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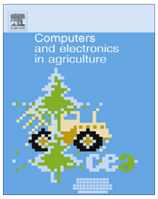

A multi-sensor approach for predicting biomass of extensively managed grassland

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ABSTRACT

Leaf area index (LAI), ultrasonic sward height (USH) and common vegetation indices (VI) derived by spectral radiometric reflection data were collected on an experimental field site with three sward types comprising a pure stand of reed canary grass (*Phalaris aruninacea*), a legume grass mixture and a diversity mixture with thirty-six species in an extensive two cut management system. Sensor measurements and biomass samplings of 0.25 m^2 subplots were conducted biweekly between May and October in 2009 and 2010. Different combinations of the sensor response values were used in multiple regression analysis to improve biomass (BM) predictions compared to exclusive sensors. Wavelength bands for sensor specific NDVI-type vegetation indices were selected from the hyperspectral data and evaluated for the biomass prediction as exclusive indices or in combination with LAI and USH. In the set of tested parameters, ultrasonic sward height was the best to predict biomass in single sensor approaches (R^2 0.73–0.76). Inclusion of LAI improved the model performance and reduced the prediction accuracy by up to 30% for complex swards, while inclusion of vegetation indices resulted only in minor improvements compared to exclusive USH. LAI acted complementary to USH in a combined prediction model, correcting for overestimations of biomass in high swards. Prediction models using exclusive LAI were barely suited to predict biomass accurately (R^2 0.36–0.44) but improved significantly when combined with waveband selected VIs ($R^2 < 0.8$). Combining all three sensors did not significantly improve the model performance.

1. Introduction

Aboveground biomass is an important parameter in studies of cultivated and natural vegetation for the development of a sustainable bio energy policy (Jing et al., 2012). Energy policies around the world are mandating for a progressive increase in renewable energy production. Marginal lands such as riparian areas and flood plains with lowered productivity and land use limitations have become target areas for sustainable energy production from energy crops to avoid competition with food production on the limited available arable land resources. Natural flood plains are disturbance-dominated ecosystems that are characterized by a high spatio-temporal habitat heterogeneity, high species-diversity and productivity along with recreational and aesthetic values (Ward et al., 1999; Tockner and Stanford, 2002). They provide a wide range of ecosystem functions, such as filtering pollutants and excess nutrients (Yates and Sheridan, 1983) and reducing erosion rates after flood events due to slowed water downstream, but these functions are challenged by river management, shifting land uses, intensification, and climate change (e.g. Tscharntke et al., 2005; Krause et al., 2011). Krause et al. (2011) identified a loss of 80% of unprotected wetland area for northern Germany over the last 50 years due to intensified management, land use change and abandonment resulting in a loss of biodiversity and other valuable functions of these ecosystems.

For this reason, energy policies are targeting sustainable second generation, non-food energy crops and biofuels which can be designed and managed appropriately to maintain biodiversity, reduce GHG emissions and maintain the basic ecosystem functions of marginal lands (Dale et al., 2010; Rowe et al., 2009; Tilman et al., 2009).

The European Union (EU) Renewable Energy Directive (2009/28/EC) (RED) is calling for 20% of the total energy production to originate from renewable resources by 2020 with biomass being a major contributor. Effective implementation strategies require economic calculations on the basis of accurate projections of expected biomass yields. A broad literature review on five important energy crops revealed that projected biomass yields tend to be overestimated on semi-commercial scale trials or on marginal land, partially due to inappropriate up-scaling from small sized experimental sites (Searle and Malins, 2014). Therefore,

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biomass projections on the basis of larger commercial scale trials are supposed to be more accurate. Direct harvesting of biomass is currently the most widely used and most accurate method of determining biomass. The main disadvantage to this method is the time involved and consequently, the high cost of each sample. Because this is barely applicable on a larger scale, samples collected only represent a small area out of large and highly variable swards (Haydock and Shaw, 1975; Harmoney et al., 1997; Sanderson et al., 2001). Because the error in yield estimates lies predominately in the variability of the swards and not in the precision of the measurements, it is better to take more samples with less precision than few measured precisely (Haydock and Shaw, 1975). Non-destructive sensing methods with a rapid sampling rate have been developed to estimate forage biomass faster and more efficiently, with varying levels of success (Schellberg et al., 2008). One rapid, non-destructive method to estimate biomass involves the measurement of the leaf area index (LAI) by remote sensing or optical instruments. The LAI is a dimensionless variable which was first defined by Watson (1947) as the total one sided foliage area per ground surface area. It has been tested for the estimation of grassland and pasture biomass with varying results (Harmoney et al., 1997; Ganguli et al., 2000; Miller-Goodman et al., 1999). Linear relationships between leaf area index (LAI) and biomass have been identified for Swards of orchardgrass (*Dactylis glomerata* L.) smooth bromegrass (*Bromus inermis* L.) and tall fescue grass (*Festuca arundinacea* L.) (Pearce et al., 1965; Engel et al., 1987; Trott et al., 1988). In contrast to destructive and tedious direct methods for the estimation of LAI by harvesting or litter traps, indirect methods use canopy properties and gap fractions to estimate the proportion of vegetative surface area (Jonckheere et al., 2004). Recent studies focus on methods to derive the leaf area index directly from hyperspectral data and vegetation indices with varying results (Darvishzadeh et al., 2008, Stagiest et al., 2010). However, it has been shown that a combination of in-situ LAI measurements, e.g. LI-COR LAI-2000, and spectral vegetation indices can provide better estimates for LAI, directly measured by harvest, than LAI or vegetation indices alone (van Wijk and Williams, 2005).

Remote sensing technology using hyperspectral reflectance measurements have become an important approach to estimate aboveground biomass at large special scales. Spectral reflection measurements have been widely used for the characterization of grassland biomass, obtained from hand-held spectral radiometers (Mutanga et al., 2004; Chen et al., 2009; Vescovo et al., 2012; Kawamura et al., 2011) but may contain large amounts of redundant information. For practical implementation at field scale, hyperspectral measurements are expensive and, therefore, the limitation of wavebands as vegetation indices is desirable. Vegetation indices (VIs) are widely used in remote sensing models for estimation of various crop characteristics (Hatfield and Prueger, 2010; Huang et al., 2012) like grassland biomass (Todd et al., 1998; Boschetti et al., 2007; Numata et al., 2007). However, the performance of VIs is highly site and sensor-specific (Huang et al., 2004). VIs based on NIR/red ratios like the normalized difference vegetation index (NDVI) indicated saturation around a leaf area index of about 2.0–2.5 (Heege et al., 2008), which limits their applicability at higher biomass levels. Modifications have been applied to reduce the saturation effects and the vulnerability to other environmental influences like soil background scattering (Elvidge and Lyon, 1985; Huete et al., 1985; Broge and Leblanc, 2001; Chen et al., 2009). Selection of distinctive narrow bands from hyperspectral data, e.g. according to the NDVI-type formula have shown improvements to traditional VIs (Blackburn, 1998; Thenkabail et al., 2000; Inoue et al., 2008). Other methods utilizing the sward height as a predictor for aboveground biomass have been successfully established in the past. It has been shown that biomass of binary and pure species grassland swards can be predicted well using non-destructive ultrasonic sward height (USH) measurements, reaching R^2 values between 0.75 and 0.82 (Fricke et al., 2011). However, sward geometry, leaf surface and sward density can impact the response signal and may lead to disproportional relationships between plant height and biomass (Hutchings 1991, 1992; Fricke et al., 2011). These limitations in USH might be overcome by a combination with other parameters that are related to sward density and lateral sward geometry, like LAI or spectral vegetation indices. Fricke and Wachendorf (2013) have already shown an increased prediction performance of a combined sensor approach using ultrasonic sward height and spectral vegetation indices for commercial binary legume grass swards. However, the increased structural and chemical complexity in swards of higher biodiversity might reduce the performance of spectral vegetation indices as a predictor and, therefore, reduce the synergy effect of a multi sensor approach. The benefit of a multisensor approach in diverse extensive grassland using USH and spectral VIs has yet to be verified.In the context of a transdisciplinary research network on regional climate adaptation (Roßnagel, 2013), three different extensively managed grassland sward types, adapted to floodplain conditions, were tested for their energy potential with a high resolution covering the extensive spatio-temporal variation in floodplain areas. The main objective of this study was to compare the effectiveness of all possible combinations of three non-destructive sensor methods including ultrasonic sward height, LAI-2000 measurements and traditional spectral vegetation indices for estimating biomass in extensively cut grassland with a complex vegetation structure. Further objective was to evaluate the inclusion of a two band NDVI-type vegetation index according to the normalized difference spectral index (NDSI) formula introduced by Inoue et al. (2008) based on wavelength selection for the common swards.

2. Materials and methods

2.1. Experimental site

A field experiment was established in autumn 2008 and measurements were conducted in the years 2009 and 2010. The experimental field site was located in a floodplain, 100 meters from the river Werra and 100 m from its tributary Gelster at the city of Witzenhausen (52°21′N, 9°52′E, altitude 137 m a.s.l.). The two year average annual rainfall was 863 mm, with an average temperature of 9.0 °C. The dominating soil type was a Fluvi-Eutric Cambisol. Prior to the experiment, the area had been used for cultivation of oats and alfalfa and is surrounded by intensified agricultural cropland.

2.2. Experimental design

Seed compositions were chosen on the basis of the development and evaluation of a utilization strategy for extensive grassland in river floodplains for bioenergy production. The compositions comprised a reed canary grass (*Phalaris arundinacea*) monoculture (RCG), a standard mixture (STA) including seven common species of grasses and legumes and a diversity mixture (DIV) of thirty-six species of grasses, herbs and a legume, which are typical for traditional grassland in river floodplains. The total study site contained 24 plots divided into three sward seed compositions and two fertilization variants in fourfold replication. The plot size was 4 m length and 1.5 m width aggregated for each replication in 4 randomized rows. An equivalent of 100 kg N per hectare of chicken manure was manually applied in March 2009 and 2010 on half of the plots. The rest remained unfertilized. All plots were harvested twice per year at the beginning of July and October with a finger bar mover at a cutting height of 5 cm.