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Vegetation greenness response to water availability in northern China from 1982 to 2006

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Abstract: An evaluation of the relationship between satellite-observed Normalized Difference Vegetation Index (NDVI) data as a proxy for vegetation greenness and water availability (rainfall and soil moisture) can greatly improve our understanding of how vegetation greenness responds to water availability fluctuations. Using Sen and Pearson's correlation methods, we analyzed the spatio-temporal variation of vegetation greenness for both the entire year and the growing season (GS,4-10) in northern China from 1982 to 2006. Although, vegetation greenness and soil moisture during the study period changed significantly for the entire study area, there was no change in rainfall. Linear correlation analysis between NDVI and rainfall revealed higher correlations using data for all seasons. Higher correlations for NDVI and soil moisture were obtained using growing season data. This study highlights how strongly vegetation greenness responds to water availability dynamics, especially in the growing season period.

Keywords: Vegetation greenness, rainfall, soil moisture, trend analysis

1. Introduction

Water availability is generally assumed to be one of the most important parameters for vegetation greenness (Zhang et al., 2010; Huber et al., 2011; Niu et al., 2015). The soil system is the key component of the Earth System as control the biological, hydrological, and geochemical cycles and contribute with services, good and resources to the humankind(Keesstra et al.,2012;Smith et al.,2015; Decock et al.,2015; Brevik et al.,2015; Berendse et al.,2015).Satellite-derived normalized difference vegetation index (NDVI) data, which potentially provides much greater spatial and temporal coverage, have recently played an important role in investigating the relationship between NDVI and water availability (rainfall and soil moisture)

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around the world. The soil genesis and development is highly determined by the vegetation as control the soil erosion and contribute to the biological diversity of the soils (Cerdà,1998; Yu and Jia,2014; Beyene,2015; Laberge et al.,2015; Keesstra et al.,2016).In arid and semi-arid regions, particularly in northern China, rainfall is a major factor controlling the vegetation growth, and affect many soil parameters and properties(Hewelke et al., 2014; Yu et al.,2015). Much work has been done in studying the relationship between vegetation greenness and rainfall (Helldén and Tottrup, 2008; Huang et al., 2012; Mu et al., 2012; Gao et al., 2014). Previous studies have relied on either the annual (growing season) or seasonal temporal scale to determine the interannual variation in NDVI and rainfall (Helldén and Tottrup 2008; Huang et al., 2012). Most studies on the greenness (NDVI as a proxy) and rainfall relationship in northern China have been based on point measurements of rainfall (Cao et al., 2011) or gridded surfaces from point observations (Mao et al., 2012). The present study presents an analysis of the trend and relationship between monthly vegetation greenness using the recent rainfall gridded datasets provided by the Climate Research Unit (CRU).

Soil moisture is defined as the quantity of water contained in soil on a volumetric or gravimetric basis (Magagi and Kerr, 2001). Current methods for obtaining soil moisture data include point measurements (Zehe et al., 2010), model simulations (Yun and Huug, 2004), and remote sensing observations (Kerr et al., 2001; Tapley et al., 2004), and many studies have examined the relationship between NDVI and soil moisture (Adegoke and Carleton, 2002; Wang et al., 2007). Because existing soil moisture data is based on site measurements and satellite data, they are impractical for soil moisture estimation at a large scale over a long period. In this study, we used long sequences of simulated soil moisture data to estimate variation in vegetation greenness. The relationships between vegetation greenness and water availability are complicated because of the time lag in the response of vegetation greenness to water availability. Previous studies investigating the potential of using NDVI to estimate rainfall and soil moisture have found correlations between both NDVI and rainfall and NDVI and soil moisture, and so the NDVI is frequently used to study rainfall and soil moisture.

However, few studies have examined the response of vegetation greenness to water availability (both rainfall and soil moisture) in northern China. In this study, we conducted a multi-variable investigation in order to better understand the relationship between vegetation

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greenness and water availability, as well as their long-term dynamics and trends in northern China. Because soil moisture data was produced by models rather than field data, we focused on rainfall to analyze the greenness and water availability lag factors.

The impact of climate and human activities on vegetation greenness variability is still a matter of debate (Warren, 2005; Helldén and Tottrup, 2008). Nevertheless, NDVI is used as a proxy to study the vegetation greenness response to rainfall variability (Herrmann et al., 2005; Fensholt et al., 2012; Gong et al.,2015), even though rainfall variability is not the only constraining factor for vegetation greenness, and other factors, such as human activities, should also be considered. For this reason, the NDVI residual time series of the NDVI, regressed against rainfall data, was used to study the effect of human activities on vegetation greenness (Herrmann et al., 2005; Huber et al., 2011).

The objective of the present study was to investigate the temporal and spatial trends and relationships between a proxy of vegetation greenness (NDVI), rainfall, and soil moisture in northern China. Specifically, we investigated the extent to which NDVI is related to rainfall at different time lags. Furthermore, NDVI residual time series of the NDVI regressed on rainfall data were used to obtain vegetation greenness trends induced by other factors than water availability.

2. Materials and methods

2.1 AVHRR GIMMS 15-day composite NDVI data

AVHRR (Advanced Very High Resolution Radiometer), GIMMS (Global Inventory Modeling and Mapping Studies), and NDVI data were used in this study. The NDVI data cover the period from 1982 to 2006 with an 8 km spatial resolution and biweekly (15 days) temporal frequency. The data was obtained from the website of the Global Land Cover Facility (http://www.landcover.org/data/gimms/). The NDVI dataset was carefully assembled from different AVHRR sensors (the AVHRR sensor onboard NOAA satellites 7, 9, 11, 14, 16, and 17) and corrected for atmospheric, calibration loss, orbit drift, volcanic eruption, and other effects not related to vegetation change (Tucker et al., 2005). In order to further reduce the influence of clouds, the original 15-day temporal resolution AVHRR GIMMS NDVI data were aggregated monthly by a maximum value composite approach (MVC).

2.2 Rainfall data

Monthly rainfall products were obtained from the Climate Research Unit (CRU), University

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of East Anglia, Norwich, UK. For monthly rainfall, the CRU dataset used an interpolation method based on the set of stations available at that moment in time (Mitchell and Jones, 2005). It was provided as a monthly sum at a 0.5 °×0.5 ° spatial resolution for the period from 1901 to 2011. Monthly accumulated rainfall data derived from CRU were used from 1981 to 2006. The CRU dataset is appropriate for our study since it is has been used successfully in many studies and is close in resolution to GIMMS and NDVI data. (Helldén and Tottrup, 2008; Piao et al., 2011).

2.3 Soil moisture data

We used the NOAA National Centers for Environmental Predictions (NCEP) Climate Prediction Center (CPC) monthly high resolution global soil moisture data set at a 0.5 ° spatial resolution for the period from 1982 to 2006 (Fan and van den Dool, 2004). Soil moisture data sets were produced using a one-layer "bucket" water balance model covering the period from 1948 to present. This model used over 17,000 gauges worldwide obtained monthly from the Climate Prediction Center (CPC). Global rainfall and monthly global temperatures were obtained from the CDAS- Re-analysis product over land (Kistler et al., 2001; Chen et al., 2002).

2.4 Data pre-processing

The analysis was restricted to include only those parts of the study area that had a long-term (1982–2006) monthly NDVI standard deviation (SD) value < 0.02 (Fensholt and Proud, 2012). Per-pixel QA information in the AVHRR GIMMS NDVI product was used to remove the NDVI data without confidence (contaminated by cloud or snow/ice). Then, a simple temporal filter was applied to fill in the gaps in the missing data and to integrate the AVHRR, GIMMS, and NDVI data (Xiao et al., 2003; Fensholt et al., 2009). In addition, rainfall and soil moisture data with a 0.5 ° resolution was resampled into a geographic type of approximately 8km×8km resolution so that it would match the NDVI.

2.5 Methods for trend analysis

The trend of monthly NDVI, rainfall, and soil moisture was obtained from a median trend (Theil-Sen) procedure for the period from 1982 to 2006 (Theil, 1950; Sen, 1968). Only areas of significant change at 95% confidence were shown. A linear regression analysis was carried out with NDVI as the dependent variable and 3-monthly cumulative rainfall as the independent variable. We used the non-parametric Mann–Kendall (MK) method for time series trend analysis since it has been commonly applied to vegetation (Fensholt et al., 2009). A positive slope ($z \geq 1.96$)

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represents a significant increase (α=0.05) in NDVI, rainfall, or soil moisture while negative slopes ($z \leq -1.96$) indicate a significant decrease (α=0.05).

3.3 Methods for correlation analysis

A linear correlation (r) analysis was applied to study the relations between NDVI/rainfall (1982-2006) and NDVI/soil moisture (1982-2006) datasets. The correlations between both NDVI/rainfall and NDVI/soil moisture were obtained for northern China in order to compare the vegetation greenness response to water availability (rainfall and soil moisture) for both the growing season data and all-year data.

3. Results and Discussions

3.1 Trend Analysis

Trend analyses were employed for NDVI, rainfall, and soil moisture data using Sen's method to investigate how they changed across the study area from 1982 to 2006. Significant trends in NDVI and annual rainfall were derived (Fig. 1and 2) for the period from 1982 to 2006.

Vegetation greenness increased for the period from 1982 to 2006 in the study area, especially in Shaanxi and Hebei Provinces, while there was little decline in vegetation greenness in Xinjiang Province. Over the whole study area, there was a significant positive trend in vegetation greenness at a 5% significance level (Fig.1). Consistent with earlier findings, vegetation greenness during the study period (1982-2006) significantly increased in several locations across the study area as illustrated in Fig. 1.The rainfall trend was found to be insignificant (Fig.2) as well as the correlation coefficient map between both NDVI and rainfall and NDVI and soil moisture (Fig.3) in the growing season.

The rainfall trend only exhibited a significant increase in western Xinjiang. Large areas in northern China did not exhibit any significant trend in rainfall at a 5% significance level over the last 25 years (Fig. 2a). Soil moisture in most areas changed significantly, with significant increases in areas distributed in Liaoning, Hebei, Qinghai, and Xinjiang Provinces, while decreasing significantly in the northern part of Inner Mongolia (Fig.2b).

The NDVI trends mapped in this study are similar in spatial variability to those reported by Huang et al., (2012) in their study from 1982 to 2007 as both studies used the "Theil-Sen method" for estimating the NDVI changes (Yin et al., 2011; Huang et al., 2012). However, it is difficult to compare this trend analysis with other studies because of differences in analytical techniques,

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significance levels, study periods, and so forth. Most previous research has been based on the NDVI, summed either annually or over the growing season, over relatively short periods, whereas in this study our analysis was based on monthly NDVI over a much longer period from 1982 to 2006. Vegetation greenness trends showed a persistent increase in all study areas. These trends in Shaanxi and Hebei Provinces could be related to forest vegetation cover characterized by deep roots, which are able to reach the water table independent of fluctuation in rainfall and soil moisture (Do et al., 2008).

3.2 Correlations Analysis

In this study, Pearson correlation coefficients were calculated among simultaneous NDVI, lagged rainfall, and simultaneous soil moisture on a pixel-by-pixel basis for two different time frames: the full year and the growing season (April to October). All correlation coefficients (r) between NDVI and water availability were statistically significant at 95% confidence intervals. The relationship analysis was conducted in order to determine the relationship between NDVI and rainfall data for different lag times (0, 1, 2 months of rainfall lags from NDVI data) in the study period (Huber et al., 2011). Rainfall exhibited a small correlation with simultaneous NDVI over 25 years; however, the time-lagged NDVI increased their correlation. Three integrated monthly rainfall time-series exhibited a better correlation with monthly NDVI. The three-month summed rainfall and NDVI data correlation analysis was then performed (Fig. 3 and 4).

According to Figures 3a and b, the significant correlations calculated from all-year data yielded more pixels than the data from only the growing season. A significant positive correlation (0.6-1.0) between NDVI and rainfall was found in large areas over the entire year, but only for a relatively limited area in the growing season (Fig. 6a).

Fig. 4 presents the correlations (r values) between the monthly NDVI and soil moisture for the entire year and the growing season in northern China. The growing season, from April to October, had the highest correlation between NDVI and soil moisture in the study area.

Correlations between the 3-month sums of monthly rainfall and soil moisture for both the entire year and the growing season in northern China in figure 5. In most parts of the study area, rainfall and soil moisture during the growing season is better than for the full year.

Correlations for both the entire year and the growing season decreased in most of the study area when the 3-month summed time lag between NDVI and rainfall was analyzed, suggesting

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that NDVI was more responsive to the three-month sum than for the entire year. Several previous studies have documented a similar correlation distributed in northern China since the early 1980s (Helldén and Tottrup, 2008; Huang et al., 2012; Mu et al., 2012). Grassland phenology dynamics are closely related to spring precipitation and increasing temperature at the early growing period(Gong et al., 2015).Also, the vegetation changes are affected by other factors, such as a chemical transmission by H + or anthropogenic activity(Kou et al., 2015; Russell and Ward, 2016).

The plant is of importance in the earth system (Lieskovský and Kenderessy, 2014; Berendse et al., 2015; Cassinari et al., 2015; Poelking et al., 2015; Beyene, 2015; Zhao et al., 2015).The weaker correlation between NDVI and soil moisture for the entire year might be explained by the large column depth (1.6m) used to model soil moisture data (Fan and van den Dool, 2004). However, the correlation between NDVI and soil moisture during the growing season is higher than for the entire year (Fig. 6b). Fensholt et al., (2010) showed that soil moisture in the upper 20-30 cm had a high correlation with shorter plant roots. The results indicate that NDVI and soil moisture had higher statistically significant correlations in the growing season, indicating that NDVI had a stronger response to soil moisture variation.

4. Conclusion

This study has evaluated the trends and correlations between NDVI, soil moisture, and lagged rainfall data during the observation period (1982-2006). Vegetation greenness and soil moisture have significantly changed in the whole study area, while rainfall remained unchanged. This study showed that NDVI is strongly correlated to simultaneous soil moisture and lagged rainfall during the growing season. Rainfall and soil moisture both exhibited similar relationships with NDVI, suggesting that NDVI is appropriate for monitoring vegetation greenness response to water availability in northern China from 1982 to 2006. The results of this study have important implications for improving our understanding of the relationship between vegetation greenness and water availability in northern China.

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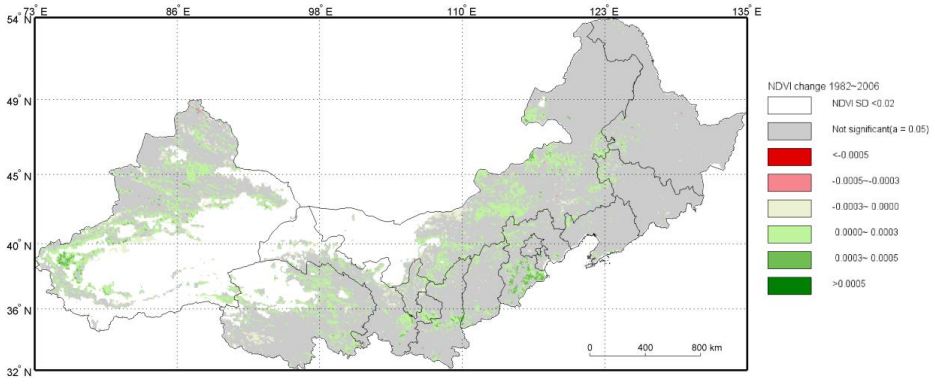
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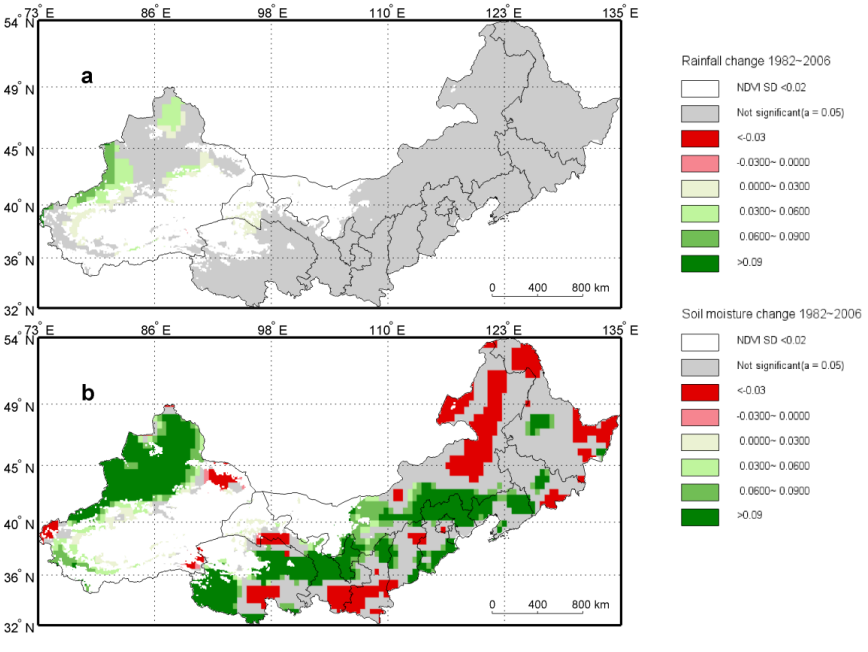
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360 Fig.1 Map of monthly NDVI trend analysis (1982–2006)



361

362 Fig.2 Trend maps for a) 3-month rainfall sum for all months per year and b) monthly soil moisture

363 data from 1982 to 2006.

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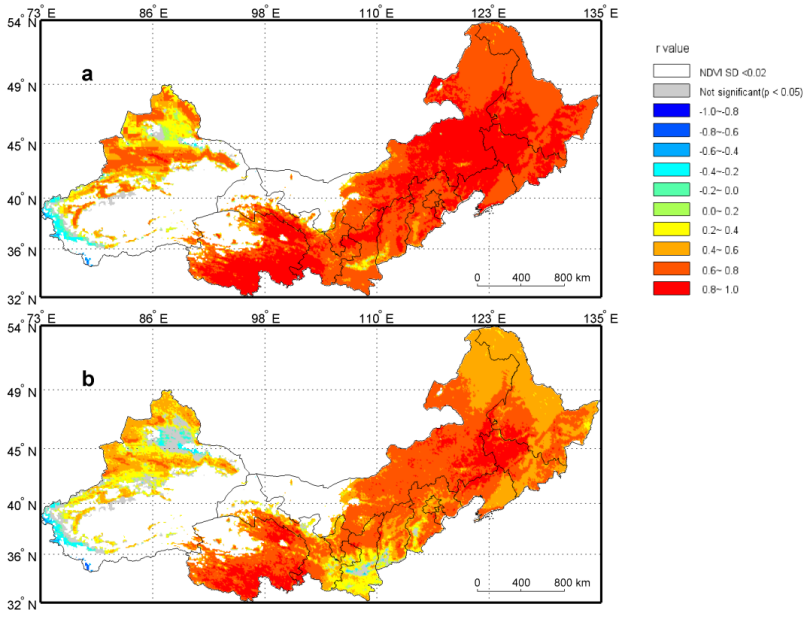


Fig.3 Linear correlation between monthly NDVI and a) 3-month sums of rainfall for all months per year and b) 3-month sums of rainfall for the growing season (GS).

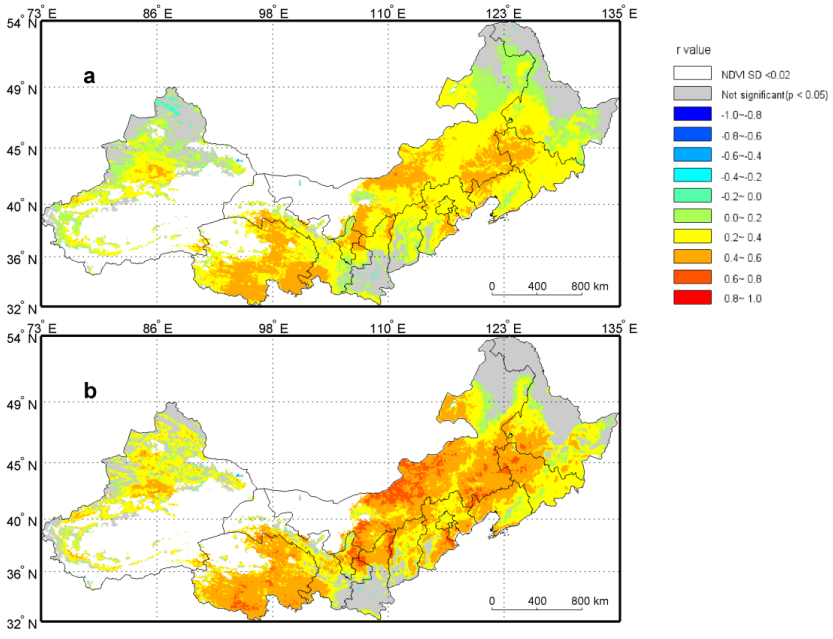
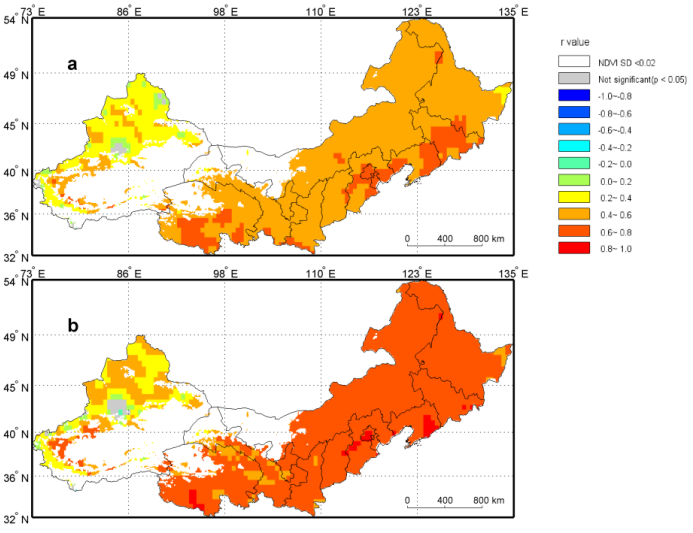


Fig.4 Linear correlation of monthly NDVI and a) soil moisture for the entire year and b) soil moisture for the growing season (GS).

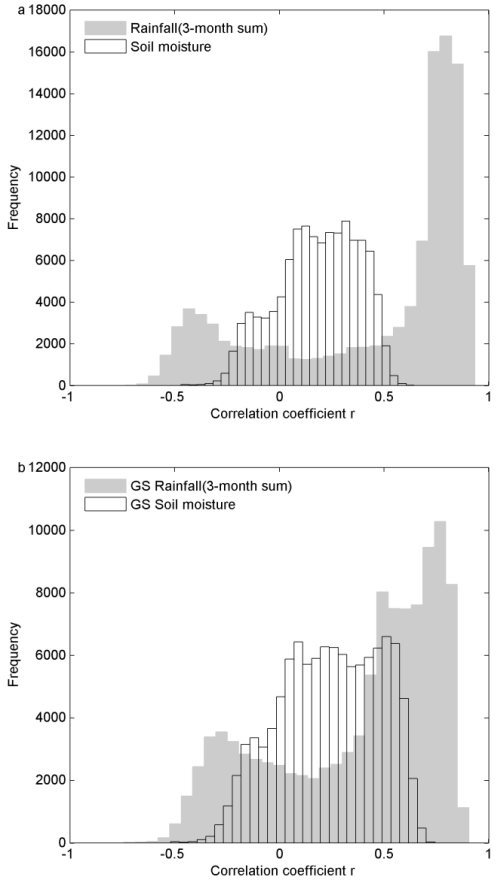
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371 Fig.5 Linear correlation of 3-month sums of rainfall and a) soil moisture for the entire year and b)

372 soil moisture for the growing season (GS).



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374 Fig.6 Histograms showing the correlation coefficients calculated between a) full year NDVI
375 (dependent var.), rainfall, and soil moisture and b) Growing season (GS) NDVI (dependent var.),
376 rainfall, and soil moisture for the northern China.