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Species-related single dead tree detection using multi-temporal ALS data and CIR imagery

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ABSTRACT

The assessment of the health conditions of trees in forests is extremely important for biodiversity, forest management, global environment monitoring, and carbon dynamics. There is a vast amount of research using remote sensing (RS) techniques for the assessment of the current condition of a forest, but only a small number of these are concerned with detection and classification of dead trees. Among the available RS techniques, only the airborne laser scanner (ALS) enables dead tree detection at the single tree level with high accuracy.

The main objective of the study was to identify spruce, pine and deciduous trees by alive or dead classifications. Three RS data sets including ALS (leaf-on and leaf-off) and color-infrared (CIR) imagery (leaf-on) were used for the study. We used intensity and structural variables from the ALS data and spectral information derived from aerial imagery for the classification procedure. Additionally, we tested the differences in the classification accuracy of all variants contained in the data integration. In the study, the random forest (RF) classifier was used. The study was carried out in the Polish part of the Białowieża Forest (BF).

In general, we can state that all classifications, with different combinations of ALS features and CIR, resulted in high overall accuracy (OA ≥ 90%) and Kappa ($\kappa > 0.86$). For the best variant ($CIR\_ALS_{WSn\text{-}FH}$), the mean values of overall accuracy and Kappa were equal to 94.3% and 0.93, respectively. The leaf-on point cloud features alone produced the lowest accuracies (OA = 75–81% and $\kappa = 0.68$–0.76). Improvements of 0-0.04 in the Kappa coefficient and 0–3.1% in the overall classification accuracy were found after the point cloud normalization for all variants. Full-height point cloud features (F) produced lower accuracies than the results based on features calculated for half of the tree height point clouds (H) and combined FH.

The importance of each of the predictors for different data sets for tree species classification provided by the RF algorithm was investigated. The lists of top features were the same, independent of intensity normalization. For the classification based on both of the point clouds (leaf–on and leaf-off), three structural features (a proportion of first returns for both half-height and full-height variants and the canopy relief ratio of points) and two intensity features from first returns and half-height variant (the coefficient of variation and skewness) were rated as the most important. In the classification based on the point cloud with CIR features, two image features were among the most important (the NDVI and mean value of reflectance in the green band).

1. Introduction

The assessment of the health conditions of trees in forests is extremely important for biodiversity, forest management, global environment monitoring and carbon dynamics. Dead trees are key indicators of forest biodiversity and ecosystem health (Moritz et al., 2014). Many aspects of forest ecology are based on living and dead components. The requirements of different species of fauna and flora are based on varied spatial distribution of both live and dead biomass as habitats (McCarney et al., 2008).

There is a vast amount of research using remote sensing (RS) techniques for the assessment of the current condition of a forest, but only a few techniques are concerned with the detection and classification of dead trees. From a wide range of RS technologies, the airborne laser scanner (ALS) is one of the most promising. The ALS allows the accurate examination of biomass, both live and dead (Sherrill et al., 2008; Kim et al., 2009b; García et al., 2010; Bright et al., 2013). Sherrill et al. (2008), using a canonical correlation analysis along with ALS

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vertical variables, examined the correlation of these data with field measurements that also included standing dead trees. The authors found that mean and maximum heights were variables that showed the highest correlation with standing, dead biomass. However, Kim et al. (2009b), using cross-validation with field data, found that intensity of reflection and canopy volume were the most important variables in live biomass estimation. In the case of dead biomass, use of intensity from ALS data was sufficient in the estimation process (Korpela et al., 2010b). In a study conducted by García et al. (2010), using ALS data, the authors found that height-related variables could be used to accurately estimate biomass. Equally important variables were inter alia variables related to canopy cover and canopy structure. Although the structural variables provided accurate biomass estimates, the intensity variables provided more explanations for variance and even more accurate biomass estimation. It was also shown that the combination of height and intensity variables allowed for a robust method of biomass estimation. In our work, in contrast to the aforementioned studies, we focus on the detection of dead trees at the level of a single tree. This may be particularly important at the stage of identification of new bark beetle hosts because even one infected tree may be the beginning of a host. In the area of our research, there is also a great deal of tourist traffic, and thus safety on hiking trails is an equally important issue.

Importantly, ALS data has been shown to enable dead tree detection at the single tree level. In the study conducted by Polewski et al. (2015), the authors presented a method for detecting standing dead trees using an ALS point cloud combined with infrared images. Through a two-step approach, they first segmented individual trees based on the point cloud, and then, using information derived from infrared images, they detected dead trees. The authors reported that the accuracy of the detection of dead trees in their study was 89%. In terms of specificity of the area and the problem of spruce bark beetle (*Ips typographus* (L.)) outbreak, a similar study was carried out by Yao et al. (2012). In their study, they presented a scheme for distinguishing between dead and live trees in the Bavarian Forest National Park. They divided trees into the two classes based on full-waveform ALS data in two seasons: leaf-on and leaf-off. The test field, as in our case study, was exposed to dieback of trees caused by a bark beetle outbreak. Apart from the commonly used segmentation method using a watershed algorithm (Soille, 1999), the authors additionally applied an innovative method of normalized cut segmentation. This allowed trees in the understory to be distinguished; they are invisible when using segmentation based only on the crown height model (CHM). Using the binary SVM classification, the authors achieved a total accuracy of 71% ($\kappa = 0.27$) in the leaf-off season and 73% ($\kappa = 0.45$) in the leaf-on season. The authors suggested that the leaf-on scenario is the most beneficial method for distinguishing living and dead trees. Additionally, the authors stated that, generally, there is no single, unique feature that would contribute to a successful classification, but considering groups of variables, geometric features appear to be the most crucial variables in the classification of live and dead trees. In some studies, authors using remote sensing data focused on the detection of dead trees in areas after wildfires (Kim et al., 2009b; Wing et al., 2015; Casas et al., 2016). The authors admitted that the discrimination of dead and living trees is possible with ALS using intensity values. Others quantified the effects of wildfires by correlating changes in forest structure from multi-temporal ALS data and from multi-temporal spectral changes from Landsat images (McCarley et al., 2017).

In other studies, authors tried to classify species, but without including dead trees. Tree species classification was carried out in Nordic and other countries (Holmgren and Persson, 2004; Ørka et al., 2009, 2010, 2012; Vauhkonen et al., 2009, 2010; Korpela et al., 2010a; Lindberg et al., 2014; Yu et al., 2014), North America (Brandtberg, 2007; Kim et al., 2009a, 2011; Suratno et al., 2009; Ko et al., 2012, 2014b) and in Western Europe (Reitberger et al., 2008; Heinzel and Koch, 2011, 2012). The aforementioned previous studies, based mainly on ALS data and using different classification methods, show that it is possible to discriminate between different species of trees in temperate forests.

The main sources of information about tree species are structural features calculated from point clouds as well as the values of intensity of reflections. Aside from the characteristics of the crown and reflection of the leaves, branches and tree bark also affect the intensity of reflection (Moffiet et al., 2005). In addition, Korpela et al. (2010a) suggested that intensity characteristics should be calculated in vertical parts of the crown, simultaneously paying attention to the need to take into account the relative height of the tree. Fassnacht et al. (2016) stated that in a mountainous area, intensity calibration could be almost impossible. Many authors emphasized that classification based on distribution of intensity in different parts of the crown undoubtedly makes it possible to distinguish individual tree species (Holmgren and Persson, 2004; Korpela et al., 2009; Ørka et al., 2009). Structural and geometrical features of tree crowns have a significant influence on the ability of tree species to discriminate between them (Reitberger et al., 2008). In leaf-off season, it is possible to get more reflections reaching deeper parts of the crown than in the leaf-on season, and there are more intermediate returns coming from the internal part of the crown that provide more information about the vertical structure of the tree and its crown (Yu et al., 2014). A disturbing factor for species-specific tree crown structure is the mutual intertwining of tree crowns. In dense stands, adjacent trees may deform the spatial distribution of tree crown points. The surroundings of a particular tree can have a fundamental impact on its growth, and as a result, neighbouring trees can change its factual structure (Holmgren and Persson, 2004).

In many of the abovementioned studies, the random forest (RF) (Breiman, 2001) classifier was used (Vauhkonen et al., 2010; Ørka et al., 2010; Yu et al., 2014; Ko et al., 2016). Ørka et al. (2010) conducted classification by the RF method for two species in the leaf-on and leaf-off seasons. Data obtained twice during the leaf-off season allowed the probability of correct classification at 93% and 98% for 412 test trees. Vauhkonen et al. (2010) for the discrimination between spruce, pine and deciduous trees in the leaf-on season achieved a total accuracy of 78%. In the studies of Ko et al. (2012, 2014b) and Yu et al. (2014), the RF algorithm obtained high grade ratings of 90%, 88% and 73% respectively, for discriminating three tree species in the leaf-on season.

To the best of our knowledge, there is no study of classification of dead trees by species. For outbreak management, species-related information about dead trees is very relevant. This is because dead spruces were host trees for bark beetles, and it is known that new infections emanate a small distance from already killed trees (Kautz et al., 2011; Fahse and Heurich, 2011; Seidl et al., 2015). Since even a single tree can be the beginning of a bark beetle host, general information (acquired from low resolution RS data, e.g., Landsat or Sentinel) about dead and alive trees is not very relevant in forest management practice. Therefore, the main objective of the study was to classify spruce, pine, and deciduous trees as alive or dead. On the basis of three high-resolution data sets (ALS (leaf-on and leaf-off) + color-infrared (CIR) imagery (leaf-on), we set the following objectives: to determine (1) which variant produces the best results of classification for spruce, pine, and deciduous trees by alive or dead classes; (2) to what extent the ALS point cloud intensity normalization improves classification accuracy and for which classes; and (3) which ALS point cloud variables and CIR-based features are most relevant for such studies. We used intensity and structural variables from ALS data and spectral information derived from aerial imagery for the classification procedure. Additionally, we tested the differences in classification accuracy of all variants included in the data integration.