.

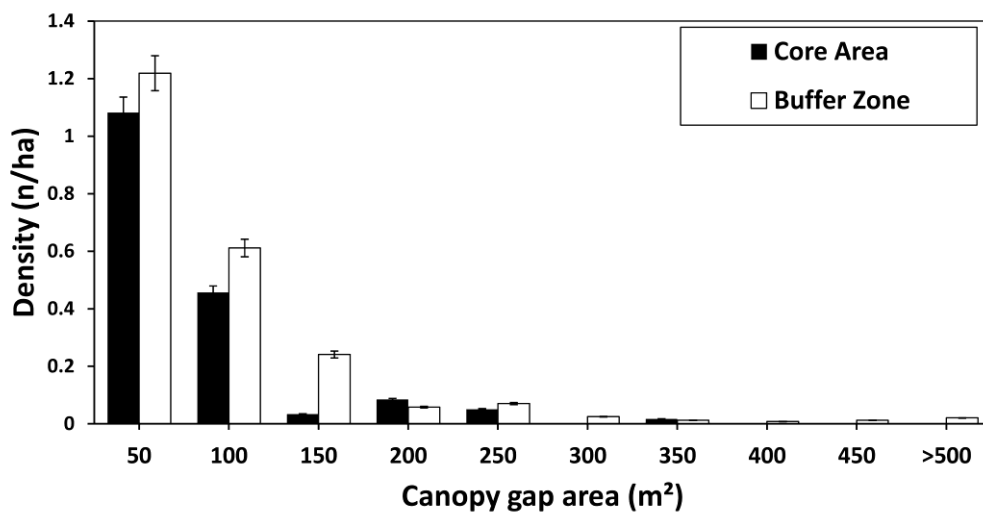


465 **Fig. 2** Comparison between spectral mean values of classified gaps (class ‘canopy gap’) and 18
 466 photointerpreted gaps from the Kompsat-2 image. Error bars represent standard deviation of
 467 spectral features.



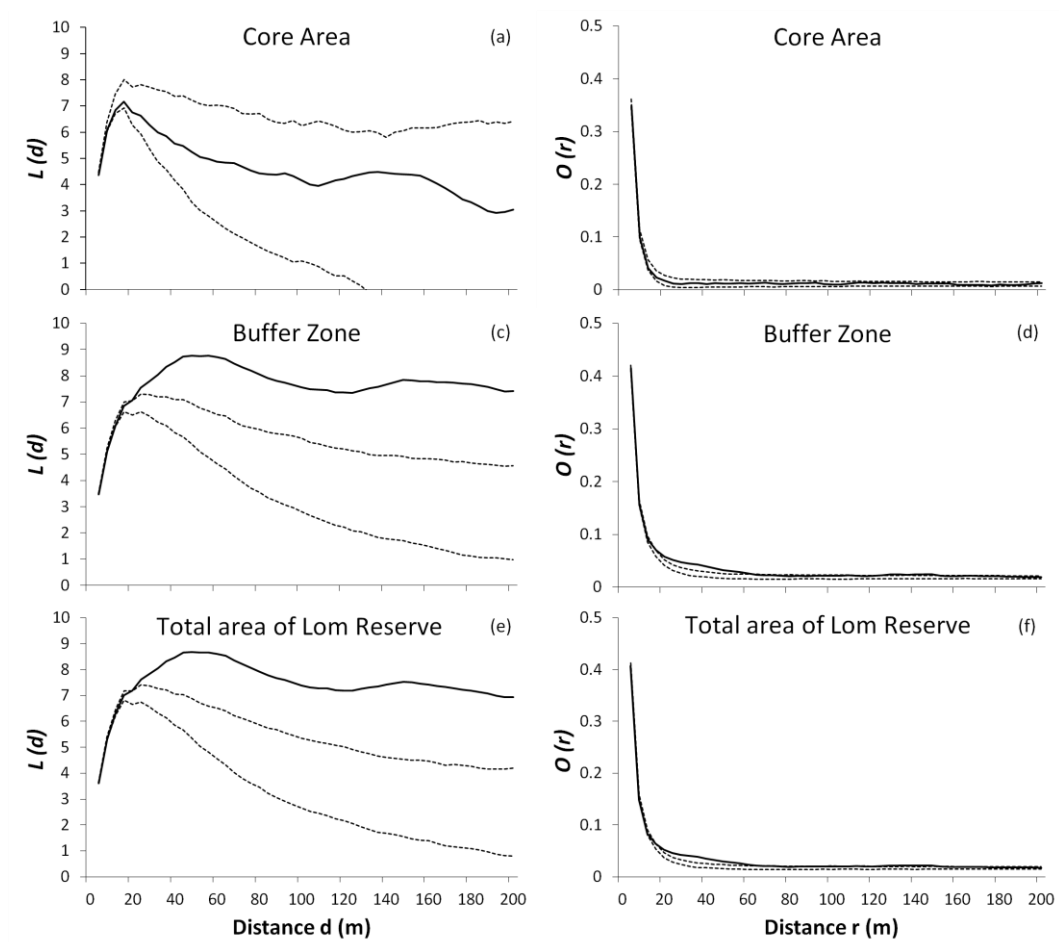
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470 **Fig. 3** Frequency distribution of canopy gap size in the core area and in the buffer zone of the Lom
 471 forest reserve in Bosnia and Herzegovina.



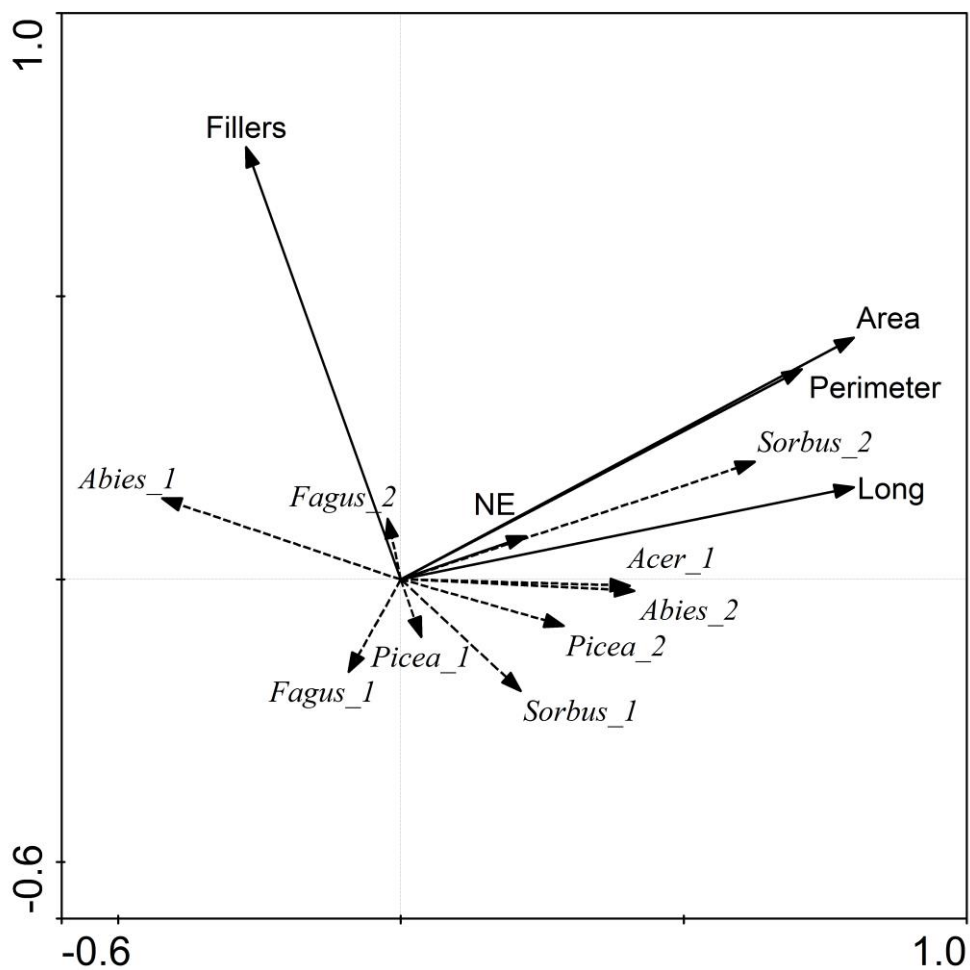
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473 **Fig. 4** Univariate Ripley's L-functions $-L(d)-$ and O-ring pair-correlation functions $-O(r)-$ of the
 474 canopy gaps of the Lom old-growth forest using the polygon-based approach respectively in the
 475 core area (a, b), the buffer zone (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.



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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 with 10000 permutations.



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