

# Application of time series analysis in soil moisture of fixed dune on Korqin Sandy Land, Northern China

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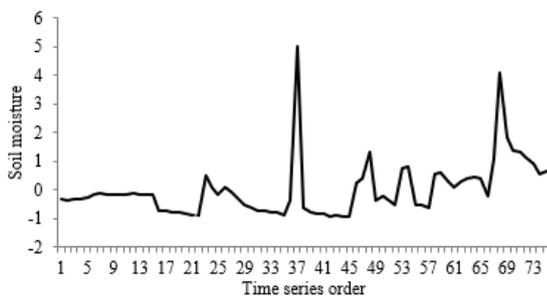
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## Graphical abstract



## Abstract

Time series analysis is a very effective method to analyze the dynamic characteristics of soil moisture at long-term scale. In this study, we have used the time series to analyze the relationship between precipitation and soil moisture on fixed dune at different soil depths (from 0 to 120 cm) during the growing season (from May to September) of 2006-2010 in Korqin Sandy Land, northern China. The results indicate that: (1) The precipitation is a relatively independent time series and has no obvious autocorrelation. Precipitation in an earlier stage has no obvious effect on the later stage in the growing season. (2) Soil moisture in different soil layers has higher autocorrelation; and the autocorrelation of soil moisture in each soil layer is significantly weakened with the increase in time lag interval. (3) The correlation coefficient between soil moisture and precipitation in each soil layer is higher at the time lag interval of  $k=0$ ; with the increase in soil depth, the correlation is gradually weakened. (4) The maximum correlation coefficients of soil moisture series and precipitation series in different soil depths were obtained at the time lag interval of  $k=0$ .

**Keywords:** Fixed dune, Korqin Sandy Land, soil moisture, time series analysis, northern China.

## 1. Introduction

Soil moisture is an important component of soil properties and direct impacts on vegetation growth and soil nutrients transforming processes (Letian *et al.*, 2012). It also plays a critical role in understanding various hydrologic processes,

such as runoff generation, evapotranspiration, water infiltration, and so on (Hotta *et al.*, 2010; Kim *et al.*, 2011; Puri *et al.*, 2011). The temporal pattern of soil moisture is a key feature of hydrologic interactions with climate (Albertson *et al.*, 2001), and hence, the temporal dynamics of soil moisture has been studied by many researchers (Kuzyakova *et al.*, 2006; Letian *et al.*, 2012; Yao *et al.*, 2013).

Soil moisture status are the main limiting factor for vegetation growth, especially in arid and semi-arid areas (Wang *et al.*, 2015; Yang *et al.*, 2018). Horqin Sand Land is one of China's four major sandy lands (Qadir *et al.*, 2008). The ecological environment here is fragile, and soil moisture is a key factor for the ecosystem stability in the region (Yao *et al.*, 2013). As is well known, due to overgrazing and unsustainable cultivation, this area has become one of the most severely deserted regions in China (Wang *et al.*, 1999; Wang *et al.*, 2016). The soil moisture dynamics and their relationship with precipitation in such dune areas have become one of the most important areas have been paid more attention for research on land-surface processes in arid China (Wang *et al.*, 1999).

Time series analysis is a statistical method of a long series data processing. Based on stochastic process theory and mathematical statistics, this method studies the statistical law followed by stochastic data series, and quantitatively predicts the future development of series (Cryer *et al.*, 2011). Studies have shown that precipitation and soil moisture have a strong correlation in a certain period of time (Jacques *et al.*, 2001). Time series analysis is a very effective method to study the long-term dynamic relationship between soil moisture and precipitation (Zhou *et al.*, 1998), (Shi *et al.*, 2004), and is thus widely used (Ford *et al.*, 2005; Kuzyakova *et al.*, 2006; Letian *et al.*, 2012; Liu *et al.*, 2008; Son *et al.*, 2007; Wang *et al.*, 2007; Wang *et al.*, 2012). Results of these studies show that precipitation series are uncorrelated, and the soil moisture in each soil layer has a high autocorrelation (Shi *et al.*, 2004; Wang *et al.*, 2007; Wang *et al.*, 2012). However, due to the influence of precipitation, evaporation, vegetation, topography, soil characteristics, and the precipitation series method used in synchronization with soil moisture, the study results of different types of land in different study areas are significantly different (Jacques *et al.*, 2001). For example,

Wang *et al.* (2007) conducted a time series analysis of soil moisture in red soil slopes, using the soil moisture data monitored once every 5 days and the precipitation data corresponding to the date of soil moisture sampling. Their results show that, the influence of precipitation on soil moisture is gradually weakened with the increase of soil depth, and the precipitation has a greater influence on soil moisture in different soil layers in 1 to 3 days after a precipitation event. Zhou *et al.* (1998) monitored soil moisture once every 5 days and the precipitation data of the cumulative amount within 5 days of the soil moisture monitoring interval at the Fengqiu Ecological Experimental Station. They suggest that the correlation diagram between the precipitation series and the soil moisture content in different soil layers has a certain periodicity. Wang *et al.* (2012) sampled the soil moisture once every month and monitored corresponding cumulative monthly precipitation in the mountainous woodlands in Beijing and reported that precipitation was significantly related to soil moisture, however, the correlation between soil moisture and precipitation was different in different soil layers (Mohammad *et al.*, 2019; D'Agata *et al.*, 2020; Achille and Enow, 2020; Abdikadir *et al.*, 2018).

Despite the time series analysis is widely used in soil moisture dynamics and their relationship with precipitation. However, there has been limited use of time series analysis to study soil moisture dynamics and their correlation with precipitation in fixed dunes of Horqin sandy land (Nwankwoala, 2019; Ibrahim *et al.*, 2020; Ch *et al.*, 2018; Siti *et al.*, 2019).

In the present study, we conducted field sampling to measure the soil moisture from May to September in 2006-2010 at different soil depths. We try to study the correlation between soil moisture and precipitation in fixed dune of Horqin Sandy Land based on the time series analysis. The goals of this study were to (a) analyze the dynamic characteristics of soil moisture time series in fixed dune; (b) explore the interrelation between soil moisture and precipitation. It is expected that these results can provide a theoretical basis and guidance for effective preservation of soil moisture in the region.

## 2. Material and methods

### 2.1. Study site description

The study site is located in the southern part of the Horqin Sand Land in eastern Inner Mongolia, China (43°55' N, 120°42' E, elevation approx. 360 m). The climate in this area is temperate, semiarid continental monsoonal, receiving an average annual precipitation of 360 mm, with 75% falling in the growing season (from June to September). The mean annual temperature is 5.8-6.4 °C. The mean annual wind velocity ranges from 3.2 to 4.1 m·s<sup>-1</sup>. The topography is characterized by dunes and inter-dune lowlands. The soils are sandy and loose in structure. The geomorphological types in the region are characterized by fixed dunes, mobile dunes, and uneven sandy lands with varying areas.

### 2.2. Data collection

The sample plot (42°939' N, 120°692' E, elevation approx. 368 m) is a long-term soil moisture observation field for fixed dunes at the Naiman Desertification Research Station. The main vegetations were *Artemisia scoparia* and *Setaria viridis*, and the vegetation coverage of the sample plot is 80%, and grazing has been prohibited for 30 years within the enclosed space, that is, there has been little or no human disturbance (Yao *et al.*, 2016).

CNC100 neutron moisture meter (Beijing) was employed for determination of soil moisture. Three neutron moisture meters at the depth of 2 m were buried at an equal interval for regular observation of soil moisture at the depth of 0-120 cm in fixed dune. From early May to the end of September in each year, soil moisture was determined once every 10 days for 5 consecutive years (2006-2010), and the measurement was repeated three times every time. The measurement values of the 3 neutron moisture meters calibrated by the traditional drying method were used to calculate the average moisture for analysis.

The daily precipitation during the same period was provided by the Naiman Desertification Research Station weather station. Since the soil moisture was monitored once every 10 days based on existing research methods (Shi *et al.*, 2004; Wang *et al.*, 2007; Wang *et al.*, 2012), the synchronizes precipitation time series was obtained by the cumulative precipitation within 10 days of each soil-moisture monitoring time interval in this paper.

#### 2.2.1. Time series analysis

The autocorrelation coefficient  $r_k$  of the time series  $X$  reflects the degree of correlation between the observed value  $X_t$  at time point  $t$  and the observed value  $X_{t-k}$  at the time lag interval  $k$ , and is expressed as follows:

$$r_k = \frac{\sum_{t=1}^N (X_t - \bar{X})(X_{t-k} - \bar{X})}{\sum_{t=1}^N (X_t - \bar{X})^2}, k = 0, 1, 2, \dots \quad (1)$$

where,  $N$  is the total number of time series observations, and  $N=75$  in this paper;  $\bar{X}$  is the average value of the series  $X$ .

Whether or not the sampling scales are the same and the variability is similar, the correlation between the two-time series can be reflected by the correlation coefficient as long as the two series are synchronized. If their sampling intervals are the same, the cross-correlation coefficient  $\phi_{XY}$  of the stationary time series  $X$  and  $Y$  with  $N$  pairs of observed values at the time lag interval  $k$  is calculated by:

$$\phi_{XY} = \frac{\omega_{XY}(k)}{[\omega_{XX}(0)\omega_{YY}(0)]^{1/2}} = \frac{\omega_{XY}(k)}{\sigma_X \sigma_Y} \quad (2)$$

where,  $\omega_{XX}(0)$  and  $\omega_{YY}(0)$  represent the variance of series  $X$  and  $Y$  respectively;  $\sigma_X$ ,  $\sigma_Y$  represent the standard deviation of the series  $X$  and  $Y$ , respectively; and  $\omega_{XY}(k)$  is the cross-covariance value of the series  $X$  and  $Y$  in the case of time lag interval  $k$ , and is represented by:

$$\omega_{XY}(k) = \sum_{t=1}^{N-k} (X_t - \bar{X})(Y_{t+k} - \bar{Y}). \quad (3)$$

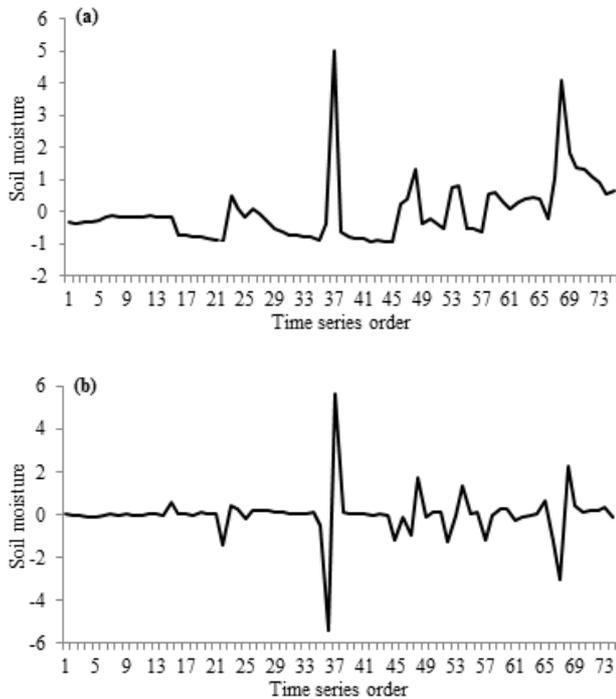
where,  $\bar{Y}$  is the average value of series  $Y$ ;  $Y_{t+k}$  represent the value of time series  $Y$  at time lag interval  $k(k=0,1,2,\dots)$ .

### 2.2.2. Data processing

The original data was standardized in order to improve data computing accuracy. The formula for data standardization is as follows:

$$X_t^* = \frac{X_t - \bar{X}}{\sigma} \quad (4)$$

where,  $X_t, X_t^*$  refer to the original data and the standardized data of the series  $X$  at the time point  $t$ , respectively, and  $\bar{X}, \sigma$  refer to the average value and standard deviation of the original data of the series  $X$ , respectively.



**Figure 1.** Soil moisture sequence of 60-80 cm after standardized (a) and first-order difference based on the standardized (b)

### 2.3. Data stationarity test

Since data used for time series analysis must satisfy the requirement of stationarity, i.e. the autocorrelation coefficient of the series is only related to the time interval, and is independent of its time point, that is, the average value of the series does not change with time. However, most time series in nature do not meet the requirements of stationarity (Li *et al.*, 2013).

In fact, differencing can be used to make non-stationary time series stationary after standardization, the commonly used first-differencing formula  $X_t^\# = X_t - X_{t-1}$ , where,  $X_t, X_t^\#$  denote the original data and the first-differencing data of the series  $X$  at the time point  $t$ .

After the first-order differencing time series of soil moisture in different soil layers in the fixed dunes undergo standardized, it was found that the soil moisture time

series of each soil layer met the requirements of stationarity (Liu, 2018).

Taking the 60-80 cm layer as an example, based on the soil moisture series diagram after standardization (Figure 1(a)) and after standardization and then first-order differencing (Figure 1(b)), it can be seen that after standardization, the soil moisture series is non-stationary, but after undergoing first-order differencing, the soil moisture series diagram satisfies the stationarity requirements.

## 3. Results and discussion

### 3.1. Autocorrelation analysis of time series

By analyzing the autocorrelation of precipitation series (Table 1), it can be seen that the autocorrelation coefficients of precipitation are all small at different time lag intervals, indicating that there is no obvious autocorrelation in the precipitation series. This is consistent with existing study results (Shi *et al.*, 2004; Wang *et al.*, 2007; Wang *et al.*, 2012), primarily because the precipitation series is a relatively independent time series, and the precipitation in the earlier stage has no significant effect on the later stage.

**Table 1.** Autocorrelation coefficients of precipitation at the different time lag interval

Time lag interval	1	2	3	4	5	6	7
Autocorrelation coefficients	0.047	-0.056	0.085	-0.074	-0.141	-0.101	-0.077

Based on the autocorrelation analysis of the soil moisture time series after first-order differencing in different soil layers of fixed dunes (Table 2), it can be found that the soil moisture in each soil layer has high autocorrelation (autocorrelation coefficients are all above 0.37) at the first time lag interval  $k=1$  (i.e., 10 days), indicating that the soil moisture in the fixed dune is most affected by its value of nearly 10 days (Khan *et al.*, 2017). The autocorrelation of soil moisture is smaller in the 40-100 cm layer, and larger in the 0-40 cm and 100-120 cm layers, indicating that the soil moisture in the 40-100 cm layer is greatly affected by external environment. This is somewhat different from related research results. For example, Liu *et al.* (2008) analyzed soil moisture in the forests in the red soil zone of Jiangxi, and showed that soil moisture autocorrelation gradually increases with the increase in soil depth. Wang *et al.* (2012) and Shi *et al.* (2004) report that the soil moisture autocorrelation coefficient is the largest in the 20-40 cm soil layer. In fact, the unsaturated flow of soil moisture is a long-term, continuous and slow process. Therefore, soil moisture in the earlier stage will have a certain influence in the later stage. However, due to different study zones, vegetation, soil textures, meteorological elements, and soil moisture monitoring time intervals, the results of different land types in different study areas differ extensively (Wang *et al.*, 2007). As the time lag interval increases, the autocorrelation of soil moisture in each soil layer is significantly weakened, which is consistent with existing study results (Wang *et al.*, 2007; Wang *et al.*, 2012).

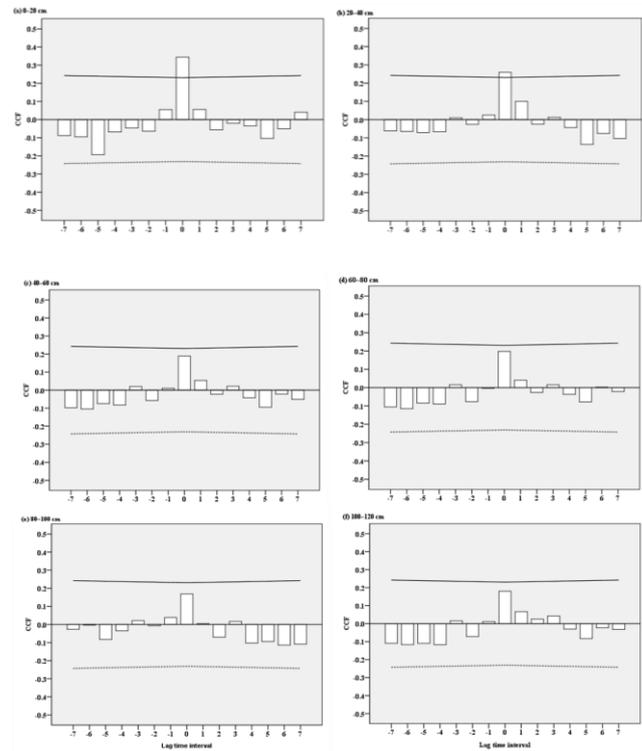
**Table 2.** Autocorrelation coefficients of soil moisture in different soil layer with different lag time interval

Lag time interval	Soil layer (cm)					
	0-20	20-40	40-60	60-80	80-100	100-120
1	0.46	0.485	0.378	0.382	0.396	0.452
2	0.186	0.259	0.204	0.195	0.244	0.291
3	0.135	0.134	0.099	0.153	0.194	0.228
4	0.101	0.097	0.065	0.135	0.175	0.205
5	0.118	0.089	0.061	0.133	0.184	0.209
6	0.198	0.082	0.040	0.094	0.141	0.162
7	0.199	0.017	-0.008	0.039	0.078	0.096

### 3.2. Cross-correlation analysis between soil moisture and precipitation

The correlation analysis between the soil moisture series (after undergoing first-order differencing) in different soil layers and the corresponding precipitation series was carried out. From the correlation function diagram (Figure 2), it can be seen that at the zeroth time lag interval (i.e.  $k=0$ ), the cross-correlation coefficient (CCF) between soil moisture in each soil layer and precipitation is higher. With the increase of soil depth, the correlation between soil moisture and precipitation is gradually weakened, indicating that the effect of precipitation on the soil moisture is higher in the shallow layer than in the deep layer, which is mainly because the vegetation coverage in fixed dunes is lower (Pan *et al.*, 2018), with less blockage of precipitation, and hence, the shallow layer of the soil is recharged by the precipitation faster (Demir *et al.*, 2019; Peng *et al.*, 2018), and the soil moisture in the shallow layer is more susceptible to precipitation than the deep layer. The correlation coefficient between soil moisture of different soil layer and precipitation is gradually weakened with the increasing of time lag interval.

As previous studies shown in the correlation function diagram of precipitation and soil moisture, when the time lag interval  $k \geq 0$ , the positive correlation coefficient appears at the initial time lag interval. During this time lag interval, the soil moisture begins to respond to precipitation and gradually increases. For the correlation function diagram of precipitation and soil moisture (Figure 2), the initial time lag interval is all  $k=0$ , indicating that the soil moisture in different soil layers of fixed dunes increase rapidly after precipitation (Oyekale, 2017). It can be judged from figure 2 that the period of the correlation function between the precipitation and the soil moisture in the 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, and 100-120 cm layers is 1.5, 2, 2, 2, 1 and 3.5 time lag intervals (1 time lag is 10 days), indicating that the values of the peaks and valleys on the precipitation diagram are separated by 1.5, 2, 2, 2, 1 and 3.5 time lag intervals, and reflected by corresponding peaks and valleys on the soil moisture dynamic diagram at the soil depth of 20 cm, 40 cm, 60 cm, 80 cm, 100 cm and 120 cm.



**Figure 2.** Cross-correlation coefficients (CCF) between soil moisture and precipitation cumulative within 10 d of each monitoring interval of soil moisture. Note:  $\square$  denote CCF, — and ..... denote confident upper bound and confident lower bound, respectively.

In addition, the maximum value of the correlation coefficient between precipitation and soil moisture, together with the corresponding time lag interval, forms a pair of parameters, indicating that the soil moisture reaches the maximum value in response to the precipitation at this time lag interval (Zhou *et al.*, 1998). The maximum correlation coefficient of precipitation and soil moisture series at the soil depth of 20 cm, 40 cm, 60 cm, 80 cm, 100 cm and 120 cm is 0.34, 0.26, 0.19, 0.20, 0.17 and 0.18, and the corresponding time lag intervals are all  $k=0$ , indicating that soil moisture in different soil layers of fixed dunes reaches the maximum value soon after a precipitation event. This is different from existing studies. For example, Zhou *et al.* (1998) showed that there are temporal differences in the response of soil moisture at different depths to precipitation. For instance, the soil moisture at soil depth of 30 cm and 60 cm reaches the maximum value at the first time lag interval after a precipitation event, while the soil moisture at soil depth of 90 cm and 110 cm reaches the maximum value at 4 and 8 time lag intervals, respectively, where one time lag interval is 5 days (Wang *et al.*, 2017). The main reason for the differences in the study results is due to different study areas, vegetation, soil texture, meteorological elements, and soil moisture monitoring time intervals (Jacques *et al.*, 2001; Wendroth *et al.*, 1999).

## 4. Conclusions

The relationship between precipitation and soil moisture time series on fixed dune at 0 to 120 cm soil layers from

May to September of 2006–2010 in Korqin Sandy Land were obtained by the time series analysis. From the study, we can draw some conclusions as follows:

- 1) The precipitation is a relatively independent time series and has no obvious autocorrelation; Soil moisture in different soil layers of fixed dunes has higher autocorrelation; with the increase in time lag interval, the autocorrelation of soil moisture in each soil layer is significantly weakened.
- 2) The cross-correlation coefficient between soil moisture and precipitation in each soil layer is higher at the time lag interval  $k=1$ , and the correlation is gradually weakened with the increase in time lag interval.
- 3) The soil moisture in different soil layers of fixed dunes increase rapidly after precipitation; And the correlation diagram between the precipitation and soil moisture in different soil layers has a certain periodicity.
- 4) The maximum correlation coefficients of precipitation and soil moisture series at different soil layers in the fixed dune are all obtained at time lag interval of  $k=0$ , hence, soil moisture in different soil layers of fixed dunes reaches the maximum value soon after a precipitation event.

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