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In situ data supporting remote sensing estimation of spruce forest parameters at the ecosystem station Bílý Kříž

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Abstract: Homolová L., Janoutová R., Lukeš P., Hanuš J., Novotný J., Brovkina O., Loayza Fernandez R. R. 2017: In situ data collection supporting remote sensing estimation of spruce forest parameters at the ecosystem station Bílý Kříž – *Beskydy,* 10 (1, 2): 75–86

Remote sensing offers an effective way of mapping vegetation parameters in a spatially continuous manner, at larger spatial scales and repeatedly in time compared to traditional in situ mapping approaches that are typically accurate, but limited to a few distributed location and few repetitions. In case of forest ecosystems, remote sensing allow to assess quantitative parameters or indicators related to forest health status such as leaf area index, leaf pigment content, chlorophyll fluorescence, etc. Development, calibration and validation of remote sensing-based methods, however, still rely on supportive in situ data. The aim of this contribution is to introduce the individual in situ components in the framework for the retrieval of forest quantitative parameters from airborne imaging spectroscopy data. All measurements were acquired during an extensive in situ/flight campaign that took place at the Norway spruce dominated study site Bílý Kříž (Moravian-Silesian Beskydy Mts., Czech Republic) during August 2016. In addition to airborne remote sensing data acquisition, the in situ activities included terrestrial laser scanning for tree 3D modelling, measurements of needle biochemical and optical properties, leaf area index measurements and spectral measurements of various natural and artificial surfaces. Leaf pigments varied between 25.2 and 49.1 µg cm^{-2} for chlorophyll a+b content, 4.9 – 10.6 µg cm^{-2} for carotenoid content depending on needle age and its adaptation to sun illumination, whereas ratio between the two pigments was stable around 4.6 – 5. 3. Specific leaf area of spruce needles varied between 49.3 and 105.8 cm^2 g^{-1}, being the highest for the shade adapted needles of the current year. Leaf area index of spruce stands of various age and densities varied between 5.3 and 9. 3.

Keywords: Airborne imaging spectroscopy, terrestrial laser scanning, leaf area index, chlorophyll content, Picea abies, radiative transfer modelling

Introduction

Remote sensing (RS) is a powerful tool for studying forest ecosystems both in space and time (Cohen and Goward 2004; Lausch et al. 2016 & 2017). In particular, airborne imaging spectroscopy (or hyperspectral RS), which offers unique combination of high spatial and spectral resolution data (Schaepman 2009), can be used to retrieve quantitative parameters on forest stands such as leaf biochemical properties including pigments, water, nitrogen content (Asner et al. 2015; Kokaly et al., 2009; Malenovský et al. 2013) leaf area index (Heiskanen et al. 2013; Schlerf and Atzberger 2006) and most recently also parameters related to plant photosynthesis such as leaf chlorophyll fluorescence (Rossini et al. 2015; Middelton et al. 2017). Often, retrievals of forest parameters from imaging spectroscopy data rely on the inversion of radiative transfer models (Banskota et al. 2015; Laurent et al. 2011; Malenovský et al., 2013). Radiative transfer models (RTMs) simulate interactions between incoming radiation and landscape elements (e.g., trees) and thus are able to compute the top-of-canopy reflectance, i.e. the same signal as captured by imaging spectrometers for varying sun-target-sensor geometries and combinations of key input variables (i.e., canopy structures, forest densities, leaf optical properties). Forest landscape representation in an RTM may vary from a simple multi-layer model representing forest as homogeneous medium (e.g., SAIL; Jacquemoud et al. 2009; Verhoef and Bach 2007) to a complex model with explicit 3D canopy structure (e.g., DART – Discrete Anisotropic Radiative Transfer model; Gastellu-Etchegorry et al. 2015). Interpretation of high spatial resolution airborne imagery require corresponding level of details in the associated RTMs, therefore complex 3D RTMs are better suited that simple 1D models. Forest canopies, particularly conifers, are challenging objects to be modelled in 3D radiative transfer, especially for their distinct crown shape and highly organized crown architecture, complex light interactions at the level of the main scattering elements (i.e. needle shoots) and often the presence of understory (Eriksson et al., 2006; Malenovský et al., 2008; Rautiainen et al., 2004; Rochdi et al., 2006).

While remote sensing technologies are able to detect forest data in high quality and large quantity, operational applications are still limited by insufficient in situ verification (Pause et al. 2016). In addition to the acquisition of RS data, supportive in situ data are required for parameterization of RTMs, constraining the retrieval algorithms and last but not least verification of remotely sensed estimates of forest parameters. This paper aims to demonstrate the importance and the irreplaceable role of in situ measurements in the context of quantitative remote sensing of coniferous forests. We present here methods for in situ data collection, results of the measurements and how the in situ component fits into the framework for the retrieval of forest quantitative parameters from airborne hyperspectral sensing. Data were collected within an extensive in situ/airborne campaign that took a place at the Bílý Kříž study site in summer 2016. This campaign mainly supported CzechGlobe's research projects for the European Space Agency (ESA).

Material and Methods

Study area

The combined in situ and flight campaign took place at the vicinity of the ecosystem station Bílý Kříž in the Moravian-Silesian Beskydy Mts. (Czech Republic, 49°30'N, 18°32'E, 800-920 m a.s.l.) in August 2016. This site is used for long-term research on tree ecophysiology and carbon fluxes as a part of national (Czech Carbon Observation System CzeCOS) and international (Integrated Carbon Observation System ICOS) research networks (Krupková et al. 2017; Urban et al. 2012). The site is covered predominantly by Norway spruce (*Picea abies*) monocultures of different age.

For the in situ measurements, seven plots were selected in the vicinity of the ecosystem station, covering spruce stands of different age, densities and site conditions (topography). Location of the plots and the schematic sampling design for measurements of leaf properties and leaf area index (LAI) are shown in Fig. 1.

Measurements of leaf biochemical and optical properties

Leaf properties, namely leaf chlorophyll a+b and carotenoids content, leaf water content, leaf mass per area and leaf optical properties (reflectance and transmittance) were measured at the peak of the growing season at the end of August 2016. As such, they are compatible with airborne hyperspectral images acquired on 31st August of the same year. Needle samples were collected from three representative trees selected within each of the seven plots. Current, one and two-years-old shoots were cut off from two branches representing sunlit (i.e., crown top) and shaded (i.e., crown bottom) illumination conditions. Six samples were analysed for each tree, resulting in 126 needle samples in total.

Leaf samples for pigment analyses were immediately frozen in a liquid nitrogen and stored in deep freeze (-80 °C) until being processed in a laboratory. Pigments were extracted according to the method of Porra et al. (1989) using the 80% acetone solvent and the pigment concentration was determined spectrophotometrically according to the empirical equations of Lichtenthaler (1987). Leaf pigment and water content values were converted from mass-based to area-based units using specific leaf area that is computed as the ratio between half of the hemisurface needle

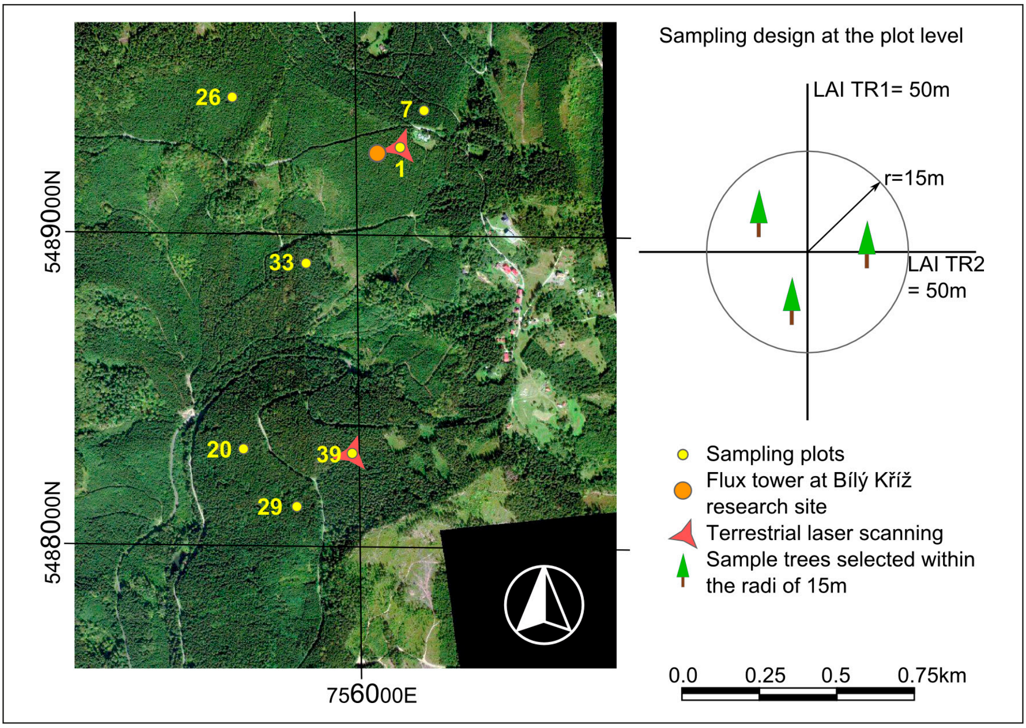

Fig. 1: In situ sampling plots at the Norway spruce dominated study site Bílý Kříž (left) and the sampling design for LAI and leaf biochemistry measurements (right).

area (Homolová et al. 2013) and the sample dry matter weight.

Leaf optical properties (LOP) between 350 and 2500 nm, i.e., directional-hemispherical reflectance and transmittance factors (DHRF and DHTF), were measured using an assembly of two ASD FieldSpec spectroradiometers attached to ASD RTS-3ZC integrating spheres (Analytical Spectral Devices, Inc., Colorado, US). Each sphere was operated with a produced-supplied halogen light source. The ASD FieldSpec 4 with the first integrating sphere was used to measure hemisperically-integrated reflectance, the FieldSpec 3 attached to the second sphere was used to measure hemisperically-integrated transmittance. This allowed for faster LOP measurements (it was not needed to change measurement mode of the sphere) and lower measurement uncertainty thanks to the fixed position of the light source. LOP measurement of narrow conifers needles is challenging (Yanez-Rausell et al. 2014a) and requires specifically designed carriers to place needles next to each other with small gaps in between (Malenovský et al. 2006; Yanez-Rausell et al. 2014b). Gap fraction, i.e., percentage of gaps between needles within the illuminated part of a carrier was estimated from carrier scans with applied mask of the actual light beam position. Final reflectance (DHRF) and transmittance (DHTF) were computed using the following formulas:

$$DHRF = \frac{\frac{(SAMPLE - STRAY) \times R_{SPECT}}{WR - STRAY}}{1 - GF} \quad (1)$$

$$DHTF = \frac{\frac{SAMPLE}{DN - GFWR - STRAY}}{1 - GF} \quad (2)$$

where SAMPLE is reflectance or transmittance of a needle sample measured in DN values, STRAY is stray light in DN values, R_{SPECT} is reflectance of the inner sphere wall, WR is a white reference reflectance in DN values and GF is gap fraction for reflectance or transmittance sample, respectively. Final signatures of reflectance and transmittance were smoothed using a Savitsky-Golay filter with 5th-degree degree polynomial.

Leaf area index

Leaf area index of the spruce forest stand was measured using three optical instruments: Plant Canopy Analyser LAI-2200 (Li-cor Biosciences Inc., US), LaiPen (Photon Systems Instrument, CZ) and digital hemispherical photographs (Canon 450D digital camera with Sigma 4.5 mm fisheye lens). Simultaneous measurements under diffuse sky conditions were taken at two 50 m long transects in a cross formation (Fig. 1). All three instruments measure so called effective LAIe (or plant area index), which must be further corrected from the effects of woody elements and foliage clumping in order to obtain “true” values LAIt (Chen 1996):

$$\text{LAIt} = (1\text{-}\alpha) * \text{LAIe} * \gamma\text{e}/\Omega\text{e} \qquad (3)$$

where α is the woody-to-total plant area ratio, γe is the needle-to-total shoot area ratio and Ωe is element clumping index. A correction factor between true and effective LAI was derived experimentally by Pokorný and Marek (2000) and Homolová et al. (2007) and it equals to LAIt = 1.6*LAIe.

Terrestrial laser scanning data

The 3D structure for selected trees at two plots (1 and 39) was measured using a terrestrial laser scanning system Riegl VZ-400 (Riegl Laser Measurement Systems, GmbH, Austria). Laser scanning inside a forest is challenging, because of mutual shadowing of neighborhood trees. In order to minimize the shadowing effect, the selected trees were scanned from multiple scan positions. The scan pattern (i.e., the angular step) of 10 mdeg resulted in the point spacing of 0.4 cm at the scanning distance between the scanner and a tree, which was about 20 m.

Processing of point cloud data was done using RiSCAN PRO (post-processing software developed by Riegl). The point clouds obtained from scanning at multiple positions were merged together using white reference balls as tie points. The final point cloud was cleaned by filtering out points with high deviation value and segmented to individual trees. A point cloud resembling one tree was further classified into two groups, wooden element and green foliage, using an intensity threshold defined manually by an operator.

Airborne imaging spectroscopy data

Airborne imaging spectroscopy (or hyperspectral) data were acquired with two pushbroom spectroradiometers, CASI operating in the visible and near infrared regions between 372 and 1044 nm and SASI operating in the shortwave infrared region between 957 and 2442 nm (ITRES Research Limited, Canada). Both sensors were operated simultaneously on board the CzechGlobe Flying Laboratory of Imaging Systems (FLIS; Hanuš et al. 2016). Images were acquired under clear sky and sunny conditions on 31^{st} August 2016 in a high resolution mode (i.e., pixel size of 1 m for CASI and 2.5 m for SASI, 72 spectral bands for CASI and 100 bands for SASI). Corrections of the hyperspectral images were preformed according to a processing chain established at CzechGlobe (Hanuš et al. 2016). Radiometric corrections were performed using the factory calibration coefficients in the RCX software (post-processing software developed by ITRES that runs under ENVI/IDL programming environment). Geometric corrections, i.e. image orthorectification and geo-referencing, were performed using the GeoCorr software provided also by ITRES. Atmospheric corrections were performed using the ATCOR-4 software (Richter and Schläpfer 2002).

Simultaneously with the airborne data acquisition, spectral signatures of homogeneous artificial surfaces (e.g. asphalt, concrete, gravel fields) were measured in situ using the ASD FieldSpec 4 spectroradiometer. These spectral signatures were subsequently used to calibrate hyperspectral images and assess the quality of the atmospheric corrections.

Results and Discussion

Leaf biochemical and optical properties

Biochemical properties (leaf pigments, water content and specific leaf area) of Norway spruce needles are summarized in Table 1. The results show high variability among the needle samples collected from branches with contrasting illumination conditions (sunlit vs. shaded) and from shoots of different age (current vs. older needles). In particular, needles of the current year (c) have lower leaf pigments content, but higher specific leaf area (SLA) than older needles.

For the sake of brevity, LOP, i.e., directional-hemispherical reflectance and transmittance factors of Norway spruce needles, are presented as mean and standard deviation computed from all the needle samples (Fig. 2.) Although the spectral signatures were measured between 350 and 2500 nm, both ends of the spectral interval were too noisy and therefore discarded and the final signatures are presented between 400 and 2300 nm. In general, spruce reflectance and transmittance spectra measured at the Bílý Kříž site are in agreement with other measurements of spruce trees for instance in Finland (Hovi et al. 2017; Lukeš et al. 2013). The leaf albedo, i.e., the sum of reflectance and transmittance, in the near infrared wavelengths is around 0.8, which is lower than for broadleaf tree species (Hovi et al. 2017, Noda et al. 2014).

Although we present here only the mean spectral signatures, spectral differences between sunlit and shaded needles, as well as between needles of different age can be observed (see also Hovi et al. 2017 or Lukeš et al. 2013). Hovi et al. (2017) observed minor differences between sun exposed and shaded needles, but needle age was an important factor explaining variation particularly in needle transmittance. The spectral differences can be to some extend related to variations in leaf biochemistry. Leaf pigments are the main absorbing compounds influencing the optical properties in the visible and the red-edge region (400 – 720 nm), whereas leaf structure (e.g. SLA) and water content are influencing optical properties in the near and short-wave infrared. Variation in needle biochemistry and optical properties can be partly considered as adaptation to different illumination conditions inside forest canopies (Niinemets 2010).

Measurement of LOP for coniferous needles is more prone to measurement errors than in case of deciduous flat leaves (Yanez et al. 2014a). This is mainly due to the irregular shape of narrow needles causing the gaps between the measured needles. The spectral measurements have to be corrected from the excess light penetrating through the gaps, therefore the gap fraction (ratio between the gaps and needles within the sample port) have to be precisely determined and corrected for (Yanez et al. 2014b).

Leaf area index

Leaf area index was measured using three optical instruments and the results in Fig. 3a shows that the LAI-2200 and LaiPen instruments provide similar measures of LAI, whereas hemispherical photography lower LAI compared to the other two instruments. The measurement principle of the two instruments (LAI-2200 and LaiPen) is similar; simultaneous below and above canopy readings are used to determine the canopy light interception at five zenith angles. The main difference between the two instruments is in their fields of view, LAI-2200 sees part of the hemisphere, whereas LaiPen measures within a narrow hemispherical sector. LaiPen measurements, however, are systematically higher than LAI-2200. Contrary, hemispherical photographs yielded lower and inconsistent estimates of spruce forest LAI.

Tab.1: Biochemical properties of Norway spruce needle samples collected from sunlit and shaded branches and from different needle age classes (c – current needles, c-1 – one-year-old needles, c-2 – two-years-old needles). Cab – leaf chlorophyll a + b content, Car – leaf carotenoid content, Ca/Cb – ratio between chlorophyll a and b, Cab/Car – ratio between chlorophylls and carotenoids, Cw – leaf water content, SLA – specific leaf area related to the needle hemisurface area.

Branch	**Sunlit**			**Shaded**		
Needle age	**c**	**c-1**	**c-2**	**c**	**c-1**	**c-2**
Cab [μg cm^{-2}]	30.0 ± 7.1	40.5 ± 7.3	49.1 ± 8.7	25.2 ± 5.2	40.0 ± 7.8	40.6 ± 6.3
Car [μg cm^{-2}]	6.1 ± 1.5	8.6 ± 1.6	10.6 ± 1.9	4.9 ± 1.2	6.9 ± 1.7	8.3 ± 1.5
Ca/Cb [-]	3.3 ± 0.3	3.2 ± 0.2	2.9 ± 0.2	3.2 ± 0.3	3.2 ± 0.2	3.0 ± 0.2
Cab/Car [-]	5.0 ± 0.4	4.7 ± 0.2	4.6 ± 0.2	5.3 ± 0.4	5.0 ± 0.2	4.9 ± 0.2
Cw [mg cm^{-2}]	21.4 ± 3.5	20.6 ± 2.6	22.8 ± 2.3	16.1 ± 1.9	16.2 ± 2.6	17.1 ± 3.0
SLA [cm^2 g^{-1}]	69.7 ± 13.5	61.1 ± 10.1	49.3 ± 7.3	105.8 ± 15.5	92.2 ± 17.3	77.2 ± 11.5

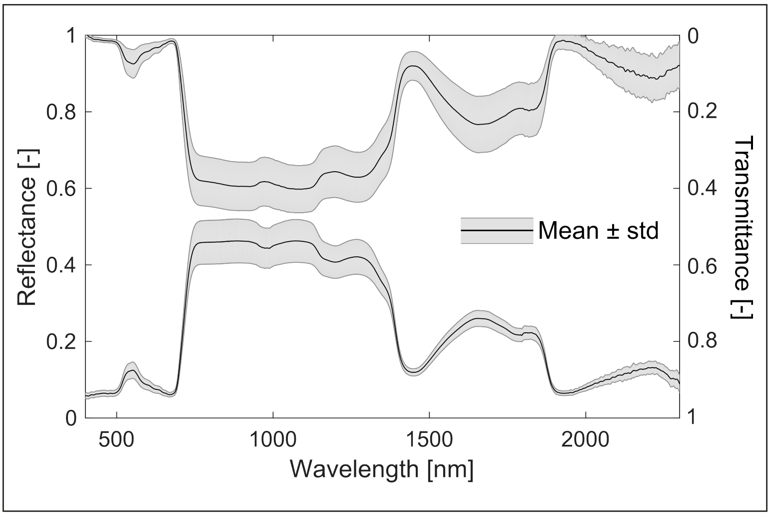

Fig. 2: Directional-hemispherical reflectance factor (bottom signature) and transmittance factor (upper signature) of Norway spruce needles.

Values of LAI (as measured by LAI-2200) varied between 5.3 and 9.3, which is in agreement with measurements done by Pokorný and Stojnič (2012), who measured LAI of 17 Norway spruce stands between 15 and 102 years located in the Těšínské Beskydy Mts. (NE part of the Czech Republic). Generally, the higher LAI values were measured in younger (cca 40 years old) than in older and sparser spruce stands (cca 100 years old).

Leaf area index and leaf biochemical properties were averaged in order to produce a single value per plot (Fig. 3 b). Leaf pigments vary little among the plots (e.g., Cab is between 32 and 41 μg cm^{-2}), but within plot variation is large (Cab std ≈ 10 μg cm^{-2}) due to sampling of sunlit and shaded needles of different age. Contrary, LAI exhibits larger variation among the plots (LAI is between 5.3 and 9.3), but little variation within a plot is observed. Data aggregated at the plot level are geo-located and primarily used for the validation of the forest canopy parameters retrieved from airborne, as well as from satellite RS data.

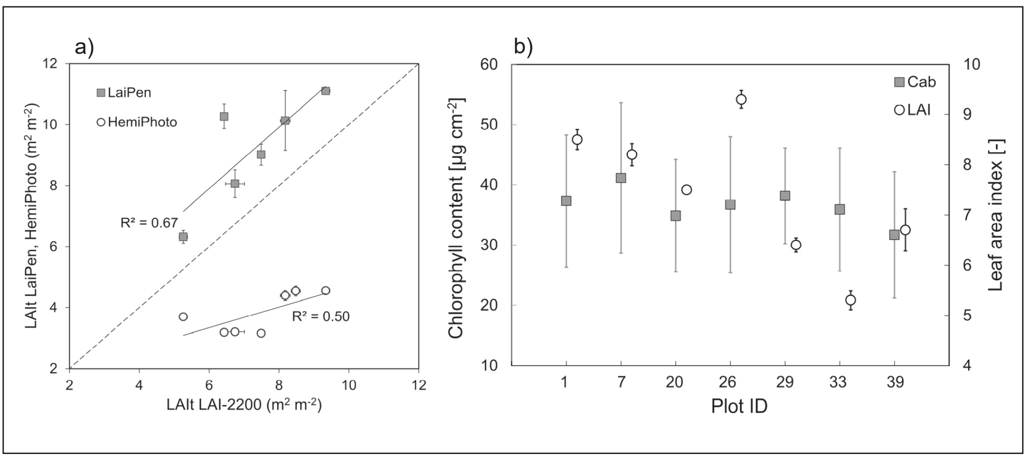

Fig. 3: Total leaf area index (LAIt) of Norway spruce forest stands measured by three optical instruments, LAI-2200, LaiPen and hemispherical photography (a) and averaged leaf area index and leaf chlorophyll content per study plot (b).

Terrestrial laser scanning

The terrestrial laser scanning allows extracting the exact 3D tree architecture (Hackenberg et al., 2014), including information about a stem, main branches and spatial distribution and density of foliage. The point cloud data of individual trees were first differentiated to wooden and foliage elements and subsequently used to reconstruct trees as 3D objects (Fig. 4.). The entire modelling procedure was developed by Janoutová (2017) and it can be briefly summarized by three main steps:

1) reconstruction of wooden skeleton including trunk and main branches (Fig. 4b),
2) scaling and transformation of the foliage point cloud and the reconstructed wooden skeleton to a site-specific tree dimensions,
3) distribution of needle shoot models within a tree crown according to the density of the foliage point cloud (Fig. 4c).

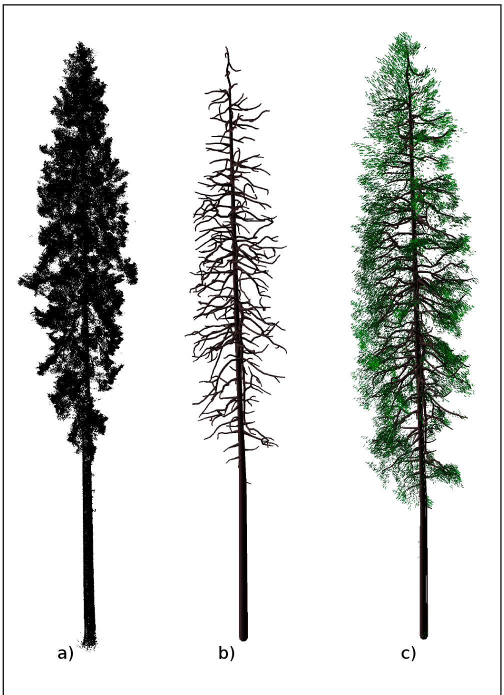

Fig. 4: Example of point cloud data for a single spruce tree obtained from the terrestrial laser scanning (a), reconstructed stem and main branches (b), and the final 3D spruce tree model composed of wooden and foliage objects (c).

In the context of the optical remote sensing of forests, the ability to create plausible 3D tree models would improve the radiative transfer modelling of spruce canopies, where the canopy structure plays an important role in the near and short-wave infrared spectral regions. Althgough, there currently are radiative transfer models available (e.g., DART) that can accommodate trees as 3D objects, computation of the radiative transfer for larger forest scenes still can be very demanding. Nevertheless, the 3D radiative transfer modelling could be better tailored for site-specific conditions thus enabling to develop robust retrieval methods for structurally complex forested areas.

Airborne imaging spectroscopy data

The final result of the airborne data acquisition is the geometrically and atmospherically corrected hypercube image mosaic of several flight lines covering the study area (only small image subsets extracted around the vicinity of the Bílý Kříž ecosystem station are shown in Fig. 5 – left panels). The final image mosaics were created separately for CASI (covering the visible and near infrared regions with the pixel size of 1 m) and SASI (covering the near and short-wave infrared regions with the pixel size of 2.5 m). Seamless combination of CASI and SASI image data of two different spatial resolutions into a single hypercube that covers the entire spectral range from 400 to 2500 nm turned out to be difficult for heterogeneous areas because of the mismatch in spectral resolution and. It will be further investigated how to better combine CASI and SASI image data for heterogeneous forest surfaces on per pixel basis.

The quality of the atmospheric corrections was evaluated by comparing the image spectra extracted from homogeneous artificial surfaces (such as parking place, asphalt road) and their counterparts measured in situ. The visual comparison shows good agreement between the image and in situ spectra (for brevity results are not shown) with maximum differences of about 3 % in the short-wave infrared bands.

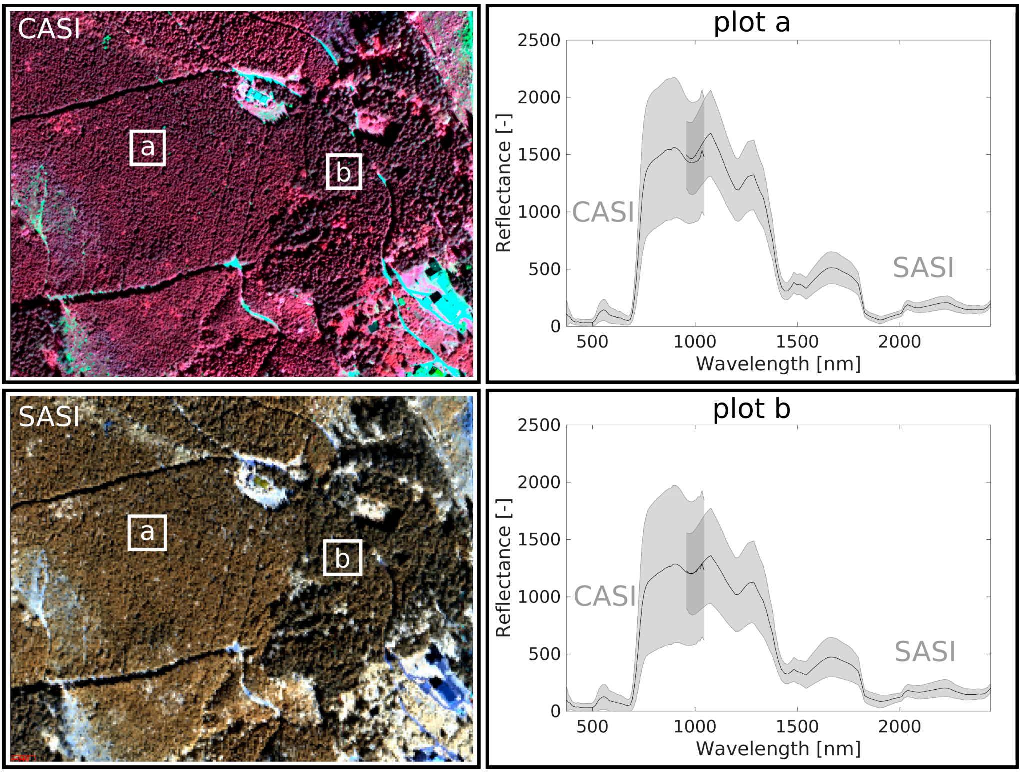

Fig. 5: Left panels show subsets of airborne hyperspectral images acquired at the Bílý Kříž study site by CASI (pixel size of 1 m displayed as false colour composite R – 864 nm, G – 647 nm, B – 552 nm) and SASI (pixel size of 2.5 m displayed as false colour composite R – 1062 nm, G – 1243 nm, B – 1692 nm) spectroradiometers. Right panels show examples of canopy spectral signatures extracted for two plots representing spruce forest of about 40 years old (plot a) and 80 years old (plot b).

Conceptual framework for the retrieval of forest quantitative parameters

All the in situ and airborne data discussed up to this point fit into a broader conceptual framework for the estimation of quantitative forest parameters from RS data (Fig. 6.). Radiative transfer modelling plays the central role in the framework as it effectively enables to scale the in situ leaf optical and biochemical properties and canopy structural measurements up to the level of airborne and satellite remote sensing reflectance observations. Therefore, forest parameters, such as leaf pigment and water content, leaf area index, canopy cover, that are at the same time the key input parameters of the forest RTM, can be estimated from RS data (Rautiainen et al., 2010).

In situ measurements contribute more or less to all steps of the retrieval framework and they can be divided into several groups according their role (Fig. 6). First, in situ data are used to correct RS images and these typically include measurements of the actual atmospheric conditions and reflectance of reference ground targets. Second, in situ data are used to parameterize radiative transfer models and these include terrestrial laser scanning data enable to model forest canopies in realistic 3D way, optical properties of needles and other forest elements (e.g., bark, forest floor cover), as well as variation and distribution of key vegetation parameters that are used as RT model inputs. Third, in situ measurements of vegetation parameters that are estimated from RS data (e.g., pigment, water content, LAI) which provide an independent validation of the RS-based products.

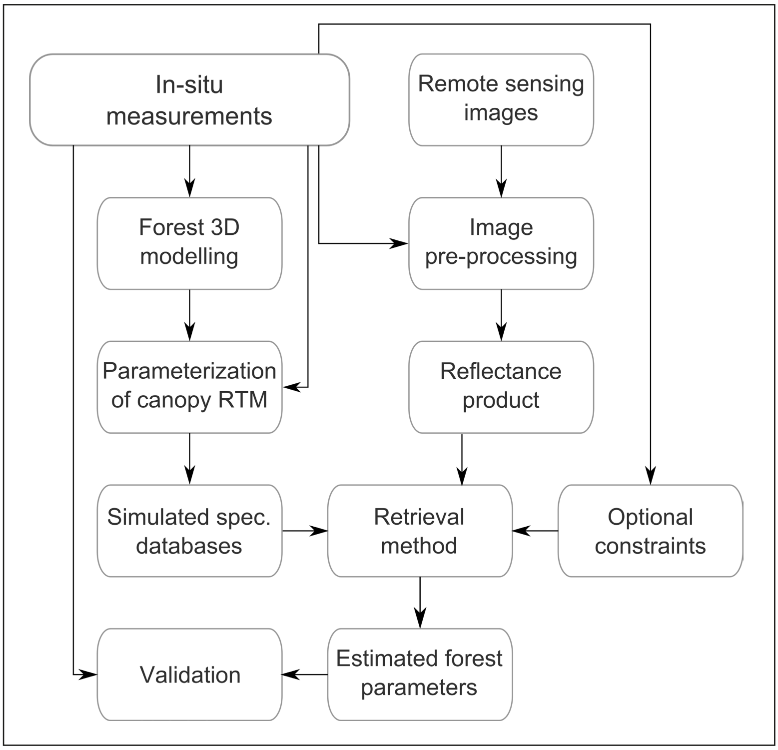

Fig. 6: Contribution of the in situ measurements to the framework for retrieval of forest quantitative parameters from remote sensing data using the radiative transfer modelling (RTM).

Conclusions

Establishing a retrieval chain for quantitative estimation of vegetation parameters from RS data requires strong support from multitude in situ measurements. We introduced here different types of in situ data and their measurement methods that are relevant for our case study presented for airborne remote sensing assessment of Norway spruce forests. In situ measurements include leaf biochemical properties that together with LAI data are primarily used for validation of RS-base products. Leaf chlorophyll content varied between 25.2 and 49.1 μg cm^{-2}, carotenoids between 4.9 and 10.6 μg cm^{-2}, leaf area index varied between 5.3 and 9.3 m^2 m^{-2}. Leaf optical properties, i.e., reflectance and transmittance are essentially used for verification and improvement of forest RT modelling. Terrestrial laser scanning data are used to model forests in 3D and such as they can improve RT modelling for forests. In this case, several trees could be extracted from the point cloud data, reconstructed using the approach developed by Janoutová (2017) and used to build-up a forest canopy scene for simulating large spectral database in the DART radiative transfer model. At the end, we presented the acquisition of airborne hyerpsectral images of the spruce study site with accompanying in situ measurements of ground reference targets to verify the quality of the image pre-processing (i.e., atmospheric corrections).

A combination of in situ and RS data can reduce uncertainty in area-wide mapping of forest biochemical and biophysical parameters. The proposed conceptual framework can be helpful to assess the potential of new satellite missions (i.e., Sentinels, FLEX) with its focus on identifying environmental processes. This framework has been implemented by CzechGlobe in the context of the ESA research projects related to exploiting the Sentinel-2 red-edge or airborne hyperspectral bands for the retrieval of vegetation biochemical and biophysical parameters.

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