Forest cover changes in Gorce NP (Poland) using photointerpretation of analogue photographs and GEOBIA of orthophotos and nDSM based on image-matching based approach

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ABSTRACT
Forest cover change can be detected with high precision using 3D geospatial data and semi-automatic analyses of Remote Sensing data. The aim of our study, performed in Gorce National Park in Poland, was to generate a land use land cover (LULC) map and use it to analyse forest cover change. The study area is a subalpine forest region that has been affected by bark beetle and wind disturbances. The Geographic Object-Based Image Analysis approach was used for classification, with Colour Infrared orthophotos and normalized Digital Surface Models generated using image-matching approach. Gathered results showed that dominating LULC class is coniferous forests (3380 ha; 47% of study area), when second largest class is deciduous forests (2204 ha; 30%). The dead Norway spruce stands (465.5 ha; 6.5%) showed significant increase comparing to 114.1 ha mapped in 1997.

Introduction
Secondary forest succession (FS) plays an important role in transforming semi-natural mountain farmland landscapes in several countries in Europe. The forest cover in Europe still increased in the last decades due to processes of artificial afforestation or natural FS. This situation is resulting typically in the mountainous regions from pasture abandonment (Kolecka et al., 2017). On the other hand, global warming and sudden atmospheric phenomena cause numerous rapid Land Use Land Cover (LULC) Changes in forest landscapes, which are particularly visible in the mountains. The dynamics of forest cover changes in mountain ecosystems, especially of stands growing in protected areas, depends on complex interactions of abiotic and biotic disturbances such as wind throw, avalanche, fire, insect damage, fungal pathogen infection and human impact. These disturbances can have a high-severity causing extensive forest damage and tree mortality. Because of this, however, they are critical drivers of forest structure and can increase the structural complexity of subalpine forests at the stand and landscape levels, resulting in a broader diversity of microhabitats compared to less-disturbed managed forests (Czarnota, 2012). Mortality-inducing disturbance is also a fundamental part of FS, with dead trees playing an important role in the rehabilitation of upper subalpine forests in smaller canopy gaps (GA) as well as larger disturbed areas (Szewczyk, Szwagrzyk, & Muter, 2011).

Though severe disturbance is a fundamental element of FS in subalpine forests, it also poses challenges from a forest inventory perspective. It is important that changes in forest cover as a result of disturbance can be mapped with accuracy through time for disturbance and forest-health monitoring. However, traditional plot-based forest inventory measurements, though very precise, may not have a sufficient areal extent to provide a comprehensive overview of disturbances, with interpolation between plots difficult or impossible.

In state forests and national parks in Poland, networks of circular sample plots are heavily relied upon for forest inventory data. In the Gorce Mountains forest, inventory measurements began in the 1970s in the Turbacz Reserve (Rutkowski, Poznański, & Przybylska, 1972). By 1992, a network of 402 (500 m²) sample plots was established throughout Gorce National Park (Gorce NP) where forest measurements are taken every 5 years. Plot measurements include the number of live and dead trees, the increase in and loss of trees, diameter at breast height, height, crown height, regeneration stage and the degree of decomposition of dead wood, among other parameters. Though this plot data are very precise, the total area it covers is only 20.1 ha, only 0.3% of Gorce NP.
In last decades, the plot-derived forest inventory data have been supplemented, and sometimes even replaced, by data and methods derived from Geographic Information Systems (GIS) and Remote Sensing (RS). Relevant RS data include airborne laser scanning (ALS) (Wezyk, Szostak, & Tompalski, 2013), multispectral and radar imagery (Holopainen et al., 2010; Rana et al., 2013), and image-based point cloud derivation from photogrammetry conducted on stereo pairs of images (St-Onge, Vega, Fournier, & Hu, 2008; White et al., 2013).

Another approach of image classification is the Geographic Object-Based Image Analysis (GEOBIA). The acronym GEOBIA was introduced by Hay and Castilla (2008) as a sub-discipline of Geographic Information Science. GEOBIA involves the development of automated methods of dividing RS imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scales for generating new information in a GIS-ready format. GEOBIA has now been recognized as a new paradigm in RS data processing by researchers and professionals alike (Blaschke et al., 2014).

Forestry applications of GEOBIA have been continually developed since de Kok, Schneider and Ammer (1999) highlighted the advantages of context in object-based classifications of alpine forest. Weidenbach, de Kok, Wezyk and Szombara (2008) used GEOBIA for the automatic detection of trees from QuickBird-2 (DigitalGlobe) images and aerial orthophotos. A variant of GEOBIA was also found to be very useful for tree crown delineation (Baatz, Hoffmann, & Willhauck, 2008). Using aerial photography (4-bands, Ground Sample Distance 1.0 m), De Chant and Kelly (2009) developed a change detection technique that tracks individual tree objects to identify trees suffering from sudden oak death. Boggs (2010) investigated the usefulness of GEOBIA for mapping tree cover in savannas based on SPOT 5 and QuickBird-2 satellite imagery. Kollár, Vekerdy and Márkus (2011), employing textural measures of analogue and digital aerial images, used GEOBIA to assess forest habitat change dynamics in riparian wetlands. Hernando, Tiede, Albrecht and Lang (2012) used digital Colour Infrared (CIR) orthophotos for object-based forest stand delineation. Moskal and Jakubauskas (2013) applied GEOBIA to aerial CIR images to examine how post-fire disturbance affects forest density and to map forest regeneration. GEOBIA was also employed by Meneguzzo, Liknes and Nelson (2013), who used high-resolution aerial imagery to map trees outside forests. There are also many examples of using GEOBIA for urban tree cover mapping based on digital aerial orthophotos, hyperspectral data, very high-resolution satellite (VHRS) images and Light Detection And Ranging data as well (MacFaden, O’Neil-Dunne, Royar, Lu, & Rundle, 2012; Moskal, Styers, & Halabisky, 2011).

Using information about the relative height of objects together with spectral information can improve the accuracy of a GEOBIA classification. Height data are often added through Crown Height Models (CHMs), which are called normalized Digital Surface Models (nDSMs) for wooded areas. For the last decade, CHMs have been principally derived from ALS point clouds which are still quite expensive to acquire. A recent alternative to ALS is digital photogrammetry and computer vision. DSMs are increasingly generated from digital photogrammetry performed on large-format aerial photos with very high overlap (80–90%), using algorithms such as Semi-Global Matching (SGM; White et al., 2013).

Our goal is to generate an up-to-date land cover map for an area of the Gorce Mountains using GEOBIA. We propose a GEOBIA workflow that is appropriate for the classification of a range of forest stands using digital CIR orthophotos and an nDSM generated from stereomatched aerial images. We then compare the results gathered from our semi-automated approach to previous studies in order to examine forest change dynamics from 1997 to 2009.

**Test area**

The study area, located in the West Beskid Mountains in South Poland, is a 9 × 8 km (7200 ha) rectangle centred at 49°33′35.63″ N; 20°9′18.70″ E. The majority of the study area (5148.9 ha, 71.5%) is located in Gorce NP (Figure 1). The park protects well-preserved old-growth Carpathian forests mainly comprised of three tree species: Fagus sylvatica L. (European beech), Abies alba Mill. (European silver fir) and Picea abies (L.) H.Karst. (Norway spruce). Though the Gorce NP was only established in December of 1980, there have been few forest management activities in the park area to date. According to Jarosz (1935), 44% of the upper subalpine Norway spruce stands in the Kudłon range in Gorce NP were characterized as virgin, or even primeval forests. Archival topographic maps from 1785 (so-called Waldau and Mieg maps) indicate a clear dominance of Norway spruce (80%), which at lower altitudes occurred single species stands. Documents from the second half of the nineteenth century show that the area of upper subalpine Norway spruce stands was three times greater than in the year 2004, with the extent of subalpine forests reaching a significantly lower elevation (Chwistek, 2010).

Over 51% of Gorce NP area is strictly protected, with human activities such as silvicultural treatments not allowed. The study area inside Gorce NP is divided into three types of protection: “strict (passive)” (3154.1 ha), “partly (active)” (1545.3 ha) and “landscape” (75.2 ha). The remaining study area inside Gorce NP is occupied by glades (GV; 374.3 ha), which are greatly overgrown with medium and high vegetation originating from secondary FS. The study area
outside Gorce NP is comprised of private forest and agricultural land covering 2051.1 ha. The altitude range of the terrain in the study is almost 720 m, from 590.7 to 1309.8 m a.s.l. North-facing slopes (NW+N+NE) occupy 46.7% of the study area, while southern (SE+S+SW), Eastern (NE, E, SE) and western (NW, W, SW) slopes occupy 31.4%, 37.87% and 34.26%, respectively. NE slopes comprise the largest share of any category, covering 16.6% of the study area.

Significant forest cover changes in Gorce NP started in 1981 as a result of sawfly (*Cephalcia falleni* (Dalm.)) outbreaks in dense Norway spruce stands on southern slopes of the Kudłoń range (Chwistek, 2001). Affected stands were at high risk of attack from spruce Bark beetles (*Ips typographus* L.). Over a 15-year period from 1992 to 2007, the percentage of Norway spruce in Gorce NP decreased by about 13%, from 43.7% to 30.7%.

**Material and methods**

The main part of the study, which is described in the following subsections, is a GEOBIA classification based on aerial orthophotos and an nDSM generated from aerial images acquired in 2009. First, the description of input data is given and then the process of nDSM generation is described. Finally, the GEOBIA workflow is presented along with a description of our accuracy assessment methodology.

To analyse the dynamics of forest changes in Gorce NP, two additional sets of data, not described in this paper, were used. For a selected part of the study area, 3D photogrammetric delineation was performed on archival analogue aerial stereo-images from 1997 (Wezyk & Mansberger, 1997, 1998). The second additional data set was measurements from the network of 402 sample plots established in Gorce NP (Chwistek, 2010).

**Materials**

For the GEOBIA approach, 4-band CIR orthophotos (R, G, B and NIR, Ground Sampling Distance (GSD) 0.25 m) and an nDSM (GSD 1.0 m) derived from stereo-matched CIR aerial digital photos (GSD 0.17–23 cm; UltraCam Xp; taken on 09 August 2009) were used. The aerial photos (6 μm; 17,310 × 11,310 pixels; $c_k = 100.5$ mm) were gathered from the Central Archive of Geodesy and Cartography (CODGiK) in Warsaw as Tagged Image File Format (TIFFs). We obtained three flight lines, each with 13 aerial photos, oriented along W–E axes with typical overlaps for aerial photos of 65% along-track, 28% between rows. The external orientation was available from CODGiK, which enabled the automatic generation of a Digital Surface Model (DSM).

For the GIS analyses, archival materials were also used. These were analogue aerial orthophotos generated from a Kodak Aerochrome 2443 in August 1997 (Wezyk & Mansberger, 1997) and a DSM generated using Match-T (INPHO) software (Wezyk & Mansberger, 1998). Additional selected GIS vector data from Gorce NP, digital forest maps and descriptive database were used. A reference Digital Terrain Model (DTM) data were also acquired from CODGiK (GSD 1.0 m; based on aerial photos workout). The spatial analyses of GEOBIA object polygons and other GIS data were performed using Esri ArcGIS version 10.2 software.

To analyse the changes in Norway spruce mortality through time for the study area, we used aerial CIR stereo-images from 1997 described above. Three-dimensional delineation of disturbed Norway spruce
spruce stands was performed using a VSD-AGH photogrammetric station (Wezyk & Mansberger, 1997, 1998).

**Generation of the height models**

For DSM generation based on point clouds from aerial CIR stereo-models, the software package RSG (Remote Sensing Graz), developed by the Joanneum Research in Graz (Austria), was used (Schardt, Hruby, & Hirschmügl, 2004). In a complex workflow, RSG geocodes and correlates aerial stereo-pairs to produce a map of disparities between the search and reference images as a first result of several forward- and backward-matching steps. Different settings can be applied; however, the robust SGM Algorithm, originally developed by the German Aerospace Centre DLR (Hirschmüller, 2008), has proven to be a robust and fast method within RSG. Disparity information was used to calculate the correct coordinates of the natural surface which is represented by the final DSM. In all, 39 aerial images were used to generate the DSM file. Next, the nDSM (GSD 1.0 m) representing the relative heights of trees and other above-ground features was created in ArcGIS using the raster calculator tool by taking the difference between the DSM and DTM raster files.

Quality assessment of the DSM was performed on photogrammetric approach using the DEPHOS SoftCopyStation. The DEPHOS system includes a powerful graphics card, LCD glasses and a precise optical manipulator, transforming a PC into a digital photogrammetric station (DEPHOS, 2016). To assess DSM accuracy, 200 random points were generated, with 40 points in each of five land cover classes: deciduous forest (DF), coniferous forest (CF), dead Norway spruce (DS), FS and open area. For each validation point, the DEPHOS operator placed measurement mark on the 3D object located in stereo-model collection vertical distance (Z). The Root Mean Square Error (RMSE) calculated from all validation points amounted to 2.01 m. In areas with dense forest canopy, it is very difficult to accurately place a measurement mark on the “ground”. In addition to this, the reference DTM from CODGiK, developed using traditional photogrammetry approach, was not free of error. These errors in the reference DTM somehow decrease the accuracy of RMSE estimates of DSM. The artefacts of DSM were another source of errors that increased the uncertainty of the nDSM.

**GEOBIA workflow**

The initial phase of our GEOBIA process was the generation of several derivative layers (used in subsequent analyses) from the CIR orthophotos. In order to reduce the internal variability of objects which occurs in very high-resolution images (Schiewe, Tufte, & Ehlers, 2001), median filter images of the NIR (NIR_med) and Red (RED_med) bands were created. The intention of median filtering was to obtain smoother objects from the segmentation process.

Using bands 4 (NIR) and 3 (Red) of the original digital orthophotos, a Normalized Difference Vegetation Index (NDVI) layer was generated. The NDVI layer was not used for segmentation, but for distinguishing between vegetated and non-vegetated areas. Based on Lee-Sigma (LS) filtering of the NDVI layer (LS dark and LS bright), an additional customized layer called “Roughness” was generated. The Roughness layer was particularly useful for identification of DS (standing trees with withered needles and skeleton trees) and for classification of forest types. The LS filter was also applied to the Red band after smoothing by Gaussian filter. This layer was used for distinguishing between the Buildings (BL) and DS classes. Principal Component Analysis (PCA) was also performed on orthophoto bands resulting in three derivatives layers. The second PCA band (PCA_2) was used for BL classification. The PCA_2 layer was also smoothed with a median filter (output: PCA_2_med) and was used for the distinction between healthy CF and DF.

After image processing, we executed an initial segmentation using the multi-resolution segmentation algorithm in eCognition (Baatz & Schape, 2000) (scale parameter: 7; shape: 0.2; compactness: 0.7; eCognition 8.7) using four input raster layers: RED_med, NIR_med, PCA_2_med and nDSM. No weights for input layers were used. After segmentation, we generalized the objects in order to increase the efficiency of data processing and to improve classification accuracy. Following the object-oriented spiral model of classification, gathered object primitives were then iteratively classified to various temporary classes, merged or re-segmented, and then finally classified to target classes (Baatz et al., 2008).

The classification workflow had a modular character (Baatz et al., 2008). After segmentation, the study area was divided into two temporary classes, vegetated and non-vegetated, primarily using NDVI and RED band values. Next, using the nDSM layer, objects were classified into either elevated or non-elevated temporary classes. Besides spectral and texture features, geometry and context information were also used to make class assignments. The asymmetry, border index, object size and relative border to class object features were especially useful for identifying the tree canopy GA. Vegetated objects with nDSM values ≤2.0 m were classified as GV and open areas with low vegetation. Secondary FS objects were identified from the vegetated class when their height was 2.0 m < nDSM < 8.0 m. Vegetated objects with nDSM values ≥8.0 m were assigned to DF, CF or DS depending on their spectral characteristics. A simplified
flow chart of the classification process is presented on Figure 2.

The final step of our GEOBIA workflow was the generalization of results. It was assumed that a single object in any class could not be smaller than 100 orthophoto pixels (~6.25 m$^2$). Objects that did not fulfill this condition were assigned to the neighbouring class, based on maximum spectral similarity to the RED_med and NIR_med layers. Throughout the classification process, the algorithms “Morphology” and “Pixel-based object resizing” were used, to smooth and improve the objects’ shapes (Trimble, 2012).

**Accuracy assessment**

Following Congalton and Green (2009), the number of required test points to generate an error matrix was calculated using the equation for a multinomial distribution. A total of 744 test points were created. Based on random sampling pattern approach (tool: “Create Random Points”; ArcGIS Esri), the 93 segments per each LULC class (intersected with points) were placed. The reference data used for step of quality control of GEOBIA were collected in 3D environment (stereo-models of aerial photographs) using the SoftCopyStation (DEPHOS). An error matrix with producer (PA) and user accuracies (UA) was generated along with the overall accuracy (OA) and Kappa coefficient.

**Results**

The outputs of our GEOBIA classification of CIR aerial orthophotos (2009) and a nDSM derived from stereomatching (SGM; RSG) are classified vector objects. These objects are the input for further GIS spatial analyses and descriptive statistics. Using the GEOBIA approach, it was possible to distinguish the eight classes (Figure 3) presented in Table 1 with an OA of 78% (Kappa = 0.75). PA and UA for each class are presented in Table 2.
Table 2 shows that the highest accuracy was achieved for the BL class, with PA and UA of 0.96 and 0.87, respectively. Relatively high accuracy was also achieved for the GA class. The lowest accuracies were obtained for the FS and CF classes. Misclassification of FS occurred mostly with CF (11 points) and GV (16 points) classes. The likely reason for these errors is inaccuracies in the nDSM data crucial for distinguishing these classes. The CF class was most commonly confused with DF (17 points). We believe the reason for this commission error is that some shaded crowns of deciduous trees were incorrectly classified as coniferous trees.

GEOBIA classification and 3D GIS spatial analyses performed on the 2009 orthophotos showed that the class DS exceeded 5% of the area greater than 975 a.s.l. The share of DS exceeded 10% in stands located 1000–1250 m a.s.l. and achieved nearly 15% at altitudes of 1125–1150 m a.s.l. Initial analysis showed that DS was mostly found on South slopes. However, after grouping the original aspect classes into either North or South, we found that a greater percentage of DS was found on northerly aspects (NW+N+NE = 47.3%) compared to southern aspect (SE+S+SW = 41.5%).

Using GEOBIA, 465.5 ha of DS were semi-automatically detected on CIR orthophotos from 2009. This is a considerable increase compared to the 114.1 ha of damaged forests delineated in the 1997...
photos, which had disturbed areas concentrated near the Kudłój and Kiczora ranges (Figure 4). Comparing the subset of the study area analysed in both periods (1997 and 2009), it was found that in 2009 the area of dead forests increased by 44.3 ha (or 38.9%). When analysing the whole study area, 158.4 additional hectares of dead trees were found in 2009 compared to 1997, likely the result of severe wind disturbance events and bark beetle outbreaks. Natural regeneration was also detected, however, with natural regeneration occurring in 93% of the damaged stands mapped in the 1997 by 2009.

Additional GIS spatial analyses were performed inside the administrative borders of Gorce NP taking into consideration different forms of protection. The tree species composition in the wider preservation area differs from that in the Gorce NP itself, with more deciduous cover extant in the park. In 2009, almost 42% of strict protections areas were covered by coniferous trees, mostly comprise of Norway spruce. In these areas, there are approximately 4.4 times more DS (350 ha) than in partly preserved areas (79 ha) because dead wood cannot be removed from strict protection zones. Living Norway spruces in areas of high mortality are often unhealthy, and are prime hosts for invasion by bark beetles. These trees are largely confined to strict protection areas, where there is 1249.8 ha of vulnerable forest at high risk of damage. Almost 700 ha of CF are located in partly protected areas where precautions such insect trap deployment can be taken to help mitigate disturbance risk. An additional 19 ha of Norway spruce stands grow in GV, and can be removed due to conservation activities oriented at the protection of grassland flora and fauna.

In contrast to the trees killed by disturbance, young, regenerating forests (FS) are found predominantly in two different vegetative communities. The first is located 625–750 m a.s.l. where secondary FS is occurring on GV and other agricultural parcels outside Gorce NP. The second community is located 1025–1250 m a.s.l. in disturbed Norway spruce stands that are largely free from human management activities. Together, the area covered by these two types of early FS is about 255 ha. The largest FS subclass was low vegetation (2.0 < FS ≤ 4.0 m) covering 176 ha of the FS area. An FS subclass representing 4.0–6.0 m high vegetation covered approximately 48 ha. The highest vegetation subclass (FS > 6.0 m) covered 30 ha and is mainly located between 1050 and 1250 m a.s.l., in the DS areas where tree mortality occurred in the 1980s (approximately 5 ha of which is in strict protection areas).

Only 374 ha of the study area in Gorce NP are GV, the composition of which has changed considerably through time due to secondary FS. Comparing GV border data from 1997 and our 2009 data, we found
that almost 30% (112 ha) of the GV class is now overgrown by CF, and 5% is overgrown by DF.

Discussion

The GEOBIA classification accuracy achieved here, with a Kappa of 0.75, is comparable to the results of other authors using similar approaches for mapping forest areas. Moskal and Jakubauskas (2013), studying fire-disturbed forests using aerial photos and GEOBIA methods, achieved classification accuracies between 68% and 78% depending on the level of image analysis (three classes in each level; total nine classes). Similar results were obtained by Moskal et al. (2011) for urban tree cover assessment using digital aerial imagery (GSD 1.0 m) and object-oriented classification, with tree cover classified with a user’s accuracy of 80% and a producer’s accuracy of 93%. Hernando et al. (2012) proposed an (Object Fate Analysis) OFA-matrix, where thematic and spatial accuracies can be assessed simultaneously, as an innovative accuracy assessment method for the results of object-based classification. Employing GEOBIA on aerial orthophotos, they achieved spatial and thematic accuracies higher than 65% for forest stand classification. Some authors also discovered that adding texture and morphometric variables to spectral data (CIR aerial photographs) may increase the OA of GEOBIA vegetation classification by 5.0% of Kappa (Kim, Madden, & Xu, 2010).

The quality of our classification was necessarily influenced by the quality of nDSM used. Our aim was to use a height model based on low-cost aerial imagery to demonstrate the power of different GIS technologies where highly precise ALS models (DTMs and nDSM) might be lacking. Despite our nDSM imperfections, it still enabled us to distinguish early FS subclasses, with height information significantly improving results over those based solely on spectral and textural information from aerial images.

Analysing forest cover changes where the aerial images from 1997 and 2009 were available, some differences in photo quality must be considered. Both the 1997 and 2006 images have the same ground resolution of 0.25 m. However, the stereo-models of analogue images from 1997 (taken with a Kodak Aerochrome 2443) were more suitable for 3D photo-interpretation using the VSD-AGH Softcopy station than the digital 2D orthophotos taken in 2009 using a Vexcel digital camera. On the other hand, the 2009 digital images had a 16-bit radiometric resolution, while the resolution of 1997 photographs was only 8-bit. Also, the 1997 photointerpretation key was prepared 2 weeks before image acquisition, while for the 2009 photos, the key was generated 2 years after the imagery was collected, which could increase the imprecision of the final photointerpretation.

Considering the differences between a fairly automated GEOBIA approach and a visual photo interpretation approach, there are several important advantages of the former. Semi-automatic GEOBIA processing is much faster than visual interpretation, which is especially important when large forest areas must be analysed. Although we incorporated some subjective thresholds into our GEOBIA rule set, this approach is still more objective than visual interpretation, where classification results are highly dependent on the judgment of an individual human classifier. With a more automated approach, it is also possible to fully utilize the high radiometric resolution of images collected by modern digital cameras. Furthermore, using GEOBIA additional information about object heights can incorporate in an automated way, saving time (and money) and increasing classification accuracies.

Our results show that forest cover has been highly dynamic in and around Gorce NP, with wind and insect disturbances the main drivers of tree mortality along with summer drought. Tree species abundance has also proven to be highly dynamic. A process of spruce decline and beech expansion has been observed for several decades (Dziwolski & Rutkowski, 1991; Przybylska, Fujak, & Mycka, 1995). In 1992, the most common species in Gorce NP was spruce (43.7%), followed by beech (38.4%) and fir (15.6%); (Chwistek, 2010). Fifteen years later, however, the percentage of Norway spruce had decreased by 13% to only 30.7% of trees in 2007. Over the same period, the percentage of beech has increased by 1.3% and fir by 10.2%, comprising 39.7% and 25.8% of overall species composition, respectively. It is likely that a warming climate over the last century has favoured mesotrophic and eutrophic tree species like fir and beech at the expense of oligotrophic spruce.

The area of GV in Gorce NP has also declined over recent decades, primarily as a result of secondary FS spurred by decrease in sheep grazing and a lack of agricultural management in general (Wezyk, 2006). The area of meadows bordering forest edges decreased between 1954 and 1997 by approximately 43 ha (21.60% of total meadow area). Similar process of secondary FS on abandoned pastures (decrease from 57% to 32% of total test area) was also observed in French Pyrenees (Sheeren, Ladet, & Ribière, 2012).

Conclusions

We expected to see Norway spruce as the dominant species in higher elevations in Gorce NP; however, our analysis shows that the percentage of spruce at these elevations is decreasing. Norway spruce stand transformations in Gorce NP have been accompanied by a process of secondary FS in GV, meadows and clearings where agricultural activity has declined. The
disappearance of subalpine GV (Wezyk, 2006) results in the loss of many rare, protected plant and animal species reliant on grassland ecosystems. The decline of agriculture and resurgence of forests has changed the aesthetic and cultural character of the landscape, with shepherd huts and mountain shelters beginning to disappear. On the other hand, 350 ha of DS in the strict protection zone of Gorce NP is a boon for scientific observation and monitoring, allowing forest ecologists to study the effects of disturbance and the processes of forest regeneration.

Using the relative height of the vegetation modelled in a nDSM derived from image stereomatching (SGM algorithm), we were able to enhance the efficiency and accuracy of segmentation and classification. The rule-set produced for this project can now be used for further projects based on CIR aerial photos.

We advocate the use of RS technology to monitor forest ecosystem dynamics in Gorce NP in the future. The analysis presented here utilizes aerial images, orthophotos and an image-derived nDSM; however, with recent advancements in technology and methodology, there are many routes to undertaking GEOBIA today. Digital aerial images are acquired over our study area every 3 years, providing excellent time-series data. When detailed DTM’s are available, nDSMs obtained from stereomatching of VHRS imagery can be produced. There are also new possibilities for frequent monitoring updates thanks to the recent availability of Sentinel-2 satellite images, and nanosatellite constellations like Planet will soon enable daily monitoring.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Baatz, M., Hoffmann, C., & Willhauck, G. (2008). Progressing from object-based to object-oriented image analysis. In T. Blaschke, S. Lang, & G.J. Hay (Eds.), Object-based image analysis: Spatial concepts for knowledge-driven remote sensing applications (1st ed., pp. 29–42). Berlin: Springer Berlin Heidelberg.

Baatz, M., & Schape, A. (2000). Multiresolution segmentation: An optimization approach for high quality multiscale image segmentation. Journal of Photogrammetry and Remote Sensing, 58(3–4), 12–23.

Blaschke, T., Hay, G.J., Kelly, M., Lang, S., Hofmann, P., Addink, E., … Tiede, D. (2014). Geographic object-based image analysis — Towards a new paradigm. ISPRS Journal of Photogrammetry and Remote Sensing, 87, 180–191. doi:10.1016/j.isprsjprs.2013.09.014

Boggs, G.S. (2010). Assessment of SPOT 5 and QuickBird remotely sensed imagery for mapping tree cover in savannas. International Journal of Applied Earth Observation and Geoinformation, 12(4), 217–224. doi:10.1016/j.jag.2009.11.001

Chwistek, K. (2001). Dynamic of tree stands in the Gorce National Park (Southern Poland) during the period 1992–1997. Nature Conservation, 58, 17–32.

Chwistek, K. (2010). Changes of the species composition and structure of stands of the Gorce National Park during the period 1992–2007. Ochrona Beskidów Zachodnich, 3, 79–92.

Congalton, R.G., & Green, K. (2009). Assessing the accuracy of remotely sensed data principles and practices (2nd ed.). Boca Raton: CRC Press, Taylor & Francis Group. doi:10.1201/9781420048568.fmat

Czarnota, P. (2012). Lichen protection needs natural forest disturbances – Examples from some Polish Western Carpathian national parks. In L. Lipnicki (Ed), Lichen protection – Lichen protected species (pp. 53–66). Gorzów Wlkp: Sonar Literacki.

De Chant, T., & Kelly, M. (2009). Individual object change detection for monitoring the impact of a forest pathogen on a Hardwood Forest. Photogrammetric Engineering & Remote Sensing, 75(8), 1005–1013. doi:10.14358/PERS.75.8.1005

de Kok, R., Schneider, T., & Ammer, U. (1999). Object-based classification and applications in the Alpine forest environment. International Archives of Photogrammetry and Remote Sensing, 32, 3–4.

DEPHOS. (2016). DEPHOS help & user manual. Dephos. Dziewolski, J., & Rutkowski, B. (1991). Tree mortality, recruitment and increment during the period 1969–1986 in a reserve at Turbacz in the Gorce Mountains. Folia Forestalni Polonica, A 31, 37–48.

Hay, G.J., & Castilla, G. (2008). Geographic object-based image analysis (GEOBIA): A new name for a new discipline. In T. Blaschke, S. Lang, & G.J. Hay (Eds.), Object-based image analysis: Spatial concepts for knowledge-driven remote sensing applications (1st ed., pp. 75–89). Berlin: Springer Berlin Heidelberg. doi:10.1007/978-3-540-77058-9

Hernando, A., Tiede, D., Albrecht, F., & Lang, S. (2012). Spatial and thematic assessment of object-based forest stand delineation using an OFA-matrix. International Journal of Applied Earth Observation and Geoinformation, 19, 214–225. doi:10.1016/j.jag.2012.05.007

Hirschmüller, H. (2008). Stereo processing by semiglobal matching and mutual information. IEEE Transactions on Pattern Analysis and Machine Intelligence, 30(2), 328–341. doi:10.1109/TPAMI.2007.1166

Holopainen, M., Haapanen, R., Karjalainen, M., Vastaranta, M., Hyyppä, I., Yu, X., … Hyyppä, H. (2010). Comparing accuracy of airborne laser scanning and TerraSAR-X radar images in the estimation of plot-level forest variables. Remote Sensing, 2(2), 432–445. doi:10.3390/rs2020432

Jarosz, S. (1935). Badania geograficzno-leśne w Gorcach [Geographical and forest research in Gorce]. Prace Rol.- Leśne PAU, 16(1), 125.
Kim, M., Madden, M., & Xu, B. (2010). GEOBIA vegetation mapping in Great Smoky Mountains National Park with spectral and non-spectral ancillary information. *Photogrammetric Engineering & Remote Sensing*, 76(2), 137–149. doi:10.14358/PERSENS.76.2.137

Kolecka, N., Kozak, J., Kaim, D., Dobosz, M., Ostafin, K., Ostapowicz, K., … Price, B. (2017). Understanding farmland abandonment in the Polish Carpathians. *Applied Geography*, 88, 62–72. doi:10.1016/j.apgeog.2017.09.002

Kollár, S., Vekerdy, Z., & Márkus, B. (2011). Forest habitat change dynamics in a riparian wetland. *Procedia Environmental Sciences*, 7, 371–376. doi:10.1016/j.proenv.2011.07.064

MacFadden, S., O’Neil-Dunne, J., Royar, A., Lu, J., & Rundle, A. (2012). High-resolution tree canopy mapping for New York City using LIDAR and object-based image analysis. *Journal of Applied Remote Sensing*, 6(1), 63561–63567. doi:10.1117/1.JRS.6.063567

Meneguzzo, D.M., Liknes, G.C., & Nelson, M.D. (2013). Mapping trees outside forests using high-resolution aerial imagery: A comparison of pixel- and object-based classification approaches. *Environmental Monitoring and Assessment*, 183(8), 6261–6275. doi:10.1007/s10661-012-3022-1

Moskal, L.M., & Jakubauskas, M. (2013). Monitoring post disturbance forest regeneration with hierarchical object-based image analysis. *Forests*, 4(4), 808–829. doi:10.3390/f4040808

Moskal, L.M., Syers, D.M., & Halabisky, M. (2011). Monitoring urban tree cover using object-based image analysis and public domain remotely sensed data. *Remote Sensing*, 3(10), 2243–2262. doi:10.3390/rs3102243

Przybylska, K., Fujak, J., & Mycza, P. (1995). Dynamika zmian zasobów leśnych w rezerwacie „Dolina Łupusznjej” Gorczańskiego Parku Narodowego w okresie kontrolnym 1982–1992 [The dynamics of changes in forest resources in the “Łupusznaya Valley” in the Gorczański National Park during the control period 1982-1992]. *Parki Narodowe I Rezerwaty Przyrody*, 14(3), 23–31.

Rana, P., Tokola, T., Korhonen, L., Xu, Q., Kumpula, T., Vihervaara, P., & Mononen, L. (2013). Training area concept in a two-phase biomass inventory using airborne laser scanning and RapidEye satellite data. *Remote Sensing*, 6(1), 285–309. doi:10.3390/rs6010285

Rutkowski, B., Poznański, R., & Przybylska, K. (1972). Wstępne wyniki zastosowania statystyczno matematycznego kontrolnego sposobu inwentaryzacji w terenie Turbacz im. Wł. Orkana w Gorcach [Preliminary results of statistical and mathematical application of a control inventory approach in the Turbacz nature reserve in Gorce]. *Zesz. Nauk. AR W Krakowie, Leśnictwo*, 7, 45–69.

Schardt, M., Hruby, W., & Hirschmugl, M. (2004). Comparison of aerial photographs and laser scanning data as methods for obtaining 3D forest stand parameters. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVI, 272–276.

Schiewe, J., Tufte, L., & Ehlers, M. (2001). Potential and problems of multi-scale segmentation methods in remote sensing. *Scientist*, 49, 34–39.

Sheeren, D., Latet, S., & Ribière, O. (2012). Assessing land cover changes in the French Pyrenees since the 1940s: A semi-automatic GEOBIA approach using aerial photographs. In *Proceedings of the AGILE 2012 Conference on Geographic Information Science* (pp. 23–27). Avignon, April, 24–27, 2012.

St-Onge, B., Vega, C., Fournier, R.A., & Hu, Y. (2008). Mapping canopy height using a combination of digital stereo-photogrammetry and lidar. *International Journal of Remote Sensing*, 29(11), 3343–3364. doi:10.1080/01431160701469040

Szewczyk, J., Szwagryzk, J., & Muter, E. (2011). Tree growth and disturbance dynamics in old-growth subalpine spruce forests of the Western Carpathians. *Canadian Journal of Forest Research*, 41(5), 938–944. doi:10.1139/i11-029

Trimble. (2012). eCognition Developer 8.7.2: Reference book. München, Germany: Trimble Germany GmbH.

Weidenbach, M., de Kok, R., Wezyk, P., & Szombara, S. (2008, September 17-19). Developing strategies for large scale forest inventories combining LiDAR data, satellite imagery and regional yield models. In R. Hill, J. Rosette, & J. Suárez (Eds.), *Proceedings of SilviLaser 2008 8th international conference on LiDAR applications in forest assessment and inventory* (p. 635). Edinburgh, UK: University Edinburgh.

Wezyk, P. (2006). The transformation of the natural environment of the Gorce Mountains based on the example of clearing use during the period 1954–1997. *studia naturae*, 54(1), 201–211.

Wezyk, P., & Mansberger, R. (1997). Przykład wykorzystania ortofotografii cyfrowej i systemu GIS w lesnictwie [An example of using digital orthophotography and GIS system in forestry]. *Archiwum Fotogrametrii, Kartografii I Teledetekcji [Archives of Photogrammetry, Cartography and Remote Sensing]*, 6, 133–151.

Wezyk, P., & Mansberger, R. (1998). Techniki fotogrametrii cyfrowej i GIS w ocenie degradacji drzewostanów świerkowych w masiwie Kudłonia w Gorcach [Techniques of digital photogrammetry and GIS in the evaluation of the degradation of Norway spruce stands in the Kudloni massif in Gorce]. *Archiwum Fotogrametrii, Kartografii I Teledetekcji [Archive of Photogrammetry, Cartography and Remote Sensing]*, 8 (21), 1–10.

Wezyk, P., Szostak, M., & Tompalski, P. (2013). Use of airborne laser scanning data for a revision and update of a digital forest map and its descriptive database: A case study from the Tatra National Park. In J. Kozak, O. Katarzyna, A. Bytnerowicz, & B. Wyżga (Eds.), *The Carpathians: Integrating nature and society towards sustainability* (pp. 615–627). Berlin, Heidelberg: Springer-Verlag.

White, J., Wulder, M., Vastaranta, M., Coops, N., Pitt, D., & Woods, M. (2013). The utility of image-based point clouds for forest inventory: A comparison with airborne laser scanning. *Forests*, 4(3), 518–536. doi:10.3390/f4030518