

Space-based spectrodirectional measurements for the improved estimation of ecosystem variables

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Abstract. In this paper, four unique information sources of the Compact High Resolution Imaging Spectrometer (CHRIS) onboard the Project for On-Board Autonomy (PROBA-1) are exploited, namely, the spectral, directional, spatial, and temporal dimensions. Based on the results of three case studies in Switzerland, the use of multi-angular CHRIS–PROBA data for monitoring complex and dynamic vegetation canopies of forests and agricultural crops is demonstrated. We conclude that simultaneous exploitation of the spectrodirectional and temporal behaviours of various vegetation canopies allows for assessing the biochemical and biophysical properties on the one hand and provides additional information on canopy structure via the directional component on the other hand. The study cases focus on various aspects of combining these information dimensions for improved retrieval of vegetation characteristics, namely, (i) the vegetation heterogeneity measurements that use the Minnaert function parameter k , (ii) an improved assessment of foliar water content (C_W) and nitrogen concentration (C_N) based on multi-angular data, and (iii) continuous leaf area index (LAI) time-profiles lead to more accurate estimates of ecosystem processes and inventorying studies. The first study's assessment of canopy structure and heterogeneity from multi-angular data using Minnaert's k successfully demonstrates the distinction between closed and medium-density canopies. The second case study shows that the assessment of plant biochemistry from remotely sensed data profits from the information gained from multi-angular datasets. A synergistic approach that integrates multiple sources of information for the estimation of LAI over the season produces promising results for crop growth monitoring in the third case study. CHRIS–PROBA's multi-angular observations at the regional scale, while having a comparable spatial resolution of Landsat satellites, can significantly contribute to a better understanding of regional surface anisotropy. This strengthens the link between field observations and canopy scale applications. The results of the three case studies clearly demonstrate the potential and value of spectrodirectional Earth observations at regional scales for ecological monitoring and modeling studies.

Résumé. Dans cet article, quatre sources différentes d'information du spectromètre compact pour télémétrie à haute résolution (CHRIS) à bord du satellite PROBA-1 sont exploitées, à savoir les dimensions spectrale, directionnelle, spatiale et temporelle. Sur la base des résultats obtenus pour trois cas d'étude en Suisse, l'utilité du spectromètre multi-angulaire CHRIS–PROBA pour la surveillance de types de végétation complexes et dynamique tels forêts et cultures agricoles est démontrée. Nous en concluons que l'exploitation simultanée du comportement spectral, directionnel et temporel de différents types de végétation permet d'une part de déterminer les propriétés biochimiques et biophysiques, et d'autre part d'obtenir des informations supplémentaires sur le type de végétation grâce à la dimension directionnelle. Les cas d'étude se concentrent sur différentes possibilités de combiner ces dimensions en vue d'améliorer la qualité de l'information obtenue sur les caractéristiques de la végétation. Plus précisément (i) les mesures de l'hétérogénéité de la végétation à l'aide du paramètre k de la fonction de Minnaert, (ii) une meilleure détermination du contenu en eau du feuillage (C_W) et de la concentration d'azote (C_N) basée sur les mesures multi-angulaires, de même que (iii) les séries temporelles continues de

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profils des indices de surface du feuillage (LAI) conduisent à une estimation plus précise des processus de l'écosystème et fournissent d'avantage d'informations lors d'inventaires. Dans le premier cas d'étude, la détermination de la structure de la végétation et de l'hétérogénéité des données multi-angulaires à l'aide de la constante k de Minnaert démontre avec succès la possibilité de distinguer les types de végétation fermés de ceux à densité moyenne. Dans le deuxième cas d'étude il est démontré que la détermination de la biochimie des plantes basée sur les données de télémessure bénéficie d'informations supplémentaires grâce aux données multi-angulaires. Pour le troisième cas, une approche synergétique qui intègre des sources multiples d'information pour l'estimation de l'indice LAI durant une saison annuelle donne des résultats prometteurs quant à la surveillance de la croissance des cultures agricoles. Les mesures multi-angulaires de CHRIS-PROBA peuvent contribuer de façon significative à une meilleure compréhension de l'anisotropie superficielle régionale tout en conservant une résolution spatiale comparable à celle des satellites Landsat, permettant ainsi d'établir un lien plus solide entre les mesures et les applications à l'échelle de la végétation. Les résultats pour les trois cas d'étude démontrent clairement le potentiel et la valeur des observations terrestres à l'échelle régionale pour la surveillance écologique et pour les études de modélisation.

Introduction

The spaceborne European Space Agency (ESA) mission CHRIS (Compact High Resolution Imaging Spectrometer) onboard the PROBA-1 (Project for On-Board Autonomy) provides multitemporal observations of selected terrestrial targets in the spectral and angular dimensions, thus describing the canopy reflectance based on independent but complementary information sources (Barnsley et al., 2004). Because of the heterogeneous and complex nature of vegetation canopies, spectral observations are limited in their ability to resolve radiative transfer processes within the canopy—a prerequisite for reliable estimates of vegetation parameters from remote sensing (Ustin et al., 2004a). Multi-angular observations of the reflectance anisotropy have proven to help predict structural surface properties, which are helpful to complement spectral measurements. Scientific efforts should thus aim at combining independent information sources, such as the spectral and directional observations of CHRIS-PROBA, for a complete and robust characterization of vegetation canopies.

For vegetated surfaces, the spectral information content of CHRIS-PROBA data may yield biochemical and biophysical properties of vegetation canopies, whereas the directional component may provide additional information on canopy structure. CHRIS-PROBA represents a rich source of information of Earth observations specifically adapted for monitoring complex and dynamic vegetation canopies, particularly in ecotones at the regional scale. The reflectance of a vegetation canopy is known to be primarily a function of leaf optical properties, nonphotosynthetic scattering elements (woody elements such as bark, branches, and twigs), canopy structure, clumping and heterogeneity, understory composition and soil background reflectance, illumination conditions, and observation geometry (Chen et al., 2000; Malenovsky et al., 2007; Schaepman-Strub et al., 2006). Hence, varying illumination and observation geometries cause directional effects in remotely sensed data, which may affect estimates of biophysical and biochemical variables. The anisotropic reflectance behaviour of plant canopies, for instance, implies that remote observations can vary without a change in the physical or chemical properties of the material

observed (Asner, 2004; Huber et al., 2008a). The complex vertical and horizontal structures of vegetation communities limit the ability to accurately derive biochemical estimates from remotely sensed data without accounting for canopy structure (Ustin et al., 2004a). It has been shown that the leaf area index (LAI), leaf orientation, and the complexity of three-dimensional (3-D) structure (including various clumping scales and canopy heterogeneity) need to be accounted for when scaling from leaf optical properties to canopy scale, allowing for solid pigment and nonpigment retrieval (Ustin et al., 2008).

Yet numerous studies have shown that bidirectional measurements contain added information about vegetation structure (Asner et al., 1998; Meyer et al., 1995; Sandmeier and Deering, 1999; Schaepman, 2007) such as LAI (Diner et al., 1999), gap fraction, leaf orientation, and foliage spatial distribution (Chen et al., 2003; 2005; Ustin et al., 2004b), or tree cover and tree height (Heiskanen, 2006; Kimes et al., 2006). Furthermore, separability of land cover types for land cover mapping can be improved with multi-angular information (Abuelgasim et al., 1996; Barnsley et al., 1997; Brown de Colstoun and Walthall, 2006; Gobron et al., 2000; Sandmeier and Deering, 1999). A recent study on the angular variation of vegetation indices revealed opportunities to provide a quick, additional source of information regarding photosynthetic versus nonphotosynthetic vegetation when exploiting the angular dimension (Verrelst et al., 2008).

This paper discusses results from three case studies that deal with the exploitation of spectral, directional, spatial, and multitemporal information contained in CHRIS-PROBA observations. The studies present exemplarily the information content and thus the potential for improved vegetation characterization provided by an Earth observation mission such as CHRIS-PROBA, which samples multiple information dimensions at Landsat-like spatial resolution. The overall focus of the paper aims at outlining the use of different information dimensions provided for the first time simultaneously by a single space-mission concept. The work was carried out within the two well-documented CHRIS-PROBA study sites that exist in Switzerland; namely, the alpine Swiss National Park (SNP) and the Swiss Plateau study site Vordemwald (VOR). We have set up a full preprocessing scheme for CHRIS-PROBA data for

geometric and atmospheric processing over mountainous terrain (Kneubühler et al., 2005), which is a prerequisite for subsequent spectrodirectional data analyses. The three case studies presented in this paper deal with (i) the assessment of canopy structure and heterogeneity from multi-angular data, (ii) the contribution of directional data for the estimation of canopy biochemistry, and (iii) the estimation of LAI, which is a key variable in the understanding and modeling of several ecophysiological processes.

The objective of this paper is to present first steps in the context of the case studies for a simultaneous exploitation of spectrodirectional behaviour of vegetation canopies, complemented by their monitoring over time. The synergistic use of the four information dimensions provided by CHRIS-PROBA data helps to solve the ill-posed problem, which arises because of the number of parameters necessary to describe the complex system of vegetation canopies. The case studies exemplify the potential of the integration of the independent information sources. Such an approach improves the estimation of biophysical and biochemical canopy characteristics relevant for applications such as ecological modeling or precision agriculture.

Data and methods

Swiss National Park (SNP)

The study site covered by CHRIS-PROBA data is located near Ofenpass within the SNP (10°14'E, 46°40'N). The Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m above sea level (ASL) with an annual precipitation of 900–1100 mm. Embedded in this environment are dry, boreal-type subalpine forests (see **Figure 1**). The south-facing floor of the Ofenpass valley is considered the core test site; it has long been subject to ecological studies (Kötz et al., 2004) and is described extensively in Schaepman et al. (2005). The forests are largely dominated by mountain pine (*Pinus montana* ssp. *arborea*) and some stone pine (*Pinus cembra*) tree species. These forest stands can be classified as woodland associations of the *Erico-Pinetum mugo*. The understorey is characterized by low but dense vegetation, composed mainly of various *Ericaceae* species by *Sesleria varia*.

Vordemwald (VOR)

The VOR study site (7°53'E, 47°16'N) is located on the Swiss Plateau in central Switzerland. The hilly area is dominated by agricultural fields in the lower parts (450–500 m ASL) and forests mainly on the hilltops (elevations up to 700 m ASL; see **Figure 2**). Agriculture concentrates on barley, wheat, maize, sugar beet, and pasture land (Kneubühler et al., 2006). The forest canopy is composed of a mixture of needleleaf and broadleaf species, dominated usually by European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L.), and partly by silver fir (*Abies alba* Mill.), whereas wet sites are dominated by European ash (*Fraxinus excelsior* L.) and black alder (*Alnus glutinosa* (L.) Gaertn). In total, nine different

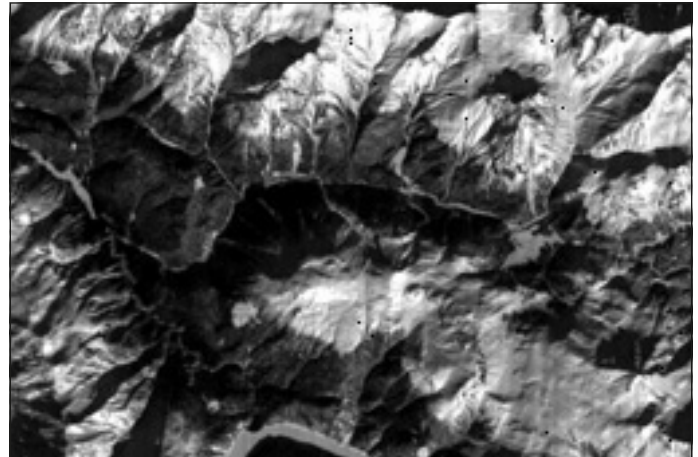


Figure 1. Subset of the geometrically and atmospherically corrected CHRIS-PROBA nadir scene acquired over the Swiss National Park study site on 17 February 2004. The Ofenpass valley stretches from left to right in the central part of the image.

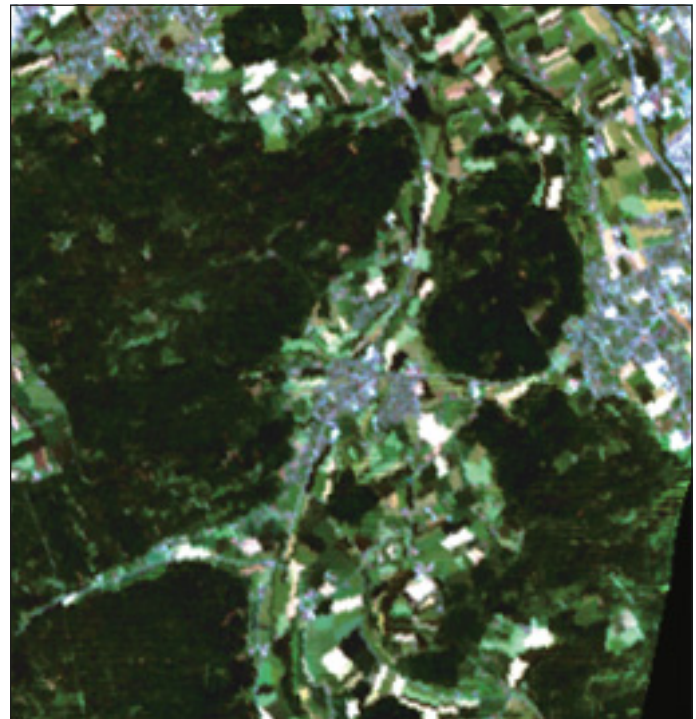


Figure 2. Subset of the geometrically and atmospherically corrected CHRIS-PROBA nadir scene acquired over the Vordemwald study site on the Swiss Plateau on 26 May 2005.

species can be found belonging to two plant functional groups (coniferous (evergreen) and broadleaf (deciduous) species).

CHRIS-PROBA data

The CHRIS sensor on the PROBA-1 provides spectral data over the visible–near-infrared spectral range of 400–1050 nm. It can be operated at different modes, reflecting both end-user needs and a necessary compromise between spatial resolution

and the number of spectral bands that can be stored onboard. PROBA-1 is an experimental ESA space platform launched on 22 October 2001. It enables the CHRIS sensor to capture five separate along-track images of a given target area, with each image recorded at a different sensor viewing angle (Barnsley et al., 2004). Early data over the SNP site were recorded in chlorophyll mode 4 (17 m ground sampling distance (GSD), 18 bands), whereas more recent acquisitions over both the SNP and VOR study sites were recorded in mode 5 (17 m GSD, half swath width, 37 bands). A total of 16 multi-angular data acquisitions between winters 2003 and 2007 have been performed over the SNP site and nine acquisitions over VOR, respectively, the latter mainly acquired during the growing seasons of 2005 and 2006. A considerable number of these acquisitions failed to coherently record all five viewing angles because of the off-nadir pointing inaccuracies of the CHRIS sensor. Additionally, the nominal fly-by-zenith angles (FZA) of the CHRIS data acquisitions (nominally listed at $\pm 55^\circ$, $\pm 36^\circ$, 0°) rarely correspond to the actual viewing geometries. These effects have been taken into account for further data processing (Kneubühler et al., 2005).

Geometric processing

Given the fact that both the SNP and VOR study sites are located in either high mountainous, rugged, or at least hilly terrain, a parametric approach for geometric correction of each dataset of a CHRIS-PROBA acquisition scenario (up to five viewing angles) was applied. This approach is based on a 3-D physical model (Toutin, 2004) that is implemented in the commercially available image processing software PCI/Geomatica (PCI Geomatics, 2006). A physical model can mathematically describe all distortions of the platform (position, velocity, orientation), the sensor (actual viewing angles, instantaneous field-of-view (IFOV), panoramic effects), the Earth (ellipsoid, relief), and the cartographic projection. Such a model needs both orbit and sensor information, as well as a small number of ground control points (GCPs) to compute and refine the parameters of the mathematical model (Toutin, 2004). The number of required GCPs depends on, for example, available orbit and sensor information, GCP accuracy, and desired final accuracy, but would normally not exceed 10 points. The method allows us to achieve a high geometric accuracy with resulting root mean square errors (RMSEs) derived from GCPs of 0.46–0.79 pixels along track and 0.39–0.73 pixels across track (Huber et al., 2008a) when using a digital surface model (DSM; swisstopo) with 2 m resolution (Schlöpfer et al., 2003).

Atmospheric processing

Atmospheric correction of the CHRIS radiance data was performed using ATCOR-2/3 (Richter, 1998), which is based on MODTRAN-4. Whereas ATCOR-2 is generally used to atmospherically correct data from optical spaceborne sensors assuming flat terrain, ATCOR-3 accounts for terrain effects by incorporating digital elevation model (DEM) data and their

derivatives, such as slope and aspect, sky view factor, and cast shadow. ATCOR-3 is therefore suitable for atmospheric correction of sensor data acquired over rugged terrain. The software has recently been adapted to include the option to process tilted sensors by accounting for varying path lengths through the atmosphere and varying transmittance. Validation of the atmospheric processing has been performed through comparison of atmospherically corrected CHRIS-PROBA data versus dedicated spectral ground measurements of an alpine meadow, performed with an Analytical Spectral Devices Inc. (ASD) FieldSpec Pro FR spectroradiometer during a CHRIS-PROBA data take, as well as on a reflective optics system imaging spectrometer (ROSIS) dataset that was acquired in the summer of 2002 over mountain pine trees (Kneubühler et al., 2005). Validation showed a good agreement between atmospherically corrected CHRIS-PROBA data (FZA = 0° dataset) and spectral ground measurements, with standard deviations within ± 1 of the ground measurements for homogenous targets and most bands.

The results of the preprocessing of the CHRIS-PROBA data are geocorrected hemispherical directional reflectance factor (HDRF; for terminology, see Schaepman-Strub et al., 2006) data, with a spatial resolution of 17 m.

Case study I: assessment of canopy structure and heterogeneity from multi-angular data

The interaction of incident radiation with the complex 3-D structure of a vegetation canopy, particularly in the case of a coniferous forest, has a significant impact on the degree of anisotropy in the reflected radiation field. However, the anisotropy of observed canopies also strongly depends on the spectral contrast between canopies and ground cover background (Widlowski et al., 2001). A bright ground cover, such as snow surface, should enhance the anisotropy and consequently the exploitation of the HDRF data observed by CHRIS-PROBA for subpixel heterogeneity and canopy structure. The influence of changing background (understorey versus snow) within a forest canopy was demonstrated using a joint leaf-canopy 3-D radiative transfer model based on the PROSPECT-FLIGHT combination (Koetz et al., 2005b). Multi-angular observations of the reflectance anisotropy have proven to help predict structural surface properties, which complement the spectral measurements, for a complete and robust characterization of vegetation canopies. This case study assesses the structure and heterogeneity of a coniferous canopy based on its degree of reflectance anisotropy, as observed by the multi-angular imaging spectrometer CHRIS.

Data

The study was performed on the SNP study site described earlier in this paper. The CHRIS-PROBA scene used was acquired over the SNP on 17 February 2004 (sun zenith: 59.7° ;

azimuth: 165.4°) under cloud-free conditions. Owing to operational constraints, only four (instead of five) viewing angles were recorded. The dataset was subsequently geometrically and atmospherically corrected, following the approach described in the preceding chapter.

Moreover, in October 2002, an airborne lidar survey of the test site was carried out. The deployed Falcon sensor (TopoSys, <http://www.toposys.de>) is a small-footprint, push-broom laser altimeter. The system provided both first- and last-pulse data with a high point density. The segmentation of the single lidar returns into tree crowns permitted the retrieval of the geometric properties of single trees, such as tree position, height, crown radius, and crown length (Morsdorf et al., 2004). Derived tree heights and positions were used to calculate a parameter set characterizing the spatial and vertical canopy structures (Widlowski et al., 2004). The vertical dimension of the canopy structure is described by the “mean effective scene height”: the mean height of all trees within the respective IFOV of CHRIS, weighted by their fractional cover. For the characterization of horizontal dimension, the ratio between the stem density and the nearest-tree-distance within the considered IFOV was used.

Methodology

CHRIS–PROBA observations at a wavelength of 631 nm were investigated and related to surface structure using the parametric Rahman–Pinty–Verstraete (RPV) model (Rahman et al., 1993), which simulates the anisotropy of a surface reflectance as a function of four parameters. The RPV parameters decompose the anisotropy into an amplitude component (r_0), a symmetric (k) and an asymmetric shape function (Q), as well as a hotspot descriptor (h). It has been shown that the RPV Minnaert function parameter k , describing the degree of anisotropy, is related to canopy structure and subpixel heterogeneity (Pinty et al., 2002; Widlowski et al., 2004). Hence, k , which quantifies the overall shape of the surface bidirectional reflectance factor (BRF), is of particular interest. Based on the k values, the anisotropy of the observed HDRF can be classified into a bell-shaped ($k > 1$) or bowl-shaped ($k < 1$) pattern. Bell-shaped BRFs are associated with heterogeneous canopies of medium density over a bright background. A bell-shaped BRF is caused by the relative contribution of uncollided radiation from the bright background for close to nadir observations. Homogeneous or closed vegetation canopies develop a bowl-shaped BRF pattern instead, provided the background brightness is sufficiently low (Pinty et al., 2002). The RPV model fitted to CHRIS–PROBA data provides the variation of k over the observed coniferous canopy, which is in turn related to proxies of 3-D surface structure provided by lidar data.

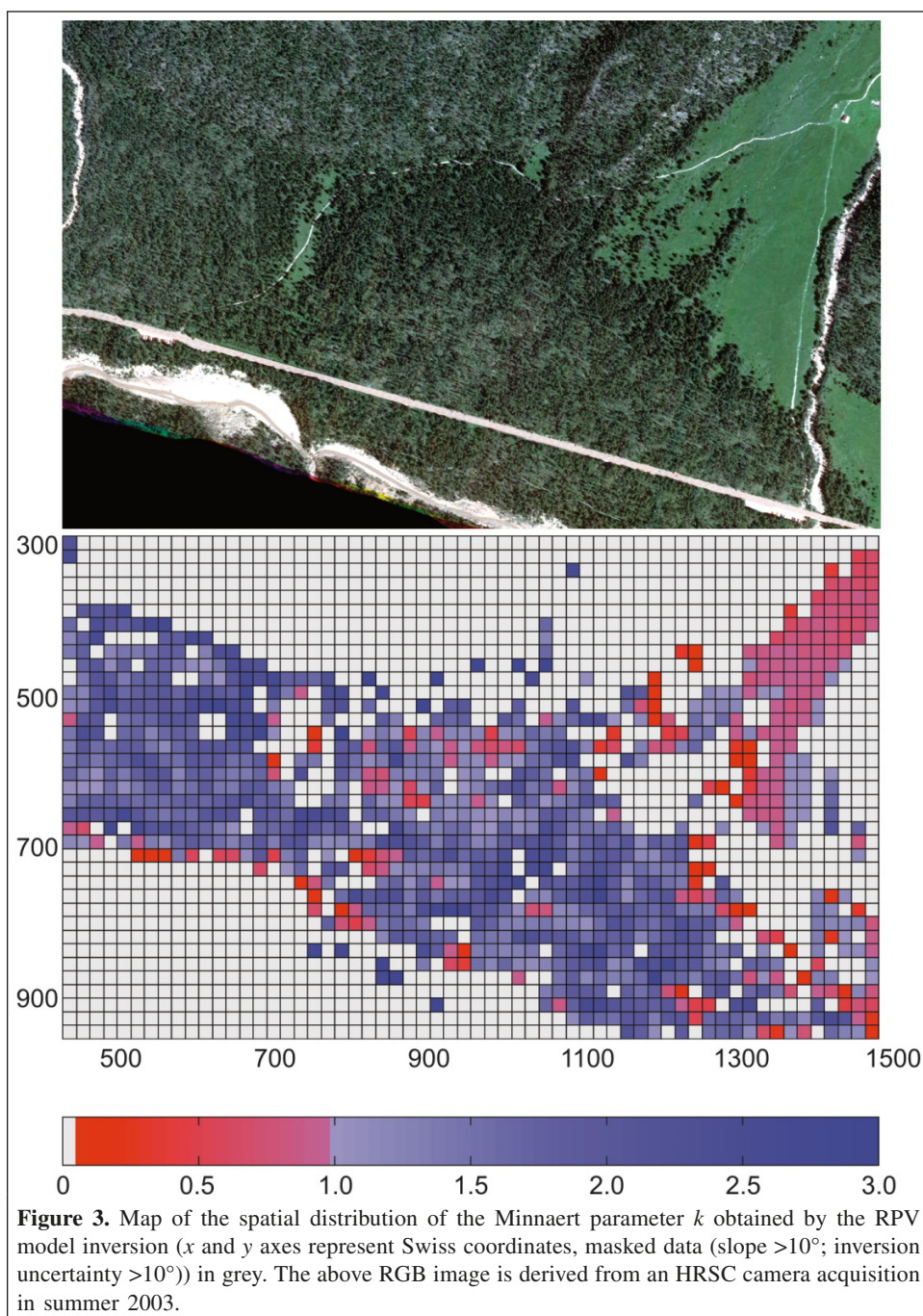
RPV model inversion was performed by fitting the HDRF provided by CHRIS–PROBA to the RPV model BRF simulations (Gobron and Lajas, 2002), described in detail in Koetz et al. (2005c). The HDRF, as observed by CHRIS, and the BRF simulated by the RPV model are assumed here to be comparable.

Results and discussion

The inversion of the RPV model against the multi-angular data over a subset of the preprocessed CHRIS–PROBA scene provided spatial fields of the RPV model parameters describing the anisotropy of the observed surface reflectance (**Figure 3**). The performance of the inversion was affected by several factors: (i) possible geolocation errors between the different viewing angles, (ii) errors due to multiple targets contributing to a pixel’s BRF signature (especially at the edges of forests and meadows or streets), (iii) errors due to using HDRF instead of BRF data, (iv) errors due to the impact of horizontal radiation transport within the heterogeneous forest (i.e., adjacency effects), and (v) errors due to sloping terrain (i.e., topography). Specifically, the latter factor may affect the inversion results because the presence of topography can lead to target occlusions as well as enhanced degrees of backscattering. Tests showed that the significant slopes in the north and south-west of the target area had an impact on the results of the inversion procedure. Thus, the subsequent interpretation of the retrieved model parameters was restricted to areas with slopes of up to 10° and inversion uncertainties below 10%. Under these conditions, measured multi-angular data were fitted by the simulated BRF within its inversion uncertainty based on the retrieved RPV parameter sets (e.g., **Figure 4**).

Generally, two dominant yet different subalpine ecosystems could be distinguished: an open snow-covered meadow and a coniferous forest, each exhibiting distinct BRF shapes (**Figure 4**). The snow-covered meadow was characterized by a bowl-shaped BRF, whereas the forest surface mainly featured a bell-shaped BRF, indicated in **Figure 4** in blue (bell shape) and red (bowl shape) colours, respectively. If tree crowns are packed densely enough to completely obscure the snow-covered background, it follows that bell-shaped reflectance anisotropy turns into a bowl-shaped BRF pattern because of insufficient spectral contrast between the canopy and the background. Similarly, a canopy that is too dense to prevent the snow from actually being deposited on the ground will also lead to bowl-shaped BRF patterns. Moreover, the rather shallow sun illumination decreases the background contrast by casting an increased number of shadows. Other bowl-shaped BRFs are observed at the southern part of the subset where a street is transecting the forest (**Figure 3**). Here, the BRF signatures associated to pixels are actually due to different surface types being viewed under different view zenith angles as CHRIS–PROBA passes by.

This case study demonstrated the successful inversion of the parametric RPV model against the independent information source of multi-angular CHRIS–PROBA observations. The RPV inversion permitted the discrimination between different surface types based on their inherent anisotropy. In addition, the Minnaert function parameter k , describing the degree of anisotropy, was linked to lidar measurements representing the 3-D structure of the canopy. Results showed the potential to distinguish between closed and medium-density canopies within a forest stand, thus delivering quantitative surface structural

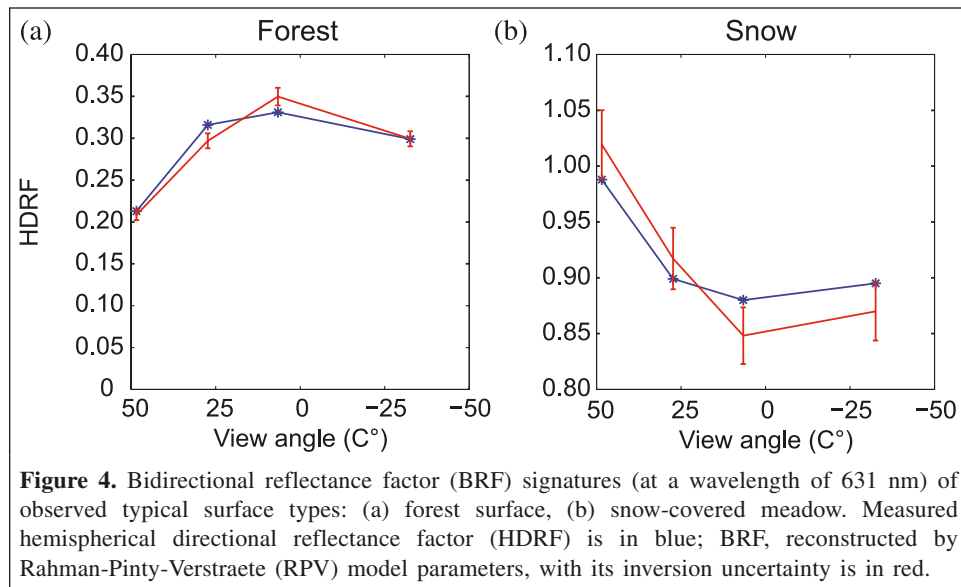


information. Finally, the serious effects of surface slope on the performance of the RPV model inversion suggest the need to account for the topography when using the RPV model.

Case study II: contribution of directional data for the estimation of canopy biochemistry

Knowledge about plant biochemistry is important for a range of environmental applications (Asner and Vitousek, 2005; Curran, 2001; Ustin et al., 2004a). It can, for instance, be used

to identify and map invasive species that have ecological and environmental impacts (Asner and Vitousek, 2005) or to detect the spatial variability of soil carbon to nitrogen (C:N) ratios through related patterns in canopy chemistry (Ollinger et al., 2002). Spatial estimates of foliar chemistry are needed to improve ecosystem models (Martin and Aber, 1997; Pan et al., 2004; Turner et al., 2004). They may also indicate the health of the forest, thus representing an important economic factor when considering forest products (Goodenough et al., 2003; 2004), but also in terms of protecting forests against natural hazards (Brang et al., 2001). However, sun and sensor geometry cause directional effects in remotely sensed data,



which can influence the estimation of biophysical and biochemical variables. The objective of the second case study is the investigation of directional CHRIS-PROBA data for an improved estimation of foliar nitrogen concentration (C_N) and water content (C_W). We investigated (i) whether the added information in remotely sensed multi-angular data can improve C_N and C_W estimates and (ii) whether certain sensor viewing angles emerge to be beneficial for estimating C_N and C_W .

Data

The study was performed on the forests of the Swiss Plateau study site VOR, as described above. In July 2004, an extensive field data campaign took place, covering 15 subplots at this study site. The subplots were chosen according to their species composition to allow the collection of a broad variety of species. At each subplot, 3–10 tree crowns were selected for foliar sampling. The trunk position of each tree was measured with a Trimble GeoXT GPS receiver, which corrects for multipath biases. The positional accuracy was further improved by applying a post-processing differential correction to the recorded data. The trees selected for leaf collection were chosen according to crown dimension and species to minimize background influences and to gain a broad range of C_N and C_W . Additionally, geographical positions, species, and biophysical properties were measured for the closest neighbouring trees from which no foliar material was collected. A detailed description of the field data sampling strategy and the subsequent laboratory analyses for the determination of the foliar samples' biochemical composition can be found in Huber et al. (2008b).

A complete CHRIS-PROBA scene (five viewing angles), acquired on 1 July 2006 over the VOR study site, was geometrically and atmospherically corrected following the preprocessing methodology described earlier in this paper. High positional accuracy of the respective multi-angular products is a prerequisite for a reliable extraction of spectral

information from the five datasets. In total, spectra of 60 field-sampled crowns were extracted from the five CHRIS-PROBA images by using the geographical trunk positions (vector data) of the sampled trees to locate the crown pixels in the images (Gorodetzky, 2005). CHRIS-PROBA data acquisition was two years after field data collection, but during the same phenological period (July). We assumed a stable C_N (Martin and Aber 1997) and C_W (Gond et al., 1999) during July and only small interannual variability for nitrogen concentration (Grassi et al., 2005) and leaf water status (Leuschner et al., 2001), justified by similar climatic conditions in 2004 and 2006 (Swiss Federal Office of Meteorology and Climatology MeteoSchiweiz, 2007).

Methodology

For subsequent analyses of spectral crown data extracted from the CHRIS-PROBA scenes and corresponding C_N and C_W quantities from laboratory measurements, four spectral datasets from each viewing angle were generated. One of the four datasets consisted of original reflectance, and the other three of variants of continuum-removed data. The datasets were defined as follows: SPEC includes original reflectance values; BNC includes band depths normalized to the waveband at the center of the absorption feature (Curran et al., 2001; Kokaly and Clark, 1999); CRDR includes continuum-removed derivative reflectance (Mutanga et al., 2004; Tsai and Philpot, 1998); and NBDI includes normalized band depth index values (Mutanga et al., 2004). For C_N , continuum removal was applied to the absorption feature located between 550 and 750 nm where the leaf water effect is minimal. Studies have shown a strong nitrogen-pigment relationship because the chlorophyll content in foliage is highly correlated with total protein and, hence, total nitrogen content (Evans, 1989; Field and Mooney, 1986; Johnson and Billow, 1996; Yoder and Pettigrew-Crosby, 1995). For C_W estimation, we were bound to the weak liquid water absorption feature at 970 nm (Curran, 1989) because of the

CHRIS sensor's spectral resolution. The regression results based solely on this feature were not satisfactory, so we additionally used the feature between 550 and 750 nm for C_W estimation, which clearly improved model calibration.

Multiple linear regression analysis was applied to fit models between the dependent variables (C_N and C_W) and all possible viewing angle combinations of the four spectral datasets (SPEC, BNC, CRDR, NBDI). To limit the number of spectral wavebands used in the regression models, this study employed a statistical variable selection method; namely, an enumerative branch-and-bound (B&B) search procedure (Miller, 2002). The basic characteristics of B&B methods have been addressed by several papers (Furnival and Wilson, 1974; Mitten, 1970; Narendra and Fukunaga, 1977). In this study, the number of selected wavebands that best explained C_N and C_W was limited to five, to avoid overfitting of the models. All models were tested for significance with the F-test at a 5% significance level.

As one objective of this case study was to determine whether assessing foliar C_N and C_W at canopy level could be improved with additional directional information, model fitting was initiated on data extracted from one viewing angle (e.g., nadir). Next, models for all possible combinations of two viewing angles (e.g., nadir and -36°) were developed. We then continued the analysis with three and four viewing angles to finally introduce the data of all five viewing angles as independent variables. In total, 31 viewing angle combinations were evaluated for each spectral dataset. The findings were evaluated by comparing the mean coefficient of determination (R^2) for each dataset, derived from models with the same number of viewing angles involved. The contribution of individual angles was evaluated by considering R^2 values for the regressions between C_N , C_W , and the spectral data for all angular combinations.

To assess the predictive capability of the models, 10-fold cross-validation with random splitting order of the data was used (Hastie et al., 2001; Huber et al., 2008b). Cross-validation is an often used procedure, where independent test data are scarce. Owing to random splitting order, each cross-validation run was iterated ten times per model to obtain a more robust cross-validation estimate from which root mean square errors (CV-RMSE) could be calculated (Huber et al., 2008b).

Results and discussion

Assessing the contribution of angular information to the model fit for an improved C_N and C_W estimation was one of the objectives of this case study. It can be concluded that the model R^2 of both C_N and C_W , regressed on the datasets SPEC, BNC, CRDR, and NBDI, increased with additional angular information for all four datasets. Adding the data of a second angle as an independent variable to the regression analyses contributes most to an increase in R^2 . Thereafter, the more that directional information is added, the smaller the resulting increase. The contribution in terms of R^2 is apparent from **Figure 5** for C_N and from **Figure 6** for C_W . Regarding C_N regressed on SPEC, the R^2 was augmented by 19%, 27%, and

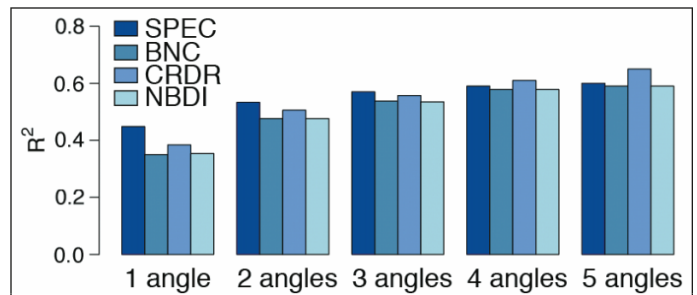


Figure 5. Model coefficient of determination (R^2) of nitrogen concentration regressed on the datasets SPEC, BNC, CRDR and NBDI, respectively. R^2 represents the mean of all models with the same number of viewing zenith angles involved. For example, the R^2 for one angle represents the mean of five monodirectional models ($\pm 36^\circ$, $\pm 55^\circ$, and nadir).

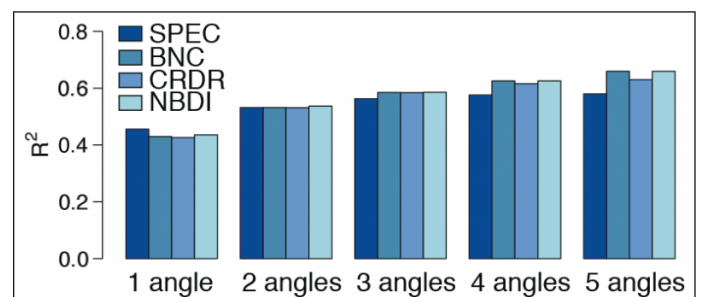


Figure 6. Model coefficient of determination (R^2) of water content regressed on the datasets SPEC, BNC, CRDR, and NBDI, respectively. R^2 represents the mean of all models with the same number of viewing zenith angles involved. For example, the R^2 for one angle represents the mean of five monodirectional models ($\pm 36^\circ$, $\pm 55^\circ$, and nadir).

32% by adding data from a second, third, and fourth viewing angle, respectively. The largest increase of R^2 was achieved with the BNC dataset by adding a second angle to the regressions (+36%). Regarding C_W , the largest increase of R^2 was observed for CRDR; it improved by 25%, 37%, and 45% (compared with monodirectional models) when adding data of a second, third, and fourth viewing angle, respectively.

Concerning the second objective of this case study (investigating whether certain sensor viewing angles turn out to be beneficial for the estimation of foliar C_N and C_W at canopy level), the chemical constituents were fitted to the 31 angular combinations of each of the four investigated datasets (SPEC, BNC, CRDR, NBDI). Starting with single-angle models for C_N and continuing with multi-angular models, the following can be said: best results were achieved for C_N trained on single-angle models with data of the nominal -36° angle for all datasets. Models developed from $+36^\circ$ data resulted in the lowest R^2 values for BNC, CRDR, and NBDI, but not for SPEC, where nadir data generated the lowest R^2 . We obtained maximum R^2 values (and minimum CV-RMSEs) with data from three viewing zenith angles for SPEC, BNC, and NBDI, whereas CRDR achieved highest model fits when using four viewing zenith angles. The four viewing zenith angles for CRDR were

$\pm 36^\circ$ and $\pm 55^\circ$. Adding data of more than four angles as independent variables to subset selection did not augment model fits for the best CRDR model any further.

In the case of leaf water content estimation, highest model fits for monodirectional models were achieved from nadir data, and lowest fits were obtained from $+36^\circ$ data, irrespective of spectral processing. For two-angle models, the combination of nadir and -55° viewing zenith angles yielded the highest R^2 values and the lowest CV-RMSEs. We obtained best model fits for SPEC using data from two viewing zenith angles, and for CRDR using three angles. BNC and NBDI achieved maximum R^2 values using four viewing zenith angles (nadir, $\pm 36^\circ$, and -55°). As with C_N estimates, using data from more than four angles did not increase the coefficients of determination any further. A more detailed discussion of the results is given in Huber et al. (2008a).

This case study showed that the assessment of canopy biochemistry from remotely sensed data profits from added information contained in multi-angular data sets as provided by CHRIS-PROBA. The findings support the potential of multi-angular Earth observations for ecological monitoring and modeling studies. In our analysis, the viewing zenith angle of -36° is located closest to the image's hotspot. The monodirectional models based on this dataset performed the best for C_N , irrespective of spectral processing.

To summarize, the following conclusions can be drawn: (i) The additional information contained in multi-angular data improved regression models for C_N and C_W estimates and lowered cross-validated RMSEs considerably; (ii) strongest effects on R^2 can be achieved when adding a second and third viewing angle; (iii) monodirectional models based on backward scattering viewing directions were generally superior to models based on forward scattering data; and (iv) untransformed reflectance data (SPEC) often outperformed continuum-removed data when using only one viewing zenith angle.

Case study III: estimation of leaf area index from multitemporal CHRIS-PROBA data

The third case study aimed at synergistically exploiting the spectral, spatial, and temporal information dimensions contained in multitemporal CHRIS-PROBA data. Such Earth observations represent a rich source of information for monitoring the dynamic vegetation status. For the assessment of vegetation phenology, the LAI is essential as it is a key variable for the understanding and modeling of several ecophysiological processes within a vegetation canopy (Myneni, 1997; Gower et al., 1999). Estimates of LAI could be incorporated into vegetation process models to provide a more accurate description of canopy, functioning with emphasis on important environmental and economical outputs such as carbon, water, and nitrogen fluxes, and stocks, canopy state, and yield for crops (Chen et al., 2003; Matsushita and Tamura, 2002). Remote sensing allows for detailed and frequent

observations of the vegetation, in particular the spatial and temporal variations of canopy characteristics (Koetz et al., 2005a; Myneni et al., 1997). In this study, a radiative transfer model (RTM) is coupled to a canopy structure dynamics model (CSDM). The coupled models are used to exploit the complementary content of the spectral and temporal information dimensions for LAI estimation over a maize canopy. The estimate of the temporal and spatial variations of LAI is improved by integrating multitemporal CHRIS-PROBA data and ground meteorological observations. Furthermore, the presented method provides continuous LAI variation over the duration of the season.

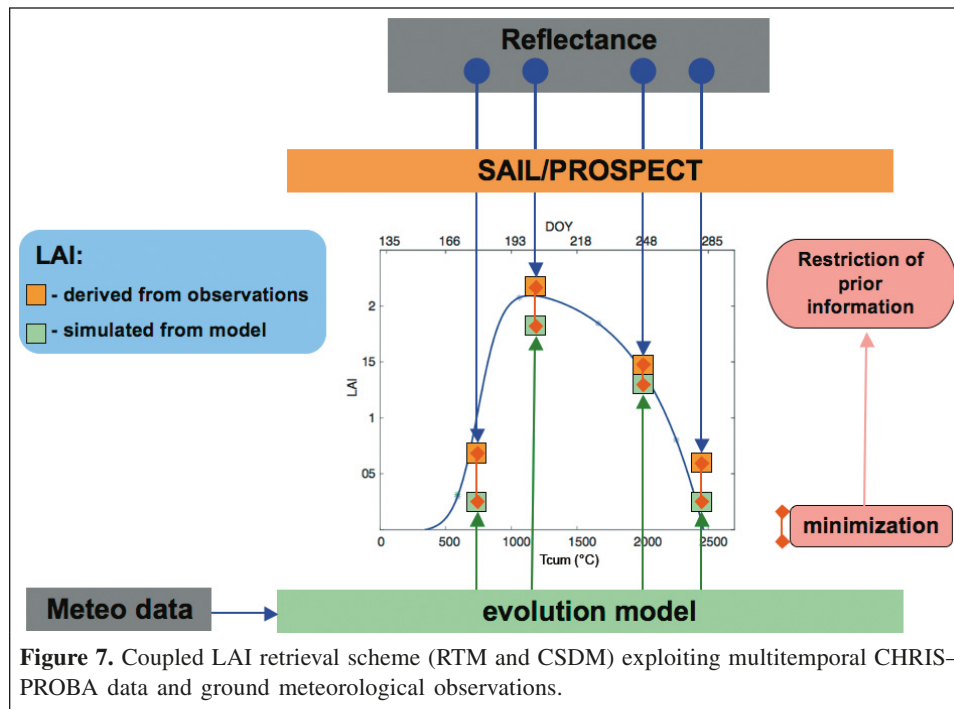
Data

CHRIS-PROBA multi-angular datasets were acquired in mode 5 over the earlier described study site VOR, on eight different dates between 26 May 2005 and 22 September 2005. Out of these datasets, four dates that represent major steps in phenology of the selected agricultural fields were selected for further processing and data exploitation. The selected dates are 26 May 2005 (day of year (DOY) 171), 20 June 2005 (DOY 196), 17 August 2005 (DOY 229), and 22 September 2005 (DOY 265). The datasets were geometrically and atmospherically corrected following the preprocessing methodology described earlier in this paper.

Within this study, the multitemporal aspect of nominal nadir acquisitions has been further exploited. The full directional information content of the dataset is described in a separate study (Kneubühler et al., 2006). Ground truth data were collected in a maize field parallel to the CHRIS-PROBA data takes on most dates. Ground data collection included spectroradiometric measurements using an ASD FieldSpec Pro FR, LAI measurements using a Li-Cor LAI-2000 plant canopy analyzer, and hemispherical photographs, as well as determination of leaf water and chlorophyll content in the laboratory. An operational meteorological station in the close vicinity of the study site provided basic meteorological observations, such as air temperature. The land use type was recorded for a large amount of agricultural fields.

Methodology

A coupling scheme to combine two models—the joint radiative transfer models (RTMs) PROSPECT-SAIL and the canopy structure dynamics model (CSDM)—was implemented to estimate LAI, based on the multitemporal remote sensing observations (Koetz et al., 2005a). The joint RTMs provide an explicit connection between the canopy biophysical variables, the view and illumination geometry, and the resulting canopy reflectance, by exploiting our knowledge of the involved physical processes (Baret et al., 2000). The RTMs have to be inverted to retrieve the biophysical variables from the measured canopy reflectance (Bacour et al., 2002; Kimes et al., 2000; Weiss et al., 2000). However, measurement and model uncertainties often lead to a large range of possible solutions, thus hindering successful inversion (Combal et al., 2002). The



regularization of such an ill-posed problem requires the input of additional information to obtain more reliable and stable solutions (Combal et al., 2002; 2003; Schaepman et al., 2005).

Knowledge of the canopy structure dynamics is highly desirable as ancillary information, to constrain the RTM inversion for the estimation of canopy characteristics. The dynamics of the canopy structure are strongly dependent on crop growth processes, which result in a relatively smooth and typical temporal LAI profile. Several simple semimechanistic models have been proposed to describe the LAI variation over time (Baret, 1986; Werker and Jaggard, 1997). Such models can be used to exploit the information on canopy structure dynamics and retrieve more robust and reliable estimates of the LAI. The use of a CSDM also allows us to derive a continuous LAI estimate, which is required in some applications, particularly those based on the forcing of agricultural growth or land surface models (Delecolle et al., 1992; Moulin et al., 1998). The concept of a coupled LAI retrieval scheme (RTM and CSDM) for the exploitation of multitemporal CHRIS-PROBA data and ground meteorological observations, employed here, is given in **Figure 7**.

The CSDM used here is a simple semimechanistic model describing the LAI dynamics (Baret, 1986). The model depends on the fact that the LAI temporal profile is governed by the net effect of growth and senescence, processes that are genetically programmed. However, the expression of this genetic potential is strongly influenced by environmental factors, represented here by the accumulated daily mean air temperature above 8 °C starting from sowing (Durand et al., 1982). Concerning the radiative transfer models in this study, the turbid medium radiative transfer model SAIL (scattering from arbitrarily inclined leaves) (Verhoef, 1984; 1985) was

used, since it describes the canopy structure in a fairly simple way while nevertheless generating realistic results. The PROSPECT model (Jacquemoud and Baret, 1990) was used to describe leaf optical properties. PROSPECT simulates leaf reflectance and transmittance spectra required by the SAIL model as a function of leaf biochemical contents and leaf structure. The full parameterization of both the CSDM and RTM, as well as the inversion of the RTM for LAI estimation, is discussed in detail in Koetz et al. (2007). The coupling of the RTM and CSDM models was based on the hypothesis that the remotely sensed observations of the LAI had to be consistent with the time profile of the LAI generated by the CSDM. Consequently, the remotely sensed LAI was recalibrated, where necessary, according to the phenologically sound LAI provided by the CSDM.

Results and discussion

For the evaluation of the LAI retrieval performance, the estimated LAI was compared with field measured LAI. The RMSE was calculated to quantify the agreement between actual (field) and estimated (model) LAI values. The results showed a robust performance of the LAI estimation with an RMSE of 0.73. Constraining the RTM inversion with prior information on the canopy structure led to relatively low inversion uncertainties. Nevertheless, when comparing estimated and measured LAI values, a consistent underestimation of the LAI is evident. This is probably due to the typical row structure of the maize canopy, which is not consistent with the RTM assumption of a homogeneous canopy. Simulations of a 3-D RTM, comparing the canopy gap fraction of heterogeneous maize canopies with turbid, homogeneous canopies, support this observation (Lopez-Lozano et al., 2007). Consequently,

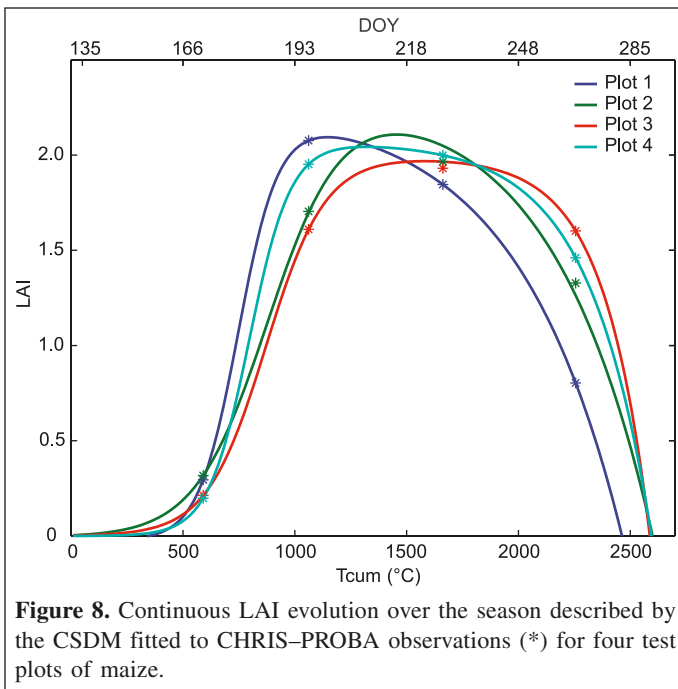


Figure 8. Continuous LAI evolution over the season described by the CSDM fitted to CHRIS-PROBA observations (*) for four test plots of maize.

interpreting the nadir remote sensing signal of a maize canopy based on a turbid RTM would lead to an underestimation of LAI values.

The incorporation of the CSDM into the retrieval algorithm permitted a continuous description of the LAI variation over the growing season. As the CSDM is capable of realistically representing the growing and senescence phases of a maize canopy, the LAI values follow a phenologically sound evolution (**Figure 8**). The CSDM fits very well to the estimated LAI values, probably because of the low temporal resolution of CHRIS observations.

This case study demonstrated the successful coupling of a joint RTM and a CSDM, thus exploiting the complementary information in the spectral and temporal dimensions and improving LAI estimation over a maize canopy. The knowledge of the canopy structure dynamics provided by the CSDM is used as ancillary information in the goal to achieve a more robust RTM inversion. Furthermore, the coupled models incorporate spaceborne remote sensing data with ground-based meteorological observations, providing a continuous LAI measurement over the season as well as the start, end, and total length of the growing period. Crop growth and surface process models require such a continuous description of the vegetation evolution. The future exploitation of the off-nadir viewing angles of CHRIS-PROBA could help to improve the clumping issue affecting the LAI estimation, as row clumping effects are most sensitive to nadir viewing angles (Lopez-Lozano et al., 2007). The proposed methodology successfully combines remote sensing observations and land surface process models. Nevertheless, the effectiveness of such an approach relies on remote sensing data of relatively high temporal frequency and at a pertinent spatial resolution.

Conclusions and outlook

Space-based spectrodirectional measurements at Landsat-like spatial resolution are currently still sparse. This particular spatial resolution is of utmost importance, since it allows us to bridge the scale gap between local measurements and observable fields with appropriate sampling schemes, later permitting an up-scaling to medium-resolution (250–1000 m) instruments. The case studies discussed above all demonstrate the combined use of spectrodirectional (and, in one case, multitemporal) measurements, thus exceeding the classical use of the directional dimension for canopy structure retrieval, and the spectral dimension for biochemistry. In particular, improved measures of canopy heterogeneity (Minnaert's k), more accurate estimates of C_W and C_N , and temporal evolution of vegetation structure for integration in dynamic vegetation models have been demonstrated.

Future studies dealing with the state and dynamics of terrestrial ecosystems should increasingly focus on integration of different approaches as presented in the case studies. Thus, scientific questions regarding the ecosystem classification and functionality described by canopy structure, plant biochemical properties, and phenological behaviour can profit from increased accuracy, since none of these phenomena is retrievable by spectral information only. The 6 years of CHRIS-PROBA operation in space have fostered closer collaboration between various Earth System sciences and made it possible to work at various scales that could be validated in the field. However, a major open issue remains: the proper linking of atmospheric compensation efforts in vegetated areas with significant topography. In addition, proper discrimination between photosynthetic and nonphotosynthetic matter as well as between canopy and understorey vegetation will be more successful using spectrodirectional approaches as well. Development of long-term time series of remote sensing data, improvement of current models, and the joint use of space and ground-based observations at the appropriate scales are further aspects where increased focus must be put.

There have been several initiatives to realize spectrodirectional imagers in space over the past few years, but proposed missions were generally not supported (e.g., SPECTRA (Rast, 2004)). Currently, combined-instrument approaches (e.g., FLORA, FLEX) or approaches with more flexible acquisition geometries (e.g., EnMAP) have been suggested. However, true spectrodirectional concepts to widen the fields of ecological monitoring and modeling will likely also remain sparse in the foreseeable future.

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