Gap pattern of the largest primeval beech forest of Europe revealed by remote sensing

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Abstract. Little is known about the gap pattern of primeval beech forests, since large-scale studies with continuous coverage are lacking. Analyses of forest structural patterns have benefitted from advances in remote sensing, especially with the launch of satellites providing data of submetric ground resolution. These developments can strongly advance our knowledge of natural forest dynamics and disturbance regimes. The Uholka-Shyrokyi Luh forest in the Ukrainian Carpathians, the largest remnant of primeval European beech (*Fagus sylvatica* L.) covering 102.8 km², is an outstanding object to analyze the frequency distribution of gap sizes and to infer processes of forest dynamics. A stereo pair of very high-resolution WorldView-2 satellite images was used to characterize the forest’s gap pattern. Canopy gaps were first digitized stereoscopically based on the image pair. In a second step, spectral properties in the red and yellow frequency bands were used to distinguish the stereoscopically mapped gap areas from non-gap areas, which enabled gap mapping over the entire study area. To validate the spectral gap mapping 338 randomly distributed samples were assigned manually to gap and non-gap areas based on the ortho-images. We found excellent agreement except for an overestimation of gaps close to clouds due to diffuse image areas. The frequency distribution of gap size revealed the forest to be structured by a small-scale mosaic of gaps mainly <200 m² (98% of the gaps). Only a few large, stand-replacing events were detected, most probably caused by a wind storm in March 2007 and a heavy wet snow fall in October 2009. The small canopy gaps reflect fine-scale processes shaping forest structure, i.e., the death of single trees or groups of a few trees and is in line with the findings of the terrestrial forest inventory. We conclude that remote sensing approaches based on very high-resolution satellite images are highly useful to characterize even small-scale forest disturbance regimes and to study long-term gap dynamics. Stereo satellite images provide two viewing angles of the study area, thus allowing for a highly accurate mapping of canopy gaps in forests with a complex topography.

Key words: canopy gap; Carpathian Biosphere Reserve; disturbance regime; *Fagus sylvatica*; forest dynamics; spectral image analysis; old-growth forest; satellite; virgin forest; WorldView-2.

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INTRODUCTION

Natural disturbances are key drivers of forest dynamics, largely shaping vertical structure as well as horizontal patterns (White 1979). The disturbance regime can be defined as the characteristics (frequency, extent and severity) of the dominant disturbance types as well as
their interactions (Frelich 2002). In temperate forests, the major natural disturbances are fire, windstorms, ice storms, droughts and insect outbreaks (Pickett and White 1985). Central European temperate forests are mainly affected by wind and, to a smaller extent, by snow and ice, while forest fire and drought are typically limited to drier areas, e.g., the Mediterranean (Schelhaas et al. 2003). European beech forests, in particular, are thought to be dominated by small-scale disturbance events, with wind as the main disturbance agent (Splechtna and Gratzer 2005, Firm et al. 2009). Given that severe stand-replacing events appear to be rare (Tabaku 2000, Drössler and von Lüpke 2005), forest dynamics are understood to be shaped by fine-scale processes (Trotsiuk et al. 2012, Hobi et al. 2014).

Disturbances in natural beech-dominated forests have been studied using a wide range of methods. Based on field mapping of tree crowns or canopy gaps, detailed information on gap sizes and vertical forest structure has been obtained in a number of studies (e.g., Koop and Hilgen 1987, Tabaku 2000, Drössler and von Lüpke 2005, Butler Manning 2007, Nagel and Svoboda 2008, Kucbel et al. 2010, Bottero et al. 2011). Dendroecological analysis has proved to be a valuable method for reconstructing past disturbance events and their frequency (e.g., Szwagrzyk and Szewczyk 2001, Piovesan et al. 2005, Šamonil et al. 2009, Šamonil et al. 2012, Trotsiuk et al. 2012, Nagel et al. 2014). These terrestrial approaches, however, require a great amount of effort to obtain field measurements and are therefore only feasible for small areas, i.e., a few hectares at most. To study the dynamics and patterns of natural beech forests, surveys at the landscape level are required. Terrestrial inventories (e.g., Commarmot et al. 2013) provide a rich picture of forest properties, but by definition they lack continuous spatial coverage, and drawing inferences on spatial patterns and underlying ecological processes is exceedingly difficult (Hobi et al. 2014). Remote sensing methods may fill this gap. Previous studies using remotely sensed image data (e.g., Zeibig et al. 2005, Kenderes et al. 2008, Garbarino et al. 2012, Rugani et al. 2013, Blackburn et al. 2014) have shown that these techniques are highly promising for the continuous mapping of disturbances at the landscape level.

Recent advances in disturbance dynamics research based on optical imagery have made use of a time-series (yearly) Landsat imagery, covering decades of change of the Earth’s surface (Cohen et al. 2010, Kennedy et al. 2010). These approaches for multi-temporal change detection can be applied, for example, to monitor forest fires, insect-related mortality, or post-disturbance regrowth at an annual time scale (e.g., Coops et al. 2010, Schroeder et al. 2011, Kennedy et al. 2012). However, the spatial resolution of Landsat is limited (28.5 m pixels), and thus these data fail to allow for reconstructing small-scale disturbance processes.

With the launch of very high-resolution satellites, starting with IKONOS in 1999, the mapping of small-scale forest disturbance events over large spatial extents has become feasible. IKONOS images, with their submetric resolution, have been used in previous studies to analyze forest structure (Kayitakire et al. 2006), the size of tree crowns (Song et al. 2010) and the severity of wind disturbance (Rich et al. 2010). This breakthrough for small-scale mapping with satellite images was followed by the launch of other satellites such as QuickBird, GeoEye-1, WorldView-1, and WorldView-2 (Jacobsen 2012). DigitalGlobe’s WorldView-2 satellite has been operational since 2010 and provides stereo imagery with a panchromatic ground sampling distance of 0.5 m. Some of the first studies based on WorldView-2 used the images to map urban tree species in Tampa (Florida, USA) (Pu and Landry 2012) and to quantify tree mortality in mixed-species woodlands (Garrity et al. 2013). An accuracy study conducted in the lowlands of Switzerland revealed the benefit of stereo WorldView-2 images for the 3D modeling of forest canopies (Hobi and Ginzler 2012), which allows for the analysis of vertical forest structure and holds potential for canopy gap detection.

We thus used stereo WorldView-2 images to characterize the disturbance regime of a unique natural beech forest, i.e., the Uholka-Shyrokyi Luh primeval beech forest in the Ukrainian Carpathians, the largest such forest in Europe (cf. Commarmot et al. 2013). Due to its remoteness and large area (102.8 km²), it can be expected that its present structure is the result of natural processes and the forest is not...
influenced by former or recent anthropogenic use. Earlier studies on this forest focused on a small-scale dendroecological assessment of tree age structure (Trotsiuk et al. 2012) and a systematic terrestrial survey of forest characteristics including tree species composition, canopy structure and gap size distribution using 500 m² plots on a regular grid (Commarmot et al. 2013, Hobi et al. 2014). The combination of these data sets with a remote sensing approach provides the potential to derive a comprehensive view of the disturbance regime at the landscape scale.

In our study, we hypothesize that the largest European primeval beech forest shows a fine-scale mosaic of canopy gaps over the entire forest area (102.8 km²) with 95% of the gaps smaller than 200 m² in size. Specifically, we will (1) characterize the density of canopy gaps and their size distribution for the entire area of the largest European primeval beech forest, (2) evaluate the potential of high-resolution WorldView-2 stereo satellite images for the detection of fine-scale canopy gaps in forests with a complex topography, and (3) draw inferences on the drivers causing these gaps by combining the canopy gap map with ancillary information from dendrochronology and the terrestrial inventory.

**Materials and Methods**

**Study area**

The study was conducted in the Uholka-Shyrokyi Luh primeval European beech (*Fagus sylvatica* L.) forest in the southwestern Ukrainian Carpathians (48°18’ N and 23°42’ E, center coordinates). The forest is an almost pure beech forest (97.3%, by basal area) characterized by a multilayered, uneven-aged canopy structure and a high abundance of old trees (Commarmot et al. 2013). A high volume of living trees of 582.1 ± 13.5 m³·ha⁻¹ and a total deadwood volume of 162.5 ± 8.4 m³·ha⁻¹ of all decay classes suggest that the forest has an old-growth character (Hobi et al. 2014). The study perimeter covers an area of 10,282 ha of forest within the Carpathian Biosphere Reserve (CBR) belonging to the transnational UNESCO World Heritage site “Primeval Beech Forests of the Carpathians and the Ancient Beech Forests of Germany”.

The Uholka-Shyrokyi Luh massif consists of flysch layers with marls and sandstone, and of Jurassic limestone and cretaceous conglomerates. The climate is temperate, with a mean annual temperature of 7.7°C (–2.7°C in January and 17.9°C in July), measured at the meteorological station of the CBR in Uholka at 430 m a.s.l. (average for 1990–2010 AD). Mean annual precipitation is 1,134 mm (1980–2010 AD). The forest reserve is divided into two parts of similar size: Uholka in the south and Shyrokyi Luh in the north. Together, they cover an altitude of 400 to 1,300 m a.s.l. and are characterized by a strongly fissured terrain with valleys of streams and hill ranges. Human impact is thought to be low, as only very few anthropogenic traces, such as waste, traces of livestock grazing, research markings and small footpaths, were found when conducting the inventory (Commarmot et al. 2013). We therefore consider this beech forest to be primeval (a synonym to virgin) based on the argument that it has never been influenced significantly by humans (Peterken 1996).

**Image source, characteristics and orientation**

An optical stereo data set acquired on July 22, 2010 by the WorldView-2 satellite was used. WorldView-2, operational since January 2010, is the first very high-resolution 8-band multispectral commercial satellite to provide a ground sampling distance of 0.5 m in the panchromatic and 1.84 m in the multispectral data (Table 1). The images have a dynamic range of 11 bits per pixel. The sensor is able to collect stereo images by looking forward (hereafter “image F”) and backward (hereafter “image B”) from its actual position (DigitalGlobe 2009), which involves viewing angles of up to 45° off-nadir (Table 2). This is called the “along-track” configuration, as the stereo images are taken from the same orbit at different angles along the flight direction by

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**Table 1. Wavelength of the eight spectral bands provided by the WorldView-2 high-resolution stereo satellite.**

<table>
<thead>
<tr>
<th>Spectral bands of WV2</th>
<th>Wavelength [nm]</th>
</tr>
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<tbody>
<tr>
<td>Coastal</td>
<td>400–450</td>
</tr>
<tr>
<td>Blue</td>
<td>450–510</td>
</tr>
<tr>
<td>Green</td>
<td>510–580</td>
</tr>
<tr>
<td>Yellow</td>
<td>585–625</td>
</tr>
<tr>
<td>Red</td>
<td>630–690</td>
</tr>
<tr>
<td>Red edge</td>
<td>705–745</td>
</tr>
<tr>
<td>Near-IR1</td>
<td>770–895</td>
</tr>
<tr>
<td>Near-IR2</td>
<td>860–1040</td>
</tr>
</tbody>
</table>
rotating the camera around its axes (Poli and Toutin 2012). This has the advantages that (1) the
time difference between the two stereo images is
very small (about a minute), and (2) the images
are acquired under the same atmospheric condi-
tions.

Image orientation was provided by the rational
polynomial coefficients (RPCs) originating from
star tracker observations and satellite ephemeris
(Fraser et al. 2006). This geometric relationship is
expressed by 80 coefficients (Grodecki and Dial
2003). To improve image orientation, ground
control points (GCPs) were measured by GPS
(Trimble Geoexplorer XH 2005) with an accuracy
of ±10 cm (standard deviation) after differential
correction. Using 9 GCPs, the image orientation
could be refined to a total root mean square error
(RMSE) of 0.59 m. Panchromatic and multispec-
tral ortho-images from WorldView-2 were then
calculated using a digital terrain model digitized
from the contour lines of a topographic map.
Since this was an ancient map of the area, its
scale, geolocation and accuracy as well as the
method for contour line generation is unknown.
No further corrections for topography or atmo-
spheric distortion were made, since we did not
plan to apply the parameters for gap mapping to
other areas and used only one image scene at a
specific time step. For all further analyses, clouds
and open areas such as pastures and flood plains
were masked out. This reduced the study
perimeter to a forested area of 9,276 ha.

Canopy gap assessment

Canopy surface model.—A 3D softcopy station
(SocetSet 5.6, BAE Systems) and commercial GIS
software (ArcMap10, ESRI) were used to generate
digital surface models (DSMs) of the forest
Canopy based on the stereo pair of panchromatic
images. The Next-Generation Automatic Terrain
Extraction (NGATE) of SocetSet 5.6 (BAE Sys-
tems 2007, DeVenecia et al. 2007) was used for
image matching, which is based on image
correlation and edge matching (Zhang et al.
2007). The available digital terrain model based
on digitized contour lines turned out to be not
accurate enough: in some areas tree heights were
unrealistically high (>60 m) and in others far too
low or even negative. Thus, the calculation of a
canopy height model was not possible, and local
statistics with moving window techniques were
calculated from the digital surface model only.
Although the accuracy of WorldView-2 DSMs
over different land cover types was found to be
high (Hobi and Ginzler 2012), this approach
failed to map the small-scale mosaic of canopy
gaps in the Uholka-Shyrokyi Luh primeval beech
forest; only larger gaps (>500 m²) could be
identified.

This failure is attributable mainly to the low
image matching success (76%), which resulted
from two factors: the complex topography of the
area and the large viewing angles of the satellite.
The differences in InTrack viewing angles (in the
direction of flight) of more than 30° led to
considerable differences in the two images, as
the screened trees were viewed from strongly
different angles. With a CrossTrack viewing
angle of −24° (across the direction of flight) the
satellite was scanning the area from the western
direction, which led to an additional tilt of the
screened objects. In combination with the rugged
topography, east-facing areas were thus in the
shadow of the satellite and exceedingly difficult
to match. The canopy surface approach could,
therefore, only be used for the mapping of large
open areas, and a spectral image analysis method
had to be developed for the extraction of canopy
gap information.

Spectral image analysis.—In a first step, forest
canopy gaps were digitized stereoscopically
using the image pair, but only large gaps visible
in both images could be digitized. In a second
step canopy gaps were mapped separately in
both multispectral ortho-images based on their
spectral information. This approach allowed for

<table>
<thead>
<tr>
<th>Image details</th>
<th>Image F (forward)</th>
<th>Image B (backward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image acquisition</td>
<td>22 July 2012, 12:52:01 GMT</td>
<td>22 July 2012, 12:51:10 GMT</td>
</tr>
<tr>
<td>Mean InTrack view angle</td>
<td>13.9°</td>
<td>−19.2°</td>
</tr>
<tr>
<td>Mean CrossTrack view angle</td>
<td>−23.4°</td>
<td>−24.6°</td>
</tr>
<tr>
<td>Mean OffNadir view angle</td>
<td>27.0°</td>
<td>30.8°</td>
</tr>
</tbody>
</table>
the delineation of small gaps as well. Minimum gap size was not defined, as only gaps visible on the ortho-images were mapped. The mean and standard deviation of the digital numbers of all gap pixels within each spectral band were calculated. For all eight spectral bands, as well as for the normalized difference vegetation index (NDVI) and the modified red-edge NDVIedge based on the red edge instead of the red band, the range of the mean ± standard deviation of the digital numbers was used to test the differentiation of gap vs. non-gap areas.

The yellow and red bands of the WorldView-2 satellite images proved most useful in separating gap from non-gap areas (Fig. 1). Consequently, their additive combination was used for the delineation of canopy gaps. Only areas that lay in the range of the mean ± one standard deviation of the digital numbers of both the yellow (210.89 ± 25.79 for ortho-image F and 255.32 ± 27.6 for ortho-image B) and the red (143.54 ± 25.24 for ortho-image F and 179.58 ± 27.29 for ortho-image B) spectral bands were classified as canopy gap areas. NDVI and NDVIedge were not suitable for separating gap and non-gap areas because their spectral properties were overlapping in a substantial part of their range.

To validate the spectral gap mapping, 338 randomly distributed samples of 2,500 m² each were used. Based on the spectral properties within each cluster, it was manually decided whether the sample was situated in a gap or a non-gap area. This manually interpreted data set was then compared to the result of the spectral gap mapping. The correct classification rate (CCR) and the kappa coefficient (K) were used as statistical measures for the validation of the canopy gap maps. Additionally, the producer’s accuracy (the probability that a gap or non-gap area existing in the manually interpreted data was classified as such) and user’s accuracy (the probability that a pixel classified as gap or non-gap area in the map existed in the manually interpreted data) were calculated.

**Gap maps**

Gap areas were classified as 1 (one) and non-gap-areas as 0 (zero). For better visibility, canopy gap maps were calculated with a raster size of 50 by 50 m, denoting gap percentage by a value between 0 (low gap percentage) and 1 (high gap percentage). Three maps of canopy gap distribution were generated: one based on the classification of ortho-image F, one based on the classification of ortho-image B, and one in which the information of both ortho-images was combined. For the latter, areas where both maps showed canopy gaps and areas where only one map showed a gap were distinguished. This information was used for the evaluation of the advantages of using a stereo pair of satellite images for such a classification instead of only one image.

**Gap and disturbance estimation in the terrestrial inventory**

Ground data were collected in a terrestrial inventory in summer 2010, where besides various tree and stand characteristics the size of canopy gaps was estimated on a systematic grid with 353 sample plots within the forested area (Commarmot et al. 2013). On 314 plots, it was estimated whether the sample plot center was in a canopy gap, distinguishing six size classes, i.e., 20–50 m², 51–200 m², 201–500 m², 501–1000 m², 1001–5000 m², >5000 m², or under a closed canopy. A gap was defined as an opening in the canopy with a minimum width of 5 m measured from crown margin to crown margin, and where gap fillers height is below one third of canopy height of the surrounding stand. Using cross-validation, the agreement between field-measured and classified gaps was estimated, and the producer’s and user’s accuracies, correct classification rate (CCR) and the kappa coefficient (K) were calculated.

**RESULTS**

**Spatial canopy gap distribution**

Gap density was found to be high in the northwestern part of Shyrokyi Luh, in some distinct regions in the central part of Uholka, and close to the western border of Uholka (Fig. 2a). Besides these areas, gap density was generally low. The terrestrial data showed a similar pattern with gaps of different sizes scattered all over the study area (Fig. 2b). The higher frequency of canopy gaps in the northwestern part of Shyrokyi Luh, however, was only partly evident from the terrestrial inventory. Conversely, some of the
larger gaps identified in the terrestrial inventory, were not mapped based on spectral information.

Canopy gap characteristics

The remote sensing approach revealed a low gap fraction of 0.75% of the studied forest area. Canopy gap sizes varied between 2.07 m² and 18,375.19 m², as no lower threshold for the gap size was applied. The average size of the spectrally classified gaps was 28.12 m² with a
standard deviation of 189.10 m². The frequency distribution of the gap sizes had a negative exponential form. Occasionally, larger stand-replacing disturbance events occurred, as evident from the few gaps ≥0.5 ha but the forest was mostly dominated by canopy gaps with an area of <200 m² (98% of the classified gaps), probably originating from the death of one to four single trees (Fig. 3). This general picture is similar to the results of the terrestrial inventory, where 60% of the measured canopy gaps were <200 m² and a few larger canopy gaps were scattered all over the study area (Fig. 2b). The share of small gaps, however, was higher in the spectrally mapped gaps (Fig. 4a) than in the gaps assessed terrestrically, while the field survey revealed a higher percentage of gaps in the larger size classes (Fig. 4b). This became evident when the spectrally mapped gaps were classified into the same size categories as in the terrestrial survey.

**Validation of canopy gap classification**

Visually, there were some differences between the classifications of ortho-image F and ortho-image B, especially near clouds (Fig. 5). Based on the accuracy statistics of the cross-validation with the training area data, the classification results of ortho-image B were found to be more reliable than those of ortho-image F (Tables 3a and 4a). This is however mostly related to clouds and diffuse image areas and not dependent on the viewing angle of the satellite. The producer's accuracy was above 65% for both ortho-images; this can be considered as being quite accurate for the mapping of canopy gaps. The low user's accuracy of ortho-image F, however, showed that the mapping based on ortho-image F failed to reliably distinguish gap- and non-gap areas in some areas. Overall, the kappa values indicated that the mapping based on ortho-image F showed only weak agreement, while the mapping based on ortho-image B showed strong agreement with gaps mapped manually in the training areas.

By additively combining the information from the two ortho-images, the mapping success of canopy gaps was generally higher. Small gaps were mostly mapped on one ortho-image only, whereas larger gaps were mapped more accurately due to the combination of the information from the two ortho-images (Fig. 6). Therefore, the mapping results of the two ortho-images were combined to obtain a gap map of the entire study perimeter.

The validation of the canopy gap maps based on the terrestrial inventory data was difficult, as
not all the sample plots could be accurately geo-referenced during the inventory. But in general the terrestrial gap data showed the same pattern as the remote sensing one. As expected, user’s and producer’s accuracies for non-gap areas were quite high in the cross-validation with the field data (Tables 3b and 4b). However, the accuracy measures for gap areas were low.

**DISCUSSION**

**Canopy gap pattern**

The Uholka-Shyrokiy Luh forest was characterized by a low gap fraction, with <1% of the area classified as gap by spectral analysis. Most studies in beech-dominated primeval forests reported higher gap fractions, varying between

![Graph showing frequency distribution of canopy gap sizes](image)

**Fig. 3.** Frequency distribution of the spectrally mapped canopy gap sizes within the study perimeter. The distribution shows few stand replacing disturbance events with gap sizes larger than 5,000 m$^2$, but most gaps are <200 m$^2$ in area.

![Graph comparing gap distribution](image)

**Fig. 4.** Comparison of the frequency distribution of the canopy gaps delineated with the remote sensing approach and (b) estimated in the terrestrial inventory using the size classes of the terrestrial inventory.
1.7% and 16% (Meyer et al. 2003, Drössler and von Lüpke 2005, Splechta and Gratzer 2005, Zeibig et al. 2005, Nagel and Svoboda 2008, Kenderes et al. 2009, Garbarino et al. 2012, Rugani et al. 2013). Differences in the gap fraction can be due to different gap definitions (e.g., Runkle 1992) and the methods of gap sampling (e.g., Yamamoto et al. 2011). Some canopy gap definitions are based on a minimum size of the gaps or a threshold of height difference compared to the surrounding canopy.

Gap fractions derived from terrestrial analyses are particularly difficult to compare to those from remote sensing approaches, as the definition of a “gap” per se is not identical. With the remote sensing approach based on spectral information used in the present study, only gaps without regeneration allowing to see the soil are mapped, whereas in the terrestrial approach, a gap was defined as an opening in the canopy where gap fillers do not exceed one third of canopy height. Thus, even 10–30 year old gaps may have been

Table 3. Cross-validation of the spectral gap mapping based (a) on the randomly distributed samples of the manually mapped canopy gaps and (b) on the terrestrial inventory data to distinguish gap from non-gap areas within ortho-image F and B.

<table>
<thead>
<tr>
<th>Area</th>
<th>Ortho-image F</th>
<th></th>
<th>Ortho-image B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spectrally mapped gaps</td>
<td></td>
<td>Spectrally mapped gaps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gap</td>
<td>No gap</td>
<td>Row total</td>
<td>Gap</td>
</tr>
<tr>
<td>a) Manually mapped gaps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap</td>
<td>257</td>
<td>47</td>
<td>304</td>
<td>299</td>
</tr>
<tr>
<td>No gap</td>
<td>5</td>
<td>29</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td>Column total</td>
<td>262</td>
<td>76</td>
<td>338</td>
<td>311</td>
</tr>
<tr>
<td>b) Field data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap</td>
<td>49</td>
<td>71</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>No gap</td>
<td>48</td>
<td>144</td>
<td>192</td>
<td>16</td>
</tr>
<tr>
<td>Column total</td>
<td>97</td>
<td>215</td>
<td>312</td>
<td>28</td>
</tr>
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</table>
assessed in the field study, while the spectral analyses probably captured mainly the most recent gaps.

This difference in gap definition may explain also why the terrestrial inventory revealed a higher percentage of large gaps, which need particularly long to close again. The area-wide continuous mapping of canopy gaps in our study revealed that not only the few large, but also the small gaps were not distributed evenly over the area but occurred clustered. The sampling design of the terrestrial inventory failed to capture such locally higher gap densities, which could be another reason for the higher share of large and lower share of small gaps in the field study compared to the remote sensing analysis.

The average gap size in our study (28.12 m²) was smaller than the mean gap size found in other studies of beech-dominated primeval forests, which ranged from 61 to 137 m² (Meyer et al. 2003, Zeibig et al. 2005, Nagel and Svoboda 2008, Kenderes et al. 2009, Bottero et al. 2011). Average gap sizes are largely influenced by the minimum gap size defined and thus not really comparable. Despite the completely different methods using different gap definitions, the gap size distribution, however, showed a similar picture, with most of the gaps being smaller than 200 m² in area.

Meyer et al. (2003) investigated the formation of canopy gaps in three Albanian primeval beech forests and found average canopy gap size to be smaller than the crown projection area of one dominant beech tree. This suggests that most canopy gaps are formed by the death of single trees. This is in line with the findings of Drössler and von Lüpke (2005) regarding Slovakian primeval beech forest reserves, where more than half of the gaps were found to be caused by the death of one tree, and 80% by the death of up to three trees. Based on the size distribution and spatial patterning of the canopy gaps found in our study, we conclude that the Uholka-Shyrokyi Luh forest is also shaped by a small-scale disturbance regime, and canopy gaps formed by single trees are prevailing. Rare disturbance events of moderate severity rather lead to locally higher densities of small gaps than to large, stand replacing ones.

Canopy gap assessment using high-resolution stereo satellite images

Spectral image analysis of high-resolution stereo satellite images proved to be highly suitable for generating maps of canopy gaps in the Uholka-Shyrokyi Luh primeval beech forest. The different viewing angles of the stereo satellite images allowed for a comprehensive mapping of canopy gaps within the study perimeter. Since small gaps were detected mostly on one image only, the additive combination of images from different viewing angles is an asset if fine-scale forest canopy gap extraction is sought. The identification of larger canopy gaps was also improved, since their shape could be identified in

<table>
<thead>
<tr>
<th>Accuracy measure</th>
<th>Ortho-image F</th>
<th>Ortho-image B</th>
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<tbody>
<tr>
<td>a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producer's accuracy gap [%]</td>
<td>84.54</td>
<td>98.68</td>
</tr>
<tr>
<td>Producer's accuracy no gap [%]</td>
<td>85.29</td>
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</tr>
<tr>
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<td>38.16</td>
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</tr>
<tr>
<td>Kohen's kappa coefficient K</td>
<td>0.45</td>
<td>0.72</td>
</tr>
<tr>
<td>Correct classification rate CCR</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Producer's accuracy gap [%]</td>
<td>40.83</td>
<td>10.00</td>
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<tr>
<td>User's accuracy gap [%]</td>
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<td>42.86</td>
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<tr>
<td>User's accuracy no gap [%]</td>
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<td>Kohen's kappa coefficient K</td>
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<td>0.02</td>
</tr>
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<td>Correct classification rate CCR</td>
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<td>60.26</td>
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Fig. 6. Example of the combination of the two canopy gap maps, showing the advantages of using a stereo pair of satellite images for gap mapping.
more detail, thus better matching their real properties.

Only a few studies on the disturbance regime of primeval beech forests have been based on satellite remote sensing methods as a landscape approach covering large areas. Garbarino et al. (2012) studied gap dynamics in an old-growth forest in Bosnia over an area of 298 ha by means of Kompsat-2 satellite images, which are comparable to those used in our study, providing a ground resolution of 1 m in the panchromatic and 4 m in the multispectral bands. Using an unsupervised pixel-based classification approach and an artificial neural network, they found good agreement between classified and photo-interpreted gaps. Apart from the overestimation of canopy gaps in diffuse areas close to clouds, the reliability of the spectral image analysis approach used in our study was quite high as well. The overestimation of gaps near clouds was stronger on ortho-image F than on ortho-image B; consequently, the user's accuracy for the classification of non-gap areas from ortho-image F was less than half of that for ortho-image B. As these areas are distinct in their extent, they can easily be masked out for the ecological interpretation.

The calculation of digital surface models of the forest canopy failed to map the fine-scale mosaic of canopy gaps within this forest, even though canopy surface models have been used widely in forest research for such purposes (Hirschmugl et al. 2007, Véga and St-Onge 2008). Provided that an accurate digital terrain model (DTM) exists, canopy height models, which have become popular for disturbance analysis by means of canopy gaps or canopy height profiles (Fujita et al. 2003, Henbo et al. 2004, Vepakomma et al. 2010), could be calculated by subtracting the terrain model from the surface model (St-Onge et al. 2008, Vepakomma et al. 2008). However, for our study area in the Ukraine, as well as for many other countries, accurate DTMs are lacking. Hence, approaches based on the calculation of local variations in canopy surface height may have high potential for disturbance analysis, as tested by Betts et al. (2005) in a small, flat Nothofagus forest area in New Zealand. As the gap definition in canopy height models is more similar to the one used in field studies, the results may be better comparable to terrestrial surveys than with our approach. However, in our case, the large viewing angles of the satellite and the complex topography of our study area limited the success of image matching during the canopy surface generation, which is the key prerequisite for such an analysis. It was only possible to map larger openings in the canopy based on the canopy surface model, and a spectral image analysis approach had to be used to map the dominating small-scale mosaic of canopy gaps in this primeval beech forest.

**Inferences regarding the disturbance regime**

Our canopy gap assessment confirms the hypothesis that the disturbance regime of the largest primeval forest in Europe is characterized by small to moderate disturbance events with canopy gaps rarely exceeding the crown projection area of a few trees and a very low frequency of stand-replacing disturbance events. Two major large-scale events have influenced our results: a wind storm in March 2007 and heavy wet snow fall in October 2009 (Local Forest Service, personal communication). These moderate disturbance events likely account for the few gaps with areas of several thousand square meters to around 2 ha in the study perimeter. Besides these rare large openings, such disturbances lead to a higher density of small canopy gaps <200 m² in locally distinct areas of the forest. This small-scale mosaic of small gaps favors the preservation of beech, since the ingrowth of other species would depend on larger canopy gaps allowing more sunlight to reach the forest floor. These findings are in line with two dendroecological analyses that suggested a small-scale mosaic of disturbance events and an absence of frequent stand-replacing disturbances (Trotsiuk et al. 2012, Hobi et al. 2014).

With the remote sensing approach used here, an area of several thousand hectares could be analyzed, which makes this assessment unique in the context of research in primeval beech forests. Our results expand the findings from studies conducted on much smaller monitoring plots, confirming that the processes shaping beech forests occur on small spatial scales. Openings of >1,000 m² in beech-dominated forests in central Europe have been documented as well (Drossler and von Lüpke 2005, Nagel and Svoboda 2008), and they play an important role in determining successional pathways of forests,
as they may induce changes in forest structure (inducing homogeneous stand structures) and tree composition (establishment of light-demanding tree species) (Leibundgut 1959, Korpel 1995, Heiri et al. 2009). This kind of natural succession was found, for example, in the Badin fir-beech virgin forest in the Western Carpathians, where, after windthrow, a high abundance of Salix caprea L. was observed (Korpel 1995). In the Uholka-Shyrokyi Luh primeval beech forest, however, the few larger disturbance events seem not to alter forest structure or composition over large areas. For example, in the terrestrial inventory no evidence of changes in tree species composition was observed, i.e., light-demanding species were unable to establish in the gaps, irrespective of their size (Hobi et al. 2014).

CONCLUSIONS

High-resolution stereo satellite images were found to provide highly valuable input data for canopy disturbance analysis at the landscape level. Given that the images are free of clouds, a complete spatial coverage can be achieved in a short period of time. These relatively new stereo satellite images hold promise for canopy gap assessments. They provide two different viewing angles of the target area and thus allow for a more reliable classification of gaps in the forest canopy compared to the use of only one image. The remote sensing approach supported the findings of previous terrestrial analyses that the largest European primeval beech forest is shaped by a small-scale disturbance regime and only a small amount of the forest area (<1%) is in the gap phase. Canopy gaps mainly smaller than 200 m² (98% of the classified gaps), corresponding to the crown projection area of one to a few trees, are the major drivers of forest dynamics in this primeval beech forest, whereas stand-replacing events are rare.

We thus hypothesize that this forest is in a dynamic equilibrium, being characterized by a small-scale mosaic of patches in different developmental phases, and that it will maintain its current structure in the long run, provided that there will be no ‘catastrophic’ events. The multi-layered, uneven-aged canopy structure with the strong dominance of beech and an exceedingly low abundance of early successional species found in the terrestrial forest inventory support this hypothesis (see Hobi et al. 2014). This suggests that gap dynamics may be characterized as a shifting of gaps opening and closing, whereas the gap fraction and frequency distribution remain roughly constant. To test this hypothesis in more detail, a spatio-temporal approach would be needed. The remote sensing method presented here allows an area-wide continuous mapping of canopy gaps with a reasonable effort and is thus useful for analyzing also remote and not easily accessible forests. As even small gaps can be reliably detected as long as they are new and not yet filled by regeneration, the method may be particularly suited to study long-term canopy dynamics and quantify annual gap formation rates. We therefore suggest, as a call to further research, the repetition of the spectral canopy gap assessments over time, so as to follow the fate of individual gaps as well as to analyze the gap size distribution over the entire forest.

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