Ecological Indicators 90 (2018) 9–17

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Relationship of root zone soil moisture with solar-induced chlorophyll fluorescence and vegetation indices in winter wheat: A comparative study based on continuous ground-measurements

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ARTICLE INFO

Keywords:
Root zone soil moisture
SIF
Vegetation indices
NDVI
NDI
rNDI

ABSTRACT

Root zone soil moisture is a critical component in the interaction between the hydrosphere, atmosphere, and biosphere. Optical reflectance of the vegetation canopy could provide abundant information about plant function and therefore has been used to detect the root zone soil moisture over large areas. Solar-induced chlorophyll fluorescence (SIF) is another signal with close ties to photosynthesis; however, its detailed relationship with soil moisture at different depths within the root zone has not been reported. In particular, little is known about the difference between SIF and reflectance-based vegetation indices (VIs) in responding to lag root zone soil moisture. In this study, we presented continuous ground measurements of VIs and SIF at 760 nm over four plots of wheat with different irrigation treatments. Results showed that both SIF and VIs positively and significantly correlated with root zone soil moisture, but with different lag responses to soil moisture changes at various depths. Their relationships also varied with the development of vegetation as well as with the status of soil moisture. Compared to VIs, SIF was still sensitive enough to measure vegetation variation even when the leaf area index or chlorophyll content was at high levels, suggesting that SIF was more feasible in root zone soil moisture monitoring over closure canopies.

1. Introduction

Soil moisture plays an important role in regulating both the water and energy balance of the land surface and is also a critical component of water and energy exchange between the hydrosphere, atmosphere, and biosphere (Ochsner et al., 2013; Ridler et al., 2014). Soil moisture in root zones links surface phenology with subsurface water storage in vegetated regions and is therefore a key parameter that controls terrestrial vegetation health conditions in arid and semi-arid regions (Houser, 2011; Wang et al., 2011). Variations in root zone soil moisture can strongly affect surface energy balance, carbon assimilation, and vegetation productivity (Wang et al., 2007). With the development of human society and the impact of climate change, the demand for water resources has increased for many aspects and water scarcity has occurred almost every year over most parts of the world (Dai, 2011; Mishra and Singh, 2010). Thus, continuous and accurate monitoring of root zone soil moisture over large areas may provide precise and timely information for the planning and management of water resources (Gu et al., 2008; Liu et al., 2012). Although soil moisture can be obtained with conventional field observations, ground measurements are time-consuming and available at a site scale, but impractical on regional scales (Holzman et al., 2014; Zhang et al., 2011).

Over the past few decades, remote sensing has provided us with systematic and feasible tools for monitoring soil moisture information over large areas in various soil and land-cover conditions (Liu et al., 2012; Swain et al., 2013). Microwave is a direct method that has been used to monitor surface soil moisture (up to 10 cm in general) under all weather conditions (Njoku et al., 2003). However, its sensitivity to soil moisture can be affected by the water content in vegetation, especially in dense vegetation landscapes (Narayan et al., 2004). Furthermore, microwave measurements cannot integrate all the information of root zone soil moisture due to its limited capacity in penetrating deeper depths of the soil profile (Liu et al., 2012; Swain et al., 2013). Optical reflectance cannot directly measure root zone soil moisture; however, it

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https://doi.org/10.1016/j.ecolind.2018.02.048
Received 6 November 2017; Received in revised form 8 January 2018; Accepted 20 February 2018
Available online 06 March 2018
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can provide abundant information about the dynamics of plant biophysical properties (e.g., photosynthesis, leaf water content, leaf area index, and chlorophyll content) (Wang and Qu, 2009). Given the critical role of root zone soil moisture in plant biophysical processes, a large number of reflectance-based vegetation indices (VIs) have been proposed to indirectly infer root zone soil moisture at multiple spatial and temporal scales (Gu et al., 2007; Wang et al., 2007). Based on ground measurements or satellite products (e.g., MODIS products), it has been widely demonstrated that most of the VIs are more or less related to root zone soil moisture (Gu et al., 2008; Liu et al., 2011; Schnur et al., 2010; Swain et al., 2013; Wang et al., 2007; Zhang et al., 2011). Furthermore, the relationship between soil moisture and VIs can be improved when using lagged soil moisture. However, time lag is dependent on vegetation species (i.e. root distribution) and climate regimes (i.e. dry or wet condition) (Liu et al., 2011; Swain et al., 2013; Wang et al., 2007). Their relationship is also influenced by soil properties (soil texture and topography) and vegetation density, because the former parameter could cause the spatial differences in soil moisture and the latter one is related to LAI and is also closely related to the phenological stages (Gu et al., 2008; Liu et al., 2012).

These VIs for soil moisture retrieval can be divided into two categories: one is the greenness-based indices that are related to leaf area index and biomass (e.g., Normalized Difference Vegetation Index, NDVI; the Enhanced Vegetation Index, EVI; wide dynamic range VI, WDRVI), chlorophyll content (e.g., the Chlorophyllred-edge Index, CIred-edge; Visible Atmospherically Resistant Index, VARI) and lignin and cellulose content (e.g., Cellulose Absorption Index, CAI); the other one is canopy-water-based indices that are sensitive to leaf water content (e.g., the Normalized Difference Water Index, NDWI; Normalized Difference Infrared Index, NDII). It is expected that canopy-water-based indices are more responsive to the variation of soil moisture because of their sensitivity to the leaf water content (Liu et al., 2011). However, no additional benefit was gained by canopy-water-based indices (e.g., NDWI and NDII), but comparable even stronger sensitivities to soil moisture fluctuations have been found in greenness based indices (e.g., NDVI and VARI) (Gu et al., 2008; Liu et al., 2012). Therefore, greenness-based-indices are better fit for soil moisture estimate (Gu et al., 2008; Liu et al., 2012). As one of the greenness based indices, NDVI not only correlated well with the biophysical parameters mentioned above but also with chlorophyll content, green leaf structure and fractional vegetation cover (Liu et al., 2012; Rouse et al., 1974). It could reflect plant health under various soil moisture situations and contain information on ecosystem function as well (Frankenberg et al., 2011; Gu et al., 2007; Lichtenthaler and Miehé, 1997). Therefore, it has been widely used as an indicator of vegetation status and the effects of drought on vegetation (Anderson et al., 2010; Caccamo et al., 2011; Rautiainen et al., 2010; Wu et al., 2014). Nevertheless, NDVI tends to be saturated at high values of leaf area index (LAI) or biomass (Chen et al., 2005; Delegido et al., 2013; Haboudane et al., 2004). To cope with the limitation of NDVI, several new VIs have been developed. For example, the normalized difference index (NDI) is a modified version of NDVI, but is a better estimator of chlorophyll content than NDVI (Richardson and Berlyn, 2002; Richardson et al., 2002). The red-edge normalized difference index (rNDI) was proposed to estimate green LAI over some crops (Delegido et al., 2013). rNDI could obtain a better correlation with LAI and also create no saturation, even at high values of LAI (Delegido et al., 2013). While NDI and rNDI have been successfully applied in estimating vegetation status (Delegido et al., 2015; Yang et al., 2015), their potential in monitoring root zone soil moisture have not been explored.

Unlike vegetation reflectance, solar-induced chlorophyll fluorescence (SIF) is reemitted by chlorophyll when the pigments absorb much more solar energy than photosynthesis requires (Porcar-Castell et al., 2014). Therefore, due to its close relationship with photosynthesis, SIF is considered as a direct probe of photosynthesis (Meroni et al., 2009). It has been used to detect information on drought at various spatial-temporal scales based on measurements from towers, aircraft, and satellite platforms (Daumard et al., 2012; Pérez-Priego et al., 2005; Rossini et al., 2015; Zarco-Tejada et al., 2009). Generally, drought-induced changes in vegetation function can result in reductions of both the photosynthesis and fluorescence yield (Fabrice Daumard and Champagne, 2010; Sun et al., 2016). Although root zone soil moisture is closely related to the development of drought, studies on the relationship between soil moisture and SIF are rare (Geruo et al., 2017; Madani et al., 2017; Sun et al., 2016). As far as we know, such studies regarding their relationship were mainly conducted based on satellite-derived SIF (e.g., Global Ozone Monitoring Instrument 2 on board Eumetsat's MetOp-A satellite, GOME-2) and simulated or observed root soil moisture (Madani et al., 2017; Sun et al., 2016). Results of the previous studies showed that SIF was significantly and positively correlated with the root zone soil moisture of the concurrent month (Geruo et al., 2017; Sun et al., 2016). The correlation between SIF and soil moisture is also related to land cover types (Geruo et al., 2017; Madani et al., 2017). Furthermore, compared to vegetation reflectance, SIF could capture more direct information about photosynthesis dynamics induced by the variation of root zone soil moisture. However, little is known about the detailed differences in their relationships with root zone soil moisture. In particular, their relationships with soil moisture in different root zone profiles have not been reported.

Winter wheat is an important field crop in China and is primarily grown in the North China Plain (NCP). The NCP is in an area with a monsoon climate, with an average rainfall from 50 to 150 mm during the winter wheat season (Liu et al., 2002; Sun et al., 2006). The average amount of precipitation cannot meet the needs of winter wheat over the entire growing season (about 450 mm) (Liu et al., 2002; Zhang et al., 2004). Therefore, water is a critical limiting factor for the production of wheat. Understanding and quantifying the soil moisture at variable depths within the wheat root zone may contribute to making reasonable, efficient irrigation scheduling to mitigate the risk of water shortage in this region. Previous studies have investigated the relationship of root zone soil moisture with reflectance-based VIs over grass and shrub (Wang et al., 2007; Zhang et al., 2011), maize and soybean (Swain et al., 2013), and grasslands with forest cover types (Liu et al., 2011). However, few studies have investigated the linkage between VIs (especially the NDI and rNDI) and root zone soil moisture over winter wheat.

In this study, about two-month time series of canopy SIF and VIs (including NDVI, NDI, and rNDI) of wheat were measured in an experimental station (located in the north of the NCP) by using an automated field spectroscopy system. Root zone soil moisture was also collected at root depths of 20 cm and 50 cm. With these measurements, our aim was to address the following questions: (i) how does SIF respond to the variation of root zone soil moisture? and (ii) What is the detailed difference in the relationship of root zone soil moisture with SIF and VIs?

2. Materials and methods

2.1. Experimental design

Field experiments were conducted at the Fangshan Comprehensive Experimental Station (39°35′N, 115°42.5′E), which is located in the north of the NCP. Winter wheat was planted on 20 October 2016 in four plots with a 4 m × 4 m grid (Fig. 1a). Before sowing, flood irrigation was used in the four plots to ensure seeds survival. Precipitation was recorded at a standard weather station about 100 m from the four plots. About 55 mm accumulated precipitation was recorded during mid-October of 2016 and late-March in 2017, while no precipitation occurred according to the records during the field campaign (28 March to 19 May 2017). An irrigation of 60 mm was separately conducted in the four plots before winter (November 7, 2016) to ensure that the wheat could endure the freezing cold (Table 1). To generate soil moisture gradient

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