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ORIGINAL PAPER

Comparison of satellite- and ground-based NDVI above different land-use types

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Abstract In order to evaluate the use of satellite (moderate resolution imaging spectroradiometer: MODIS) and ground-measured (hyperspectral spectrometer and broadband micrometeorological sensors) normalized difference vegetation index (NDVI), this study compares NDVI derived from five experimental (FLUXNET) field sites (grassland, winter wheat, corn, spruce, and beech) in Germany in June 2006 and April-September 2007. In addition, the spatial variability of ground radiation measured within one specific land-use class (for grass and winter wheat) was investigated to analyze the accuracy of the FLUXNET tower values. Furthermore, the angular dependence of spectrometer values on viewing angles was determined in order to enhance the spatial representativeness of spectrometer measurements which, especially above trees, are affected by soil parts and the tower structure when measured in nadir. The best agreement between the satellite- and ground-measured NDVI was found for winter wheat (2006) with values from 0.79–0.88 followed by grass (2006), showing NDVI values between 0.71 and 0.86. The spatial variability of NDVI within one land-use type was lower than the differences caused by the different NDVI determination methods. Above more open canopies (corn, beech), spectrometer measurements with 60° viewing angle in solar plane direction were found to better correspond to satellite-derived NDVI. Together with broadband NDVI, our ground-based results can complement satellite-derived NDVI.

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1 Introduction

Seasonal changes in the spectral reflectance of the land surface are a complex problem in the interpretation of satellite imagery and a challenging research topic in remote sensing. Spectral reflectance is often expressed as an algebraic combination of spectral bands called vegetation indices (Huemmrich et al. 1999). Vegetation indices like the normalized difference vegetation index (NDVI) are widely used to monitor seasonal, inter-annual, and long-term variations of structural, phenological, and biophysical parameters of vegetation cover (Huete and Liu 1994; Leprieur et al. 2000; Huete et al. 2002; Jiang et al. 2006; Barbosa et al. 2006; Piao et al. 2006). In remote sensing applications, the NDVI is one of the basic parameters, e.g., for vegetation development and energy flux determination. Vegetation indices are spectral transformations of at least two spectral bands, chosen specifically to enhance the contribution of vegetation properties to surface reflectance (Falk et al. 2004). The strength of the NDVI lies in its ratio-based concept, thus reducing many forms of multiplicative noise present in the sensor bands (Huete et al. 2002). The main disadvantages of the NDVI are the inherent nonlinearity of ratio-based indices, scaling problems, asymptotic saturated signals over high biomass conditions, and its high sensitivity to canopy background variations (Huete et al. 2002). Further error sources include cloud contamination and insufficient atmospheric transfer corrections for atmospheric aerosols, gases, and water vapor. All these effects result in a decrease of the observed NDVI.

A ground-based NDVI measurement can be obtained using hyperspectral spectrometer data (Hill et al. 2006). By combining the measured ground reflectance of land-use types with the spectral range (filter response functions) of satellite NDVI bands, one can determine channel-specific reflections and thus an NDVI that is not influenced by any atmospheric effects. Additionally, a ground-based spectrometer can provide highly resolved (increment of 0.2 nm) spectral reflection patterns that can be used for the validation of satellite-derived reflectances. Studies investigating spectrometer-measured reflectance and Landsat TM/ETM+ (thematic mapper/enhanced thematic mapper) retrieved surface reflectance showed comparable results (Fang et al. 2005; Vermote et al. 2002).

As an alternative to satellite or ground-based spectral derived NDVI, several authors (Huemmrich et al. 1999; Wang et al. 2004; Falk et al. 2004; Jenkins et al. 2007; Wilson and Meyers 2007) calculated NDVI from tower-mounted photosynthetically active radiation (PAR) and global radiation (*Rg*) sensors (incoming and reflected parts, respectively) above canopies. The advantage of this *broadband* NDVI is that a temporal resolution of 1 day or higher is achieved without any effects of atmospheric disturbances or angular geometry.

Huemmrich et al. (1999) compared broadband and narrowband nadir-view NDVI (from a helicopter modular multiband radiometer) for four Boreal sites and the results indicated that the tower values are close to the radiometer NDVI, but that the range of the tower data in NDVI is not as large as in the radiometer NDVI.

Wang et al. (2004) found good agreement between broadband and narrow-band nadir-viewed NDVI for a coniferous pine forest. However, they also pointed out that a comparison of both measures may indicate different values, while seasonal patterns should correspond if both are similar indicators for changes in vegetation characteristics. Wilson and Meyers (2007) showed large scatter between MODIS (moderate resolution imaging spectroradiometer) and tower-derived NDVI for all their test sites (grassland, crops, and pine- and deciduous forests) but with closer values for grassland and crops. Nevertheless, they pointed out that the tower-derived visible and near-infrared wavebands offered potential that above canopy, tower observations could be used to determine vegetation indices during the growing season. In addition, the results of Wilson and Meyers (2007) indicate that vegetation indices derived from satellite data such as MODIS, might be limited by the apparent role of local climate and soil-canopy conditions, and tower-based measurements therefore have the potential to overcome some of the challenges associated with satellite products by providing vegetation information above the canopy that combines contributions of the vegetation and the background at field levels. However, for large-scale applications, satellite inferred NDVI time series remain important (Wang et al. 2004), though their limited temporal and spatial resolution make it difficult to compare them directly with surface observations (Huemmrich et al. 1999). On the other hand, a combination of both methods offers the chance to characterize a given landscape at high resolution, both in time and space.

This study analyses NDVI determined by three different methods (satellite measurements, ground-based spectrometer measurements of spectral reflection, and in-situ broadband measurements of radiation) and discusses their potential uses and constraints. Our main objective has been to see if our in-situ measurements of NDVI can complement the broad-scale satellite derived measurements by data of high spatial and temporal resolution that are free from atmospheric effects. Measurements on different spatial and temporal scales above five land use types (grassland, winter wheat, corn, spruce, and beech), represented by research stations of the Department of Meteorology of Technische Universität Dresden are used. They offer a valuable data set for the NDVI comparison as well as for investigations of the spatial variability of radiation and NDVI and the angular dependence of spectral reflectance and NDVI. Both are useful for interpreting the resulting NDVI in respect to their representativeness for the respective land-use type and concerning an enhancement of the spatial representation of nadir-view measurements, especially for open-canopy sites. Our analyses are based on data from June 2006 and from April through September 2007.

2 Test area and measuring conditions

All measurement sites either were located within (grass and forest sites) or near (crop site) the *Tharandter Wald*. This forest area covers 60 km^2 and is situated 20 km southwest of Dresden, Germany. Most of the terrain is only marginally influenced by relief. Figure 1 shows the spatial distribution of the sites.

The land uses found at the different sites include spruce (Tharandt, since 1996), grassland (Grillenburg, since 2003), crop rotation (Klingenberg, since 2004), and beech (Landberg, since 2006). They are shown in detail in Table 1.

At all sites the observations include eddy covariance flux (CO_2, latent heat, sensible heat, momentum flux) and meteorological measurements (full radiation budget including PAR, air temperature and humidity, wind speed and direction, and precipitation). At selected sites, biomass and soil variables (soil respiration, soil temperature and moisture, bole temperature, bole increment, litter fall, sap flow, stem flow, above-ground biomass and leaf area index LAI (Grünwald and Bernhofer 2007, Grünwald, pers. comm., 2008)) are monitored. The stations are also included in the

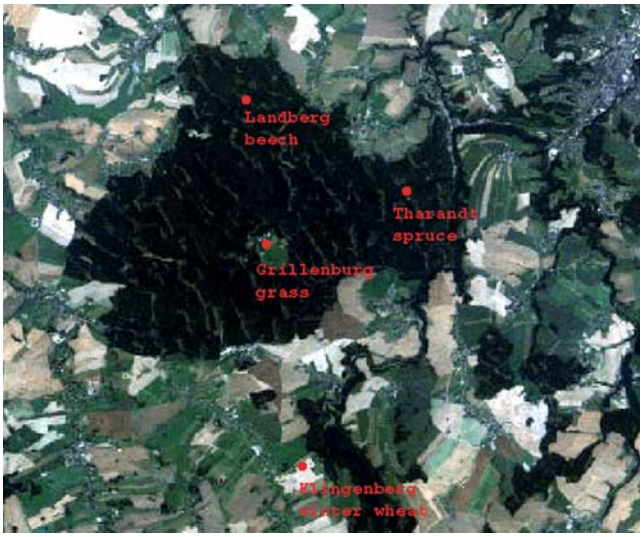

Fig. 1 Overview of the measurement sites in the Tharandter Wald; Landsat-based scene from 1992, (Podlasly, pers. comm., 1997)

FLUXNET network, which coordinates regional and global analysis of observations from about 400 micrometeorological tower sites (Fluxnet 2007). An overview about the measurement dates and weather conditions is given in Table 2.

3 Data

3.1 Satellite data (narrowband space measurements)

Two different MODIS products have been used for the analyses: (a) Data from the FLUXNET network database via MODIS ASCII subsets and, (b) data from the Earth Observing System Data Gateway.

a) The purpose of the FLUXNET MODIS ASCII subset (MODIS 2007a) is to provide summaries of selected MODIS land products for the community to be used for model and remote sensing product validation and to characterize field sites (Baldocchi et al. 2001; Reichstein et al. 2003a, 2003b, 2007b; Fluxnet 2007). The ASCII subsets are pixel values of land products for a 7×7 km area centered on flux towers or field sites from around the world. For 2007 data of vegetation indices were provided every 16 days (*sampling* products) with a spatial resolution of 250 m as a gridded level-three product in the sinusoidal projection. Therefore, the vegetation index-product Terra (MOD13Q1, version 004) and Aqua (MYD13Q1, version 004) are available with signed center-pixel, marking the station.
b) In addition, NDVI and reflection products from the Earth Observing System Data Gateway (MODIS 2007b) have been used. The reflectance products MOD09GQK (Terra) and MYD09GQK (Aqua) are estimated for each band to produce a measurement equivalent to a ground-level measurement with no atmospheric scattering or absorption. These 09GQK data in version 004 are provided as a *daily* 250-m gridded-level-2G product, in the sinusoidal projection. The NDVI can be derived by combining channel 1 and 2 (see Sect. 4.1). The vegetation index-product, which is also given in this database: MOD13Q1 and MYD13Q1 (16-day *sampling* products) have been used for the tower stations where no FLUXNET data were available, e.g., for 2006. While searching the

Table 1 Characteristics of the four measurement sites (data from Mellmann et al. 2003; Grünwald and Bernhofer 2007; Göckede et al. 2008)

Station	Land-use type and patch size	Vegetation height	LAI	Specific feature
Grillenburg 50°56′58″N, 13°30′45″E, 385 m a.s.l. (above see level)	Grass *(62 ha)*	10–75 cm [25 cm, 2006] [15–70 cm, 2007]	0.5–6 [1.97, 2006] [2.6–4.64, 2007]	Management: unfertilized, 2–4 cuts/year
Klingenberg 50°53′34″N, 13°31′21″E, 480 m a.s.l.	Winter wheat (2006) corn (2007) *(55 ha)*	[55 cm, 2006] [0–220 cm, 2007]	[2.55] [0.3–2.17 for April-August; 4.6 in July]	Crop rotation management: mineral/organic fertilizer, Herbicides, Tillage, 1 harvest/year
Tharandter Wald, Anchor station 50°47′N, 13°43′E, 735 m a.s.l.	Spruce *(150 ha)*	29 m (117 years old, 2008)*)	7.6 (2007)*)	Management: commercial thinning in April 2002, disturbance: storm "Kyrill" on 18.01.2007 (windspeed_max=9.5 m/s)
Landberg 50°59′33″N, 13°29′25″E, 400 m a.s.l.	Beech *(36 ha)*	30 m (100 years old, 2008)*)	0–3.9 (2007)	

*) values refer to the vicinity of the tower
Data in brackets show values during the campaign measurements; LAI from harvest (Grillenburg, Klingenberg), harvest-based allometric functions (Tharandt), and measurements with the Plant Canopy Analyser LI2000 (Landberg)

Table 2 Specifications of the measurements (date, time, and cloud coverage)

Land-use type	Measurement date	Time (Central European Summer Time)	Cloud coverage
Grass	June 13, 2006	11:55–12:30	No clouds
	April 16, 2007	12:10–12:40	Cumulus, cloud coverage of 3/8–5/8 for 2007 measurements
	June 7, 2007	11:00–11:45	
	August 13, 2007	12:50–13:15	
	August 25, 2007	12:40–13:20	
Winter wheat	June 13, 2006	10:30–11:00	No clouds
Corn	April 16, 2007	14:00–14:25	Cumulus, cloud coverage of 3/8–5/8 for 2007 measurements
	August 25, 2007	11:30–13:10	
Spruce	June 23, 2006	11:00–12:15	Changing weather conditions, cumulus and stratus, cloud coverage of 6/8
Beech	June 23, 2006	13:15–14.00	Changing weather conditions, cumulus and stratus, cloud coverage of 6/8
	September 20, 2007	11:50–12:40	Cumulus, cloud coverage of 3/8

geographical coordinates in the satellite scene with respect to the tower stations, the mean NDVI value for the concerning pixel and the immediately surrounding eight pixels, was determined.

3.2 Spectrometer data (hyperspectral ground measurements)

For the spectral reflection measurements an adapted newly designed spectrometer with an excellent spectral accuracy has been used. The setup uses a UV/VIS-spectrometer getSpec-PDA, covering the spectrum of 380–1100 nm with a resolution of 0.2 nm, an optical fiber with 400-μm core diameter, a collimating lens Col-UV/VIS and a white standard Spectralon (getReflex) with 99% reflection as reference material. Noise at the end of the spectrum limited the useful data range to between 380 and 900 nm. The white reflection standard was pivoted into the optical path for reflection measurements (http://www.getspec.de/) with a field-of-view of 26°, thereby resulting in a monitored area of 0.12 m^2 (assuming a measurement height of 1.2 m above the canopy (except for the forest sites). A 12 V/12 A battery supplied power for the spectrometers. To stabilize the measurement system, a tripod was used as the holder for the optical fiber. The reflection data were directly stored on a laptop with the integrated spectrometer software spec32 (http://www.getspec.de/www/getspec.nsf/main_de.html). Measurements are ideal under clear-sky conditions due to the fast calibration (~30 s) of the spectrometer. A completely covered sky also allows measurements but with a necessary integrating time of up to 1 hour. The measurements were accomplished for solar elevation angles ranging from ~40° (September) to 60° (June), in the solar principal plane. Measurement height for grass and crop was nearly 1 m above the canopy; spruce and beech measurements took place at the top of the towers at 41 and 36 m height, respectively.

3.3 Tower and mobile experimental radiation data (broadband ground measurements)

3.3.1 Tower stations

Crop-site Above winter wheat and corn (measurement height at 1.80 m) the fixed measurement system was composed of a *CRN1* net radiometer by Kipp&Zonen. The sensor is robust and fully weatherproof and consists of four separate sensors with pair-wise equal sensitivity including two pyranometers for solar radiation (*CM3*, spectral range: 305–2800 nm) and two pyrgeometers for thermal infrared measurements (CG3, spectral range: 5–50 μm).

Grass-site In 2006, only one pyranometer *CM5* (305–2800 nm, by Kipp&Zonen) was available for global radiation. The reflected part of the shortwave radiation has been available after autumn 2006 only. Measurement height was 1.50 m.

Beech-site The measurement system above beech was also composed of a *CRN1* net radiometer (by Kipp&Zonen, consisting of the same devices as mentioned for the crop-site) in 36 m above ground, stabilized on an extension arm.

Spruce-site Above spruce, two pyranometers *CM7* (by Kipp&Zonen) for net shortwave radiation (with a spectral range of 305–2800 nm) 41 m above ground have been available, installed on an extension arm.

Incoming and reflected PAR at all stations have been recorded by a Licor *LI-190SA* quantum sensor measuring the photon density in the range of 400–700 nm. Overall data availability at the permanent stations was every 10 min, except the data of global radiation at Grillenburg in 2006 with measurements every 30 min.

3.3.2 Mobil measurement setup

In addition to the fixed-tower measuring devices of the stations, a hand-held measuring setup for global radiation and PAR (broadband) was established to investigate spatial variability by five measurements within a 25× 25 m^2 grid (measuring the corner points and the center) above grass and winter wheat. The system consisted of a pyranometer *CM7B* by Kipp&Zonen with a spectral range of 305–2800 nm (consisting of two *CM6B* pyranometer sensors, facing skyward and down toward the top of the canopy, measuring the half-space, respectively) and was completed by two quantum sensors (incoming and reflected PAR, facing skyward and downward) *Quantum SKP 215* by Skye (spectral range 400–700 nm). All instruments were fixed on extension arms and leveled to realize an undisturbed measurement nearly 1 m above the canopy. The measurements were always leveled to the sun (azimuth). Above spruce and beech no hand-held global radiation and PAR measurements were carried out as the small tower-platform restricted the use and applicability of the mobile system. To avoid influences from disturbing the other flux measurements, the mobile measurements were accomplished about 20 m away from the permanent stations still measuring the same land-use characteristics.

4 Methods of determining the NDVI

The definition of NDVI (Rouse et al. 1974) uses the striking differences in green leaf absorption in the red (VIS) and near-infrared (NIR) bands.

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \tag{1}$$

4.1 Satellite-derived NDVI

As described in Chap. 3.1, the NDVI sampling products of the FLUXNET research sites, with a spatial resolution of 250 m (MOD13Q1, MYD13Q1) were used. Additionally, the given daily reflectance products (MYD / MOD09GQK, 250 m) for channel 1 (VIS: 610–680 nm) and 2 (NIR: 820–900 nm) were utilized. The NDVI is then given as

$$NDVI = \frac{(\rho_{ch2} - \rho_{ch1})}{(\rho_{ch2} + \rho_{ch1})} \tag{2}$$

with ρ_{ch1} and ρ_{ch2} being the surface bidirectional reflectance factors of the MODIS bands. The algorithm for the atmospheric correction (after the work of Van Leeuwen et al. 1999), is shown in detail in the paper by Huete et al. (2002).

The satellite signal is influenced e.g., by cloud contamination, atmospheric variability, and bidirectional reflectance. These factors are considered as undesirable noise in vegetation studies (Wang et al. 2004). To eliminate the effects, compositing methods have been developed, and the given MODIS NDVI- products are arranged as follows.

The common procedure is the maximum-value composite technique (MVC). MVC selects the maximum NDVI value for each pixel during the 16-day period. MVC is known to select pixels with a large view and solar zenith angles, which may not always be cloud-free (Cihlar et al. 1997). However, the MVC approach will strongly increase the selection of off-nadir pixels (due to strong anisotropy of vegetated surfaces), which exhibit higher NDVI values when viewed skewly (Huete et al. 2002). This is especially important for MODIS as a whiskbroom sensor, increasing the pixel size with the scan angle up to factor 4 (Van Leeuwen et al. 1999; Wang et al. 2004) and thus altering the influence of off-nadir pixels.

Due to clouds, the number of acceptable pixels during the 16-day compositing period is less than ten and often less than five, especially when considering a mean global cloud cover of 50–60% (Huete et al. 2002). To constrain the strong angular variations in the MVC method, the CV-MVC (constrained view-angle maximum-value composite) and BRDF-C (bidirectional reflectance distribution function composite) techniques were designed (Huete et al. 2002). The CV-MVC compares the two largest values and selects the observation closest to nadir view to represent the 16-day composite cycle. This method is used if less than five and, more than one day are cloud-free. In case of more than five cloud-free days the BRDF-C method can be used. If there is only one good observation available, the vegetation indices are computed from this observation. If no cloud-free pixel is available over the 16-day cycle, the MVC method for the NDVI is used. The technique employed depends on the number and quality of observations.

4.2 Spectrometer-derived NDVI

The precise *channel-specific* spectral reflectance ρ can be obtained by weighting the spectrum of the land use $\psi(\lambda)$ stepwise with the filter response function $\varphi(\lambda)$ of the satellite for the given range $(\lambda_1 \ldots \lambda_2)$ of the filter response function:

$$\rho = \frac{\sum_{i=1}^{N} \varphi(\lambda_i) \cdot \psi(\lambda_i)}{\sum_{i=1}^{N} \varphi(\lambda_i)} \tag{3}$$

N is the number of sampling points of $\psi(\lambda)$ between λ_1 and λ_2. This weighted sum is divided by the sum of the weighting factors to get the spectral reflectance of the respective channel, taking the shape of the response function into account. After calculating the reflectance of channel 1

(for λ: 610–680 nm) and channel 2 (for λ: 820–900 nm) of MODIS using Eq. (3), NDVI is derived according to Eq. (2).

4.3 Broadband NDVI

For broadband in-situ NDVI Huemmrich et al. (1999), Wang et al. (2004), Wilson and Meyers (2007), and Jenkins et al. (2007) proposed replacing the red domain (VIS) with the photosynthetic active radiation (PAR) and the near-infrared domain with the difference between shortwave radiation and PAR, so that

$$\rho_{PAR} = \frac{PAR_{refl}}{PAR_{in}} \tag{4}$$

and

$$\rho_{NIR} = \frac{Rg_{refl} - PAR_{refl}}{Rg_{in} - PAR_{in}} \tag{5}$$

can be combined to give

$$NDVI_b = \frac{(\rho_{NIR} - \rho_{PAR})}{(\rho_{NIR} + \rho_{PAR})} \tag{6}$$

with ρ_{PAR} as the ratio of incoming (PAR_{in}) and reflected PAR (PAR_{refl}), and ρ_{NIR} as NIR-reflectance inferred by the reflected global radiation (Rg_{refl}) and reflected PAR (PAR_{refl}) as well as global radiation (Rg_{in}) and incoming PAR (PAR_{in}). The broadband NDVI ($NDVI_{\mathrm{b}}$) uses a PAR wavelength band of 400–700 nm and an NIR band that is effectively between 700 and 2800 nm with little perturbation due to a minor influence of the 280–400 nm sensitivity of the shortwave instrument (Huemmrich et al. 1999).

It is important to note that the quantum sensors measure photon flux density (µmol m^{-2} s^{-1}) while the pyranometers measure radiation in energy units (Wm^{-2}). Huemmrich et al. (1999) suggested a conversion factor of 1/4 Jµmol^{-1} whereas Ross and Sulev (2000) 1/4.6 Jµmol^{-1} to express PAR in Wm^{-2}. In this study the conversion was done following Ross and Sulev (2000).

5 Results and discussion

We determined a comprehensive data set with a lot of data per land-use type. Thus, before analyzing the NDVI determined by different methods (5.3), spatial variability within land-use classes (5.1) and angular dependence of spectrometer measurements (5.2) will be investigated.

5.1 Spatial variability of radiation

5.1.1 Tower- and mobile-based investigations (2006)

Figure 2a–d illustrates the comparison of the mobile and station measurements of radiation components for winter wheat and grass. The left side of Fig. 2a and c shows the mean incoming global radiation Rg_{in}, reflected global radiation Rg_{refl}, incoming PAR_{in} and reflected PAR_{refl} of the five individual measurement points (mobile measurements) within one land-use type and its variability (minimum/maximum). The right side of the figures shows the averaged values of the tower measurements (10:30–11:00 above winter wheat and 11:55–12:30 CEST above grass). Figure 2b and d present the inferred shortwave (sw) and PAR albedo.

For *winter wheat* (Fig. 2a), the comparison between mobile and fixed-tower data shows differences in Rg_{in} of 6% (789.71 Wm^{-2} versus 754.25 Wm^{-2}, respectively) with small variations within the land use type. In contrast, mobile Rg_{refl} varies largely between 121 Wm^{-2} and 187 Wm^{-2}. This is caused by a patchy surface with alternating areas of dense wheat vegetation and soil-dominated areas. The difference between mobile and tower measurement for Rg_{refl} is 9% (147.6 to 134.85 Wm^{-2}). Larger differences occur between mobile PAR_{in} and fixed tower PAR_{in} (391 Wm^{-2} and 323 Wm^{-2}, 21%), and between PAR_{refl} values (13 Wm^{-2} and 10.6 Wm^{-2}, 23%). We attribute this to differences in calibration, timing or leveling, but it should not influence the derived NDVI too much, as it relies on normalized values. The small values of PAR_{refl} show the high proportion of vegetation. The variation within land use type is negligible, ranging from 12–15 Wm^{-2}.

Regarding the *grass* values (Fig. 2c), differences of only 5% (908 to 864 Wm-^{2}) are noticed for Rg_{in} between mobile mean value and fixed-tower measurement. The variation within land use type is only about 3% (ranging from 888 to 921 Wm-^{2}) for the day of perfect radiation conditions. Reflected global radiation Rg_{refl} from the mobile measurements ranges between 171 and 184 Wm^{-2} and has smaller variations than the reflection of wheat, shown above. Differences in PAR_{in} (mobil: 448 Wm^{-2}, station: 345 Wm^{-2}) with nearly 30% are as significant as shown for wheat. PAR_{refl} differs with 21 Wm^{-2} to 15.9 Wm^{-2} (i.e., 30 %), respectively. Variations within the land-use type are small. Due to the later measurement time, the incoming global radiation, quantified for grass (near the maximum at noon), is about 150 Wm^{-2} higher than for winter wheat.

Regarding the resulting albedo for both land-use types (Fig. 2b and d), a big variability within the wheat mobile measurements is obvious, ranging from 17–24%. The mean value of 18.7% is in good agreement compared to the station with mean value of 17.8%. For grass tower albedo values were not available due to the missing Rg_{refl}. Mobile measurements show a mean albedo of 20% with significantly lower variability than for wheat. PAR albedo values for both land-use types are in good agreement for mobile and tower measurements with slightly higher results for grass.

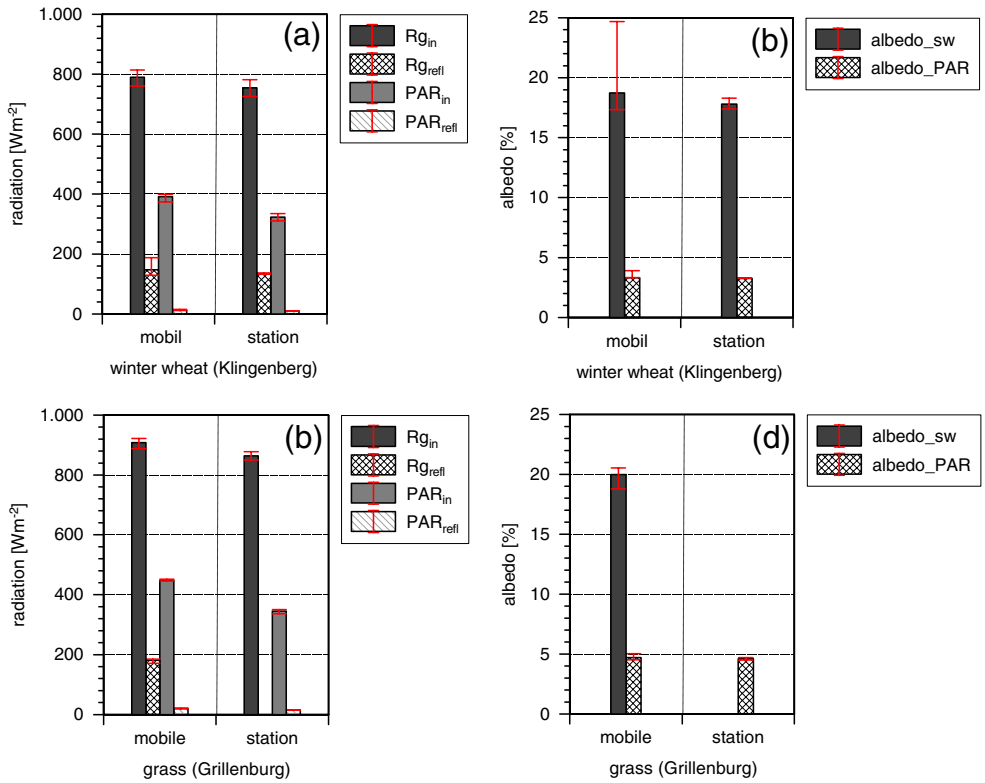

Fig. 2 Shortwave radiation and PAR (hand-held/tower) above crop (**a**) and grass (**c**) and resulting albedo and PAR-albedo for crop (**b**) and grass (**d**); (for hand-held measurements: mean, minimum and maximum of the five measurements within one land-use type; for tower measurements: mean, min, and max of the 10-min data within the measurement period); for measurements 2006

The tower measurements of radiation and PAR above the *forest* sites and the resulting albedo are shown in Fig. 3. Although the radiation measurements above spruce were timed at 11:00 CEST and above beech at 13:00 CEST, the values at the spruce site are more than 100 Wm^{-2} higher (683 Wm^{-2} compared to 540 Wm^{-2} for global radiation and 379 Wm^{-2} compared to 271.04 Wm^{-2} for PAR, respectively). This illustrates the cloudy and rapidly changing situation on that day (June 23, 2006). In contrast, the values of reflected global radiation are about 50% higher for beech than for spruce due to the darker color of the coniferous trees (75 Wm^{-2} and 48 Wm^{-2}, respectively). The same pattern can be seen for reflected PAR with 12 Wm^{-2} for beech and 4.9 Wm^{-2} for spruce. Figure 3b shows the shortwave- and PAR albedo for spruce and beech. Despite the unfavorable conditions of the measurements, the spruce albedo is in excellent agreement with values reported earlier (Bernhofer et al. 2003).

5.1.2 Spectrometer-based investigations (2006)

Spectrometer measurements (five per land-use type: measuring the corners and the center-point within the 25×25 m^2 grid) were accomplished both to analyze the variability within one land-use type and to infer the spectral NDVI (Fig. 4a-d).

Except for bare soil, all land-use types show a peak in reflectivity near 550 nm, notably pronounced for grass. At this peak, the variability between the measurements within one land-use type differs only slightly for grass and wheat and more significantly for spruce with reflection values from 4 up to 12%. The peak is in the green range of the

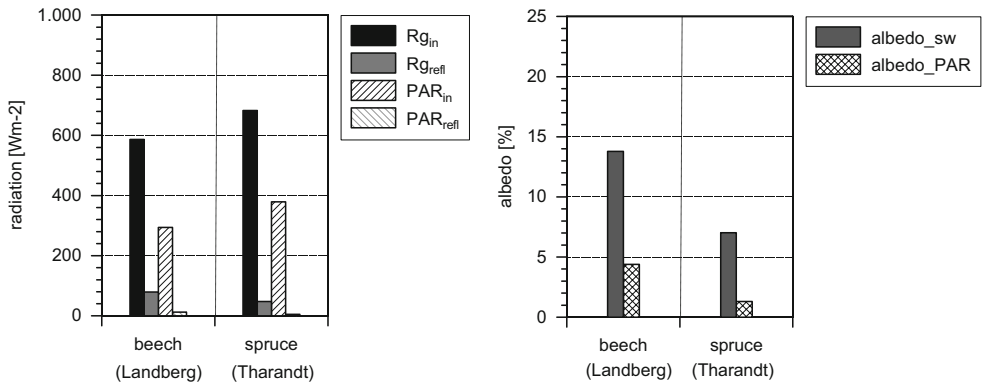

Fig. 3 Shortwave radiation and PAR (station) above forest (*left*) and resulting albedo and PAR-Albedo (*right*), 2006

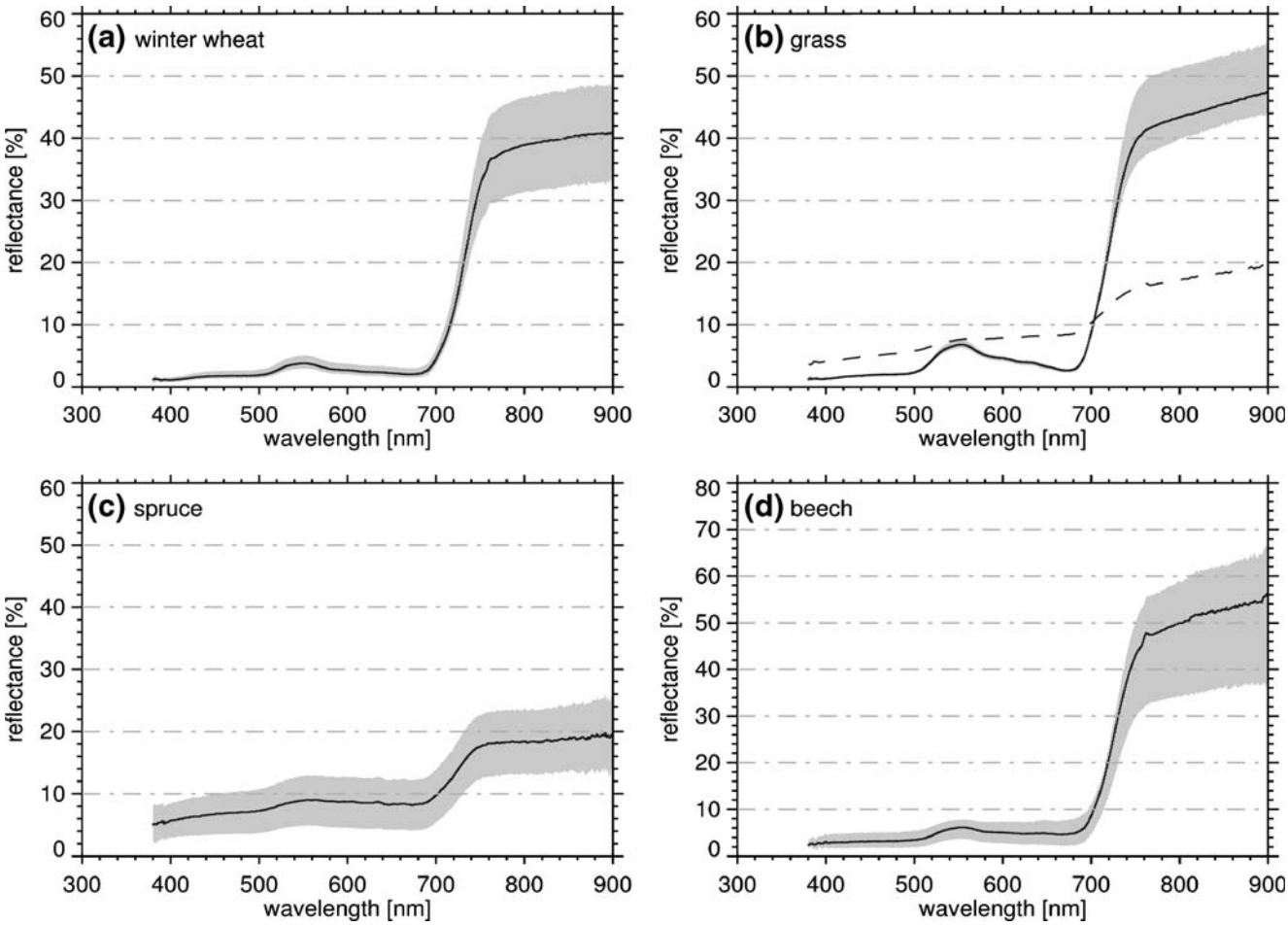

Fig. 4 **a** Spectral reflectance of the different land use types in 2006 (five measurements), *dashed line* in (**b**): soil reflectance

visible spectrum and caused by the chlorophyll of the plants. In the red part of the visible spectrum, most of the incoming radiation is used for photosynthesis and absorbed by foliar pigments. A significant depression can be found around 690 nm for all land-use types (without soil) before a reflectance jump occurs, even for soil at longer wavelengths.

The reflectivity characteristics of soil and spruce are similar, even regarding the increase between 700 and 750 nm. This might be due to the limited height of the tower measurements and a considerable proportion of soil that can affect the spectrometer measurement with its limited field of view. After this significant reflection jump in the NIR band, reflectance is generally higher, and is determined by differences in the internal leaf structure, water absorption, and absorption features of other biochemical contents (Van Til et al. 2004).

Special attention should be given to the wide range of the beech values for NIR. At a wavelength of 900 nm, the reflectance values range from 37 up to 67%. A reason for this variability was the changing cloud conditions with cloud coverage of 6/8 and parts with cloud clearance. On a day with strong cloud movement, the calibration is another source of uncertainty. This seems to be the case not only for beech but also for spruce. The measurements were taken at relatively sunny conditions. If during calibration cloud cover is different, an overestimation of the measured reflection is the consequence leading to this high variability in reflectance and higher values in the NIR part of the spectrum.

To sum up, the single measurements for winter wheat and grass show the effective variability within land-use type in the small target area of 25 m^2. The measurement conditions were very stable, and thus variability occurs due to the heterogeneous surface characteristics, especially pronounced in the NIR. For the forest measurements, higher variations in their spectra are obvious, both in VIS and NIR. The main reason is found in the changing weather conditions and therefore calibration problems. Nevertheless, tower spectrometer measurements for forest are generally rare and thus useful for NDVI determination.

Figure 5 combines the results for all land-use types showing the mean of the single measurements. In the shortwave range of the spectrum, winter wheat shows

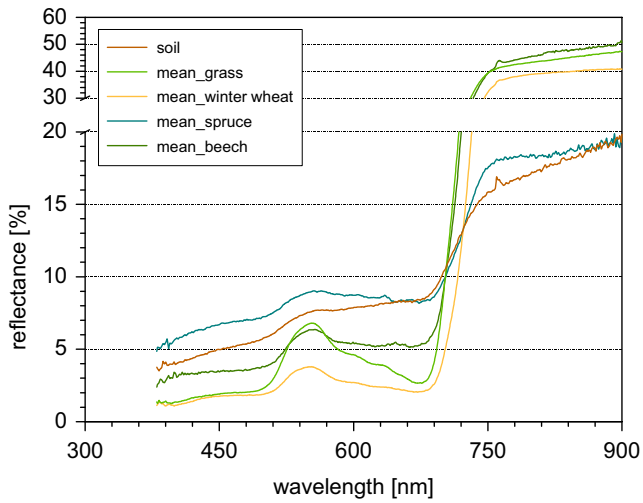

Fig. 5 Spectral reflectance of five different land-use types in 2006 (mean of five measurements); note the stretched *y*-axis up to 20%

the smallest values followed by grass, beech, soil, and spruce. Only for the peak at 550 nm do the grass values exceed those of beech. Further to the right, this graph decreases due to stronger absorption processes. At about 710 nm, all land-use types show nearly the same value of 10% reflectance. In the NIR band, the soil and spruce values illustrate very similar behavior with values of 15–20%, whereas the remaining land-use types show higher values of up to 50% for grass and beech and up to 40% for wheat, with similar patterns. These measurements clearly explain the weak relationship between the reflectivity of a surface type in the visible and that in the NIR-band of the spectrum (Petty 2004).

5.2 Investigation of angular effects of radiation

Spectrometer measurements in nadir view show significantly lower NDVI values (Table 3) for the measurements above spruce (2006), corn (2007), and beech (2007) compared to the other results. In particular, these measurements were possibly too much influenced by the tower structure and mixed patches of soil and trees. Thus in 2007, the angular dependence of the spectrometer measurements for corn, grass, and beech was investigated (Fig. 6). The effect of overlapping trees that might appear denser by observing skewly is therefore known (defined here as the *occlusion effect*) and is accepted for an enhancement of the spatial representativeness of the data.

Note that there was only one measurement per angle and date, in contrast to 2006, where a measurement grid was

Table 3 Comparison of NDVI by all methods

Land-use type	NDVI broadband ground measurements		NDVI spectral, due to MODIS bands, ground measurements	NDVI MODIS spectral, space measurements	
	Hand-held experimental	Tower measurement	Spectrometer nadir, (*and 60° for the measurements in 2007*)	Terra (T), Aqua (A) 16-day sampling 250 m (NDVI-product MOD/MYD13Q1)	Terra (T), Aqua (A) on a daily basis 250 m (NDVI inferred from the reflection product MOD/MYD 09GQK)
Grass 2006					
June 13	0.77	-	0.86	- , 0.71 (A)	0.84 (T), 0.86 (A)
Grass 2007					
April 16	-	0.77	0.79 (*0.81*)	0.80 (T), 0.78 (A)	0.68 (T), 0.57 (A)
June 7	-	0.74	0.82 (*0.83*)	0.85 (T), 0.88 (A)	0.74 (T), -
August 13	-	0.75	0.88 (*0.87*)	0.88 (T), 0.88 (A)	0.79 (T), 0.61 (A)
August 25	-	0.58	0.62 (*0.56*)	0.88 (T), 0.80 (A)	0.67 (T), 0.76 (A)
Winter wheat 2006					
June 13	0.81	0.79	0.89	- , 0.88 (A)	0.85 (T), 0.88 (A)
Corn 2007					
April 16	-	0.59	0.20 (*0.18*)	0.29 (T), 0.33 (A)	0.45 (T), 0.49 (A)
August 25	-	0.55	0.67 (*0.82*)	0.77 (T), 0.75 (A)	0.49 (T), cloud (A)
Spruce 2006					
June 23	-	0.77	0.39	- , 0.82 (A)	- , cloud (A)
Beech 2006					
June 23	-	0.68	0.82	- , 0.79 (A)	- , cloud (A)
Beech 2007					
September 20	-	0.64	0.42 (*0.84*)	0.86 (T), 0.78 (A)	0.95 (T), cloud (A)

-Missing data

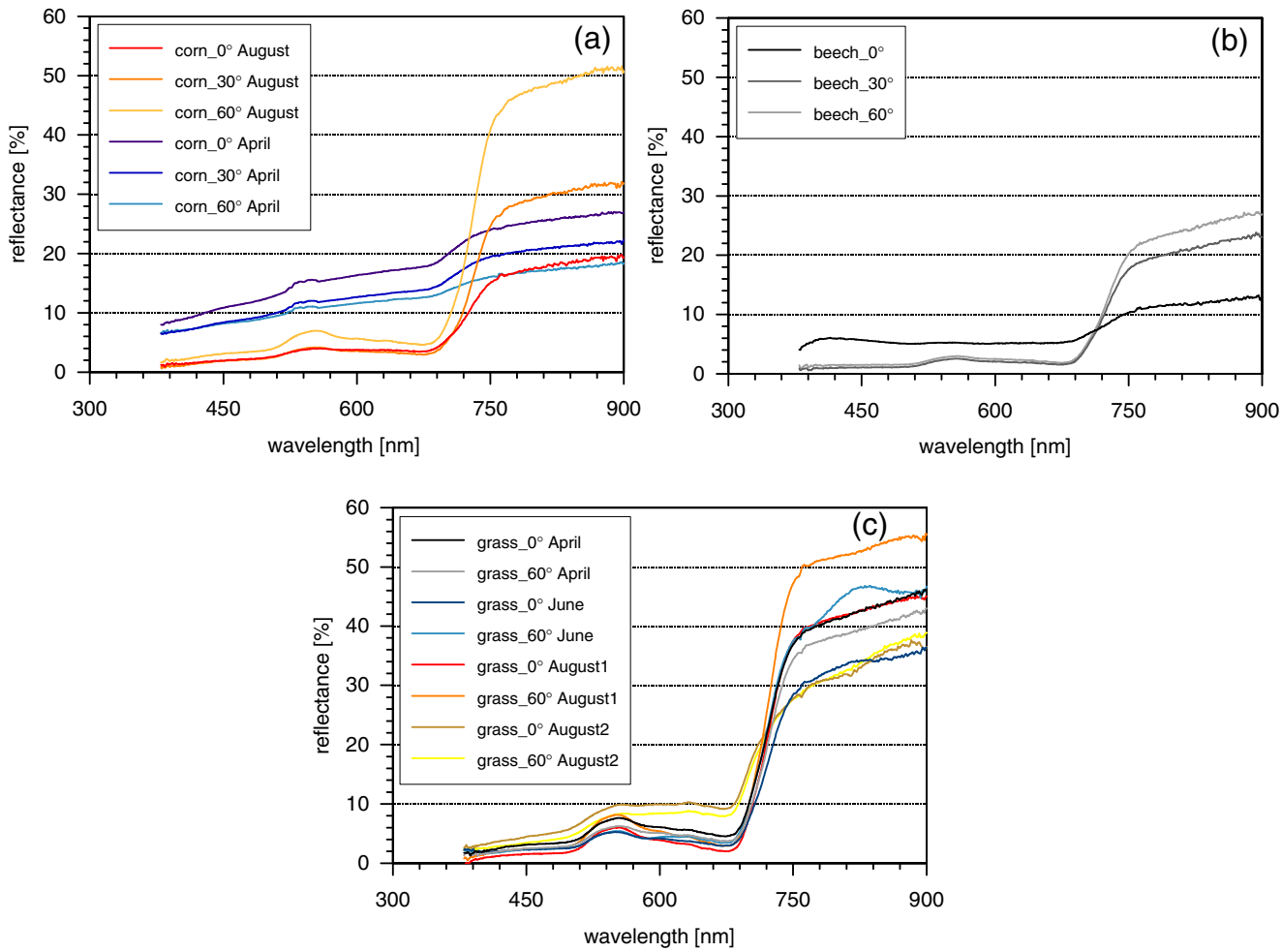

Fig. 6 Spectral reflectance of grass, corn, and beech for different measurement dates and angles in 2007

used to get information about spatial variability of radiation measurements.

The spectral reflectance for *corn* at 0° (nadir), 30 and 60° (angles with respect to nadir) is shown for the April (blue) and August (red) measurements in Fig. 6a. The April data are at all angles close to the soil-values of 2006 (Fig. 4, upper right, dashed line) with higher reflectance values in the visible part of the spectra. It can be outlined that the smaller the angle the bigger the reflection in the entire spectrum. This is inconsistent with other studies with the same spectrometer (Fan, pers. comm., 2006), but probably caused by very dry soil conditions at this time. In August, typical vegetation spectra are found comparable to the measurements for winter wheat in 2006. Maxima in the visible part are at 4% for 0 and 30°, and 6% for 60°. After the reflectance jump at 700 nm, the reflectance is separated clearly, with maxima values of 50% for 60°, 32% for 30°, and 20% for nadir direction at a wavelength of 900 nm. Disney et al. (2004) confirm that the spectra obtained at larger view angles are a few percent higher in the NIR than in the VIS. This is consistent with the angular signature of vegetation reflectance which typically exhibits increasing reflectance with view angles away from nadir. The reason is the increasing volume scattering caused by the longer (viewing) path length through the canopy at higher viewing angles (Disney et al. 2004).

Figure 6b shows the September measurement for *beech* with the three given viewing angles. The nadir measurement is almost identical to the soil data of 2006 but with lower values in the NIR. Measuring from a tower in nadir direction leads to problems with the soil part of an open forest. Taking the measurements at 30 and 60° into account, the patterns are typical for vegetation spectra, providing smaller reflection in the VIS part but significantly larger reflection in the NIR part as compared to the nadir view. Maximum values in the VIS part are found to be 3% (30 and 60°) at the wavelength mentioned above. In the NIR part the values start to separate with a maximum value of 28%.

Figure 6c shows the spectrum for *grass* on four dates and at two measurement angles (nadir and 60°). Regarding the VIS part of the spectrum it can be pointed out that the

nadir views for almost all months (except the first August measurement) show higher reflections than the angular measurements at 60°. Except for the April measurements, this behavior reverses for all measurements in the NIR part, as is strongly seen for June (blue) and for the first August measurement. Taking into account that in April and at the end of August the grass was cut in stripes and therefore the color of the grass varied depending on the viewing angle, the differences compared to the earlier measurements are explainable.

5.3 NDVI

Before presenting the results for NDVI derived by three different methods, this section examines the spatial representativeness of the data comparing hand-held and spectrometer NDVI of grass and winter wheat (measurements from 2006). Figure 7 shows mean and variability (minimum/maximum values) of the five measurements within the 25×25 m^2 grid. For *grass*, the ranges of NDVI, and thus the spatial uncertainty, show lower variations for each method than the difference of the averages of the NDVI determined by the two different methods. Differences between these two methods are caused by significantly different values for reflection, especially in the NIR. Comparing broadband versus spectral reflection for grass in this part of the spectrum, we find a broadband-NIR reflection of 35% whereas the spectral determined NIR reflection from the spectrometer data in dependence of MODIS band 2 shows 45%. The same is found for winter wheat with 32 and 40% respectively. Differences in the VIS between the methods are with 1% higher broadband VIS reflections negligible. Hence, the variations in the NDVI seem to be predominantly dependent on the NIR. For *winter wheat*, we have found larger variations within the mobile NDVI, almost possessing the same range as the difference between the two methods (mobile broadband and spectrometer, respectively). However, spatial variability within the grid is smaller compared to the differences caused by the methods.

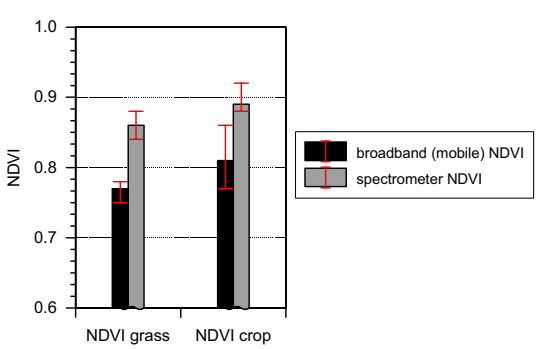

Fig. 7 Mean values of NDVI for grass and winter wheat, and the minimum and maximum value of the five measurements within one land-use type, determined from the hand-held radiation measurement (broadband NDVI) and from spectrometer data (spectrometer NDVI) 2006

Table 3 summarizes the final NDVI, determined with different methods: derived from mobile and tower measurements as broadband NDVI (columns 1–2), from spectrometer data using spectral bands 1 and 2 from MODIS (column 3), and satellite data from different sources (columns 4–5).

Note that in 2006 the tower measurements were added with hand-held measurements, while in 2007 the NDVI determination was carried out with spectrometer measurements using additional viewing angles (30° and 60°) to investigate angular dependence of spectral reflectance and thus NDVI.

Grass site: For grass in 2006, all inferred NDVI values are in the range of 0.71–0.86, with a maximum difference of 0.15. Spectrometer- and daily MODIS NDVI (calculated from the MOD/MYD09GQK-products) are in the same range. Significantly lower values are found for the MODIS sampling NDVI (MOD/MYD13Q1) and the broadband NDVI based on the hand-held measurements. In 2007, a good agreement between spectrometer and MODIS sampling NDVI could be found, whereas broadband NDVI is more comparable to the MODIS daily NDVI. The range of minimum and maximum NDVI for all methods is 0.14–0.32 depending on the seasonal stage. The largest variations between all methods are obtained for both August measurements with differences of 0.27 and 0.32. The differences between *daily* MODIS NDVI and the *sampling* product could be caused by very thin clouds in the daily product and by the sampling methods of the 16-day product. Differences between the sampling products themselves could be actuated by the different sampling periods for Aqua and Terra, starting at different days. The angular dependence of the spectrometer measurements for NDVI is marginal.

Crop site: NDVI values for *wheat* range from 0.79–0.89, the difference is within 0.1. Spectrometer-based NDVI correspond very well with both MODIS NDVI. The broadband NDVI of both, tower and mobile measurements, were also in agreement with each other, but up to 0.1 lower compared to the spectral-based NDVI.

For *corn*, a similar trend as for the grass-site is found concerning the spectrometer (nadir) and MODIS sampling NDVI, but with lower absolute values, especially for the April measurement. The variability between the methods is significantly higher with differences up to 0.41 for April and 0.26 for August (60° spectrometer measurement not included). Angular dependence is obvious for the August measurement over corn, when the plants reached a height of

nearly 2 m but also soil patches were still visible in between. The damage caused by hail on August 23, 2007, (11:40–12:10 CEST) had also some influence on plant structure and leaf color.

Beech site: In 2006, spectral-based NDVI are in sufficient agreement (spectrometer: *NDVI= 0.82* and MODIS sampling: *NDVI= 0.79*) whereas the broadband NDVI shows a significantly lower value with *NDVI= 0.68*. In 2007, beech shows the highest variability of all land use types with NDVI ranging from 0.42 (spectrometer, nadir view) to 0.95 (Terra daily reflection). Tower and MODIS sampling data were between those values. At 60°, viewing angle, an NDVI of 0.84, is measured compared to the nadir NDVI of 0.42, which included parts of the soil underneath. The value of 0.84 is comparable to MODIS sampling NDVI with the values of 0.86 (Terra) and 0.78 (Aqua). A significantly lower NDVI (0.64) is calculated from the broadband tower data.

Spruce site: Here the spectral based MODIS sampling NDVI is in good agreement to the broadband (tower) NDVI (0.82 and 0.77, respectively) but shows no comparability to the spectrometer measurement (*NDVI= 0.39*) at all. Especially the low NDVI value for spruce inferred from the spectrometer data shows the influence of the nadir measurement (soil data) and possible disturbance by the tower itself.

The data from 2007 seem to be very variable not only for the different determination methods for NDVI but also for the same platform, e.g., regarding MODIS composites or daily products. A seasonal dependence is only noticeable for corn reflecting the growth of this fast growing crop between April and August.

Summarizing, Fig. 8 displays the comparison of satellite-(daily measurements) to in-situ NDVI, for spectral and broadband measurements above four land-use types. The question was whether in-situ data (especially the broadband measurements) can complement the satellite results. Even though Fig. 8 shows considerable scatter, the overall agreement is acceptable. The land-use types can be delineated clearly (shown by the ellipses) in the figure and illustrate better comparability for grass and winter wheat than for corn and beech. Broadband measurements are shown with standard deviation for the 30-min measurement period and are close to the 1:1-agreement (with exception to the beech value) and thus similar to the satellite results. Correlation is found to be *R= 0.51* for broadband and *R= 0.67* for spectrometer NDVI, respectively. Correlation to MODIS sampling NDVI is much better for the spectrometer-based NDVI (*R= 0.91*) but significantly lower for broadband NDVI (*R= 0.41*, not shown). However, daily MODIS NDVI should be used for the comparison due to the in-situ data, representing values at a given time.

Mean differences of all the broadband and spectrometer NDVI compared to the daily MODIS NDVI are 0.031 and 0.034, respectively, and thus in the same range (note, that broadband NDVI rather underestimates MODIS NDVI, while spectrometer NDVI overestimates the MODIS values). Even for the MODIS sampling NDVI nearly same mean differences are found with 0.082 for broadband and 0.086 for spectrometer NDVI. Thus both ground-based NDVI are assumed to be useful for supporting satellite measurements.

5.4 Discussion

As shown in the previous chapter (Table 3 and Fig. 8), an explicit conclusion regarding the comparability of satellite and ground-based NDVI is hampered due to various effects that influence the different methods of NDVI determination.

(1) In most cases (including 2006), our broadband NDVI is lower compared to the spectral-based NDVI. This finding is similar to the results by Wilson and Meyers (2007), who found satellite-derived NDVI exceeding the broadband NDVI, with particularly large differences in the case of forest sites and smaller differences

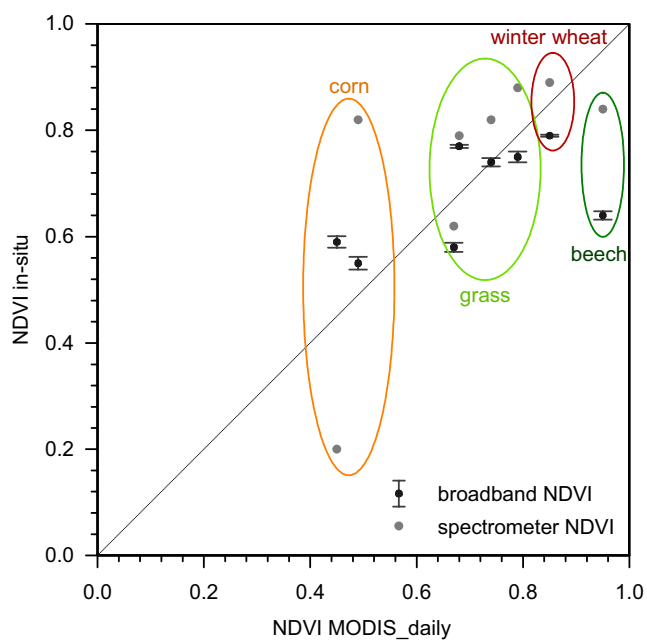

Fig. 8 MODIS NDVI (daily results) vs. in-situ NDVI (broadband and spectrometer) for measurements above grass (2007), corn (2007), beech (2007), and winter wheat (2006), broadband NDVI (mean) is with standard deviation for the measurement period (30-40 min), Correlation is *R= 0.51* for broadband and *R= 0.67* for spectrometer measurement

in the case of grasslands and crops (note that they sampled the broadband NDVI to 16day composites). However, they pointed out that despite large scatter for the regression, the overall agreement for most of the sites was good. For measurements under completely perfect weather conditions (for grass and winter wheat) we also find close agreement between the different NDVI values. The results are comparable to Jenkins et al. 2007 as well (who compared daily tower data and 16-day MODIS composites), with lower broadband NDVI values when using the traditional MODIS-NIR channel for NDVI determination.

(2) Satellite-derived results are strongly influenced by atmospheric effects, strong effects of temporal sampling, remaining cloud cover, and data processing (Wang et al. 2004). Differences between our satellite-derived results (sampling vs. daily data) are thus explainable, especially in the case of cloudy periods as seen in Table 2 for grassland and corn in 2007. Daily products can provide incorrect reflection values caused by very thin clouds, which are hard to detect. Moreover, the whiskbroom sensors like MODIS alter the pixel size by a factor of 4 with increasing scan angles. Thus, for non-sampled MODIS products, the daily values are influenced by the angle in that they exhibit higher NDVI values when viewed skewly (Huete et al. 2002). However, in our study they are treated as nadir views. Sampling products reduces cloud and angle effects but considerable noise can still remain in these data after application of the various compositing methods. Therefore, missing data or periods with clouds often lead to a sudden and large decrease in NDVI (Wang et al. 2004). In addition, a larger footprint including mixed land-use information in data with coarser spatial resolution hampers the comparison to in-situ measurements, where only few trees appear in the field of view of the tower-mounted instruments (Jenkins et al. 2007).

(3) Spectrometer measurements offer large potential in providing hyperspectral ground data, but our results also show the difficulties of using the data. The instrument is actually intended for laboratory measurements, without the influence by wind and changing weather conditions. Thus, an application for field measurements is constrained by these factors. Our measurements were obtained between 11:00 and 14:00 local time. During this period, the radiation fluxes measured at a fixed point from the tower above the canopy correspond to smaller solar zenith angles, an assumption which has been sufficient to limit the effects of BRDF on VIS and NIR (Wilson and Meyers 2007). As mentioned above, solar elevation angles of 50–55° were ideal for minimizing external effects from the atmospheric conditions and changes in solar position (Zhao et al. 2007). During our measurements, solar elevation angles were between 40 (September) and 60° (June) and thus, resulting uncertainties, especially for the off-nadir measurements can not completely excluded. However, the results clearly show that the spectrometer-measured values primarily depend on the position of the spectrometer (height, direction of the instrument arm, viewing angle). Nadir measurements are useful for low and dense canopies that are not influenced by any soil within the footprint. Directed towards the plants, the signal obviously shows the typical plant signature in reflection and, as a further result, higher NDVI values, as it was also outlined by Disney et al. (2004). The "*occlusion effect*" that occurs for skewly viewed canopies, assuming a closer canopy and an increase in reflection in NIR due to longer path lengths (and volume scattering, Disney et al. 2004) and along with that also an increase in NDVI, is therefore used for the study.

(4) Any comparison with spectral-based NDVI must recognize that the wavelength used for the spectrometer or satellite-derived NDVI (VIS: 610 nm–680 nm, and NIR: 820 nm–900 nm) are quite different from those used in broadband NDVI calculations (VIS: 400–700 nm, NIR: 305–2800 nm minus VIS). For the spectrometer method, no broadband NDVI was calculated due to the limited range of our spectrometer (usable data only up to 900 nm). Thus, differences between broadband and spectral-based data, especially in the NIR (10% for grass and 8% for winter wheat, respectively) can cause significant NDVI differences, with higher values for the narrowband method. However, Zhao et al. (2007) claimed that narrowband-derived vegetation indices suffered from non-optimal ranges used for the determination e.g., for NDVI. They suggested for the red channel a change of the central wavelength to 700 nm to avoid the fast saturation in chlorophyll absorption seen in the narrow band 660–680 nm, which is often used for satellites. Additionally, they found that the red-NIR band position was even more important than the bandwidth for deriving the NDVI. Thus, a wavelength shift, at least for the spectrometer measurements to this more useful wavelength, should produce more stable and correct results and therefore could provide greater accuracy in our comparisons.

(5) For the comparison of NDVI for different land-use types, the highest values are found for beech (measured in September 2007), with $NDVI = 0.95$ followed by grass measurements in 2006 and 2007. Corn, measured in April 2007, shows the lowest NDVI for several

methods with values around 0.20 (spectrometer) or 0.33 (MODIS sampling). Differences of NDVI for the different land-use types depend on season, leaf structure, color of the leaves (especially yellow color of beech leaves in September with less chlorophyll and less VIS reflection compared to the measurements in June 2006) and further influences, leading to characteristic reflectance patterns, as seen in Fig. 5. The reflectance in the blue, green, and red regions of the spectrum is primarily determined by pigments and often by chlorophyll concentration (Zhao et al. 2007). The reflectance of plants in the NIR is mainly determined by the arrangement of cells within the mesophyll layer of the leaves and by canopy structure (Kumar et al. 2001, Mutanga et al. 2003). Thus, differences in NDVI for different land use types are explainable, at least based on narrowband determinations.

6 Conclusion

In this study, NDVI determination methods using satellite (MODIS) data, and data from local measurements (global and PAR radiation) have been discussed and compared. In addition to the narrowband (satellite) and broadband (tower) data we have used hyperspectral reflectances from a spectrometer to infer NDVI. Our objective was a comparison of NDVI above five different land use types (grass, winter wheat, corn, spruce, and beech) in order to find out whether ground-based data can complement satellite-based vegetation information by offering highly resolved temporal data without atmospheric effects or background noise.

This unique dataset was enhanced by radiation measurements (global- and PAR radiation and their reflected counterparts) using a mobile measurement setup to investigate *spatial variability* within land-use classes (five measurements within a 25×25 m^2 grid for grass and winter wheat). These measurements have been used to evaluate the representativeness of the broadband tower measurements. Regarding Fig. 7, it can be pointed out that variability within one land-use type is smaller than the differences caused by the different determination methods. Thus, the tower NDVI is representative for the investigated land-use types.

Our second focus was on the investigation of the *angular dependence* of spectrometer measurements. Spectrometer measurements offer a hyperspectral dataset and were used for the determination of NDVI, using the filter response functions of the MODIS sensor and the measured land-use reflectance. Detailed ground-based time series of spectrometer measurements (and thus for NDVI) are rare. One reason is that most spectroradiometers are not designed to operate automatically and are exposed to the weather, which constrains data collection (Wang et al. 2004). Further, to compare the data to broadband or satellite derived NDVI, nadir-view measurements are common. As shown by our results, the nadir measurements provide comparable results to other methods only for closed low canopies (grass and winter wheat) measured under ideal sunny conditions. For more open vegetation or for tower measurements above trees, the soil parts as well as the effect of the tower construction significantly influences the NDVI. To enhance the spatial representativeness for these measurements, angular measurements were carried out using viewing angles of 30 and 60° in forward observation direction. As expected, the influence of the angular measurements was marginal for grass, whereas for corn and beech, the viewing angle significantly influenced the resulting NDVI. This was mainly caused by the NIR measurements with strong increases for reflectance. We are aware of the uncertainties caused by overlapping trees that appear denser observed under larger angles compared, e.g., to a satellite view. This effect is defined here as *occlusion effect*. However, with measurements at 30 and 60°, the patterns are typical for vegetation spectra, providing smaller reflection in the VIS part but significantly larger reflection in the NIR part as compared to the nadir view (Disney et al. 2004). The resulting NDVI for corn and beech (Table 2, for 60°) were then in good agreement with satellite-derived NDVI. However, better results can be expected from using angular measurements, and averaging the nadir and angular spectrometer measurements, and weighting these new values with the covered area for soil and plants, to take the plant characteristics and the special measurement setup into account.

The comparison of NDVI of one satellite and two ground-based methods shows results in good agreement to each other, perfect measuring conditions and a cloudless day provided. The best results are found for the winter wheat and grass measurements in 2006 with maximum differences of 0.1 and 0.15, respectively, for the different methods. Larger differences are obtained for the forest measurements. A detailed analysis of the uncertainties resulting in different NDVI is provided (in Sect. 5.4). In fact, an error estimation would be necessary to definitely evaluate the applicability of the various methods. Therefore constant and durable measurements are necessary to infer NDVI under stable and comparable conditions.

Summarizing all results, we conclude that a ground-based network of NDVI measurements (enhanced by special spectrometer data) provides a very powerful tool for supporting remote sensing NDVI estimates. Ground-based NDVI may be more related to canopy physiology (Wang et al. 2004) and offer the potential to overcome

some of the challenges associated with satellite products, especially for small-scale ecosystems by providing vegetation information above the canopy that combines contributions of the vegetation of interest and the background at field scale (Wilson and Meyers 2007). Another advantage of the ground-based NDVI is the possibility to construct a temporally detailed NDVI time series at each location. Moreover, one can use the broadband NDVI directly as input for models that simulate ecosystem functions (Wang et al. 2004). Existing tower-based networks (FLUXNET, Baldocchi et al. 2001) provide anchor stations for such activities, and their potential is improved by instruments being installed at an increasing number of sites.

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