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Radiative transfer modeling within a heterogeneous canopy for estimation of forest fire fuel properties

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Abstract

Imaging spectrometer data were acquired over conifer stands to retrieve spatially distributed information on canopy structure and foliage water content, which may be used to assess fire risk and to manage the impact of forest fires. The study relied on a comprehensive field campaign using stratified systematic unaligned sampling ranging from full spectroradiometric characterization of the canopy to conventional measurements of biochemical and biophysical variables. Airborne imaging spectrometer data (DAIS7915 and ROSIS) were acquired parallel to the ground measurements, describing the canopy reflectance of the observed forest. Coniferous canopies are highly heterogeneous and thus the transfer of incident radiation within the canopy is dominated by its structure. We demonstrated the viability of radiative transfer representation and compared the performance of two hybrid canopy reflectance models, GeoSAIL and FLIGHT, within this heterogeneous medium. Despite the different nature and canopy representation of these models, they yielded similar results. Subsequently, the inversion of a hyperspectral GeoSAIL version demonstrated the feasibility of estimating structure and foliage water content of a coniferous canopy based on radiative transfer modeling. Estimates of the canopy variables showed reasonably accurate results and were validated through ground measurements.

Keywords: Imaging spectroscopy; radiative transfer; coniferous canopy; canopy structure; foliage water content; forest fire

1. Introduction

Three major forces are essential for understanding forest fire risk and specifically fire behavior—weather, fuel and topography—as illustrated by the *fire environment triangle* (Countryman, 1972; Pyne et al., 1996). Within this concept, the fire fuel component introduces high uncertainty to the prediction of fire hazard due to its high spatial and temporal variability.

Fire risk and behavior depend heavily on the fuel properties such as the quantity of biomass, partitioning of living and dead biomass, moisture content, and the vertical and horizontal structure of the canopy (Chuvieco et al., 2002; Lynham et al., 2002). Accurate information on forest fuel properties at high spatial and temporal resolutions is vital for understanding the processes involved in initiation and propagation of forest fires (Chuvieco, 2003; Keane et al., 2001). Remote sensing offers the potential to provide spatially distributed information on biomass, canopy structure, and fuel moisture to assess fire risk and to mitigate the impact of forest fires (Chuvieco & Congalton, 1989; Dennison et al., 2003; Fraser & Li, 2002; Leblon, 2000; Roberts et al., 2003).

The spectral reflectance of a plant canopy is known to be primarily a function of the foliage optical properties, the canopy structure, the understory and soil background reflectance, the illumination conditions, and finally, the viewing geometry (Chen et al., 2000; Goel, 1988). Radiative transfer modeling takes into account physical processes describing the interaction of radiation with the diverse canopy components at foliage and canopy levels. Consequently, a physically based approach of coupled leaf and canopy radiative transfer models (RTMs) provides an adequate way to assess canopy variables, such as vegetation water content and leaf area index (LAI). Radiative transfer models have already been

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successfully employed with homogeneous canopies to derive quantitative information on canopy structure and foliage biochemistry (Fourty & Baret, 1997; Jacquemoud et al., 2000; Weiss et al., 1999). Over the past few years, research in this area has been extended to the full characterization of the radiative transfer within heterogeneous canopies such as deciduous and coniferous forests (Dawson et al., 1999; Gastellu-Etchegorry & Bruniquel-Pinel, 2001). Forest canopies are characterized by high horizontal and vertical heterogeneity. Coniferous forests, in particular, exhibit a complex canopy structure which has to be considered at the needle and shoot levels, assessing the well-known clumping effect of needles, at the crown level, and at the forest stand level (Cescatti, 1998; Chen et al., 1997a; Chen & Leblanc, 1997; Williams, 1991). Consequently, the radiative transfer within a forest canopy depends on the spatial distribution of the canopy elements relative to each other and on the subsequent complex radiative processes such as multiple scattering, mutual shading of the crowns, and shading of the background. In this case, three-dimensional canopy radiative transfer models are required to parameterize the heterogeneous canopy structure appropriately (e.g. Chen & Leblanc, 1997; Govaerts & Verstraete, 1998; Huemmrich, 2001; North, 1996). Unfortunately, the inverse solution of a RTM is not necessarily unique, limiting the estimation of canopy variables. The ill-posed nature of the RTM inversion increases with the complexity of the observed medium and the employed model (Combal et al., 2003). However, various physically based canopy reflectance models have been used to estimate biophysical and biochemical variables of heterogeneous canopies with promising results (Demarez & Gastellu-Etchegorry, 2000; Gemmell et al., 2002; Hu et al., 2000; Kimes et al., 2002; Kuusk, 1998; Zarco-Tejada et al., 2001).

Imaging spectrometry from air- or spaceborne platforms gives access to the spectral features of canopy reflectance caused by the complex absorption and scattering processes within the canopy (Asner et al., 2000; Rast, 2001; Schaepman et al., in press). In this study, we utilized two hybrid radiative transfer models applied to imaging spectrometer data acquired over a coniferous forest to estimate canopy variables relevant for the description of forest fuel properties. The specific objective of this study is to evaluate the ability of the two selected radiative transfer models, FLIGHT (North, 1996) and GeoSAIL (Huemmrich, 2001), to represent the complex nature, and consequently, the reflectance of a heterogeneous canopy. We compare the two radiative transfer models and assessed the influence of the different complex canopy representations—inherent to the selected models—on the characterization of the canopy reflectance. The inversion of GeoSAIL assesses subsequently the feasibility of canopy variable estimation by radiative transfer modeling and imaging spectroscopy over a heterogeneous canopy. The final validation involves a comprehensive canopy characterization based on ground measurements along with a quality assessment of the imaging spectrometer data (Kötz et al., 2003). This enabled a full validation of the proposed methodology including the definition of the relevant uncertainties of all contributing error sources based on ground measurements, the image data, and the model inversion.

1.1. Background: fuel properties and remote sensing

Imaging spectroscopy can provide a number of canopy properties relevant for forest fire issues such as green vegetation water content (Ceccato et al., 2001; Gao & Goetz, 1995; Penuelas et al., 1997; Serrano et al., 2000; Ustin et al., 1998) or biomass loads (De Jong et al., 2003; Roberts et al., 2003). However, canopy parameters assessed by remote sensing are not necessarily directly compatible with the requirements of the fire research and management community. In the forest fire literature, vegetation water content is traditionally expressed as fuel moisture content (FMC), defined as the percentage of water weight over sample dry weight (Chuvieco et al., 2002). Whereas in remote sensing, water content in vegetation is characterized by the equivalent water thickness (EWT: water content per leaf area; Danson et al., 1992; Tucker, 1980) because this variable is directly related to the leaf optical properties (Ceccato et al., 2001, 2002b). However, EWT derived from remote sensing is easily converted into FMC values by introducing information on the specific leaf weight (Chuvieco et al., 2003a). Another important fuel property is the biomass present in the canopy, commonly expressed as fuel loading, which is usually taken into account within the respective fuel model (Pyne et al., 1996). Remote sensing observations are best related to canopy biomass by the green leaf area relative to ground surface, the LAI. Foliage biomass can be directly computed from LAI using the specific leaf weight (Keane et al., 2001; Scott & Reinhardt, 2001).

The proposed approach of this study provided all canopy characteristics—EWT, LAI, and leaf dry matter—necessary to describe two important fuel properties, live fuel moisture, and green fuel loading of conifer tree crowns with remote sensing data. Moreover, estimates of the canopy cover can complement the information on the presence of canopy fuels and help to calculate variation of dead fuel moisture (Chuvieco et al., 2003b; Finney, 1998). A direct measure of the live fuel moisture and biomass, as presented here, can be a valuable input for fire behavior modeling. Both live fuel moisture and biomass ideally represent the high temporal and spatial variability of fuels due to numerous influencing environmental factors. Spatial information on live fuel properties is especially critical to fire propagation and could therefore improve predictions of fire behavior models significantly (Carlson & Burgan, 2003; Finney, 1998; Sero-Guillaume & Margerit, 2002).

2. Study site and data description

The study area for the acquisition of the field data is located in the Eastern Ofenpass valley which is part of the

Swiss National Park (SNP). The Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l, with an annual precipitation of 900–1100 mm. Embedded in this environment are boreal type forests where few, but very impacting (stand-replacing) fires, were observed. The ecology, and in particular, the natural fire regime of these stands are subject to ongoing long-term fire history and disturbance studies in the same area (Allgöwer et al., 2003).

The south-facing Ofenpass forests, the location of the field measurement, are largely dominated by mountain pine (*Pinus montana* ssp. *arborea*) and some stone pine *(Pinus cembra* L.), a second tree specie that is of interest for natural succession (Lauber & Wagner, 1996; Zoller, 1992, 1995). These forest stands can be classified as woodland associations of *Erico–Pinetum mugo* (Zoller, 1995). The understory is characterized by low and dense vegetation composed mainly of various Ericaceae and *Sesleria* species. The study area has been also subject to previous fuel modeling studies where three main fuel models could be identified through extensive field studies (Allgöwer et al., 1998). Therein, model A 'mixed conifers' equals the association *Rhodendro ferruginei–Laricetum*, Model B 'mountain pine' the *Erico–Pinetum mugo*, and model C 'dwarfed mountain pine' the *Erico–Pinetum mugo prostratae*. In the present study, the field measurement were taken within forest stands corresponding to the model B because this is the dominant fuel type of the area.

2.1. Sampling scheme

Four core test sites (labeled LWF1, LWF2, STA1, and STA2) and several additional distributed point samples described the canopy and the spectral characteristics of the study area. The core test sites were selected following a stratified sampling scheme to cover different canopy densities within a stand of *P. montana* ssp. *arborea* (Fig. 1). They were set up accordingly to the elementary sampling units of the VALERI scheme (Baret, 2004). Each site was defined by nine sampling points, evenly spaced in a grid spacing of 10 m, covering a square area of 20×20 m. The coordinates of the sampling points were georeferenced by nondifferential GPS receivers. Measurements of the biophysical and biochemical variables describing the canopy were performed at all sampling points between the 7th and the 15th of August 2002. Mean values of the core test sites are presented in Table 1.

2.2. Canopy structure

Canopy structure was described using two different methods, well known in the literature and adapted to heterogeneous canopies (Chen et al., 1997b; Smolander & Stenberg, 1996). Measurements were carried out using two canopy analyzer LAI2000 (LICOR, 1992) and hemispherical photographs to provide canopy structure variables (EYE-CAN, 2003), separately for the crown and understory layer.

The LAI2000 was used to estimate two canopy variables the effective leaf area index (LAI) and the gap fraction. The LAI2000 provided an effective plant area index representing green foliage and woody area rather than just the green leaf area per unit ground surface area. The clumping effects at the shoot and crown level, typical for coniferous foliage, were corrected following an approach proposed by Chen et al. (1997b). Values for the clumping index of mature *Pinus banksiana* canopies, a tree specie similar to the investigated species, were applied (Chen et al., 1997b). The uncertainties associated with the LAI and the gap fraction provided by the LAI2000 were assessed based on the standard deviation of five reference measurements taken at each measurement point. Observed LAI values ranged between 1.78 and 3.99, whereas the measurement uncertainties amounted to 22%.

Hemispherical photographs taken parallel with the LAI2000 measurements allowed the separation of the canopy into its constituent foliage and wood fractions, i.e., needles, trunk and branches (Jonckheere et al., in press; Weiss et al., in press). The algorithm used relied on a supervised neural network training to classify the photograph into its image elements (EYE-CAN, 2003). Subsequently, the classification technique allowed woody parts and green foliage, and their respective gap fractions, to be distinguished based on their respective colors.

Forest stand measurements of the Long-term Forest Ecosystem Research program of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) were used to describe the basic geometric primitives of the canopy (Fig. 1). Stem density, tree height and crown radius were measured within this program over an area of 2 ha comprising a number of 2456 trees (Table 1). Additionally, the height of the crown base was visually estimated during the field campaign of this study.

2.3. Biochemistry of the canopy

Standard wet-laboratory procedures were used for determination of foliage water, chlorophyll content, and dry matter. The samples were collected from the upper part of the tree crowns, each consisting of one branch carrying newly developed and old needles. Due to the temporal variability of the biochemical parameters, the samples were collected on the same day as the overflight, placed in iced, air sealed containers and analyzed in the laboratory during the following 2 days.

The difference between fresh and dry weight allowed for the calculation of water content expressed either as relative value per unit mass [fuel moisture content (FMC) percentage (%)] or per unit leaf area as equivalent water thickness (EWT; g/cm^2 or cm). The concentration of photosynthetic pigments (chlorophyll a and b) within the foliage was determined by a CADAS 100 spectrophotometer using the

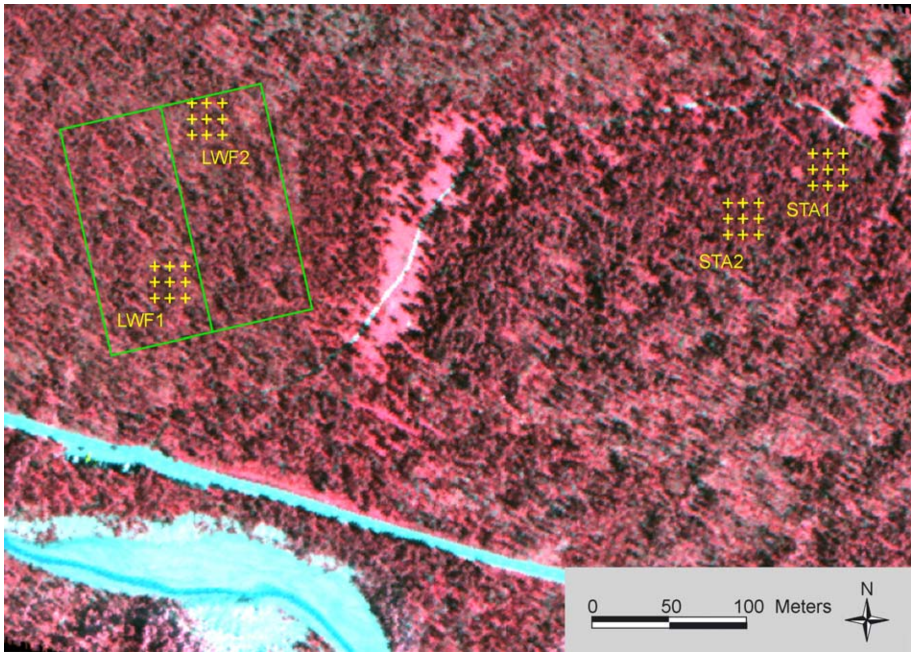

Fig. 1. Airborne imaging spectrometer data over the four core test sites (yellow crosses indicate the sampling points). The image composite represents geocoded and atmospherically corrected data of the spectrometer ROSIS in spatial resolution of 1 m resolving the heterogeneity of the observed forest. The long-term Forest Ecosystem Research site of WSL where forest stand characteristics are acquired is indicated by the rectangle.

Table 1
Field observations of canopy variables including relative measurement errors relevant for the canopy parameterization of the RTMs PROSPECT, GeoSAIL and FLIGHT

	Unit	LWF1	LWF2	STA1	STA2
Foliage parameters (PROSPECT)					
Water content	g/cm^2	0.047 (7.5%)	0.045 (7.5%)	0.049 (7.5%)	0.042 (7.5%)
Dry matter	g/cm^2	0.038 (7.5%)	0.036 (7.5%)	0.038 (7.5%)	0.035 (7.5%)
Fuel moisture content[a]	%	123.7	125.0	128.9	120.0
Chlorophyll content	μg/cm^2	61.8 (1.54%)	75.1 (1.54%)	59.0 (1.54%)	62.8 (1.54%)
Mesophyll structure	unitless	3.78 (22%)			
Canopy structure (overstory)					
LAI	unitless	2.18 (13%)	1.78 (22%)	3.89 (19%)	3.99 (17%)
Fractional cover	%	0.55 (13%)	0.46 (22%)	0.77 (19%)	0.79 (17%)
Wood fraction	%	0.3	0.3	0.3	0.4
Crown shape		Cone			
Tree distribution		Poisson distribution			
FLIGHT					
Tree height	m	11.93 ± 2.9			
Crown radius	m	1.765			
Crown base	m	7			
Trunk diameter	m	0.179 (at ground)			
Leaf angle distribution		Spherical			
GeoSAIL					
Crown height width ratio	unitless	2.83			
Hotspot	unitless	0.1			
Leaf angle distribution		Average leaf angle: 58.43° (foliage) and 30° (woody parts)			

The spectral properties of the woody parts and understory were characterized by spectroradiometric field measurements (Fig. 2).
[a] Calculated after (Chuvieco et al., 2003a,b).

equations of Lichtenthaler (1987). The pigment concentrations were converted to [μg/cm^2] by relating the concentration to the leaf area of the sample.

The observed biochemical concentrations showed only a low variability (Table 1) which could be explained by the relative constant environmental measurement conditions. Uncertainties of the estimates of the foliage biochemistry were derived from the accuracy specifications of the respectively involved instruments and reference readings of the measurements.

2.4. Spectral properties of canopy components

The spectral properties of several canopy components, including the reflectance of the understory, woody parts, and the foliage, were measured in the field with the ASD field spectroradiometer (Analytical Spectral Devices, 1997). Field spectra were collected during the overflight in nadir measurement configuration, 1.5 m above the ground and within 2 h of solar noon under clear sky conditions. All spectra were converted to absolute reflectance by reference measurements over a Spectralon panel with known spectral properties. The spectral characteristics of branches and bark of trunks were assessed from several selected samples. For the understory, reflectance transects consisting of 10 to 40 spectroradiometric measurements were acquired at each test site (Fig. 2). Measurements of the understory reflectance were affected by shadowing of the crowns. Consequently, spectra lower than one standard deviation relative to the average of the transect were discarded, regarding them as reflectance of shadows.

The acquisition of the reflectance of coniferous foliage involved an ASD field spectroradiometer coupled with an integrating sphere LICOR1800 (LI-COR, 1983) and a custom-made light source for improved illumination. The gap fraction of samples not covering the instrument port was assessed with a high-resolution digital camera and subsequent image analysis. The gap effects on the reflectance measurements were corrected by taking proportionally into account the spectral properties of the background following the approach of Daughtry et al. (1989).

2.5. Imaging spectrometer data

The imaging spectrometer data were acquired on the 14th of August parallel to the ground measurements and simultaneously with the DAIS7915 (Chang et al., 1993) and ROSIS sensors (Doerffer et al., 1989). The local illumination and observation conditions were summarized by a solar zenith angle of 45.3°, a solar azimuth angle of 122.9°, and the flight heading of 293°. This study concentrated on the data recorded by the DAIS7915 imaging spectrometer Kennedy scanner which covered a spectral range from the visible to the thermal infrared (VIS/NIR, 0.5–1.1 μm; SWIR1, 1.6–1.8 μm; SWIR2, 2–2.5 μm; MIR, 3–5 μm; TIR, 8.7–13 μm) with 79 bands. The airborne campaign was organized to cover the Ofenpass valley, providing imaging spectrometer data in a spatial resolution of 5 m. The flight line was oriented close to the principal plane of

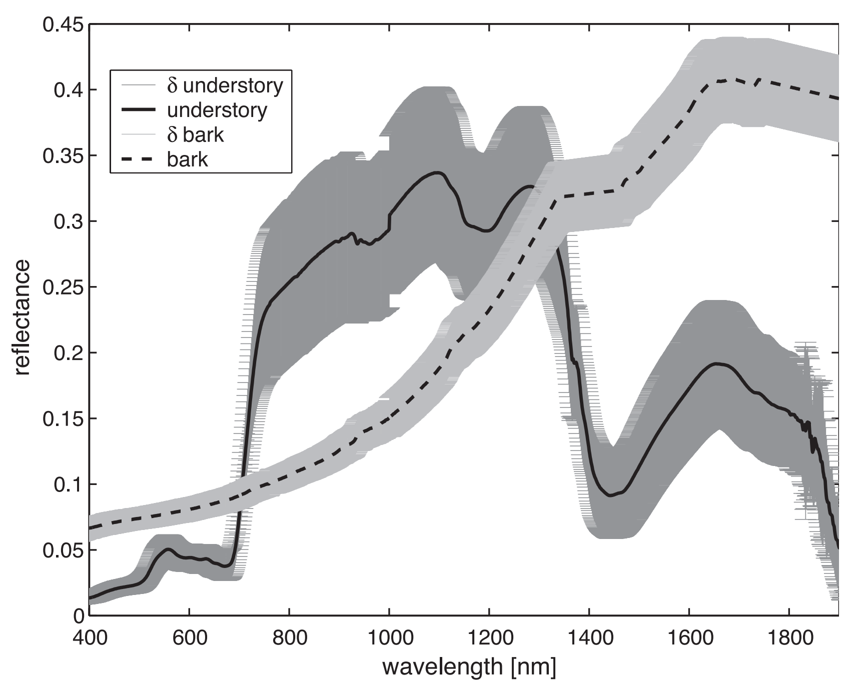

Fig. 2. Reflectance of the canopy components understory and bark representing the spectral properties of the background and the woody parts necessary for the radiative transfer parameterization. Error bars indicate the variability (one standard deviation, number of measurements: 35 understory spectra, 10 bark spectra) of the measurements.

the sun during the overflight time to minimize directional effects (Beisl, 2001). The images were geoatmospherically processed with the modules PARGE and ATCOR4 to obtain geocoded top-of-canopy reflectances (Richter & Schläpfer, 2002; Schläpfer et al., 2003; Schläpfer & Richter, 2002).

The spectroradiometric measurements of selected reference targets in the field also allowed a validation of the retrieved surface reflectance and a subsequent vicarious calibration of the imaging spectrometer data (Secker et al., 2001). The quality of the vicarious calibration and radiometric correction was assessed, taking ground spectroradiometric measurements of a homogeneous meadow as reference. The reflectance derived from the imaging spectrometer DAIS7915 yielded absolute differences relative to ground reflectance of 0.4% close to 550 nm and 0.8% in the NIR, which corresponded to 8% (550 nm), respectively, to 2% (NIR) of relative deviation. An image quality assessment at radiance level revealed a list of bad bands which were discarded from analysis, leaving a number of 34 bands in the wavelength range of 0.5–1.8 μm.

Mean reflectance values were calculated over an area of 30 × 30 m for each intensive test site, representing the canopy reflectance of the stand scene characterized by the corresponding ground measurements.

3. Radiative transfer modeling for canopy parameter estimation

Two well-known hybrid radiative transfer models of different complexity, GeoSAIL (Huemmrich, 2001) and FLIGHT (North, 1996), were used to describe the canopy reflectance at the scene level. A scene was here defined as an area of 30 × 30 m, fulfilling the assumption of the RTMs which both characterized the canopy reflectance for a scene whose components, such as crown or shadow, were small compared to the absolute modeled area. The radiative transfer at the foliage level was characterized by the model PROSPECT (Jacquemoud et al., 1996) which provided the foliage optical properties as a function of the biochemistry and is coupled to both of the employed canopy RTM. The leaf model PROSPECT was chosen due to its small number of parameters and its wide validation including the application to coniferous foliage (Kuusk & Nilson, 2000; Zarco-Tejada et al., 2004).

The relatively simple radiative transfer model GeoSAIL can describe the canopy reflectance of a complete scene including discontinuities in the canopy and shadowed scene components. The RTM combines a simple geometric model with the SAIL model (Verhoef, 1984) that provides the reflectance and transmittance of the tree crowns. The geometric model determines the fraction of the illuminated and shadowed scene components as a function of canopy coverage, crown shape, and illumination angle. All trees are assumed to be identical, with no crown overlap nor does the model account for mutual shading. The radiative transfer within the crowns is calculated using SAIL which considers the canopy as a horizontal, homogeneous, turbid, and infinitely extended vegetation layer composed of Lambertian scatterers. The SAIL version within GeoSAIL is adapted to account for the contribution of multiple canopy components with different optical properties, leaf area index, and foliage inclination angles but is limited to 10 wavelength bands. For the coupling of GeoSAIL with PROSPECT, a SAIL version (Weiss et al., 2001) capable of dealing with an unlimited number of bands and multiple canopy components, such as foliage and branches, was implemented. Subsequently, we discriminate between the initial GeoSAIL model and the here-adapted GeoSAIL version.

FLIGHT is a three-dimensional ray-tracing model using Monte Carlo techniques for the radiative transfer within crown boundaries and deterministic ray tracing between the crowns and other canopy components. The canopy structure is represented by geometric primitives defined by the crown shape and size, tree height, position, and distribution. Contrary to GeoSAIL, the geometric representation of FLIGHT deals explicitly with crown overlapping, mutual shading, and multiple scattering between crowns. Each crown is assumed to be homogeneous, characterized by its structural variables as well as by its foliage optical properties. The characterization of the crown may vary for each tree. FLIGHT calculates directional reflectance by accumulating photons in predefined solid view angles. The precision of the simulated reflectance (δ_{FLIGHT}) is directly related to the number of viewing angles (n_Θ, number of zenith angles; n_Ψ, number of azimuth angles) and the number of photons (n_{photons}):

$$\delta_{\mathrm{FLIGHT}} = \sqrt{\frac{n_\Theta \cdot n_\Psi}{n_{\mathrm{photons}}}} \tag{1}$$

3.1. RTM parameterization and error propagation

Canopy reflectance at the scene level was simulated by the two selected canopy radiative transfer models coupled with the leaf model PROSPECT. The radiative transfer was parameterized at the foliage and canopy level by the average field data of the four core test sites describing the biochemical and biophysical properties of the canopy (Table 1).

The input parameters describing the foliage biochemistry as required by PROSPECT were provided by ground measurements. The mesophyll structure parameter N was inverted by iterative minimization of PROSPECT from the average foliage reflectance measured with the Licor1800 integrating sphere, while the biochemistry was set to stand values. Uncertainty of the N parameter estimation was assessed by inversion over the variability of foliage reflectance measurements. The foliage reflectance showed a high variability due to errors in the assessment of gaps within the observed foliage sample. Consequently, the *N* parameter was subject to an uncertainty of 22%. The spectral properties of the remaining canopy components such as the understory and woody parts were characterized by ground spectroradiometric measurements and were assumed to be inherent to all test sites (Fig. 2). Woody parts were treated as opaque foliage elements thus only reflecting or absorbing incident radiation. The structural parameterization within the crown relied on the total LAI of the overstory, corrected for clumping effects. The derived wood fraction allowed resolving the total overstory LAI into its green foliage and woody parts. The average inclination angle could be parameterized separately for the two foliage elements in GeoSAIL; spherical distribution for green foliage; and plagiophile distribution for woody parts. FLIGHT parameterization assumed both elements to be spherically distributed because no separate treatment was possible. The tree geometry relevant within the respective RTM was based on the forest stand characteristics describing tree height, crown radius, and crown length. Trees were horizontally distributed within the scene according to a Poisson distribution.

Uncertainties in the radiative transfer parameterization introduced by the measurements and the related instrument errors were included in the model simulations represented by the relative standard error for each parameter (Table 1). Standard error propagation was applied assuming linear independency of the input parameters to assess the effect of ground data uncertainties on canopy reflectance (ISO, 1995). An approximation of the accuracy of canopy reflectance simulated by FLIGHT (relative standard error of 1.9% for the settings: 1 million photons, 19 zenith and 72 azimuth angles) as a function of the photon number was also included in the error propagation. For GeoSAIL, no approximation of the model accuracy was needed due to the analytical nature of the model. Uncertainties related to the assumptions within the radiative transfer representation made by the models were not accounted for.

3.2. Inversion of GeoSAIL

Due to its low computational costs and its comparable performance to FLIGHT (Fig. 3), GeoSAIL was chosen for the estimation of canopy variables by model inversion. The inversion of GeoSAIL was based on lookup tables (LUT), that were generated by precomputing the canopy reflectance for 130,000 canopy realizations while considering the measurement configuration. The parameters corresponding to each canopy realization were randomly drawn following a uniform distribution. The range of each variable was defined based on ground measurements performed in this study and on experimental data presented in literature (Ceccato et al., 2001; Chen et al., 1997b; Dungan et al., 1996; Gond et al., 1999; Table 2). The selected ranges corresponded to a distribution of the respective variable typical for the observed coniferous canopy. Consequently, the generation of the LUT allowed for the implementation of general prior information depending on the specific vegetation type. Tree geometry and spectral properties of the understory and

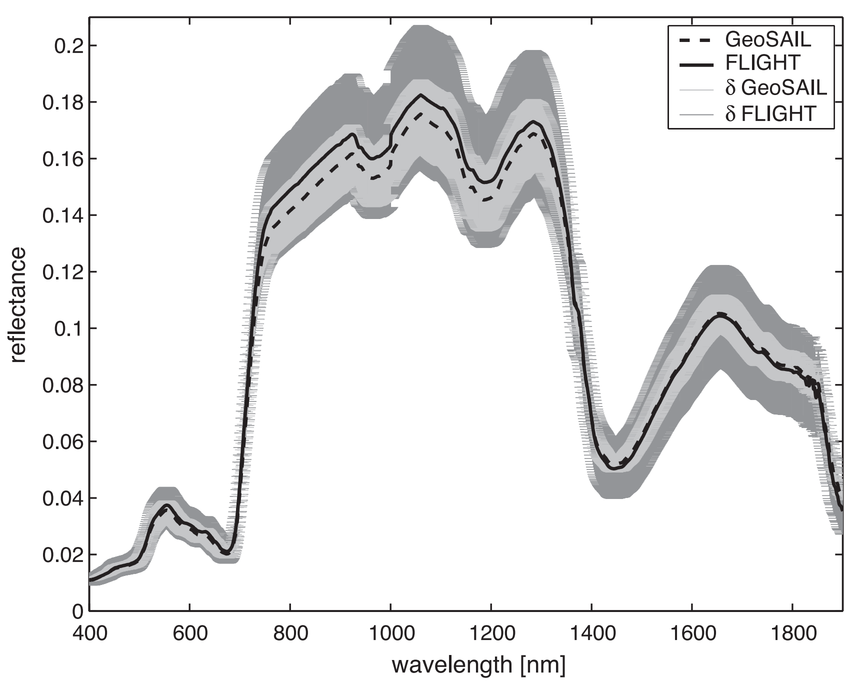

Fig. 3. Comparison of simulated canopy reflectance by GeoSAIL and FLIGHT for the core test site LWF1, including their respective uncertainties ($\delta_{GeoSAIL}$, δ_{FLIGHT}). The root-mean-square error over the whole wavelength range amounted to 0.9% reflectance.

Table 2
Specific ranges for each parameter describing the space of canopy realizations for the generation of the lookup table

RTM parameter	Unit	Minimum	Maximum
LAI	unitless	1	5
Fractional cover	%	0.4	0.85
Wood fraction	%	0.25	0.45
Chlorophyll content	$\mu g/cm^2$	55	80
Water content	g/cm^2	0.025	0.065
Dry matter	g/cm^2	0.02	0.05
N	unitless	2	5

woody parts were specified by the forest stand characteristics and ground measurements.

The model inversion was carried out by minimizing the merit function χ^2, defined as the distance between the canopy reflectance ρ_{mes}, acquired by the DAIS7915, and the simulated reflectance ρ_{sim} found in the LUT. The distance criterion was weighted using the uncertainty of the spectroradiometric measurements δ_{DAIS} related to calibration of the DAIS sensor and the atmospheric correction of the imaging spectrometer data.

$$\chi^2 = \sum_{i=1}^{n_\lambda} \frac{1}{\delta^i_{\text{DAIS}}} \left(\rho^i_{\text{mes}} - \rho^i_{\text{sim}}\right)^2 \qquad (2)$$

where n_λ is the number of finally included imaging spectrometer bands. Canopy realizations found within a tolerance of 20% of the minimal calculated distance χ^2 were considered as possible solutions; their median defined the final solution, and their standard deviation, the uncertainty of the inversion.

4. Results and discussion

A prerequisite of the proposed radiative transfer modeling approach was to determine the validity of the chosen models for the representation of the radiative transfer within the complex forest structure. Precise and comprehensive canopy parameterization of the radiative transfer models enabled a comparison of simulated canopy reflectance with actual canopy reflectance acquired by the imaging spectrometer as well as an intercomparison of the two presented models.

Despite the different nature of the two radiative transfer models and their significant different levels of complexity to represent the canopy structure, they performed comparably (Fig. 3). Relative deviation amounted up to 20% for certain wavelength ranges of low reflectance. In general, however, relative deviations were around 5%. Absolute deviation showed only a small offset between model simulations as the root-mean-square error over all wavelengths of below 1% reflectance demonstrated. It could thus be concluded that canopy reflectance characterized by the two models matched well within their respective uncertainties.

Forward simulations of canopy reflectance with GeoSAIL also demonstrated the ability of the RTM to scale-up canopy variables from the foliage to the canopy level, characterizing canopy reflectance within model and measurement uncertainties (Fig. 4). The measured canopy reflectance was well represented in the near infrared for all observed stand densities. In the visible and above 1500 nm, canopy reflectance was overestimated for higher canopy densities, as observed at sites STA1 and STA2. The imaging spectrometer

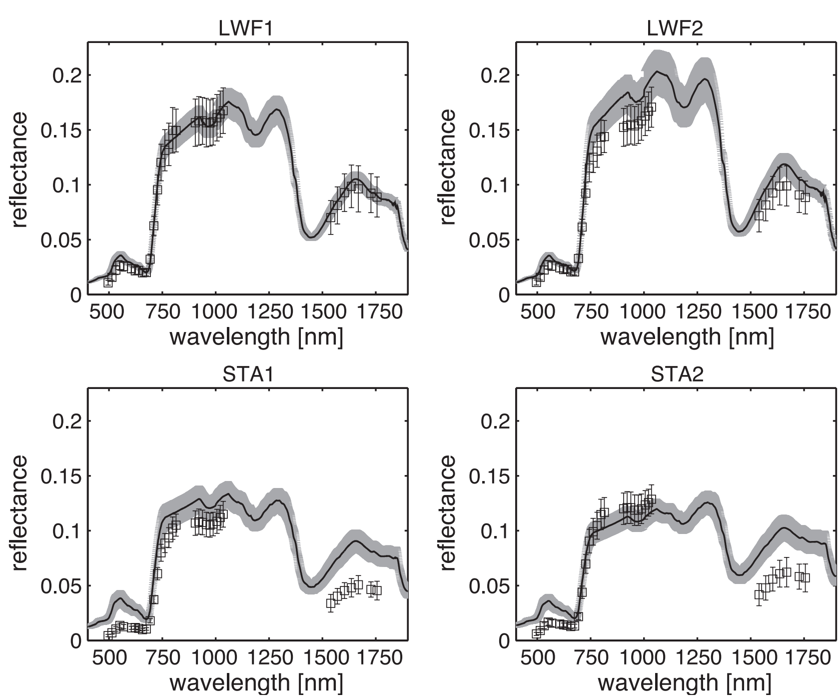

Fig. 4. Simulated (GeoSAIL) and measured canopy reflectance of the four core test sites. Error bars represent the uncertainties of the RTM approach (solid grey) and of the DAIS measurements including errors of radiometric correction and spatial variability (black squares with error bars).

ROSIS showed significantly higher reflectance in the visible than the investigated DAIS data, indicating calibration problems especially for low reflectance values. The effects could be also attributed to mutual shadowing effects which were not accounted for by the GeoSAIL radiative transfer representation although FLIGHT showed similar behavior. It should also be stated here that low signal to noise ratio (SNR) for wavelengths above 1.8 μm prevented the use of these bands specifically sensitive to leaf water content. Modern imaging spectrometers like AVIRIS, Hymap, and APEX are able to provide more stable and reliable data improving especially the capability of foliar biochemistry estimation (Cocks et al., 1998; Green et al., 1998; Schaepman et al., 2003). In addition, the potential of fuel properties mapping with spaceborne imaging spectrometers has been shown for the case of Hyperion, although the low SNR and image artifacts of the Hyperion data limited its use for the estimation of fuel moisture (Roberts et al., 2003; Ustin et al., 2002). The effect of uncertainties of the canopy parameterization on canopy reflectance was considered using standard error propagation. Main error sources were the uncertainties connected to the measurements of the LAI and the fractional cover, as well as the mesophyll structure parameter. These parameters, difficult to determine in the field, were already measured with important errors and propagated efficiently through the radiative transfer and affected the canopy reflectance significantly.

The forward simulation of canopy reflectance and the comparison of the selected radiative transfer models showed the potential of estimating forest canopy variables based on the relative simple and easily invertible model GeoSAIL. Inverting GeoSAIL for measured canopy reflectance subsequently

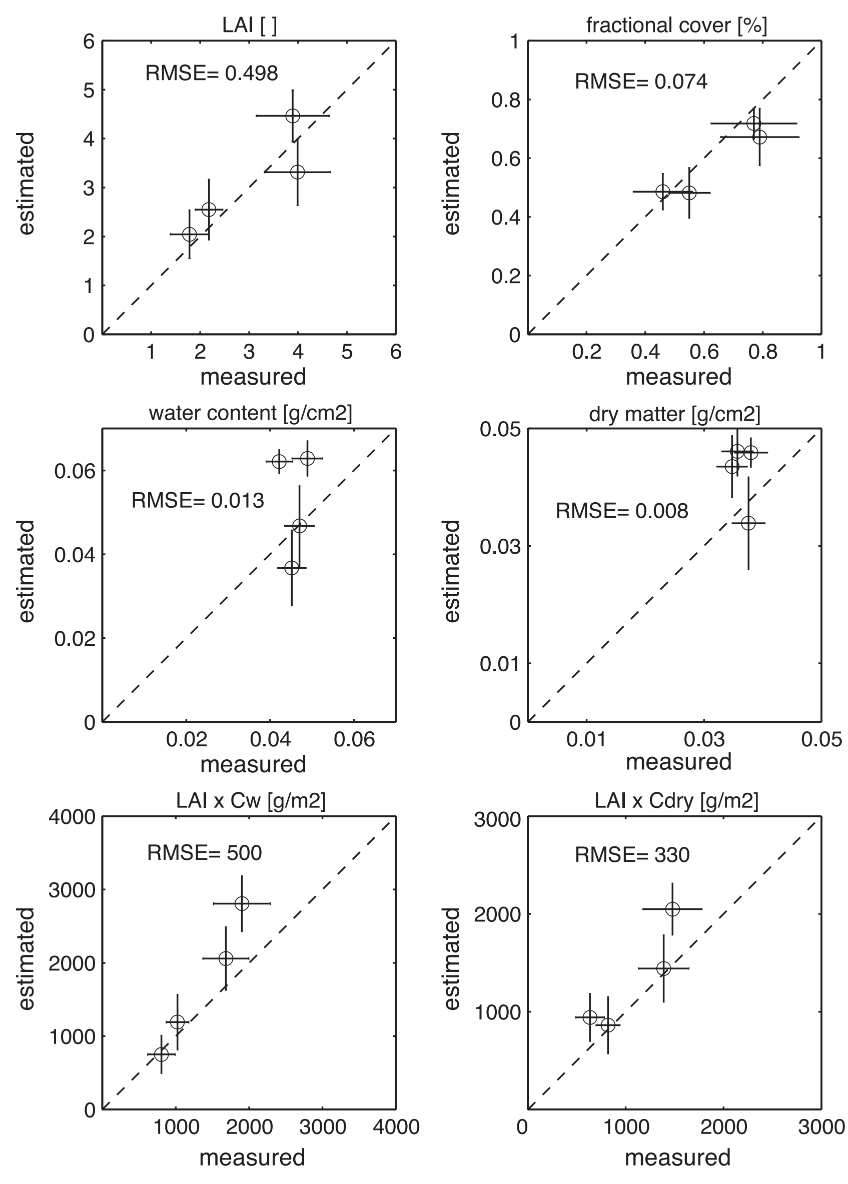

Fig. 5. Performance of model inversion: estimates and measurements of canopy parameters are presented; error bars represent the uncertainties related to the ground measurements and model inversion, respectively (LAI × Cw, canopy water content; LAI × Cdry, canopy dry matter content).

assessed the feasibility of estimating canopy variables employing a radiative transfer model. Fig. 5 presents the results of the forest variable estimation relative to the ground measurements of the respective variable, while also indicating the uncertainties associated to the inversion process and ground measurements. The model inversion performed well with reasonable root-mean-square errors and within uncertainties for the variables describing the canopy structure such as LAI and fractional cover. The estimation of the foliage variables presented less-stable results, but the average accuracy of estimates still amounted to 71.6% and 78.2%, respectively, for foliage water content and dry matter. The estimation of chlorophyll foliage content showed poor results probably due to the effects in the visible already observed and discussed for the simulated canopy reflectance. A limitation was caused by the variation of foliage variables, which was not sufficiently large for a thorough validation due to the observed canopy homogenous in terms of specie, phenology, and environmental conditions. Gond et al. (1999) presented seasonal observations of biochemical and biophysical parameters, which showed for evergreen species, e.g., *Pinus sylvestirs* L., a similar, rather stable temporal evolution. Leaf water content increased by 10% in spring due to bud burst and LAI did not vary significantly over the season. For the observed forest stand in this study, the spatial variation of the canopy structure can be consequently regarded as the most significant source of variability relevant for the canopy fuel properties.

The 120–128.9% FMC we observed in this study is similar to FMC values of 95–146% observed for a burnt canopy of Lodgepole pine (*Pinus contorta*) in the Yellowstone National Park, suggesting considerable fire risk for the Swiss National Park (Hartford & Rothermel, 1991). The product of LAI and foliage water or dry matter content represented the canopy content of the respective biochemical constituent which could present an additional quantity most relevant to the inflammability and the combustion of forests (Ceccato et al., 2002a). The derived LAI along with the wood fraction of the canopy could serve as indication of the amount and quality of biomass available to combustion. The estimates of the canopy characterization could finally define site-specific physical descriptions of fuel types necessary for the initialization of forest behavior models such as FARSITE (Finney, 1998; Miller & Yool, 2002).

5. Conclusion

The estimation of crown forest fire fuel properties by radiative transfer modeling was successfully demonstrated for a heterogeneous canopy like a conifer forest. The coupled radiative transfer models, PROSPECT and GeoSAIL, exploited efficiently canopy reflectance acquired by imaging spectrometry to assess quantitatively and independently the canopy structure, as well as the foliage water content of the observed forest. Both canopy variables provided information on the vegetation status vital to the management of forests with respect to possible wildland fires. The hyperspectral extension of GeoSAIL supported the robustness and reliability of the combined assessment of biophysical and biochemical variables.

An important step within this study was the validation of two radiative transfer models of different complexity for the proposed application. A field campaign provided comprehensive information on the canopy for the forward simulation of canopy reflectance including the measurement uncertainties. The results of the subsequent comparison of simulated and observed canopy reflectance proved the ability of both models to represent the radiative transfer within a heterogeneous canopy independently of the model complexity. Both radiative transfer models actually performed comparably simulating canopy reflectance within their own uncertainties. The implication of the similar model performances was important because it allowed us to employ the relative simple and analytical model GeoSAIL instead of the complex ray-tracing model, FLIGHT, which significantly reduced the computational cost of the model inversion. Finally, the results of the model inversion proved the ability of radiative transfer modeling to quantitatively assess the canopy variables under investigation while taking the involved uncertainties into account. The derived canopy characterization presented the actual spatial distribution of fuel properties as they occur on the landscape. The increased spatial resolution of quantitative information on fuel properties could help to increase the accuracy of fire behavior and ignition prediction.

The successful canopy variable estimation could be partly attributed to the prior information which was implicitly taken into account during the generation of the lookup table with site-specific model parameter ranges derived from experimental data. The necessary information could also be provided by ancillary information as forest inventory or by additional remote sensing data, such as provided by a LIDAR (Morsdorf et al., in press; Riano et al., 2003). Besides, more stable imaging spectrometer data, supplementary information on canopy structure identified as the major source of uncertainty when characterizing canopy reflectance by radiative transfer models, would be helpful to improve the performance of the presented approach. Consequently, the geometrical representation of the canopy by a LIDAR system would offer an optimal complement to the radiometric information. Future research will also focus on a suitable inversion technique for the optimal introduction of ancillary information into the retrieval algorithm.

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