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Combining ultrasonic sward height and spectral signatures to assess the biomass of legume–grass swards

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ABSTRACT

In binary mixtures of either white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.) or lucerne (*Medicago sativa* L.) with perennial ryegrass (*Lolium perenne* L.) as well as in pure swards of each single species, biomass has been assessed measuring sward height with an ultrasonic distance sensor and spectral-radiometric reflections. Measurements and sampling of reference data were conducted along a wide range of biomass levels on 0.25 m^2 subplots at 17 dates in 4 growth periods defined by 4 main cuts between September 2005 and September 2006. To improve biomass (BM) predictions on exclusive ultrasonic sward height (USH) by complementation of vegetation indices (VIs), a collection of existing and hyperspectral VIs have been evaluated in combination with USH. While red/NIR-based VIs performed suboptimal, indices representing bands related to water absorption or the NIR-shoulder showed better predictions. Best prediction accuracies were achieved by a combination of USH with sward-specifically selected 1 nm bands using the normalized spectral vegetation index (NDSI) reaching R^2-values of 0.83 in common swards and 0.88–0.90 for species-specific calibrations, respectively. Broadening of bands up to 100 nm did only marginally reduce prediction accuracies. Using fixed NDSI bands selected from common swards instead of sward specific selected ones, did not significantly reduce prediction accuracy. It is identified that VIs act complementarily to USH and can avoid overestimations of BM frequently observed in grassland by the exclusive use of USH. Both, bandwidth flexibility and fixed NDSI band configurations can facilitate a configuration of sensors for legume–grass swards in a wide range of yield levels.

1. Introduction

The effectiveness of yield mapping is primarily determined by the specification of the sensor system (Schellberg et al., 2008). Remote sensing as a non-destructive on-ground application is one option for yield data acquisition in standing swards. Mounted on vehicles appropriate sensors can enable an online assessment of biomass (BM) and other functional crop properties while standard agricultural measures are conducted (Heege et al., 2008; Biewer et al., 2009; Robertson et al., 2012). In organic farming legume–grass swards account for a substantial fraction of the crop rotation and BM assessment is of great importance to consider BM productivity and nitrogen cycling on field and farm levels (Kayser et al., 2010). In these swards types the assessment of BM can be conducted by measuring sward height with an ultrasonic distance sensor (Fricke et al., 2011). Hereafter, crop height measured with an ultrasonic sensor is referred to ultrasonic sward height (USH). In addition to grassland swards ultrasonic distance sensors have been investigated in different crops. In winter wheat Reusch (2009) used a specific configuration of an ultrasonic sensor retrieving multiple echoes from different leaf layers achieving high prediction accuracies (R^2 = 0.85–0.93). Recent studies focus on the assessment of plant heights in wild blueberries to analyse site specific variation and interpret fruit yield relationships (Farooque et al., 2013) or ultrasonic plant height measurements were used to discriminate weeds and wild blueberry plants in order to steer an automated variable-rate sprayer for spot application (Zaman et al., 2011). The same principle can be used for the detection of weeds in cereals for a site-specific weed management (Andújar et al., 2012).

Although in grassland swards of different species compositions BM can be predicted well with ultrasonic distance measurements reaching R^2 values between 0.75 and 0.82 (Fricke et al., 2011), the crop geometry, leaf surface and density of plants take influence on sonic reflections and may lead to disproportional relationships between plant height and BM (Hutchings, 1991, 1992; Fricke et al., 2011).

To overcome these limitations, the idea of this study was, to compensate the relationship between BM and USH with a sensor measurement related to sward density. In this sense the implementation of spectral vegetation indices (VIs) is of interest as they are strongly correlated to the leaf area index (LAI) and have been

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frequently evaluated for the prediction of biomass in grassland (Weiser et al., 1986; Mutanga and Skidmore, 2004; Boschetti et al., 2007; Numata et al., 2007; Chen et al., 2009; Vescovo et al., 2011; Flynn et al., 2008; Kawamura et al., 2011).

However, also BM predictions based on VIs are often limited by either background scattering of soil reflections (Elvidge and Lyon, 1985; Huete et al., 1985) or saturation effects expressed by a limited increase of vegetation index values at high biomass levels (Mutanga and Skidmore, 2004; Chen et al., 2009). Saturation of VI values especially occur when leaf area index (LAI) values exceed 2.0–2.5 (Serrano et al., 2000; Heege et al., 2008) which is frequently passed over in legume–grass mixtures (Joggi et al., 1983; Virkajärvi, 2003). Furthermore, the LAI maybe impaired by biochemical properties like chlorophyll content (Goel, 1989; Jacqemoud et al., 2000). Those interferences were frequent for traditional VIs as the normalized difference vegetation index (NDVI) calculated as $(R_{nir} - R_{red})/R_{nir} + R_{red})$ (Rouse et al., 1974). Modifications of VIs were e.g. motivated by reducing the above mentioned saturation effects or influences of soil background scattering (Elvidge and Lyon, 1985; Huete et al., 1985; Bannari et al., 1995; Broge and Leblanc, 2000; Chen et al., 2009). Improvements have been made by the choice of distinct narrow bands (Blackburn, 1998; Thenkabail et al., 2000; Mutanga and Skidmore, 2004). Against this background the NDVI-formula with reflectance values of selected wavelengths $(R_{band2} - R_{band1}/R_{band2} + R_{band1})$ defined as normalized difference spectral index (NDSI) by Inoue et al. (2008) allows a selection of the most prominent wavelength combinations and was used to estimate LAI, biomass and chlorophyll content (Ferwerda et al., 2005; Hansen and Schjoerring, 2003), as well as pasture growth rate and pasture P and K (Kawamura et al., 2011).

Especially in grassland vegetation it is a challenge to adapt remote sensing measures due to big variations in species composition and phenological development (Schellberg et al., 2008). Particularly simple and low cost equipment like ultrasonic distance sensors and 2-band-spectrometers are sensitive to sward-borne variation. By reason of interactions between sensors properties and sward characteristics a combination of sensors can complement one another (Lan et al., 2009). Even though such combination of sensors have been suggested for the assessment of different crop or soil properties (Lee et al., 2010), only few studies have investigated such strategies (Mahmood et al., 2012; Scotford and Miller, 2004) achieving improvements of 0.05–0.1 R^2-scores by combining USH and NDVI compared to exclusive NDVI (Jones et al., 2004). The purpose of the present study is to analyze the potential of ultrasonic distance measurements in combination with spectral-radiometric VIs and to address the following main objectives:

- Evaluate the benefit of an ultrasonic and spectral sensor combination in comparison to exclusive use of either one concerning the prediction quality of biomass in legume grass swards.
- Determine the potential of sward-specific wavelength selection for a configuration of the NDSI and to locate spectral regions of interest for a reliable sensor configuration.
- Analyse bandwidth effects on prediction quality for sward adapted two-band VI (NDSI) configurations either in exclusive use or in combination with USH.
- Evaluate compensation effects of the two-sensor system.

2. Materials and methods

2.1. Experimental design and management regime

The study is based on a grassland field experiment conducted during 2005 and 2006 on the experimental farm Neu Eichenberg of the University of Kassel (51°23′ N, 9°54′ E, 227 m above sea level; soil type: sandy loam; soil ph-value: 6.4; average annual rainfall: 550 mm; annual mean temperature: 9.9 °C). Sward plots of size 29 m^2 $plot^{-1}$ (2.9 × 10 m) were composed of binary mixtures of perennial ryegrass (*Lolium perenne* L., var. Fenema) with red clover (*Trifolium pratense* L., var. Pirat), white clover (*Trifolium repens* L., var. Klondike) or lucerne (*Medicago sativa* L., var. Ameristand), respectively, as well as pure swards of each species. To increase growth variation in the year of sward establishment (2005), additional pure grass swards were set up and fertilized with five N treatments: 0, 40, 80, 120, 160 kg N ha^{-1}. Overall 11 treatments replicated 4 times in 2005 (44 plots) and 7 treatments replicated 3 times in 2006 (21 plots) were disposed for data assessment at the respective sampling dates.

The cutting regime was configured with one main cut in the year of sward establishment 2005 and three main cuts in 2006. Within these four growth periods measurements of USH and spectral reflectance as well as the sampling of reference biomass were taken biweekly due to slow sward establishment in 2005 ($n = 74$) and weekly in 2006 ($n = 220$) at 17 dates between 5th September 2005 and 25th September 2006. Plant development stages ranged from leaf development to heading (ryegrass), flowering (red clover) or development of fruits (white clover), respectively. Lucerne swards were damaged by frost in winter 2005/2006 and due to a limited availability of intact swards, sampling was defined to the main cutting dates. Here, the range of plant development at sampling dates was reduced from booting to flowering.

2.2. Sensor measurements

In the course of sampling intervals sensor measurements took place prior to reference data assessment. Due to unstable weather conditions along the growth periods not all plots could be measured with both sensors at the same time. Hence, for this study only those samples were selected, where both sensor measurements could be properly assessed in order to simulate a combined sensor configuration as it would be used in practical applications.

Spectral and ultrasonic sensors were subsequently mounted above the same sub plot according to the following descriptions.

2.2.1. Hyperspectral reflectance

Spectral measurements were conducted as the first step in the course of sensor measurements one day before sampling on 0.25 m^2 subplots used for reference data acquisition. Canopy reflectance was assessed using a Spectrometer of type FieldSpec Pro JR (Analytical Spectral Devices, Boulder, CO) measuring irradiance from swards in the range from 350 to 2500 nm (Fig. 1) with a spectral resolution of 3 nm (350–1000 nm) and 30 nm (1000–2500 nm). Measurements were subsequently interpolated by the Analytical Spectral Devices (ASD) software RS3 to produce readings at an interval of 1 nm. The sensor optic had a field of view of 25°, which was stabilized on a tripod at a height of 1.07 m above soil. Readings were taken on cloudless days with almost uniform lighting intensity between 10:00 and 14:00 h Central European Time. Spectral calibrations were performed at least after every sixth measurement using a Spectralon panel (Labsphere, Inc., North Sutton, NH). Each spectrum was composed of four measurements representing a total of 40 replicated scans.

2.2.2. Processing of spectral data

Prior to spectral analysis, spectra were smoothed using 11 convoluting integers and a polynomial of degree five (Savitzky and Golay, 1964; Erasmi and Dobers, 2004). Three wavelengths regions (1351–1439 nm, 1791–2019 nm, and 2351–2500 nm) were visually identified and omitted due to instrument noise, stray light effects or high atmospheric water absorption, remaining 1877 1 nm spectral channels in the range of 355–2350 nm for the selection of wavelengths to calculate common narrow and broad