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Trajectory based detection of forest-change impacts on surface soil moisture at a basin scale [Poyang Lake Basin, China]

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SUMMARY

Surface soil moisture plays a critical role in hydrological processes, but varies with both natural and anthropogenic influences. Land cover change unavoidably alters surface property and subsequent soil moisture, and its contribution is yet hard to isolate from the mixed influences. In combination with trajectory analysis, this paper proposes a novel approach for detection of forest-change impacts on surface soil moisture variation with an examination over the Poyang Lake Basin, China from 2003 to 2009. Soil moisture in permanent forest trajectory represents a synthetic result of natural influences and serves as a reference for isolating soil moisture alternation due to land cover change at a basin scale. Our results showed that soil moisture decreased in all forest trajectories, while the absolute decrease was lower for permanent forest trajectory (2.53%) than the whole basin (2.61%), afforestation trajectories (2.70%) and deforestation trajectories (2.81%). Moreover, afforestation has a high capacity to hold more soil moisture, but may take more than 6 years to reach its maximum capacity. Soil moisture increased from 14.09% to 14.94% for the afforestation trajectories with tree aging from 1 to 6 years. Finally, land cover change may affect soil moisture alternation toward different transformation directions. Absolute soil moisture decreases by 0.08% for the whole basin, 0.17% for afforestation and 0.28% for deforestation trajectories, accounting for 3.13%, 6.47% and 10.07% of the total decrease in soil moisture. More specifically, the transformation from woody Savannas, cropland and other lands to forest generated absolute soil moisture deceases of 0.20%, −0.08% and 0.27%, accounting for 7.26%, −3.52% and 9.57% of the decreases. On the other hand, the reverse transformation generated soil moisture deceases of 0.29%, 0.21% and 0.35%, accounting for 10.43%, 7.69% and 12.14% of the total decrease. Our findings should be valuable for evaluating the impacts of land cover change on soil moisture alternation and promoting effective management of water resources.

1. Introduction

Surface soil moisture plays a critical role in hydrological processes, for which its spatial and temporal distribution strongly influences evapotranspiration (Liang et al., 2010), precipitation (Koster et al., 2004; Taylor et al., 2012), and hot extremes (Hirschi et al., 2011). Thus, it is very important to understand soil moisture variation and identify its influence factors and their contributions. The influences can be divided into two groups: natural and anthropogenic effects. The former includes climate (Holsten et al., 2009), soil texture (English et al., 2005) and terrain (Zhu and Lin, 2011). The latter is commonly characterized by land cover change (Sterling et al., 2012; Yang et al., 2012). These factors influence soil moisture with complex interactions, and a single factor cannot explain the full variation of soil moisture (Gómez-Plaza et al., 2001). For example, soil moisture responses vary with rainfall events even for the same land cover (He et al., 2012; Wang et al., 2013). A high air temperature may result in soil moisture deficit through evapotranspiration, but its relationship with land cover is highly non-linear (Mahmood and Hubbard, 2005; Lofgren et al., 2011). The complex interactions lead to difficulties in isolating the influence of a single factor on soil moisture at a large scale. Separation of the natural and anthropogenic influences on soil moisture remains as a challenge. Clarification of the issue will be helpful for effective management of water resources and climatic adaptation.

The anthropogenic effects on hydrological processes have received increasing attentions in recent decade (Barnett et al., 2008; Savva et al., 2013). Land cover change unavoidably alters soil property including infiltration and field capacity (Mapa, 1995; Wang et al., 2012; Savva et al., 2013), which may influence soil

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moisture strongly. Effects of land cover change on soil moisture have been investigated, but reported results varied with locations and times, largely due to complex variation of soil moisture. For example, Mapa (1995) demonstrated that reforested land had the highest steady infiltration rate and soil moisture retention in Kandy of Sri Lanka. In contrast, Yang et al. (2012) reported soil moisture deficits in all land covers changed with plantation in a semi-arid area of the Loess Plateau, China. Giraldo et al. (2008) showed that soil moisture was higher in grassland than bare soil in south Georgia, USA, but Zhang and Schilling (2006) revealed an opposite trend at the Neal Smith National Wildlife Refuge in the Walnut Creek watershed, USA.

Existing studies focused on comparative analysis of soil moisture variability in different land covers, but few have identified soil moisture change generated purely from land cover transformation. Wang et al. (2010) reported that soil moisture decreased by 60–100% in areas transformed from forestland into grassland in the Yongding River Basin of China. Yang et al. (2012) reported that deep soil moisture decreased by more than 35% after vegetation restoration. Yet, few studies clearly differentiated the relative contributions from natural and anthropogenic influences. Models are often adopted to simulate soil moisture variation in different land-cover change scenarios (Sheikh et al., 2009; Li et al., 2009), but the linkages between land-cover change and hydrological processes are too complex to be covered with a single model (Hörmann et al., 2005). Comparative analysis of experimental areas with similar natural condition provides a practical way to evaluate the effects of land cover change on soil moisture. It has been applied in relatively small areas (Venkatesh et al., 2011; Wang et al., 2013). At a large scale, it is usually difficult to find areas with similar condition, which hampers its application.

Notably, trajectory analysis has been proposed and applied for studying land cover change (Kasperson et al. 1995; Mertens and Lambin, 2000). Trajectories are defined as the trends among the relationships over time between the factors shaping the changing nature of human-environment relations and their effects within a particular region (Kasperson et al., 1995). A land cover change trajectory refers to the succession areas of land cover types in time series (Lambin, 1997; Mertens and Lambin, 2000; Petit and Lambin, 2001). A particular region can be divided into several groups according to land cover transformation (Liu and Zhou, 2005; Zhou et al., 2008). It provides an effective way to select experimental areas for comparative analysis of environmental alternations in different land covers (Feng et al., 2013).

In combination with trajectory analysis, this paper proposed a novel approach to isolate the contribution of land cover change on soil moisture. It was then applied for a case examination over the Poyang Lake Basin, China. The structure of this paper is divided into four parts. Section 2 details study materials and methods used. Section 3 describes spatio-temporal variation of soil moisture and its driving factors, and discusses the effects of land cover change on soil moisture. Section 4 comes to conclusions. The study should be valuable for understanding the effects of land cover change on soil moisture, and effective management of water resources undergoing anthropogenic change.

2. Data and methods

2.1. Study area

Hydrological processes had been extensively investigated in the Poyang Lake Basin of China Examples include evapotranspiration (Li and Zhang, 2011), precipitation (Fu et al., 2011) and runoff (Guo et al., 2011). Soil moisture variation and its driving factors remain unknown, leaving a gap for understanding of complete water cycle at a basin scale (Liu et al., 2012a). The Poyang Lake Basin lies between 24°29′ and 30°04′N, 113°34′ and 118°28′E, with an area of 1.622×10^5 km^2 (Fig. 1). The basin contains the China's largest freshwater lake, which plays an important ecological and hydrological role in the middle and lower Yangtze River (Hu et al., 2007). It has a subtropical humid climate with an annual mean air temperature of 17.5 °C and a multi-year mean of annual precipitation of 1635.9 mm for 1960–2010. Poyang Lake receives water flows from five main tributaries, including Ganjiang, Fuhe, Xingjiang, Raohe and Xiushui. Its annual discharge to the Yangtze River comprises 15.6% of the total flows of the River (Zhu and Zhang, 1997).

2.2. Data pre-processing

2.2.1. Soil moisture

Remote sensing is capable of capturing soil moisture in its spatial consistent view at a large scale, particularly microwave remote sensing (Liu et al., 2012b). This study selected the Level-3 land surface product (AE_Land3) of the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) onboard NASA's Aqua satellite. The data sets were acquired from the National Snow & Ice Data Center (NSIDC, http://nsidc.org/data/ae_land3.html). It includes daily surface soil moisture, vegetation water content, brightness temperature and quality control items. Soil moisture data has a declared accuracy within 6% at a spatial resolution of 25 km (Njoku et al., 2003; Njoku and Chan, 2006), which has been examined in the United Sates (Sahoo et al., 2008), Europe (Brocca et al., 2011), Australia (Draper et al., 2009) and China (Zhang et al., 2011). In this study, daily soil moisture was segmented for the Poyang Lake Basin with a spatial analyst tool of "Extract by Mask" in ArcGIS. Then, annual mean soil moisture was calculated from the daily values.

In addition, two time series in-situ data sets were used to calibrate and validate the AMSR-E soil moisture. The first one was obtained from the Qianyanzhou Ecology Station (26°44′N, 115°03′E), covered by subtropical evergreen coniferous plantation (Wang et al., 2011). The second one is available from the Nankang station, located at 25°41′N, 114°42′E and covered by paddy and arachis hypogasa (http://cdc.cma.gov.cn/home.do).

2.2.2. Land cover

MODIS/Terra + Aqua Land Cover Type Yearly L3 Global 500 m SIN Grid V005 (MCD12Q1 Version 5) data is available for extracting land covers from 2003 to 2009. The data sets contain the land covers classified from five different classification systems, including the International Geosphere – Biosphere Programme (IGBP), the University of Maryland (UMD), the MODIS LAI/FPAR, the net primary production (NPP) and the plant functional type (PFT) classification (Friedl et al., 2010). This study selected the IGBP classification for its high classification accuracy. The overall accuracy of this classification was 75%, with both the user's and the producer's accuracy over 70% for most land cover classes (Herold et al., 2008; Friedl et al., 2010). To analyze the main land cover change, the land cover types were grouped into six categories, namely (1) forest (F for short): lands dominated by trees with a percent cover greater than 60%, including Evergreen Needleleaf Forest, Evergreen Broadleaf Forest, Deciduous Needleleaf Forest, Deciduous Broadleaf Forest and Mixed Forest; (2) grassland (G), lands with herbaceous types of cover and forest cover is less than 30%, including Closed Shrublands, Open Shrublands, Savannas and grasslands; (3) Woody Savannas (WS), the transition zone between forest and grassland with the forest between 30–60% and forest cover height exceeds 2 m; (4) Croplands (C): including Croplands and Cropland/Natural Vegetation Mosaic; (5) water (W), which mainly refers the lakes, reservoirs, and rivers and (6) other lands (O): including Permanent