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Research papers

Influences of sampling size and pattern on the uncertainty of correlation estimation between soil water content and its influencing factors

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ABSTRACT

In this study, seven random combination sampling strategies were applied to investigate the uncertainties in estimating the hillslope mean soil water content (SWC) and correlation coefficients between the SWC and soil/terrain properties on a tea + bamboo hillslope. One of the sampling strategies is the global random sampling and the other six are the stratified random sampling on the top, middle, toe, top + mid, top + toe and mid + toe slope positions. When each sampling strategy was applied, sample sizes were gradually reduced and each sampling size contained 3000 replicates. Under each sampling size of each sampling strategy, the relative errors (REs) and coefficients of variation (CVs) of the estimated hillslope mean SWC and correlation coefficients between the SWC and soil/terrain properties were calculated to quantify the accuracy and uncertainty. The results showed that the uncertainty of the estimations decreased as the sampling size increasing. However, larger sample sizes were required to reduce the uncertainty in correlation coefficient estimation than in hillslope mean SWC estimation. Under global random sampling, 12 randomly sampled sites on this hillslope were adequate to estimate the hillslope mean SWC with RE and CV ≤10%. However, at least 72 randomly sampled sites were needed to ensure the estimated correlation coefficients with REs and CVs ≤10%. Comparing with all sampling strategies, reducing sampling sites on the middle slope had the least influence on the estimation of hillslope mean SWC and correlation coefficients. Under this strategy, 60 sites (10 on the middle slope and 50 on the top and toe slopes) were enough to ensure the estimated correlation coefficients with REs and CVs ≤10%. This suggested that when designing the SWC sampling, the proportion of sites on the middle slope can be reduced to 16.7% of the total number of sites. Findings of this study will be useful for the optimal SWC sampling design.

1. Introduction

Soil water content (SWC) plays a critical role in the transport and cycle of nutrient, water, and energy by affecting hydrological, biogeochemical, geomorphologic, and other natural processes (Robinson et al., 2009; Joshi and Mohanty, 2010; Penna et al., 2013). The SWCs vary greatly in time and space scales, and are affected by the heterogeneous soil properties, topographic features, vegetation characteristics and atmospheric dynamics (Famiglietti et al., 1998). Explicit and exact understanding of the SWC influencing factors is essential for predicting SWC, revealing hydrological dynamics (e.g., surface and subsurface flow, evapotranspiration), and down-scaling remote sensing products (Jacobs et al., 2004; Starr, 2005; Joshi and Mohanty, 2010; Manns and Berg, 2014).

The SWC has been reported to be individually or jointly controlled by soil properties and topographic features (Famiglietti et al., 1998; Joshi and Mohanty, 2010; Joshi et al., 2011; Hu and Si, 2014). A common believe is that under the wet state, SWC is predominantly controlled by lateral water movement related to catchment terrain (nonlocal), while soil properties and local terrain are the dominant (local) controls under the dry state (Grayson et al., 1997; Western et al., 1999). This has been further extended by considering different soil depths, soil/terrain variation degrees and land uses in recent studies. For example, Zhu and Lin (2011) found that in the areas with slope <8%, soil exerted significant influence on SWC; whereas in the areas with slope >8%, terrain attributes showed more significant impacts. Huang et al. (2016) indicated that the first-order controls of SWC were different in the top layer (0–10 cm), intermediate layer (10–30 cm), and deeper layer (>30 cm).

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What's more, SWC variability and its controlling factors vary from point scale to global level. Wagenet (1998) summarized the factors controlling SWC from aggregate (pore size and organic coatings), field (soil texture, organic matter, and precipitation), landscape (soil texture and plant community), regional (geomorphology and land use), to global (biome type and climate) scales. Gaur and Mohanty (2016) also indicated that the dominance of soil properties on SWC dynamics typically decreased from airborne to satellite footprint scales whereas the influences of topography and vegetation increased with increasing support scale.

However, most of previous studies on SWC and its controlling factors were conducted on fixed sampling sizes and sampling patterns. For example, Famiglietti et al. (1998) relied on 21 SWC sampling points with 10-m spatial resolution along a transect to reveal the variability of SWC and the influences of soil/terrain properties on it. In the study by Lin et al. (2006), surface and subsurface SWC measured on 128 and 30 sites respectively, were used to reveal the spatial patterns of surface and subsurface SWC and their interactions with soils and topography. In the study by Brocca et al. (2010), surface SWC measurements were carried out for seven fields on a regular configuration of five by six nodes (grid-step of 10 m) to reveal the spatial-temporal variability of SWC. As reported by previous studies, sampling size and pattern had great influence on estimating the spatial variability of the soil variables related to SWC, such as carbon content (Simbahan and Dobermann, 2006), clay content (Kerry and Oliver, 2007). Therefore, it is reasonable to believe that sample size and pattern also have great influences on the uncertainty of estimating the correlations between SWC and its controlling factors. However, this uncertainty cannot be evaluated by the fix sampling size and pattern that have been commonly used in previous studies.

Resampling analysis is one of common approaches for investigating the influences of sampling size and pattern on the uncertainty of estimating target variables. It has been applied to various applications including determining the optimal sampling strategy for soil mapping (e.g. Simbahan and Dobermann, 2006; Carré et al., 2007; Vašát et al., 2010) and estimating the mean SWC (e.g. Brocca et al., 2010, 2012; Gao et al., 2013; Liao et al., 2017). Several resampling strategies have been developed, including the statistical (e.g., Vinnikov et al., 1999; Famiglietti et al., 2008), geostatistical (e.g., Simbahan and Dobermann, 2006; Kerry and Oliver, 2007), and random combination methods (e.g., Wang et al., 2008; Brocca et al., 2010). As having the advantage of requiring less input information than other methods, the random combination method (e.g., global random sampling and stratified random sampling) has became more popular (Wang et al., 2008; Brus et al., 2011). For example, Wang et al. (2008) applied this method to estimate the necessary sampling size of SWC at different scales (squares with sides of 10, 20, 40, 80, and 160 m); Liao et al. (2017) compared the accuracy of this method with temporal stability analysis and K-means clustering for identifying representation locations to predict the mean SWC. Therefore, it is promising to adopt this method to reveal the uncertainty in estimating the correlations between SWC and its controlling factors as affected by sampling size and pattern. However, to our knowledge, this has not been reported in previous studies.

Therefore, in this study, the global random sampling and stratified random sampling based on slope positions were conducted on a mixed land use hillslope. The objectives were to: (i) determine the accuracy and uncertainty in estimating the hillslope mean SWC as influenced by sampling size and pattern; (ii) determine the accuracy and uncertainty in estimating the correlation coefficients between SWC and soil/terrain properties as influenced by sampling size and pattern; (iii) determine the necessary sampling size and optimal sampling pattern in describing the correlations between SWC and soil/terrain properties.

2. Materials and methods

2.1. Study hillslope

This study was conducted on a hillslope (31°21′N, 119°03′E) (has an area of 0.6 ha) in the hilly area of Taihu Lake Basin, China (Fig. 1). This study area has a north subtropical-middle subtropical transition monsoon climate, with the annual mean temperature and mean precipitation of 15.9 °C and 1157 mm, respectively. Green tea (*Camellia sinensis (L.) O. Kuntze*) and Moso bamboo (*Phyllostachys edulis (Carr.) H. de Lehaie*) are two dominated plants on the hillslope. The elevation ranges from 77 to 88 m and the slope ranges from 0 to 21%. The soil type is shallow lithosols according to the FAO soil classification (Orthents according to Soil Taxonomy). Parent material is quartz sandstone. The soil texture is silt loam with silt content generally greater than 60%. Surface (0–20 cm) soil organic matter contents were about 2% on this hillslope. The depth to bedrock varies from <0.3 m at the summit slope position to about 1.0 m at the foot slope position.

2.2. SWC measurement

For monitoring SWC (volumetric SWC in this study), access polyvinyl chloride tubes were installed at 77 sites on this hillslope, with a spatial resolution of ~8 m (Fig. 1). Because of the rock fragments and plant roots, tubes were hard to be installed at the exact prearranged locations at some sites, thus the actual spatial distribution of the sampling sites was not rigid grid, especially in the bamboo field. The total sampling sites are different between the tea garden field (39 sites) and bamboo forest field (38 sites). However, the areas of these two fields are close (about 0.3 ha each). Therefore, the densities of sampling sites' spatial distribution are considered to be similar in the tea garden and bamboo forest fields.

A portable time-domain reflectrometry TRIME-PICO-IPH SWC probe (IMKO, Ettlingen, Germany) was used to collect the SWC data of these 77 sites on 43 dates from January 2013 to March 2016, with a frequency of one to two times a month. This arrangement of the measurements was sufficient for capturing different soil water content status, e.g. during the wet, medium and dry soil water conditions, in different seasons, and after typical precipitation events. For example, soil water content data was collected 1, 3 and 5 days after typical storms occurred on 9th May 2013 and 2nd June 2014 to capture the soil water drying process. The factory-set calibration curve that translates the dielectric constant of the soil into soil water content was used for all measurements. Before the campaign on each survey date, the SWC probe was calibrated in buckets with dry and saturated beads following the standard procedure in the user manual. The SWC was measured at the depth interval of 0–20 cm (note that this probe has a length of 18 cm). For each site, the probe was twisted in the access tube to face different directions and 2–3 readings were then taken. The average of these readings was used as the final SWC for each site on a specific date. In addition, an automatic weather station was installed on this hillslope to record the meteorological data.

2.3. Soil properties and topographic features

Around each SWC access tube (within 1-m distance), soil samples at the depth interval of 0–20 cm were collected using a hand auger. Soil samples were collected on 9th December 2012, before the application of fertilizer in the tea garden field (no fertilizer was applied in bamboo forest field), to capture the soil properties under natural condition. Three subsamples were collected for each site and then fully mixed. These samples were air dried, weighted, ground and sieved through a 2 mm polyethylene sieve. Particles larger than 2