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Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor

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A B S T R A C T

The regional mapping of grass nutrients is of interest in the sustainable planning and management of livestock and wildlife grazing. The objective of this study was to estimate and map foliar and canopy nitrogen (N) at a regional scale using a recent high resolution spaceborne multispectral sensor (i.e. RapidEye) in the Kruger National Park (KNP) and its surrounding areas, South Africa. The RapidEye sensor contains five spectral bands in the visible-to-near infrared (VNIR), including a red-edge band centered at 710 nm. The importance of the red-edge band for estimating foliar chlorophyll and N concentrations has been demonstrated in many previous studies, mostly using field spectroscopy. The utility of the red-edge band of the RapidEye sensor for estimating grass N was investigated in this study. A two-step approach was adopted involving (i) vegetation indices and (ii) the integration of vegetation indices with environmental or ancillary variables using a stepwise multiple linear regression (SMLR) and a non-linear spatial least squares regression (PLSR). The model involving the simple ratio (SR) index (R_{805}/R_{710}) defined as SR54, altitude and the interaction between SR54 and altitude (SR54 * altitude) yielded the highest accuracy for canopy N estimation, while the non-linear PLSR yielded the highest accuracy for foliar N estimation through the integration of remote sensing (SR54) and environmental variables. The study demonstrated the possibility to map grass nutrients at a regional scale provided there is a spaceborne sensor encompassing the red edge waveband with a high spatial resolution.

1. Introduction

Regional mapping of grass nitrogen (N) as an indicator of grass quality provides essential information for sustainable planning and management of livestock and wildlife grazing. Grass N concentration is positively correlated to protein content (Clifton et al., 1994; Wang et al., 2004) and is a major nutrient for herbivores (Prins and Beekman, 1989; Prins and van Langevelde, 2008). Grass N generally correlates with soil fertility levels (Ben-Shahar and Coe, 1992; Olff et al., 2002). Therefore, grass N concentrations could be used as a proxy for soil fertility levels. Grass quality affects the distribution and grazing behaviour of livestock and wildlife (Ben-Shahar and Coe, 1992; Heitkönig and Owen-Smith, 1998; McNaughton, 1990). For example, large herbivores concentrate in highly nutritious areas in southern Africa (Grant and Scholes, 2006; Owen-Smith and Danckwerts, 1997) and herbivore diversity increases with increasing soil fertility levels (Olff et al., 2002). Spatial and regional information about grass nutrients is useful to guide farmers, planners and managers towards sustainable management of their grazing land. To capture the landscape or spatial variation of nutrients, remote sensing could play a pivotal role.

Remote sensing techniques have been developed over the past decades to extract information about biophysical and biochemical parameters of vegetation such as leaf area index, chlorophyll, phosphorus, fibre, lignin, and N (Asner et al., 1998; Darvishzadeh et al., 2008; Ramoelo et al., 2011b). The conventional approach relates a specific vegetation parameter to vegetation indices derived from remote sensing data using a variety of statistical regression techniques (Darvishzadeh et al., 2008; Haboudane et al., 2004; Hansen and Schjoerring, 2003). For estimating foliar biochemical (e.g. N) concentrations, traditional broadband indices such as normalized difference vegetation index (NDVI) (Rouse et al., 1974), soil line concept (SLC), simple ratio (SR) (Baret and Guyot, 1991), and soil-adjusted vegetation index (SAVI) (Huete, 1988) are not conducive. These broadband vegetation indices saturate at high canopy cover (Mutanga and Skidmore, 2004; Tucker, 1977) and are insensitive to subtle changes in the foliar N concentration.

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The more recent success in estimating foliar N and chlorophyll concentrations has been possible due to the development of hyperspectral remote sensing. Studies using hyperspectral remote sensing have highlighted the utility of red-edge bands for estimating foliar N and chlorophyll concentrations (Cho and Skidmore, 2006; Darvishzadeh et al., 2008; Huang et al., 2004). The red-edge is the region of abrupt change in leaf reflectance between 680 and 780 nm, mainly influenced by the concerted effect of spectral absorption in the red wavelengths and scattering in the near infrared region (Clevers et al., 2002; Gates et al., 1965; Horler et al., 1983). Cho and Skidmore (2006) developed a technique to compute the red-edge position (REP), which is highly sensitive to foliar chlorophyll. REP is known to be insensitive to background effects (Elvidge and Chen, 1995) and is highly correlated to foliar N (Cho and Skidmore, 2006). Chlorophyll is positively correlated to foliar N (Haboudane et al., 2004; Hansen and Schjoerring, 2003; Yoder and Pettigrew-Crosby, 1995). Vegetation indices computed from red-edge bands, also known as narrow-band indices, have provided improved estimates of foliar N compared to conventional broad-band indices derived from red (680 nm) and near infrared (800 nm) (Hansen and Schjoerring, 2003; Mutanga and Skidmore, 2007).

Other hyperspectral techniques in foliar N estimation involve the use of N and protein absorption features in the visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) (Huang et al., 2004; Schlerf et al., 2010; Skidmore et al., 2010). Several studies argued that the use of selected absorption features surpasses the use of the full spectrum for foliar biochemical and biophysical estimation (Cho et al., 2007; Darvishzadeh et al., 2008), because it reduces the chance of using redundant data. The drawback to using this approach for regional estimation of foliar biochemical concentrations is that there are limited satellite sensors which sample electromagnetic energy using the full spectrum (400–2500 nm), with narrow bands adequately resolving these absorption features. Satellite sensors with strategically placed spectral bands in the red-edge region are likely to provide successful estimates of biochemical concentrations, and more specifically foliar N. However, as these sensors are scarce, foliar N concentration is seldom mapped on a regional scale. For example, conventional multispectral satellite sensors such as SPOT, Landsat, and ASTER lack specific spectral bands in the red-edge region and their spatial resolutions are relatively coarse. The MERIS sensor has a standard band setting allowing the computation and approximation of the red-edge position (Clevers et al., 2002), but the spatial resolution is too coarse, especially for savannas, which are a complex and heterogeneous mosaic of grass and trees. The emergence of multispectral sensors such as WorldView-2 (USA), SumbandilaSAT (South Africa) and RapidEye (Germany) with red-edge bands at high spatial resolution (i.e. 6.5 m) could provide an opportunity for rangeland resource quality assessment at a regional level. The potential of RapidEye imagery has been demonstrated for crop assessment (Eitel et al., 2007; Vuolo et al., 2010), and provides a scope for testing this in the heterogeneous savanna ecosystems.

In addition, a few studies have highlighted the need to integrate environmental or ancillary and remote sensing variables to estimate foliar biochemical concentrations at a regional scale (Cho et al., 2009; Knox et al., 2011; Ramoelo et al., 2011a), which could be a crucial step towards improving regional estimation and mapping. A combination of factors such as edaphic (geology and soils), topographic (slope, aspect, and altitude), and climatic (precipitation and temperature) factors are known to influence the distribution of foliar biochemical concentrations in a very complex way (Ben-Shahar and Coe, 1992; Ferwerda et al., 2006; Skidmore et al., 2011). Ramoelo et al. (2011a) showed that geology, slope, temperature, and land use types were the main contributing environmental variables when modeling foliar N in combination with in situ hyperspectral remote sensing variables. However, where environmental data sets are readily available at a regional scale, their resolution is relatively coarse rendering them unsuitable as sole input in the estimation of foliar biochemical concentrations. The use of remote sensing could address this issue of resolution and scale, for instance regional maps could be derived at a resolution of 5–10 m based on data from the newly developed spaceborne sensors. The assumption is that a modeling approach which integrates remote sensing and environmental variables potentially yields higher foliar N estimation accuracy than approaches using either remote sensing or environmental variables (Cho et al., 2009; Knox et al., 2011; Ramoelo et al., 2011a). The objectives of this study were twofold; (1) to investigate the utility of the red-edge band of the RapidEye sensor for estimating grass N concentrations using various vegetation indices derived from the RapidEye data, and to determine which vegetation index correlates highly with grass foliar as well as canopy N and (2) to integrate this vegetation index with the environmental variables to estimate and map grass foliar and canopy N at a regional scale.

2. Materials and methods

2.1. Study area

The study area is located in the north-eastern part of South Africa (Fig. 1) and covers a total area of approximately 5000 km^2. Protected areas such as the privately owned Sabi Sands Game Reserve (SGR) and the state -owned Kruger National Park (KNP), as well as the communal lands in Bushbuckridge are the main land tenures. The main vegetation types are "Tshokwane-Hlane basalt lowveld", "granite lowveld", "gabbro grassy bushveld", and "Delagoa lowveld" (Mucina and Rutherford, 2006). The Tshokwane-Hlane basalt lowveld is characterized by open tree savannas and occurs in the highly fertile black, brown or red clayey soils derived from the basalt substrate. The granite lowveld comprises dense thickets and occur in uplands with sandy soils and clayey in the bottomlands, and are low in fertility compared to the basalt-derived soils. Gabbro grassy bushveld constitutes an open savanna and are found in fertile dark vertic soils with 20–50% clay (Mucina and Rutherford, 2006). The Delagoa lowveld is characterized by dense thickets and occurs in shale and lesser sandstone layers interspersed by sheets and dykes of Jurassic dolerite (Mucina and Rutherford, 2006). The soils are rich in sodium, but the fertility is lower than in the basaltic-derived soils. There is an evident precipitation gradient from the western part (800 mm/year) to the eastern part (580 mm/year) of the study area (Venter et al., 2003). The annual mean temperature is about 22 °C. Geology includes granite and gneiss with local intrusions of gabbro in the west and basalt as well as shale in the eastern part towards Mozambique (Venter et al., 2003). The contrasting geological substrates (and associated soil types) together with the precipitation influence, clearly define the patterns and gradients in soil moisture and nutrients. Topography is mostly undulating in the granitic sites and flat in the basalt areas, with an average height of 450 m. Rangelands in the protected areas are grazed by wild herbivores while the communal rangelands support the grazing of livestock, thus determining various grazing or land use intensities.

2.2. Data collection

2.2.1. Field data collection and chemical analysis

The field data were collected using a road sampling technique since deep penetration into the savanna landscape was limited by management and logistical restrictions. Field work was undertaken in April 2010, the same month the satellite imagery was collected. The areas along the main roads covering the study area