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Variation and directional anisotropy of reflectance at the crown scale — Implications for tree species classification in digital aerial images

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ABSTRACT

Tree species classification is still solved at insufficient reliability in airborne optical data. The variation caused by directional reflectance anisotropy hampers image-based solutions. In addition, trees show considerable within-species variation in reflectance properties. We examined these phenomena at the single-tree level, using the Leica ADS40 line sensor and XPro software, which constitute the first photogrammetric large-format multispectral system to provide target reflectance images. To analyze the influence of illumination conditions in the canopy, we developed a method in which the crown shape as well as between-tree occlusions and shading were modeled, using dense LiDAR data. The precision of the ADS40 reflectance images in well-defined surfaces was 5% as coefficient of variation when 1−4-km image data were fused. The range of reflectance anisotropy was ±30% for trees near the solar principal plane, with differences between bands and species. Because of the anisotropy differences observed, the spectral separability of the tree species in different bands is dependent on the view-illumination geometry. The within-species variation was high; the coefficient of variation was 13−31%. The contribution of tree and stand variables to anisotropy-normalized reflectance variation was examined. The effects of the species composition of adjacent trees were substantial in NIR and this variation hampers spectral classification in mixed stands. We also studied species- and band-specific intracrown brightness patterns, and we suggest their use as high-order image features in species classification. A species classification accuracy of up to 80% was obtained using 4-km data, which showed the high potential of the ADS40.

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1. Introduction

Recent progress in remote sensing (RS) of forests has been achieved mainly due to improvements in airborne LiDAR, digital photogrammetry and imputation techniques (McRoberts et al., 2010; Næsset, 2002). Airborne pulsed LiDAR sensors are efficient tools for 3D probing of the complex forest canopy and underlying terrain. Concurrently with the implementation of LiDAR, photogrammetric film cameras were replaced by digital sensors that provide images with enhanced radiometric and geometric properties (Honkavaara et al., 2009; Jacobsen et al., 2010). In forestry, aerial images are currently regarded as a complement to LiDAR, above all to support tree species recognition, which is a crucial task on technical, economic and ecological grounds (Leckie et al., 2003; Packalén et al., 2009). The fusion of aerial images and LiDAR has improved the estimation accuracy of forest parameters at increased costs, system complexity and weather risks — the latter being particularly important in Scandinavia. For reasons of cost-efficiency, LiDAR acquisitions are performed at high altitudes, and consequently the low-sampling rate data have low predictive power in species discrimination. Aerial images are also acquired from high altitudes to rapidly cover large regions during the short cycles of appropriate weather.

In Scandinavia, photogrammetric cameras that used color-infrared film have been largely replaced since 2005 by digital multilens, large-format frame cameras that follow the PAN-sharpening principle. These produce high-resolution panchromatic (PAN) and lower-resolution multispectral data. The resolution ratio of PAN to color images varies between camera models and recent developments resulted in smaller resolution differences. From flying altitudes of 4–8 km, the multispectral resolution is 1–3 m, which is coarse for individual tree analysis, but feasible in area-based analysis. The new sensors are relatively calibrated to a uniform response and since they employ CCD-arrays, the digital numbers (DNs) of pixels are in linear dependence with the at-sensor radiance (ASR) (Graham & Koh, 2002). In radiometric terms, this is a major improvement over scanned film images, in which variations in the film material, film storage, development and scanning all affect the radiometry. Relative calibration

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means that the DNs measure the variation in the ASR across the focal plane. Absolute calibration (Dinguirard & Slater, 1999) is needed for converting the DNs into target reflectances by physical modeling. This requires elimination of atmospheric effects, which are considerable at altitudes above 3 km. Calibration of airborne images to accurate target reflectances would make image-to-image calibration superfluous, even in multitemporal data. Moreover, the assessment of true target-related effects would be possible, and reflectance calibration is a prerequisite for physically based RS, i.e. for the inversion of image data to scene attributes (Woodcock et al., 1997). However, accurate reflectance calibration is very challenging.

Among commercial photogrammetric large-format mapping cameras, calibration of the sensor to measure the ASR was first implemented in the Leica Geosystems ADS40 line scanner camera (Fricker, 2007). Absolute calibration is also being developed for other photogrammetric cameras (Ryan & Pagnutti, 2009). The ADS40 makes observations in the visible and near-infrared (NIR) range in four ~50 nm wide bands. In addition to the high radiometric quality, the ADS40 can provide subpixel geometric accuracy. The exterior orientation is established for each image line and requires the use of direct sensor orientation and platform stabilization, similar to LiDAR sensors. A correction chain to produce ASR and target-reflectance images is realized in XPro postprocessing software (Beisl, 2006; Beisl et al., 2008). The sensor acquires 12 000-pixel-wide image carpets with a ±32° field-of-view (FOV) and it provides a multispectral stereo view with a nadir and a 16° backward direction, while there are three PAN image lines. Fig. 1 illustrates the stereo geometry of the multispectral image lines over a forest scene.

Reflectance anisotropy and the high within-species reflectance variation in aerial images hamper the use of spectral signatures of trees (Leckie et al., 2005). Anisotropy is a basic property of natural objects, and it means that the brightness observed is dependent on the illumination and observation geometry (Schaepman-Strub et al., 2006). It has been widely studied at the canopy level, although we found almost no research that would apply to individual crowns. Most studies in aerial image-based tree species classification omit the anisotropy effects (Haara & Haarala, 2002; Korpela, 2004; Waser et al., 2010) or apply global corrections (Gougeon, 2010). Li & Strahler (1986) showed that the geometric nature of the canopy is the major factor explaining the strong anisotropy of directional reflectance at the canopy level. Knowledge of the between-species differences of tree-level anisotropy would support the optimization of tree species classification in multiangular data. On the other hand, the line-scanner principle limits the variation in the view-illumination geometry to one dimension, which confines the anisotropy compared with frame image data (Fig. 1).

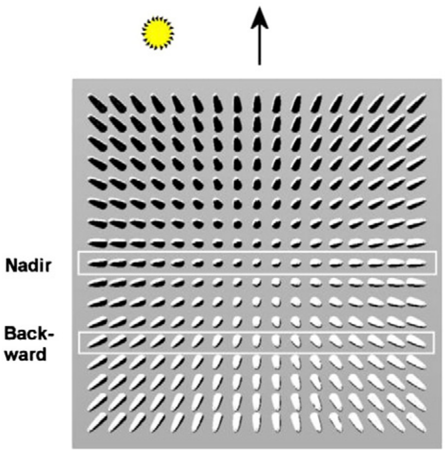

Fig. 1. Illustration of the view-illumination geometry of trees in the focal plane of a nadir-looking aerial camera. The flying direction is upwards and the direction of the Sun is 26° to the left of the upward direction. The white rectangles depict the nadir- and backward-viewing CCDs in the ADS40 line sensor, which was used in this study.

Our data-driven study had four objectives enabled by the ADS40/XPro reflectance data. We confined to single trees and the three commercially important species in Finland, and examined the factors affecting 1) reflectance variation and 2) directional reflectance anisotropy. Photogrammetric line sensors have not been used in forest applications in Finland and we tested whether 3) the ADS40 offers improvements in tree species classification. Previous research suggests that spectral signatures from the sunlit and shaded parts of the crown are to some extent independent and their co-use may improve species classification accuracy (Korpela, 2004; Larsen, 2007; Puttonen et al., 2009). There are also contradicting results that emphasize the advantage of sunlit signatures (Leckie et al., 2005). The co-use of LiDAR with images allows better description of the within-canopy illumination, because the geometry of the upper canopy can be reconstructed from dense LiDAR data (Puttonen et al., 2009). Despite the ambiguities involved in defining the intracanopy illumination, 4) we developed a method for the partitioning of tree crowns according to the illumination conditions.

Section 2 describes the experimental setup and the new method for the partitioning of tree crowns into illumination classes. The results of the experiments follow in Section 3 and the discussion of results and concluding remarks close the article.

2. Material and methods

2.1. Test site and ground truth

The experiments were carried out in the boreal forests of Hyytiälä, southern Finland (61°50′N, 24°20′E). A description of the 2×6-km study area can be found in Korpela et al. (2010). We used reference trees measured in 2005–2009 in 121 0.04−1.8-ha plots. The trees were positioned accurately and recorded for species (*sp*), diameter-at-breast-height ($d_{1.3}$) and crown status. Sample tree measurements of the crown base height (h_c), height (h), and crown width (d_{cr}) were available. The status of all trees was visually verified in aerial images and dense LiDAR data, and the treetop positions were updated. Trees that were discernible in images or in the LiDAR point cloud formed the reference trees ($N = 15\,197$). Most suppressed and intermediate trees were unseen. The treetop 3D positions, *sp*, h, and $d_{1.3}$ were known for all trees, as well as the relative height (h_{rel}), which was estimated, using a local dominant height given by LiDAR. The site fertility was obtained from a botanical site description and maps. The basal area of the 10 closest trees, weighted by the inverse distance, was used for determining a proximity class that describes the dominant species among the adjacent trees. We estimated the mean age of trees per plot separately for the dominant and suppressed trees, using field measurements, old aerial images and forest management plans. Only 3.8% of the trees had an $h_{rel}<0.5$; thus, the study applies to

Table 1
Number of living pines, spruces and birches by site fertility (fertile 2−barren 6) and age classes.

Site/age	2	3	4	5	6	Sum
<40 years	586	2143	828	5	–	3562
40−60	79	4308	1614	–	2	6003
60−80	225	1544	138	43	25	1975
80−100	–	877	241	453	39	1610
100−120	72	1174	213	91	8	1558
>120 years	63	385	41	–	–	489
Sum	1025	10,431	3075	592	74	15,197

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