Separation of soil and canopy reflectance signatures of Mid German agricultural soils

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ABSTRACT

Remote sensing can provide visual indications of crop growth during production season. In past, spectral optical estimations were well performed in the ability to be correlated with crop and soil properties but were not consistent within the whole production season. To better quantify vegetation properties gathered via remote sensing, models of soil reflectance under changing moisture conditions are needed. Signatures of reflected radiation were acquired for several Mid German agricultural soils in laboratory and field experiments. Results were evaluated at near-infrared spectral region at the wavelength of 850 nm. The selected soils represented different soil colors and brightness values reflecting a broad range of soil properties. At the wavelength of 850 nm soil reflectance ranged between 10% (black peat) and 74% (white quartz sand). The reflectance of topsoils varied from 21% to 32%. An interrelation was found between soil brightness rating values and spectral optical reflectance values in form of a linear regression. Increases of soil water content from 0% to 25% decreased signatures of soil reflectance at 850 nm of two different soil types about 40%. The interrelation of soil reflectance and soil moisture revealed a non-linear exponential function. Using knowledge of the individual signature of soil reflectance as well as the soil water content at the measurement, soil reflectance could be predicted. As a result, a clear separation is established between soil reflectance and reflectance of the vegetation cover if the vegetation index is known.

Keywords: near-infrared; reflectance; regression analysis; soil brightness; soil moisture; soil type

During the past several years, estimates of biomass, ground cover, leaf area index and nitrogen (N) supply as a function of spectral reflectance measurements have shown promising results (Casanova et al. 1998, Gao et al. 2000, Broge and Leblanc 2001, Huete et al. 2002, Wiesler et al. 2002, Leon et al. 2003). In most cases, vegetation indices have been proposed as proper estimators through contrasting reflectances in the red and near-infrared regions of the spectrum (Horler et al. 1983, Aparicio et al. 2002, Hansen and Schjoerring 2003). Near-infrared spectrometry (NIRS) is successfully used in precision agriculture and in industrial controlling of material properties (Paul et al. 2002, Sims and Gamon 2002). Nowadays, complete courses of spectral optical characteristics of canopies are required as input and validation parameters for crop growth models. Generally, disturbing effects like nutrient deficiencies (Masoni et al. 1996), sun-angle and canopy architecture (Pinter et al. 1985), soil background (Bausch 1993, Gao et al. 2000) as well as variety differences and plant development (Behrens et al. 2004) negatively impaired measurements of canopy reflectance, particularly concerning the whole production season (Leon et al. 2003).

Elimination of these disturbing factors is needed. Thus, a first step should be the quantitative separation between soil background signals and canopy reflectance.

Basically, contents of organic matter and minerals (Fe and Mn) in soil as well as water availability were the characteristics mainly influencing soil color and soil brightness (Schachtschabel et al. 1992). Bowers and Hanks (1965) concluded that reflectance spectra are strongly affected by soil moisture content, organic matter content and particle size. Al-Abbas et al. (1972) could show that light reflectance negatively correlates with organic matter and clay content. Henderson et al. (1992) found that reflectance of organic matter correlated with organic C content, humic acids and fulvic acids and responded to concentrations of Fe and Mn oxides. Chang et al. (2001) and Leon et al. (2003) used near-infrared spectrometry as a rapid soil testing technique for precision of the soil management to predict a broad range of chemical, physical and biochemical soil properties from soil samples. In a further step, Shepherd and Wals (2002) developed reflectance spectral libraries for characterization of soil properties of African topsoils. Lobell and Asner (2002) showed that the reflection of soil samples of different North American ecosystem types varied in relation to changes in soil moisture independent of the soil type. Most of these measurements are done with laboratory measurements under controlled measurement conditions.

Nevertheless, there is still a lack of information on the characteristics of reflection signals of agricultural soils gathered under site specific field conditions.

In this study, the relations between soil brightness as well as soil water content and the reflection signatures of soils were assessed in laboratory and field experiments. Soil brightness and soil moisture content were selected because the corresponding data are easy to collect. The goal of this research was to establish a clear separation between reflectance due to soil type as well as soil moisture and crop canopy reflectance.

MATERIAL AND METHODS

Soil reflectance measurements were carried out by means of two configurations of devices adopted either to the laboratory or to field experiments.

Laboratory experiments

For laboratory experiments soil samples of different Mid German agricultural field sites were taken in 2003 (Table 1), oven-dried at 75°C until constant weight and then passed through a 2 mm sieve. Soil type was determined after the FAO World Reference Base (WRB) of soils (Driessen et al. 2001). Thereafter, soil brightness values were expressed as rating values relative to the Munsell scale. In amendment to the original method, soil brightness ratings are determined for dried soil samples. White quartz sand and black peat were used as the higher (10) and the lower boundary (0), respectively. Expressed on mass basis, five different soil water contents (0, 5, 10, 15 and 20%) were adjusted to the topsoils Nordhausen and Bad Lauchstaedt.

Soil reflectance measurements were done with 20 replications, using a diode array spectroradiometer (Zeiss Corona, 400–1700 nm, Carl Zeiss Jena GmbH, Jena, Germany) combined with a light fibre diffuse optical reflectance measuring head (OMK) as described more in detail by Paul et al. (2002). The measurement was referenced to a $BaSO_4$ standard using measuring cells of optical glass (23 × 32 mm, filling height 10 mm).

Field experiments

In 2003, winter oilseed rape (*Brassica napus* L. cv. Lirajet) and barley (*Hordeum vulgare* L. cv. Barke) were grown on a haplic Chernozem in a plot design at Bad Lauchstaedt near Halle/Saale (11°52'E, 51°23'N) without N fertilization (–N) and with N fertilization (+N): oilseed rape 240 kg N/ha and barley 100 kg N/ha, including soil mineral content in 0–90 cm soil depth, in spring. Sowing date was August 22, 2002 (oilseed rape) with a density of 80 plants per m^2 and March 26, 2003 (barley) with a density of 320 plants per m^2. For each species, the experimental plots (10 × 3 m^2) were arranged in a block design with four replications. In both experiments, areas of 4 m^2 were kept free of vegetation for soil reflectance measurements. Spectral optical measurements (each 15 measurement replications) were done with a two spectroradiometers configuration using one measuring channel and one standard channel to measure canopy and soil reflectance. Reflectance of both spectrometers was calibrated using two PTFE (Polytetraflourethylen) panels (20 × 20 × 0.7 cm). Reflectance measurements were taken from nadir at 1 m height, resulting in a 0.50 m measuring diameter and sunny weather conditions with clear sky. For soil reflectance measurements, soil samples (soil depth 0–20 cm) were taken after the measurement, as described by Dematte and Garcia (1999). Water content of the soil samples was determined gravimetrically before and after the oven drying at 75°C.

Re-calculation of canopy reflectance

Separation of soil (R_S) and canopy reflectance (R_C) was calculated from soil and mixed reflectance (R_M) and soil cover index (*SCI*) after equation 1:

Table 1. Properties of the soils

No.	WRB-Classification	Soil depth	Location		Longitude/Latitude
1	ferric Cambisol	topsoil (0–5 cm)	Nordhausen	NDHt	10°47'E, 51°30'N
2	haplic Luvisol	topsoil (0–5 cm)	Goettingen	GOEt	9°56'E, 51°32'N
3	haplic Luvisol	topsoil (0–5 cm)	Hattorf/Harz	HATt	10°14'E, 51°39'N
4	haplic Chernozem	topsoil (0–5 cm)	Bad Lauchsteadt	BLSt	11°52'E, 51°23'N
5	haplic Chernozem	subsoil (60–70 cm)	Bad Lauchstaedt	BLSs	11°52'E, 51°23'N

$$R_C = [(R_M - R_S) \times (100 - SCI)]/SCI \quad (1)$$

The soil cover index (canopy area per soil area) was photographically estimated from nadir direction of 1 m^2 as an example on May 28, 2003 with a value of 0.93 without N fertilization according to Kraft (2002).

To show the effect of separated soil/canopy reflectance on vegetation indices, normalized difference vegetation index (NDVI) was calculated in equation 2 after Bausch (1993) as an example as follows:

$$NDVI = (R_{780} - R_{670})/(R_{780} + R_{670}) \quad (2)$$

Statistics

Data were subjected to analyses of variance (ANOVA). Results of the Tukey test and the *F*-test are given in figures ($P < 0.05$). Correlation coefficients (r^2) were calculated (***, ** and * indicate significance at the $P < 0.001$, 0.01 and 0.05 level, respectively).

RESULTS

Laboratory experiments

One easy method to characterize soil properties is to describe soil color and brightness. The parameters resulted from soil status and varying compositions of silicates, metals and organic matter in soil. Table 2 shows that the selected soils had different tints. The hue of the topsoils seemed darker from NDHt to BLSt. The subsoil (BLSs) showed a paler color compared to the four topsoils due to a lower content of organic matter. Quartz sand and black peat were defined as experimental treatments. Highest rating values of the agricultural soils were allocated to the ochre subsoil (BLSs). The topsoils had lower brightness values but differed in soil color. The ferric Cambisol (NDHt) appeared red and brighter than the two brown Luvisols (GOEt, HATt). The lowest values were assigned to the near black Chernozem (BLSt).

Spectral optical signatures of the dried soils differed considerably (Figure 1). As expected quartz sand always shows the highest reflections values and peat the lowest ones. Moreover, the reflectance values of the topsoils varied significantly. Reflectance signatures of the different soils coursed slightly parallel except the NDH topsoil. Here, the reflectance increased faster up to 600 nm due to the higher iron content of the ferric Cambisol. After that, the course of reflectance developed a comparably flat after 600 nm.

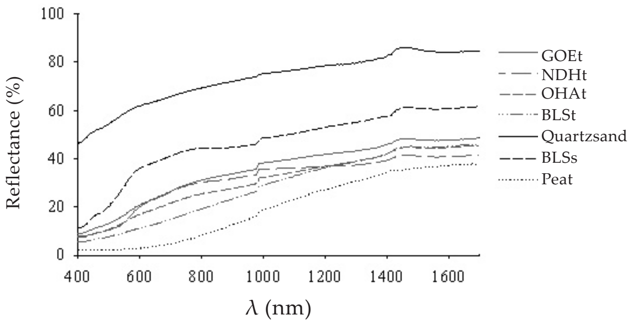

Figure 1. Soil reflectance at different wavelengths (λ) measured with laboratory configλuration OMK as affected by soil type and origin (*n* = 20)

Differences between reflectances of the different soils were examined more in detail at the selected near-infrared wavelength of 850 nm (Figure 2). The highest soil reflection was found for quartz -sand (74%) and the lowest (10%) for peat. Among the agricultural soils the subsoil of Bad Lauchstaedt (BLSs) showed the highest reflection value of 44%. The topsoils ranged between 32% (GOEt) and 21% (BLSt). Reflection values of the pale soils were throughout higher than those of the dark ones. The consideration of soil type and origin of soil

Table 2. Soil colors and rating values of soil brightness as affected by soil type and origin

Soil	Origin	Soil depth	Soil color	Rating value of soil brightness
Cambisol	Nordhausen	topsoil	red	5
Luvisol	Goettingen	topsoil	brown	4
Luvisol	Hattorf	topsoil	brown	4
Chernozem	Bad Lauchstaedt	topsoil	black	2
Quartzsand	–	–	white	10
Chernozem	Bad Lauchstaedt	subsoil	ochre	7
Peat	–	–	black	0

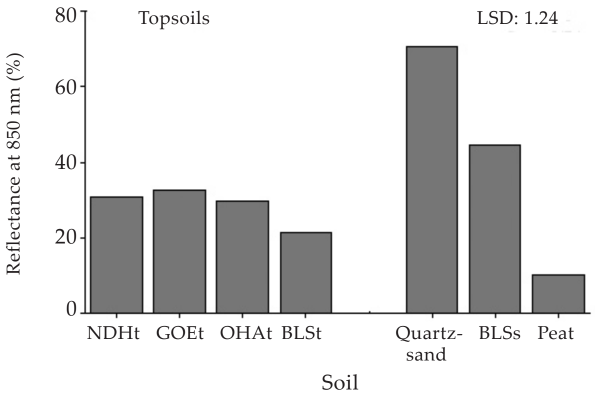

Figure 2. Reflection values at 850 nm measured with laboratory configuration OMK as affected by soil type and origin; all soils are significantly different at $P < 0.05$ (Tukey, n = 20)

reflectance is important for mixed reflection signals of vegetation and soil. A comparison of the reflection values at 850 nm and the rating values of soil brightness revealed a highly significant linear regression (Figure 3) indicating that the disturbing action of soil type could be eliminated by rating and standardization of soil brightness.

The impact of soil moisture content on spectral optical reflection was investigated in a second laboratory experiment. Two topsoils differing in soil brightness, i.e. BLSt (Bad Lauchstaedt) and NDHt (Nordhausen) were dried and then re-moisten gradually to soil moisture contents from 0 to 25% per mass. Spectral optical measurements showed that the reflection characteristics of both soils differ fundamentally (Figure 4). All curves of both soils coursed parallel. The reflection values

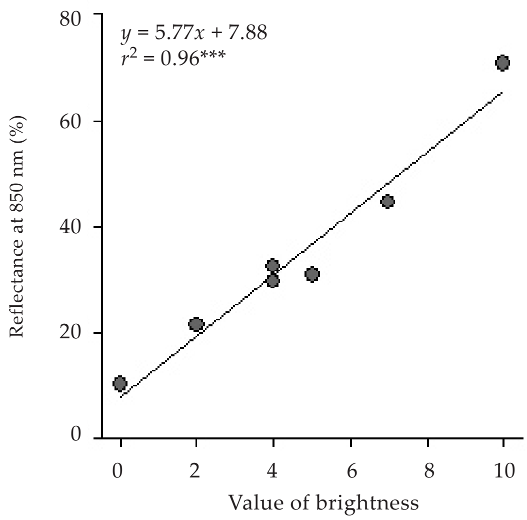

Figure 3. Relation between reflection values of soils at 850 nm measured with laboratory configuration OMK and rating of soil brightness (n = 20, *** indicates significance at the $P < 0.001$ level)

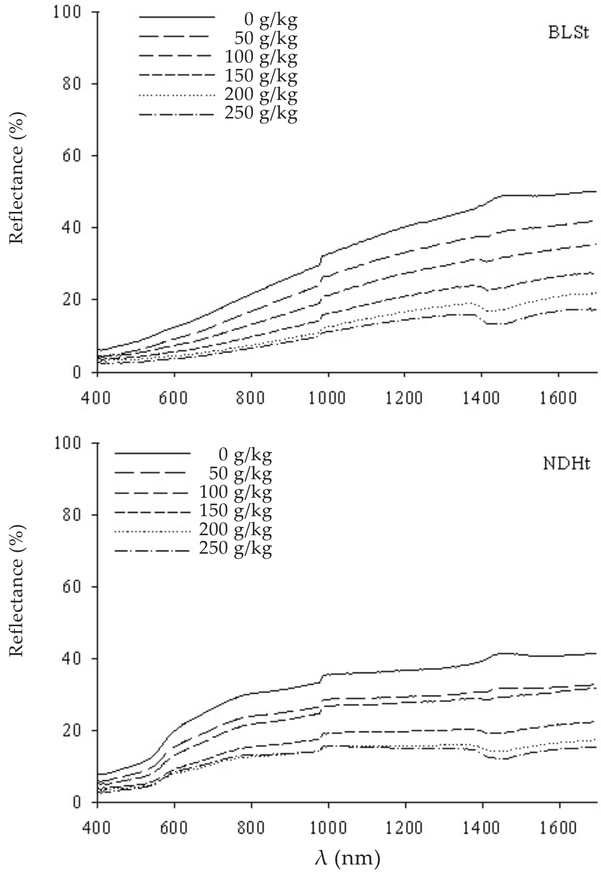

Figure 4. Soil reflectance at different wavelengths (λ) of two soils as affected by varied soil moisture contents (g/kg) measured with laboratory configuration OMK (n = 20)

of both soils were compared at a wavelength of 850 nm at increasing soil moisture contents. The reflection values of both soils decreased significantly when soil moisture contents increased (Figure 5). A strong negative relation between the reflection values and moisture contents was expressed in a non-linear exponential function. Based on these results the impact of soil moisture content on reflection characteristics could be verified.

Field experiments

The impact of soil moisture content on spectral reflectance signatures was estimated in field experiments. Reflectance measurements were conducted during the growth periods of oilseed rape and barley on areas kept free of vegetation. Figure 6 shows that the soil moisture content (0–20 cm) decreases from spring to summer whereas soil reflectance signals increased with increasing soil desiccation. A strong negative non-linear relation was found expressed in an exponential function (Figure 7). These results are in agreement with the data from

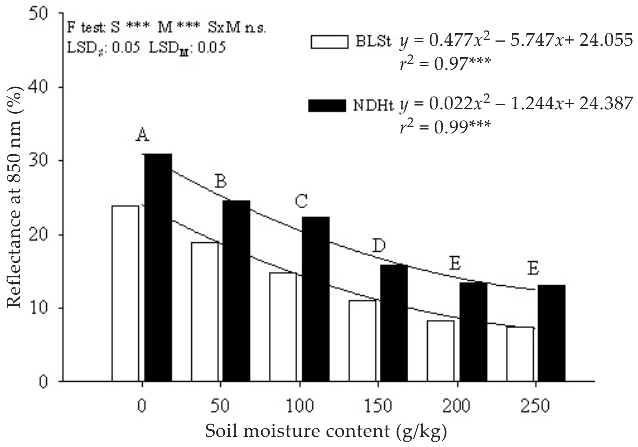

Figure 5. Reflection values at 850 nm of two different agricultural soils (S): Bad Lauchstaedt (white) and Nordhausen (black) as affected by varied soil moisture contents (M) measured with laboratory configuration OMK (means followed by different letters are significantly different at $P < 0.05$, Tukey, $n = 20$) and relations between reflectance at 850 nm and soil moisture content ($n = 20$, *** indicates significance at the $P < 0.001$ level)

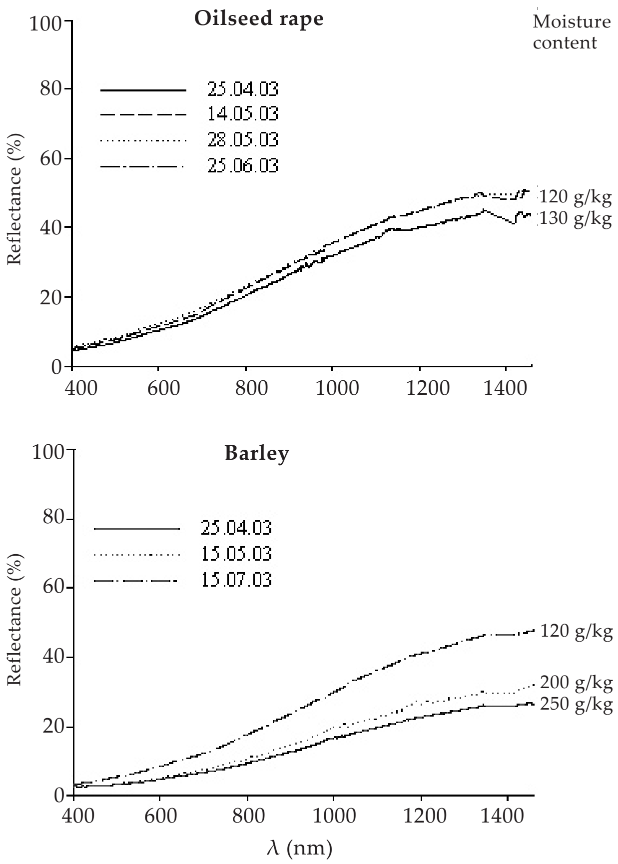

Figure 6. Soil reflectance at different wavelengths (λ) as affected by soil moisture content of the topsoil (0–20 cm) during vegetation of winter oilseed rape and barley measured with field configuration ($n = 15$)

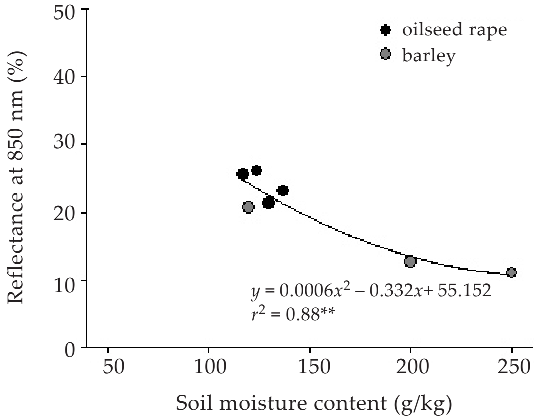

Figure 7. Relation between soil reflection values at 850 nm and soil moisture content during vegetation of winter oilseed rape (black) and barley (grey) ($n = 7$, ** indicates significance at the $P < 0.01$ level)

laboratory experiments. But field measurements resulted in higher reflectance values compared with laboratory measurements.

Additionally, spectral optical measurements were carried out to investigate the reflectances of soils and oilseed rape canopies. In early growth stages and in treatments with reduced N fertilization, the canopy covered the soil still incompletely. Then mixed reflection signatures of canopy and soil were measured and the corresponding data were pooled to one value. Spectral reflection signatures of soils on May 28, 2003 differed from those of N-fertilized and unfertilized oilseed rape canopies as presented in Figure 8. As known, soils have different courses of reflectance than canopies. N-unfertilized canopies showed a lower reflectance in a range of 700 to 1300 nm than N-fertilized canopies and resulted in a remarkable reduction on calculated index values. For example, NDVI decreased from 0.88 (+N) to

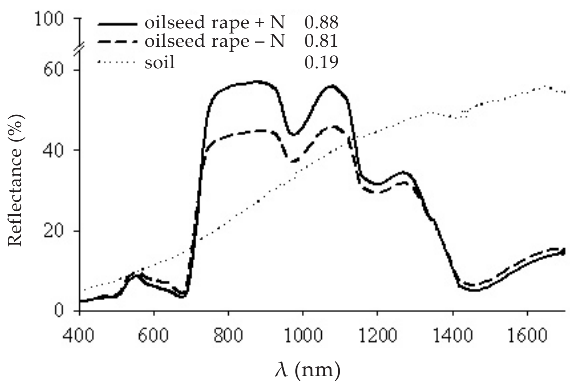

Figure 8. Spectral reflectance at different wavelengths (λ) of bare soil and oilseed rape canopies (–N, +N) and reflection index NDVI (given as numbers) at May 28, 2003 with the field configuration ($n = 60$)

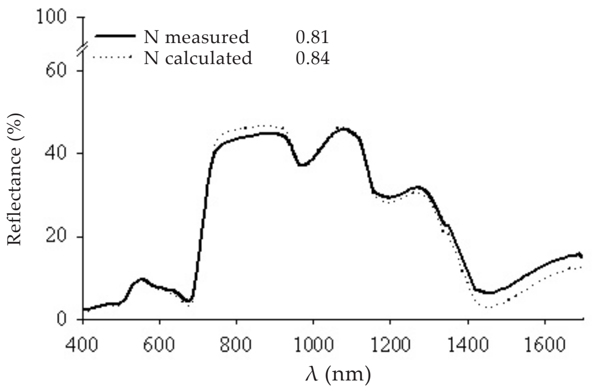

Figure 9. Spectral reflectance at different wavelengths (λ) of oilseed rape canopy (–N) and reflection index NDVI (given as numbers) at May 28, 2003 measured with field configuration (line) and re-calculated after equation 1 (dotted) (n = 60)

0.81. This could be due to canopy properties like lower N content and/or influence of the lower soil reflectance on the mixed signal, based on lower soil cover index. To clear the reason, soil cover index (SCI) was evaluated from photography with a value of 0.93. After a re-calculation of the reflectance signature under consideration of SCI after equation 1, the influence of soil reflectance was separated from canopy reflectance. The re-calculated canopy reflectance differed from mixed reflectance. It increased in a range of 700–950 nm and decreased from 1150 to 1650 nm in comparison with the measured mixed signature (Figure 9). This increase around the red edge inflection point (~720 nm) resulted in remarkable increase of NDVI from 0.81 (meas.) to 0.84 (calc.).

DISCUSSION

During early growth stages as well as under conditions of reduced N fertilization mixed reflection signals existing from characteristics of soil and canopy reflectance were measured by remote sensing (Duke and Guérif 1998). The influence of soil reflectance decreases with increasing biomass formation. To describe courses of state values of crop canopies with remote sensing with higher precision, it is necessary to separate the influence of soil reflectance from canopy reflectance (Lobell and Asner 2002).

But soil reflection signature depends on many factors like soil type, clay content, particle size and the contents of organic matter, mineral nutrients, metals and soil moisture (Bowers and Hanks 1965, Chang et al. 2001, Chen et al. 2004). Additionally, some of these soil properties like soil moisture content and soil nutrient states vary seasonally (Lobell and Asner 2002). Dematte and Garcia (1999) as well as Lobell and Asner (2002) showed that soils of widely varying ecosystems differ in soil reflectance. Therefore, it is necessary to determine fundamental relations between reflection signatures and state values.

Our experience showed that reflectance measurements of bare soils related to each canopy measurement are work-intensive and not usable in practice, because the measuring area must be kept free of vegetation during whole growth period. It is easier to depict signature of soil reflectance that belongs to the canopy measurement, if general relations between soil properties and soil reflectance are known. Therefore several laboratory and field experiments were carried out.

In the first laboratory experiment, the multiplicity of soil properties was aggregated to two main factors mostly influencing soil color and brightness: (a) soil type, primarily governed by contents of organic matter and metals, and (b) soil moisture content. Soil color and brightness are easy to estimate by ratings associated to the Munssel scale. In deviation from the original method our rating was done with dry soils, as the effect of soil moisture content on soil reflectance should be examined separately. We found significant differences between the soil colors and brightness values of the four agricultural topsoils (GOE > NDH > HAT > BLS) as well as between the two different soil depths of soil of Bad Lauchstaedt (subsoil > topsoil).

Similar differences were proved with near-infrared reflection spectrometry in the laboratory configuration. The reflectance signatures of the agricultural soils varied the same. Each of the soils could be individually characterized. Compared to the results of Dematte and Garcia (1999) as well as Lobell and Asner (2002), this is an extension of knowledge because the soils used in our study originated from similar ecosystems. Furthermore, a linear relationship was found between the soil brightness values and the soil reflectance values at 850 nm in which the reflection value at 850 nm was used as an example for other reflection values and indices. Hence, the disturbing action of soil type negatively influencing soil/canopy reflectance could be normalized and also eliminated by fast ratings of soil brightness.

Also, soil moisture content influenced the reflectance of soils. The reflectance value at the wavelength 850 nm of the Luvisol as well as the Chernozem decreased about 40% with increasing soil moisture from 0% to 25%. The signatures of the two Mid German agricultural soils showed nearly constant courses that only varied in their soil type-depending height. This relationship was depicted by exponential curves confirming further investigations of Lobell and Asner (2002) considering soils of different ecosystems. Thus, the disturbing factor of soil moisture could be eliminated.

Most results to investigate physical and chemical soil properties presented in past were carried out in laboratory measurements (overview in Shepherd and Wals 2002). But there is still a lack of information concerning measurements of soil reflectance directly on field. The comparison of laboratory and field measurements of the same topsoil (Bad Lauchstaedt) in our experiments resulted in comparable reflection signatures and the same information considering the exponential relation between reflectance and soil moisture content. But the reflectance of the field experiments was always higher than that of the laboratory experiments. These differences were led back on different measurement conditions like standardization of the spectrometers and light conditions at the measurement. Additionally, it may be possible that gradients in moisture content existed in the soil profile of the field experiments whereas the re-moistening of the soils was uniform in the laboratory experiment. However, laboratory experiments represented the fundamental relations of soil reflectance and soil type as well as soil moisture content. Field observations are generally necessary to calculate the algorithms.

Our experience shows that it is possible to depict the signature of soil reflectance that belongs to a canopy reflectance measurement.

To separate canopy and soil reflectance, soil cover index on measuring date was evaluated in a treatment with reduced N fertilization for example on May 28, 2003. The reflectance signature of the canopy was re-calculated after equation 1 and compared with the measured mixed signature. As a result, reflectance at wavelengths between 700 and 950 nm increased in comparison to the mixed reflectance and decreased behind 1150 nm. For this example, the differences between measured and re-calculated signatures were small because of the high soil cover index of 0.93. Despite of these small differences, the re-calculation caused a remarkable increase of NDVI. Our results show that the reduction in NDVI in the N-unfertilized oilseed rape canopy on May 28, 2003 was led back on lower canopy N content (57%) and on influence of soil reflectance (43%) compared with high N supply. Regarding courses of reflection values and/or reflection indices, differences in re-calculated canopy reflectance signatures will increase in earlier growth stages with smaller soil cover indices. Considering time courses of reflection indices, the successful separation of soil and canopy reflectance will lead to a higher precision in remote sensing.

In summary, significant interrelations between spectral optical reflection signatures and physical properties were found for Mid German agricultural soils. Algorithms were established to normalize soil type and soil moisture content of the reflection signature. Considering the soil coverage, the soil reflectance could be clearly separated from canopy reflectance.

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ABSTRAKT

Separace optické odrazivosti půd a rostlinného krytu na zemědělských půdách středního Německa

Dálkový průzkum Země (DPZ) může poskytnout vizuální údaje o růstu plodin během vegetačního období. V minulosti byly prováděny dobré spektrální optické odhady, které korelovaly s vlastnostmi půdy a rostlin, nebyly však konzistentní během celého období růstu. Modely odrazivosti půdy při měnící se vlhkosti jsou nezbytné pro lepší kvantifikaci vlastností porostu z údajů DPZ. Byly získány zápisy odrazivosti pro několik zemědělských půd středního Německa v laboratorních a polních pokusech. Výsledky byly hodnoceny v infračervené oblasti spektra při vlnové délce 850 nm. Vybrané půdy představovaly různé barvy a odstíny půdy odrážející široký rozsah půdních vlastností. Při vlnové délce 850 nm se odrazivost půdy pohybovala v rozmezí 10 % (černá rašelina) až 74 % (bílý křemenný písek). Odrazivost svrchní vrstvy půdy se pohybovala v rozmezí 21 % až 32 %. Regresí byl zjištěn lineární vztah mezi hodnotami odstínu půdy a spektrální optickou odrazivostí. Zvýšení půdní vlhkosti z 0 na 25 % snížilo odrazivost půdy při 850 nm u dvou různých půd o zhruba 40 %. Vztah mezi odrazivostí půdy a půdní vlhkostí byl popsán nelineární exponenciální funkcí. Půdní odrazivost lze předpovídat s využitím znalosti individuálního zápisu půdní odrazivosti a obsahu vody v půdě. Jako výsledek lze jasně oddělit půdní odrazivost a odrazivost rostlinného krytu, pokud je znám vegetační index.

Klíčová slova: blízké infračervené spektrum; odrazivost; regresní analýza; odstín; vlhkost půdy; půdní typ

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