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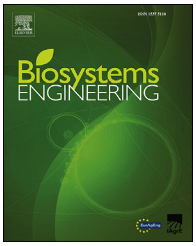

Special Issue: Proximal Soil Sensing

Research Paper

Using electromagnetic induction method to reveal dynamics of soil water and salt during continual rainfall events

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ARTICLE INFO

Article history:
Received 8 August 2015
Received in revised form
12 March 2016
Accepted 31 March 2016
Published online xxx

Keywords:
ECa
Soil spatial variability
Vegetation pattern
Achnatherum splendens
Field scale
Qinghai Lake

The spatial patterns and dynamics of soil water and salt at the field scale between rainfall events are not well understood due to a lack of appropriate instruments for measurements. In this study, we conducted time series EMI surveys and then mapped apparent electrical conductivity (ECa) to estimate the relative changes in soil water and salt in an *Achnatherum splendens* steppe ecosystem in Qinghai Lake watershed, China. The results indicated that ECa could be used as a surrogate for interpreting changes of water and salt content in soil. The ECa images clearly showed that ECa values increased rapidly after rainfall events, and the increased amplitudes of ECa values in soils under *A. splendens* (AS) were obviously greater than that of soil in the interspaces between *A. splendens* tussocks (IAS). This demonstrated that rainwater infiltrated faster and in greater quantity into the soils under AS because of their coarse-textured surface soils with greater macroporosity and higher hydraulic conductivity as compared to the interspace soils. Moreover, the increasing salinity in AS and decreasing salinity in IAS after rainfall events suggested that overland flow might perhaps have occurred from the interspaces into *A. splendens* areas. The temporal stability of ECa maps demonstrated that there was great soil variability at the study plot, especially in soil salt. This study highlighted that the time series ECa images could qualitatively capture dynamics of soil water and salt at the field scale after rainfall events, and it linked the dynamics of soil water and salt to vegetation variability.

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http://dx.doi.org/10.1016/j.biosystemseng.2016.03.011

Please cite this article in press as: Jiang, Z.-Y., et al., Using electromagnetic induction method to reveal dynamics of soil water and salt during continual rainfall events, *Biosystems Engineering* (2016), http://dx.doi.org/10.1016/j.biosystemseng.2016.03.011

1. Introduction

Soil water and salinity are two fundamental abiotic factors that greatly affect plant growth and distribution in water-limited ecosystems (Chaves, Flexas, & Pinheiro, 2008; Rodriguez Iturbe, D'Odorico, Porporato, & Ridolfi, 1999; Zhu, 2001). Meanwhile, the spatial variability of vegetation and soil also directly determine the dynamics of soil water and salt during and between rainfall events (Rosenbaum et al., 2012). It is widely acknowledged that improving comprehension of the dynamics of soil water and salt can provide beneficial insights into understanding soil hydrological processes and soil complexities (Blume, Zehe, & Bronstert, 2009; Lin, 2006; Robinson et al., 2008b). However, capturing the spatial patterns and dynamics of soil water and salt caused by rainfall pulses poses a challenge in understanding the interactions between soil and vegetation variability due to the limitations of appropriate instruments or methods.

Previous studies have indicated that soil water (or salt) has been well studied at the point or landscape scale (Famiglietti et al., 1999; Li, Zhang, Peng, Hu, & Ma, 2013b), but spatial and temporal dynamics at the field scale were not well understood because of the lack of high spatial and temporal resolution data (Krause, Lewandowski, Dahm, & Tockner, 2015; Lin, Kogelmann, Walker, & Bruns, 2006). Sampling points using augers or sensors is not only time-consuming but also weakly representative, and the resolution of remote sensing is too coarse for field scale investigation. Hence, real-time measurements at high resolution are needed to satisfy our understanding of the dynamics of soil water and salt at the field scale. The electromagnetic induction (EMI) method, which is non-invasive, convenient and rapid, can generate massive amounts of geo-referenced data from soils in a short time and has the potential to bridge this gap (Robinson et al., 2008a). Apparent electrical conductivity (ECa), measured using EMI method, is a depth-weighted average conductivity for a column of soil to a specific depth (Greenhouse & Slaine, 1983) and was reported to be influenced by various soil properties including clay content, soil water, salt and temperature (Ekwue & Bartholomew, 2011; Friedman, 2005;). Thus, ECa measurements have been considered to infer these soil properties of interest, by assuming relative homogeneity of other properties since the late 1970s (Abdu, Robinson, & Jones, 2007; Doolittle & Brevik, 2014). Originally used to estimate soil salinity (Rhoades, Chanduvi, & Lesch, 1999), the application of EMI has been extended to many fields of soil study including identifying soil texture (Abdu, Robinson, Seyfried, & Jones, 2008; James, Waine, Bradley, Taylor, & Godwin, 2003), estimating soil water content (McCutcheon, Farahani, Stednick, Buchleiter, & Green, 2006; Robinson et al., 2009), inferring topsoil depth in claypan soils (Sudduth, Drummond, & Kitchen, 2001), and assessing organic matter content (Martinez, Vanderlinden, Ordóñez, & Muriel, 2009). During recent years, the EMI method has been used to investigate the relationship between soil, water and vegetation (Atwell, Wuddivira, Gobin, & Robinson, 2013; Doolittle & Brevik, 2014; Robinson, Abdu, Lebron, & Jones, 2012; Robinson, Lebron, & Ignacio Querejeta, 2010). Robinson et al. (2008a) discovered distinct linkages between aboveground vegetation patterns and the distribution of belowground soil properties using ECa as an indicator of soil texture. Zhu, Lin, and Doolittle (2010) used repeated EMI surveys to determine soil moisture changes between 1997, 2006, 2008 and 2009 in the same agricultural field. However, previous studies mainly focused on spatial variability of soil and vegetation or single soil property changes by EMI with time-resolution of months or years. Few studies have attempted to use EMI to trace soil water and salt dynamics simultaneously with a time-resolution of individual rainfall events.

In arid/semiarid regions, intense rainfall events contribute greatly to soil moisture dynamics and can trigger major ecological events such as plant germination (Loik, Breshears, Lauenroth, & Belnap, 2004; Schwinning & Sala, 2004). Hence, this study focused on the short duration of less than one month and used the EMI method to obtain a series of ECa images following continual and intense rainfall events. Here we have two hypotheses: (1) the EMI method can be used to interpret dynamics of soil water and salt simultaneously at the field scale at the time-resolution of short rainfall events; (2) the spatial patterns and dynamics of soil water/salt are influenced by the spatial variability of soil and vegetation. Therefore, the first objective of this study was to use the EMI method to acquire a time series of ECa images to explore the dynamics of soil water and salt simultaneously at the time scale of frequent individual rainfall events. The second objective was to use the clustered and deep-rooted grass of *Achnatherum splendens* as an indicator plant to determine the interactions between the dynamics of soil water/salt and spatial pattern of the grass *A. splendens*.

2. Materials and methods

2.1. Study site description

This study was conducted in an *A. splendens* steppe ecosystem in the northern part of Qinghai Lake, NE Qinghai-Tibet Plateau, China. The grass *A. splendens* is mainly distributed around Qinghai Lake from northwest to southeast (Fig. 1). The climate of the study site is semi-arid with mean annual temperature of −3.3 °C. Mean annual precipitation is 378.2 mm with nearly 80% occurring from July to October. The weather is cold, dry and windy in winter but warm and wet in summer. The *A. splendens* steppe ecosystem is a typical ecosystem type in the Qinghai Lake watershed, and the dominant species in the steppe are *A. splendens*, *Stipa krylovii Poa malaca Keng* and *Artemisia frigida Willd* (Chen & Peng, 1993).

We established a 60 × 60 m^2 *A. splendens* plot as the study site (37°14′52.7″ N, 100°14′8.5″ E, Figs. 1 and 2). The landscape of the *A. splendens* plot mainly consisted of mosaics of two elements: the tall grass *A. splendens* (AS) tussocks; and interspaces between the *A. splendens* (IAS) tussocks populated with short grasses, such as *S. krylovii and C. ivanouae* (Fig. 1). The spatial distribution of *A. splendens* tussocks in the 60 × 60 m^2 experimental area was as fragmented patterns (Fig. 2). The crown sizes of individual *A. splendens* tussocks were 0.5–4.5 m long by 0.2–3 m wide, and their height varied between 0.5 and 2 m. The topography is relatively flat and elevation is about 3210 m. The zonal soils are chestnut and

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