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Assessing drought vulnerability using soil moisture-based water use efficiency measurements obtained from multi-sensor satellite data in Northeast Asia dryland regions

Nayoung Do, Sinkyu Kang*

Department of Environment Science, Kangwon National University, Chuncheon 200-701, Republic of Korea

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Advanced Very High Resolution Radiometer (AVHRR) Normalized-Difference Vegetation Index (NDVI) and soil moisture data from the Special Sensor Microwave Imager (SSM/I) were utilized to derive Soil Moisture Use Efficiency (SMUE). SMUE, serving here as a proxy for the commonly used Water Use Efficiency (WUE), was used to evaluate drought vulnerability (i.e., the degree of drought stress and sensitivity) in the Northeast Asia drylands for the period of 1987–2006. SMUE was defined as the ratio of June–August NDVI accumulation ($NDVI_{acc}$) to average soil moisture (SM_{avg}). This ratio was utilized to derive two additional indices representing drought stress (DSI) and sensitivity (DVI). We confined our vulnerability analyses to low NDVI regions because the determination of SSM/I soil moisture is unreliable in areas with high biomass. Both DSI and DVI identified high drought vulnerability in regions of the eastern Kazakhstan grasslands, western portions of the Hexi Corridor in the mid-north of China, the Gobi region, and the southwestern Mongolia grasslands. The identified vulnerable regions covered most of regions with land-degradation expansions or increased sand storm occurrence reported from previous individual studies. This study demonstrated the applicability of our SMUE-based vulnerability indices for identifying drought vulnerability across wide geographic regions.

1. Introduction

Plant-available water exerts a considerable effect on the primary productivity of vegetation in arid and semi-arid regions that provides foods for livestock and functions to prevent land degradation (Bai et al., 2008a; Los et al., 2006). Severe droughts can cause changes in species composition and ecosystem characteristics, such as primary productivity and evapotranspiration. This effect sometimes results in a loss of regional economic value and causes land degradation (Millennium Ecosystem Assessment, 2005; Saizen et al., 2010). Rain use efficiency (RUE) has been proposed as a practical and objective indicator of drought stress and land degradation in arid and semi-arid regions (Le Houerou, 1984; Nicholson et al., 1998; Prince et al., 1998; Veron et al., 2006).

The RUE is the ratio between aboveground primary production and precipitation. This ratio has been used as a practical proxy for water use efficiency (WUE), which is normally defined as primary productivity (either gross or net) divided by plant transpiration or ecosystem evapotranspiration (Sinclair et al., 1984). The WUE is applied to study eco-physiological characteristics of plant water use and the effect of severe climate on the status of plant physiology (Delucia and Heckathorn, 1989; Reich et al., 1989; Reichstein et al., 2002). Both RUE and WUE tend to increase with drought stress (Prince et al., 1998; Reich et al., 1989), indicating higher drought vulnerability.

Later Le Houerou (1984), it was found that RUE has a baseline conservative value in the various arid zones of the world. Deviations from the conservative values of RUE have been applied as a useful index of the ecosystem vulnerability of land degradation (Prince et al., 1998). The relationships between RUE and land degradation were widely investigated in arid and semi-arid regions at local (Varnamkhasti et al., 1995), regional (Diouf and Lambin, 2001; Wessels et al., 2004) and sub-continental scales (Los et al., 2006; Prince et al., 1998). Bai et al. (2008b) investigated the applied relationship of RUE with plant functional structure and aridity across the Inner Mongolian grasslands of China. Prince et al. (1998) indicated that those previous attempts applying RUE in identifying ecosystem vulnerability of land degradation assumed,

* Corresponding author. Tel.: +82 33 250 8578; fax: +82 33 251 3991.
E-mail address: kangsk@kangwon.ac.kr (S. Kang).

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either implicitly or explicitly, conservative relationships between precipitation and evapotranspiration in the process of land degradation. The assumption, however, fails sometimes because allocation of precipitation to various land surface hydrological processes can be changed with different species composition and vegetation cover fraction altered as a result of land degradation (Prince et al., 1998). Under the circumstances, the RUE analysis could lead to uncertainty in studies of ecosystem vulnerability of land degradation to drought stress.

Plant water use is closely associated with the control of plant-available soil water by stomata conductance (Farquar and Sharkey, 1982; Jarvis, 1976). In particular, strong linear relationships between evapotranspiration and soil moisture were found for arid grassland and shrubland (Kurc and Small, 2004). Relations between soil moisture and precipitation are temporally and spatially inconsistent because, besides precipitation, soil moisture is determined by multiple hydrological processes (i.e., evapotranspiration, runoff, percolation, and sub-surface flows). Accordingly, because soil moisture per unit rainfall was characterized differently in various soil types and climatic regimes (Farrar et al., 1994), it is unreliable to substitute soil moisture with precipitation across large pedo-geographic and hydro-climatic regions. Hence, at a large regional scale, such as that of the Northeast Asian drylands, soil moisture could be a better proxy variable of the rate of evapotranspiration than precipitation. Compare with RUE, however, soil moisture-based WUE was rarely applied to the drought vulnerability measures of large areas in spite of the meaningful relationship between soil moisture and grassland primary productivity (Briggs and Knapp, 1995; Malo and Nicholson, 1990), variability (Knapp et al., 2002), and evapotranspiration (Kurc and Small, 2004).

Numerous satellite-based analyses of RUE and WUE have contributed to our understanding of large-scale spatial and interannual variations of land degradation progress or vulnerability patterns. Those studies represented vegetation productivity using gross primary productivity (GPP) (Lu and Zhuang, 2010; Ryu et al., 2011), net primary productivity (NPP) (Bai et al., 2008b; Prince et al., 1998), or, indirectly, the normalized-difference vegetation index (NDVI) (Los et al., 2006; Wessels et al., 2007). Annual precipitation or evapotranspiration were derived from either climatological datasets (Los et al., 2006), the Tropical Applications of Meteorology using SATellite (TAMSAT) meteosat precipitation (Justice et al., 1991), or the Moderate Resolution Imaging Spectroradiometer (MODIS) evapotranspiration study (Lu and Zhuang, 2010; Mu et al., 2011; Ryu et al., 2011). The recently development of long-term soil moisture datasets from various microwave remote sensing images (Liu et al., 2011; Owe et al., 2008, 2001) provided an alternative tool for assessing the ecosystem vulnerability to drought stress over large geographic areas from the soil moisture-based WUE.

In this study, we developed a soil moisture-based WUE index (hereafter designated SMUE) based on the National Oceanic and Atmospheric Administration (NOAA) Global Inventory Modeling and Mapping Studies (GIMMS) Advanced Very High Resolution Radiometer (AVHRR) NDVI and the Special Sensor Microwave Imager (SSM/I) soil moisture (SM). The SMUE was applied to assess ecosystem vulnerability to drought stress in the Northeast Asia dryland regions during the period of 1987–2006.

2. Materials and methods

2.1. Assessment of drought vulnerability

2.1.1. Concepts of vulnerability measurement

Our vulnerability assessment was conceptually based on a definition by Adger (2006): "… vulnerability is degree to which a system is susceptible to and is unable to cope with adverse effects… The key parameters of vulnerability are the stress to which a system is exposed, its sensitivity, and its adaptive capacity". The conceptual and practical complexity of assessing vulnerability was also cited by Walker and Salt (2006). For quantitative assessment of vulnerability based on satellite data, we defined vulnerability as the sensitivity of ecosystem characteristics (i.e., productivity or WUE) to drought stress. Thus, our vulnerability assessment does not contain measures of adaptive capacity. In this study, the productivity, WUE, and drought stress were represented by the NDVI-based productivity index, the SMUE, and the deviation of SMUE relative to the base SMUE, respectively (Table 1). Each measure is quantitatively defined in the following sections.

Stomatal behavior has considerable effects on WUE by controlling rates of photosynthetic assimilation and transpiration through changes in partial pressure of intercellular CO_2 and leaf temperature and water potential (Farquar and Sharkey, 1982). As well, changes in species composition or vegetation cover fraction can alter WUE because C4 plant has lower photorespitation loss and hence, higher assimilation efficiency than C3 plant (Chapin et al., 2002), and also because sparse vegetation cover increases partitioning of energy and water to sensible heat and soil evaporation, respectively (Li et al., 2000). It is known that WUE increases with temporary stomata closure (Krishnan et al., 2006) and long drought conditions (Reichstein et al., 2002). A higher WUE was also detected where vegetation was adapted to frequent drought stress (Li et al., 2008) or where C4 plants were dominant (Rawson et al., 1977). Similarly, higher RUE was also observed with less precipitation (Bai et al., 2008b; Huxman et al., 2004; Prince et al., 1998). Furthermore, extreme drought may result in a reduction of WUE, which is most likely associated with the impairment of photosynthetic organs (Reichstein et al., 2002) or the destruction of vegetation cover.

We therefore proposed a hypothetical pattern of temporal WUE change with respect to water stress as illustrated in Fig. 1. The hypothetical WUE curve depicts field evidence collectively, i.e., the baseline WUE (WUE_{base}) at low and moderate water stress, increase with soil dryness, and decrease under severe drought condition. The WUE_{base} may vary with the local species composition, acclimation, and land degradation. These characteristics affect patterns of productivity and evapotranspiration responses to drought stress. The relative change of WUE relative to WUE_{base} could be a useful indicator of water stress to which the local ecosystem responds with changes in the WUE. The rate of WUE change (i.e., the slope of WUE curve) can serve as an index of sensitivity to drought stress.

We presume that the spatial pattern of the WUE-drought relationship is similar to the abovementioned temporal relationship but with different values and rates of change depending on species composition, climatic regimes, and historical disturbances. However, field evidence of the WUE response to dryness is difficult to find with the exception of Bai et al. (2008b), who reported field evidences of spatial RUE patterns similar to the hypothesized WUE curve (Fig. 1) in two Mongolia steppe communities in China (refer Fig. 5 in the cited reference).

2.1.2. Soil moisture use efficiency (SMUE)

The annual accumulated NDVI was widely adopted as an indirect measure of vegetation productivity in dryland regions (Farrar et al., 1994; Prince, 1991; Prince et al., 1998; Tucker et al., 1985). Sites with a high rate of carbon gain generally have a high NDVI because of their high chlorophyll content (low reflectance of the red band) and high leaf area (high reflectance of near infra-red). Hence, the NDVI is known as a good indicator of the photosynthetic rate (i.e., GPP at canopy level). The NDVI has been utilized to estimate the fraction of absorbed photosynthetically active