Development of a New Soil Moisture Index Using SMOS Satellite Soil Moisture Products: Case study in Southwestern Mongolia

Oyudari Vova[1], Pavel Groisman[2], Martin Kappas[3], Tsolmon Renchin[4], and Steven Fassnacht[5]

[1]University of Göttingen
[2]Hydrology Science and Services Corporation
[3]University of Goettingen
[4]National University of Mongolia
[5]Ecosystem Science and Sustainability - Watershed Science Department, Colorado State University; Cooperative Institute for Research in the Atmosphere, Fort Collins, USA

November 26, 2022

Abstract

A new soil moisture index for monitoring drought occurrence and intensity is presented. The index is based on the integration of different remote sensing products and in situ observations. Due to a shortage of precipitation, droughts reduce vegetation productivity, and thus, aggravate the impact of moisture stress on pastureland. The spatial distribution of soil moisture index with high-resolution images in Mongolia is still being one of the essential goals in the remote sensing and rangeland community. Specifically, we examined a new composite Gobi soil moisture index (GI) based on the combination of Ocean Salinity (SMOS) Soil Moisture, several products from the MODIS satellite, and in situ Soil Moisture (SM) observations. A multiple linear regression method was used for the estimation of GI soil moisture index. The former includes the surface soil moisture from the Soil Moisture and Ocean Salinity (SMOS) mission, the Moderate Resolution Imaging Spectroradiometer (MODIS) derived land surface temperature (LST), normalized difference vegetation index (NDVI), potential evapotranspiration (PET). The latter includes a standardized precipitation index (SPI) from in-situ data. The validation of the approach is based on the relationship between SPI and in-situ soil moisture (SM) observations, and their comparison to remote sensing (RS) – derived indices. The results show that the correlation was statistically significant between GI and in-situ SM observations from the meteorological stations at 10 – 15 cm depths ($p < 0.0001$). The correlation between GI and SPI, as represented by the correlation coefficient (r) was 0.64. The GI empirical equations that utilize at least three key atmospheric variables are (a) NDVI, (b) land surface temperature, and (c) potential evapotranspiration. The established new GI soil moisture index was retrieved at the 1 km spatial resolution for Southwest Mongolia from 2000 to 2018, and their two summer months (July, August) were used for monitoring drought and vegetation response to the varying soil/climatic conditions. Now, based on the assessment of drought severity, the new soil moisture index allowed us to assess a large-scale spatial coherence of droughts across the Southwestern part of Mongolia.

Development of a New Soil Moisture Index Using SMOS Satellite Soil Moisture Products: A case study in Southwestern Mongolia

Oyudari Vova, Martin Kappas, Pavel Groisman, Tsolmon Renchin, and Steven Fassnacht

Cartography, GIS and Remote Sensing Department, Institute of Geography, University of Göttingen, Germany; NC State University Research Scholar at National Centers for Environment Information, USA; Department of Physics, National University of Mongolia; Department of Ecosystem Science and Sustainability – Watershed Science, Colorado State University, Fort Collins, CO, United States.

Presented at:

Abstract

The shortage of precipitation in Mongolian regions exacerbates droughts. Consequently, it reduces vegetation productivity and aggravates moisture stress on pastureland. Because national meteorological network is scarce, a new generation of soil moisture data with a high spatial resolution can be alternative for various applications such as drought monitoring, wild or anthropogenic forest fires, agricultural management, and water management. Modern remote sensing products provide us with an opportunity to overcome such a scarcity of in situ local measurement networks. In particular, we suggest a new index named “Gobi soil moisture index (GI)”, which uses soil moisture as a proxy for monitoring of drought occurrence and intensity at ~ 1 km spatial resolution. This index integrates several different remote sensing products with in situ observations, based on multiple linear regression method for soil moisture and ocean salinity (SMOS) mission product, three moderate resolution imaging spectroradiometer (MODIS) satellite products, i.e., land surface temperature (LST), the normalized difference vegetation index (NDVI) and potential evapotranspiration (PET), and in situ soil moisture (SM) and precipitation observations. With soil moisture, evapotranspiration, and land surface

temperature, the GI index indicates the response and vulnerability of arid and semi-arid vegetation to drought severity-associated changes in evapotranspiration. The new established soil moisture index GI was used to monitor grassland drought and vegetation response to varying soil/climatic conditions, for southwest Mongolia from 2000 to 2018 and its two summer months (July, August). The results show that the correlation was statistically significant between GI (model) and SMOS SM data, and in-situ SM observations from the regional meteorological stations at 10 – 15 cm depths ($p < 0.0001$). We also retrieved a subset of Soil Moisture Active/Passive (SMAP) soil moisture data and compared it with our GI estimates. A high correlation between SMAP SM and GI (0.85) is statistically significant at the 0.01 level and confirms that GI is a good overall tool to monitor droughts. Empirical GI equations can be easily transferable and scalable over most extratropical land and represent a useful model in areas with scarce gauge coverage. In addition, it is an affordable tool that can identify droughts in soil moisture.

In the past, soil moisture drought maps were not used for drought projections in Mongolia. Now, based on the evaluation of the severity of the drought, the new soil moisture index allowed us to assess the large-scale spatial coherence of droughts in the southwest part of Mongolia.

Introduction

In recent years, the severity of various environmental hazards is expected to continue increasing due to climate change. Droughts have affected many regions of the world, with the greatest impact on the agricultural and livestock sector. The lack of precipitation and other climatic factors (such as high temperatures, high winds, dust storms, low humidity, soil moisture deficit) aggravate the severity of the drought event. Droughts in Mongolia occur every 2-3 years; half of the country has been affected by a drought once every 4-5 years, and have always had significant socioeconomic and environmental impacts. The largest droughts occurred in 2000, 2002, 2007, when most of the regions of the country were affected by extremely dry and hot weather.

During the past 60 years, regional temperatures in Southern Mongolia have increased by 0.1 – 3.7 ˚C, spring precipitation has decreased by 17%, and summer precipitation has decreased by 11%. It is very important to investigate the pasture responses to soil moisture deficit and to summer droughts that are crucial for the nation. The meteorological drought refers to precipitation shortages, agricultural (or soil moisture) drought also accounts for soil moisture deficit, and hydrological drought is related to water resources (supply) in the forms of streamflow, groundwater, and/or evapotranspiration deficit. The meteorological and agricultural droughts occur when precipitation and available soil moisture decrease, which can cause vegetation stress and adversely affect grassland.

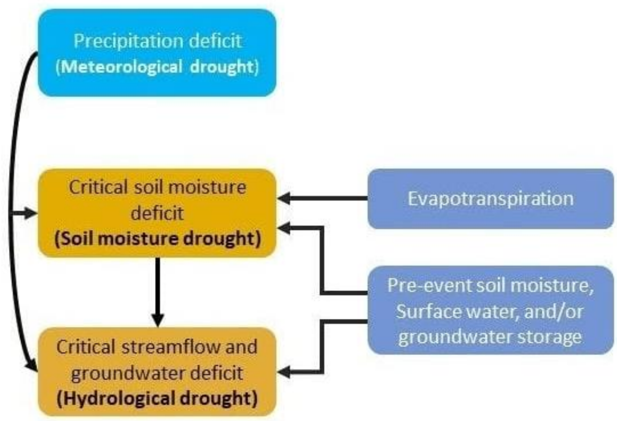


Figure 1. Drought types, causal processes, and their drivers of occurrences.

In this context, soil moisture is considered a significant variable of agriculture drought in an arid and semi-arid land. Depending on the moisture conditions and the deficiency of water for a specified area, drought indices can be classified as precipitation indices, water balance indices, soil moisture indices, and aridity indices.

Due to the expansion of drought and desertification in Mongolia, it is necessary to develop methods for the evaluation of large-scale drought that affects vegetation (pastures). In this research, we attempted to build higher spatial resolution (1km) soil moisture drought maps in order to assess their dynamics.

Study Area

This research was conducted in the Bayankhongor Province. The province is located in the southwest of Mongolia and covers an area of 116,000 square kilometers. It includes the southern region of the Khangai mountain range, the eastern ridges of the Altai Mountains, and the unique Gobi Desert to the south (Figure 2). The province climate is continental semi-arid with mean annual temperatures ranging from 0 ° C to 7 ° C in the north and 0 ° C to 8 ° C in the southern regions.

The province suffers from a shortage of water and has an average annual precipitation of 80–160 mm. The vegetation growth season is short and depends on antecedent soil moisture and regional rainfall. Short grasses, semi-shrubs, and woody plants are the dominant vegetation. The type of soil in the province has a vertical distribution by elevation: white loamy and sandy soil (below 1300 m above sea level, ASL), gray-stony soil (in the range of 1300-2000 m ASL), and dark brown soil (above 2000 m ASL).

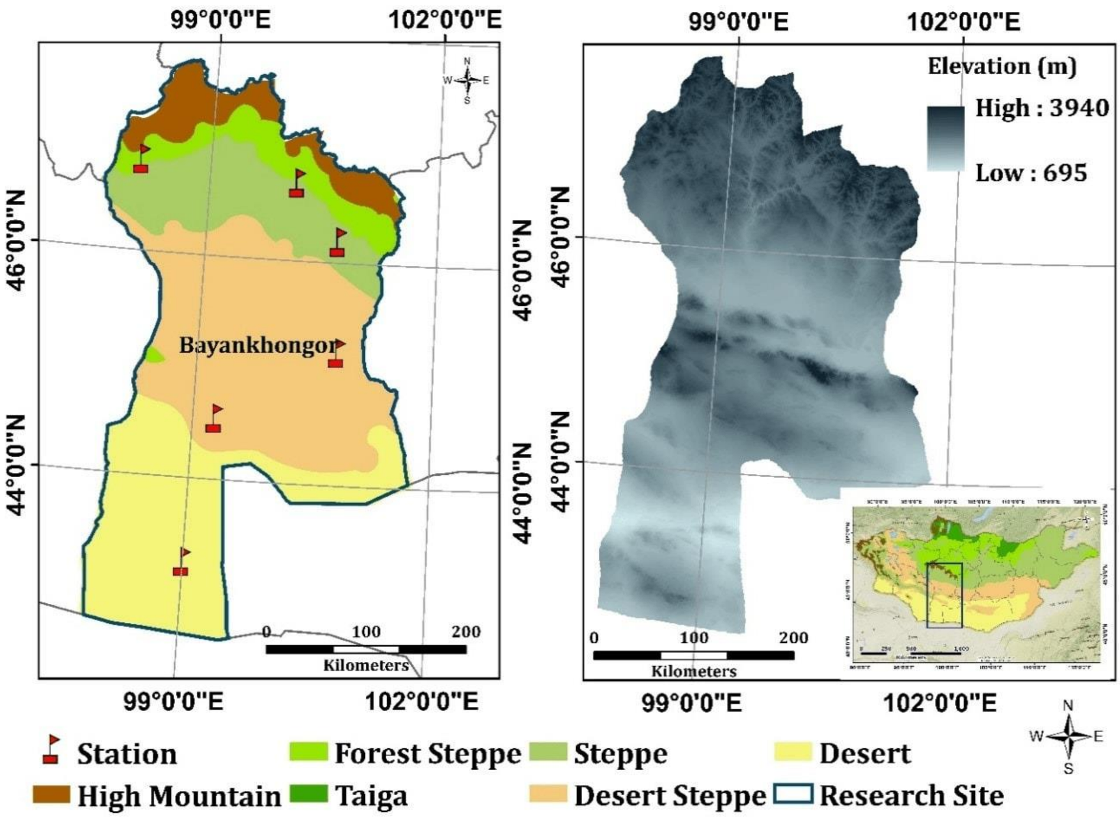


Figure 2. Geographical location and vegetation zone maps of Bayankhongor Province. (a) Meteorological station distribution and vegetation zones, data sourced from the Information and Research Institute of Meteorology, Hydrology, and Environment (IRIMHE) of Mongolia. (b) Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) data.

The selected meteorological stations are representative of the surrounding geomorphologic and vegetation conditions. The locations of the meteorological stations were classified into three vegetation zones: steppe, semi-desert steppe, and desert (Table 1). These zones form vegetation belts at different altitudes (from mountains to plains) and latitudes (from north to south).

Table 1. Meteorological stations of the in-situ SM measurements data in Bayankhongor province with location information and vegetation zones.

Meteorological station	Province name	Vegetation zones	Latitude (N)	Longitude (E)	Elevation (m)
Bayanbulag	Bayankhongor	steppe	46° 49'32 N	98° 40'10 E	2398
Galuut	Bayankhongor	steppe	46° 43'30 N	100° 8'35 E	2102
Bayankhongor	Bayankhongor	steppe	46° 11'40 N	100° 42'2 E	1877
Bogd	Bayankhongor	semi-desert	45° 40'10 N	100° 7'75 E	1264
Shinejinst	Bayankhongor	semi-desert	44° 32'13 N	99° 17'34 E	2216
Ekhiingol	Bayankhongor	desert	43° 14'48 N	99° 21'14 E	1011

Research objective (s)

The main objective of our study was to integrate the monthly average SMOS SM and the MODIS-based NDVI / LST / PET data using the multiple linear regression (MLR) model to build an appropriate model for drought assessments.

Specifically, we intended:

- to evaluate the developed soil moisture index (GDI) against seven drought indices (TCI, NMDI, VSWI, NDVI, NDWI, NDDI SPI),
- to evaluate the GDI by verifying it with the help of in situ SM observations from meteorological stations and after verification
- to apply the GDI to produce regional-wide GI 1 km soil moisture drought maps for summer months (July and August) from 2010 to 2018 in Southwestern Mongolia.

Data and Methods

Data

A new integrated soil moisture index (GI) is developed based on the monthly average SMOS SM and NDVI, LST, PET (MODIS) data.

In situ data included soil moisture, precipitation, and air temperature from meteorological stations that were applied at the validation stage of this investigation.

Methods

The multiple linear regression model has been extensively used in many previous works for the purpose of downscaling the coarse-scale soil moisture product.

The multiple linear regression (MLR) model was applied to build the index. The drought assessment based on GDI was conducted in a three-stage process (Figure 3).

1. the GDI model assessment was performed by comparing the spatial-temporal evolution of GI with other remote sensing indices (TCI, NMDI, VSWI, NDWI, NDDI) and with the SPI index, using Pearson's correlation coefficient (R).

2. in situ SM observations and SMOS SM was correlated with GDI to quantify and estimate the effectiveness of the purposed soil moisture drought index.

The model demonstrates how the SMOS SM satellite data depend on NDVI, LST, and PET derived from the MODIS products and describes how the single response variable, SMOS SM, depends linearly on several predictor variables. The six different drought indices TCI-Temperature Condition Index, NMDI-Normalized Multi-Band Drought Index, NDVI-Normalized Difference Vegetation Index, VSWI-Vegetation Supply Water Index, NDDI- Normalized Difference Drought Index, NDWI- Normalized Difference Water Index (were derived from remote sensing products (MODIS / TERRA) and the standardized precipitation index (SPI) was calculated as an alternative to verify the effectiveness and reliability of the GDI.

The remote sensing-based drought indices were tested in further comparative analysis. These drought indices are often applied to arid or semi-arid regions to represent pasture conditions and drought monitoring.

We assume that the proposed drought index, GDI, depends on the variables NDVI, LST, and PET (Equation 1).

$$\boldsymbol{GI = \mathrm{F}\ (\mathrm{NDVI, LST, PET})}$$

Under this assumption, a multidimensional linear regression model was selected (Equation 2):

$$y_i = b0 + b1 * x_i1 + b2 * x_i2 + b3 * x_i3$$

Parameters of this combination (the regression coefficients) shown in Table 2 were estimated using monthly data for the common period of observations 'availability (2000-2015).

Table 2. Parameters of this combination (the regression coefficients)

Independent variables of the model	Regression Coefficient Estimates		t	Collinearity Statistics	
	β	Std. Error		Tolerance	VIF
(Constant)	-1.197	.040	-4.897		
NDVI	1.246	.132	9.454	.591	1.692
LST(Celsius)	-0.0008	.001	-.524	.781	1.280
PET	0.003	.001	4.490	.724	1.382
Dependent variable GDI					

Here, y_i is the dependent variable (GDI that is a linear approximation of SMOS SM by three independent variables, NDVI, LST, and PET); β_0 is the intercept, $\beta_1 - \beta_3$ are the coefficients; x_i is the corresponding independent variables. Equation (2) represents the relationship between the dependent variable, GDI, and the independent variables as a weighted average in which the regression coefficients ('s) are the weight coefficients. The parameters of this model for all independent variables (NDVI, LST, and PET) and the characteristics of the goodness of fit of SMOS SM by GDI.

Substituting β estimates from Equation 2, we have a linear model for the integrated soil moisture drought index (GDI, Equation 3):

$$\boldsymbol{GDI = -0.060+1.246*NDVI-0.0008*LST+0.003*PET}$$

The drought classification used in this study is based on the US Drought Monitor. Hence, the negative GDI values indicate relatively dry conditions, while the positive values are typical for more wet conditions.

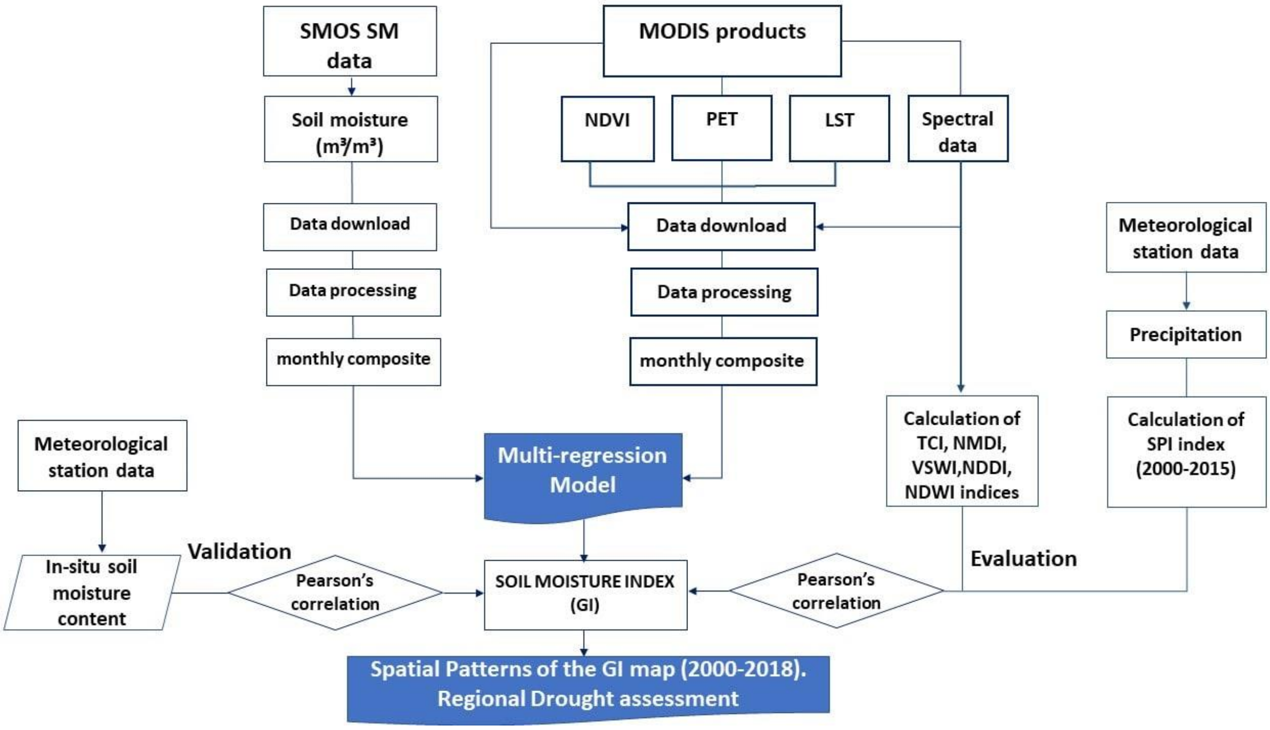


Figure 3. Flowchart of processing of the GDI drought model of this study.

Results

- **Comparison of Remote sensing derived drought indices and the SPI with GI**

To assess the reliability of the GDI, it was necessary to compare it with other well-known drought indices of remote sensing that are widely used globally for drought monitoring. The SPI is used because it is an appropriate indicator to assess the influence of precipitation or (drought conditions) in the growing season on the vegetation productivity period, as well as in the areas of temperature-driven drought where precipitation is relatively sufficient and high temperatures are the dominant factor in areas of water stress.

Table 3. Year-wise correlation between SPI and GDI, NMDI and GDI, VSWI and GDI, NDWI and GDI, NDVI and GDI, TCI and GDI, NDDI and GDI, Stars (*) indicate the best interannual correlations and reference GDI for individual years from April to September.

Correlation coefficients (r) between GDI, SPI, and the RS-based drought indices	
SPI/GDI	0.64
NMDI/GDI	-0.91*
VSWI/GDI	0.97*
NDWI/GDI	0.81
NDVI/GDI	0.96*
TCI/GDI	0.68
NDDI/GDI	0.78*

The comparative dynamics of the explored drought indices overlap well with the GDI and show a remarkable seasonal similarity. During the observation period, droughts occurred in the spring months of April, May, and in the summer period from July and August (Figure. 4)

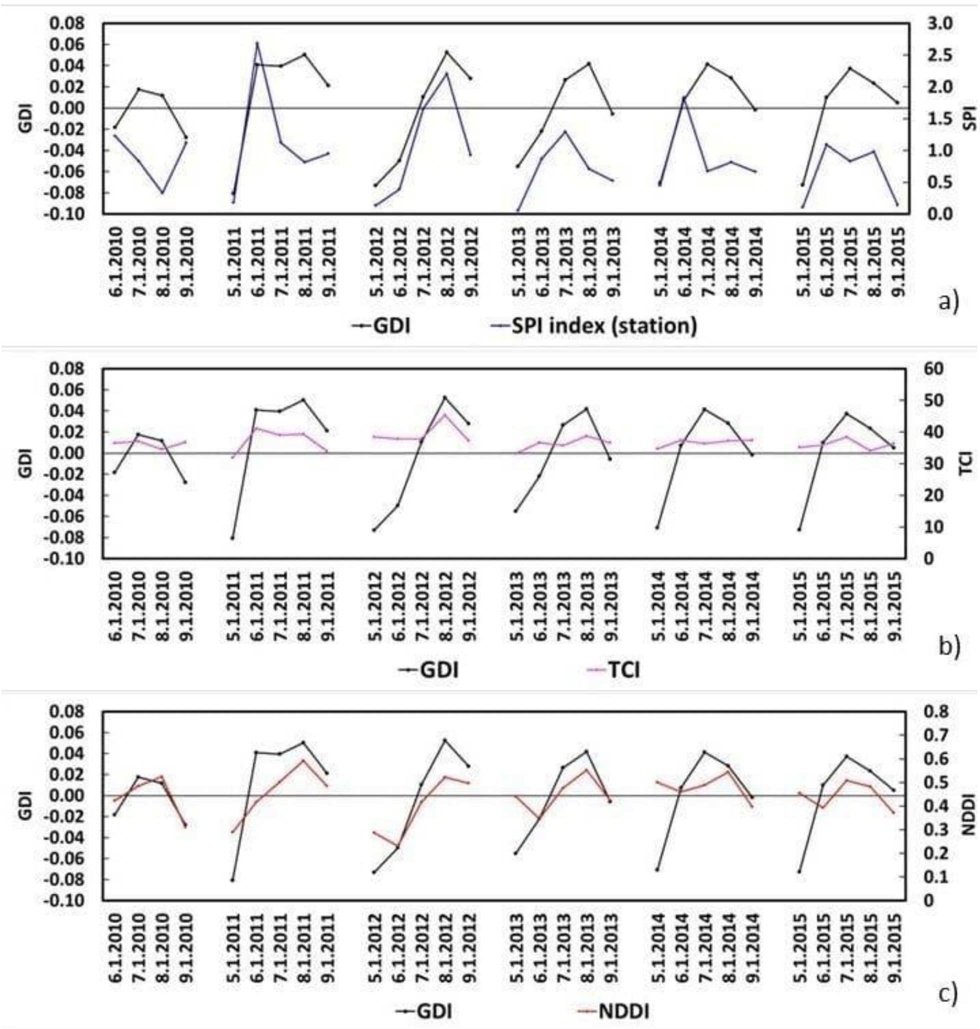


Figure 4. Dynamics of the spatially averaged GDI and SPI (a), two of the Remote Sensing derived drought indices TCI (b), and NDDI (c). Time series span from April to September during the 2010-2015 period.

- **Validation of the GDI soil moisture drought index by the in-situ SM observations**

The effectiveness of the GDI soil moisture index was assessed by its validation with in situ SM measurements at six meteorological stations in the study region. The results show that the correlation was statistically significant between GDI and in-situ SM observations from the meteorological stations at 10 – 15 cm depths ($p < 0.0001$).

Figure 5 presents monthly variations of the in-situ SM observations and the GDI from April to September during the 2010 – 2015 period. The GDI has successfully captured the seasonal difference of the in-situ SM observations. When in situ SM observations are substantially lower in April, May, and August, the GDI values follow the same seasonal pattern. Thus, the GDI recognizes both spring and summer droughts, which is helpful for agrometeorological drought early warnings.

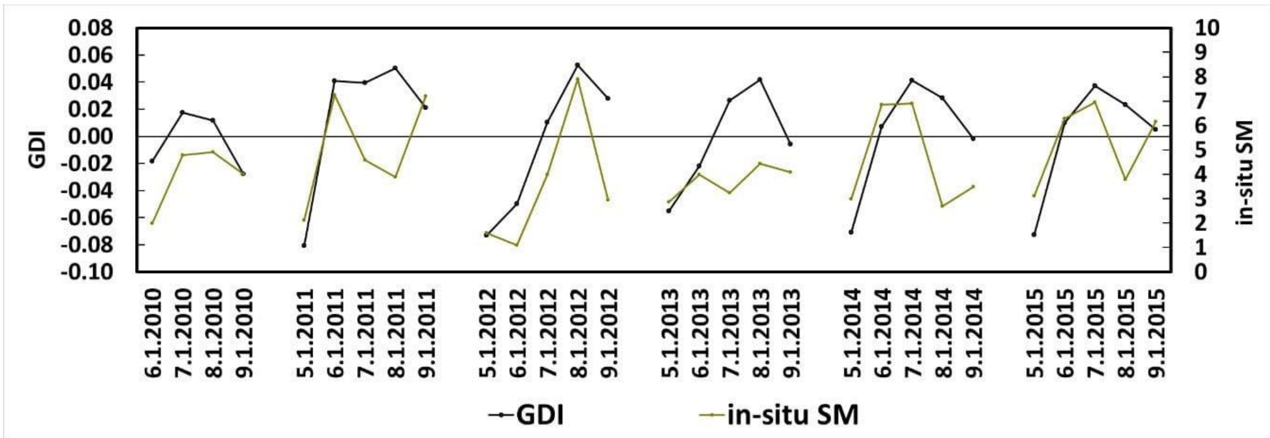


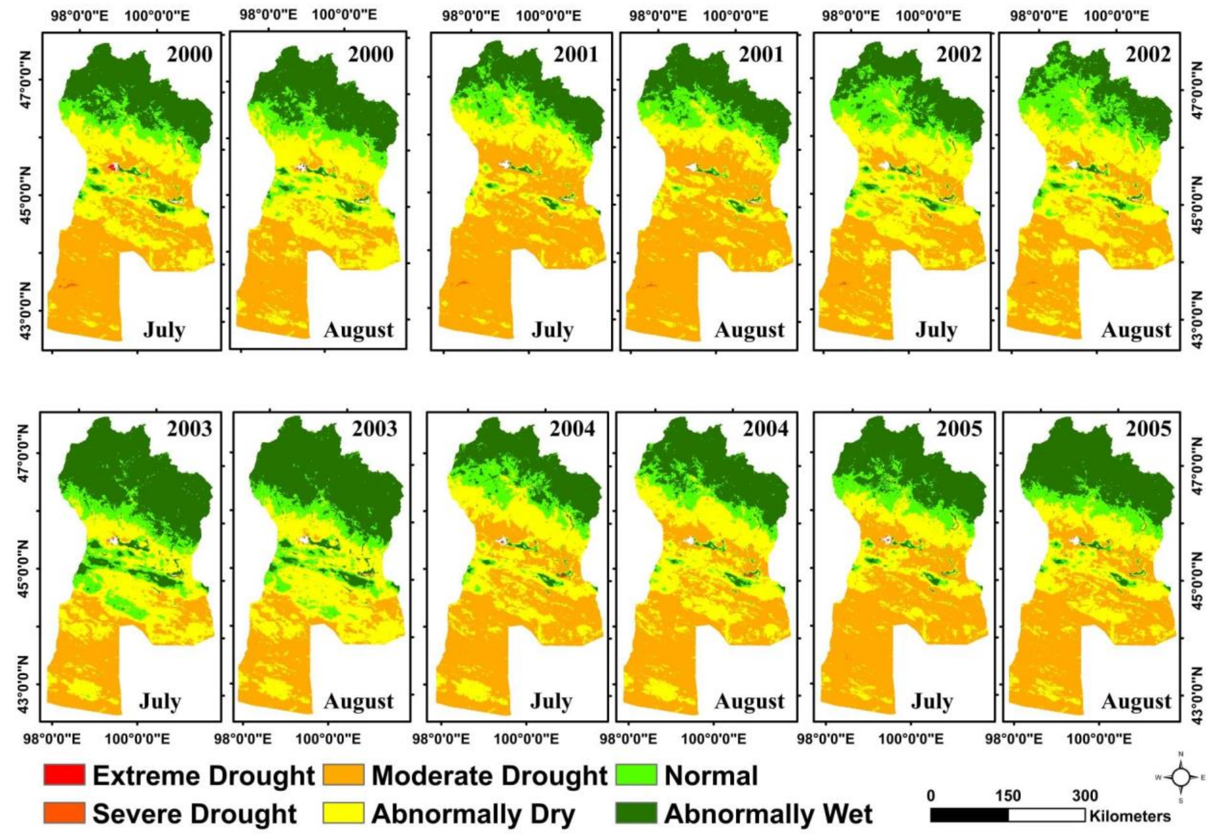
Figure 5. Spatial and temporal variations of monthly averaged in situ SM observations and the GDI at six stations in Bayankhongor province.

- **Spatial and Temporal Patterns of Drought intensity**

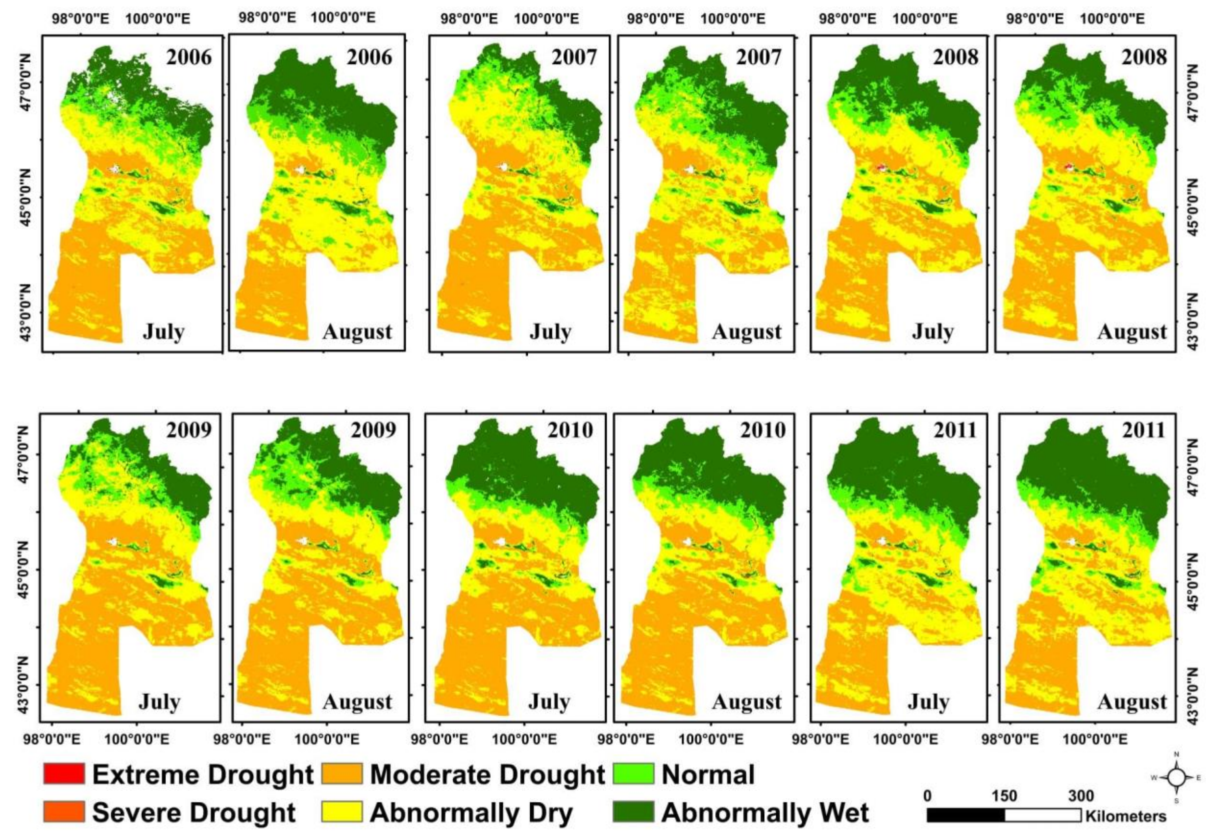
The spatial distribution GDI maps were produced for July and August, which have the highest vegetation growth and play a major role during the grazing season. The new integrated soil moisture drought index can help monitor pasture conditions and can potentially serve as an early warning to take appropriate drought management actions and to help the herder.

From 1999 to 2002, the worst drought events had occurred in the consecutive summers across the country, and in 2009 and 2010 drought happened again throughout the entire of Mongolia. According to the spatial-temporal pattern of GDI shown in Figure 6a, moderate to severe drought occurred in some areas of southern and central Bayankhongor, especially in 2001 and 2002. In 2001, the drought occurred mainly in southwestern Bayankhongor, and in the years 2007 and 2009 in July in northwestern Bayankhongor. The intensity of the drought was high in July 2001 and August 2002. In 2001, the drought occurred mainly in southwestern Bayankhongor, and in the years 2007 and 2009 in July in northwestern Bayankhongor (Figure 6b).

a.


98°0'0"E
100°0'0"E
47°0'0"N
45°0'0"N
43°0'0"N
2000
2001
2002
2003
2004
2005
July
August
Extreme Drought
Severe Drought
Moderate Drought
Abnormally Dry
Normal
Abnormally Wet
0
150
300
Kilometers
N
W
E
S

b.


98°0'0"E
100°0'0"E
47°0'0"N
45°0'0"N
43°0'0"N
2006
2007
2008
2009
2010
2011
July
August
Extreme Drought
Severe Drought
Moderate Drought
Abnormally Dry
Normal
Abnormally Wet
0
150
300
Kilometers
N
W
E
S

c.

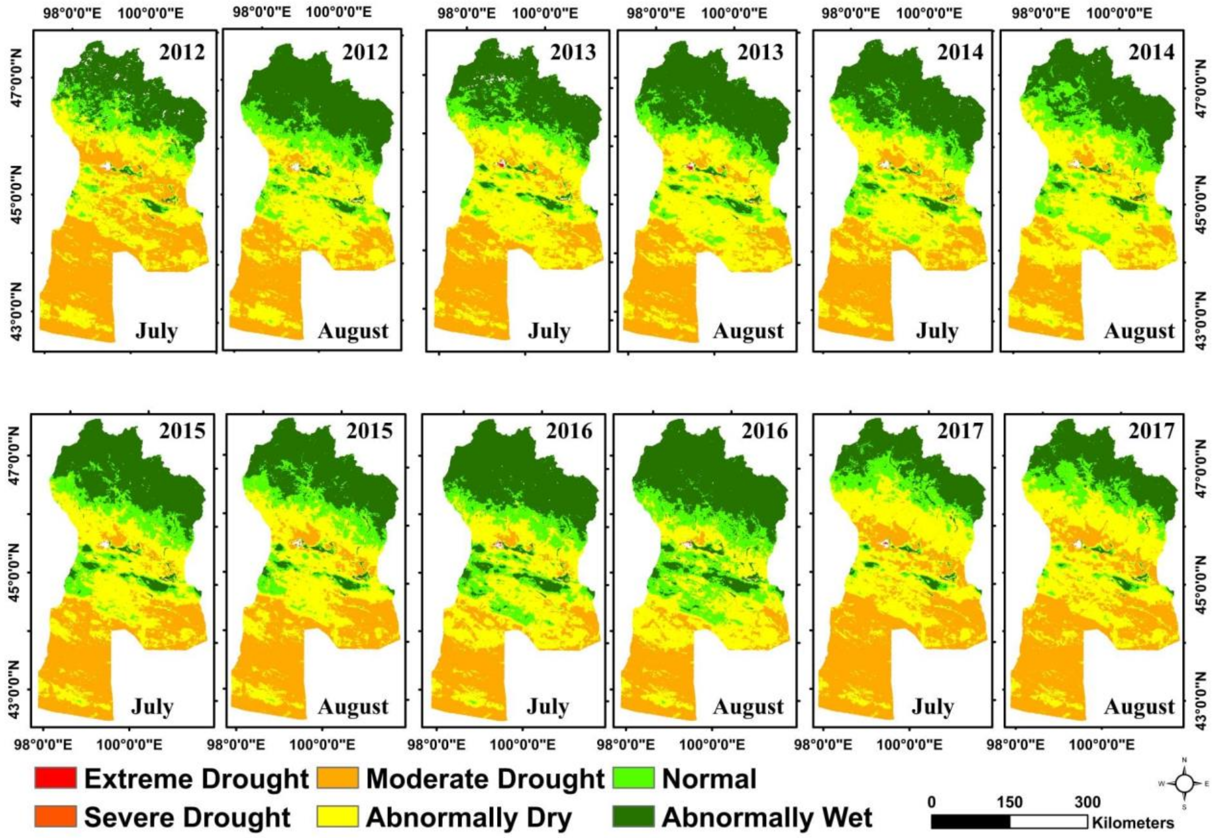


Figure 6 a-c. Spatiotemporal drought severity maps for July and August during the 2000 - 2017 period in Bayankhongor province based on GDI.

Vegetation with a relatively fast response to lack of precipitation during the dry season is mainly concentrated in the northwestern steppe and is nearly absent in the southern desert zone of the province. In dry and hot climate zones, water evaporates faster. Considering jointly evaporation (PET), vegetation (NDVI), and temperature (LST) as reference data, the GDI was able to detect sufficiently steady drought conditions in the Gobi region.

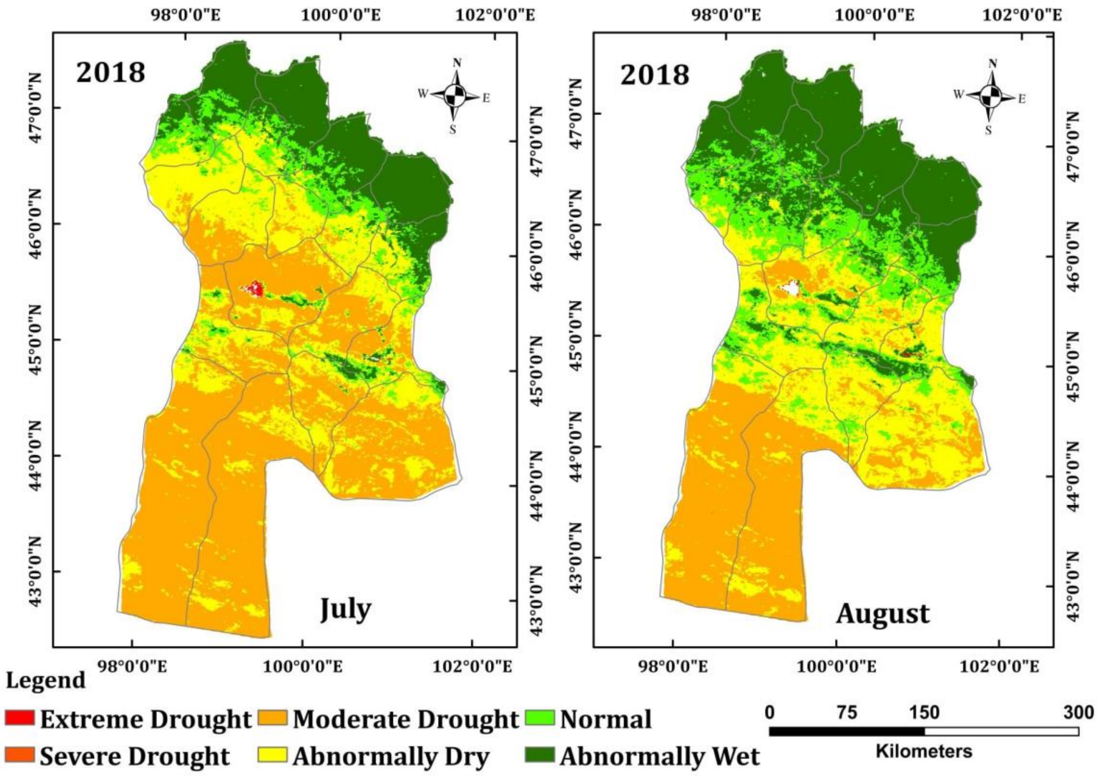


Figure 7. Spatiotemporal drought severity maps for July and August period in Bayankhongor province based on GDI.

We found that the spatial changes in the monthly averaged NDVI, NDDI, NDWI, and VSWI during the 2000-2018 period in Bayankhongor province are strongly associated with the general distribution of the drought maps of the GDI. In particular, droughts during the 2000 – 2002 period were severe and extreme throughout the Mongolian plateau. Furthermore, the years 2004, 2005, 2007, and 2009 were also highly affected by droughts in Mongolia. We can see that the dynamics of NDDI and VSWI are quite similar, hence these dynamics remain quite stable (Figure 8).

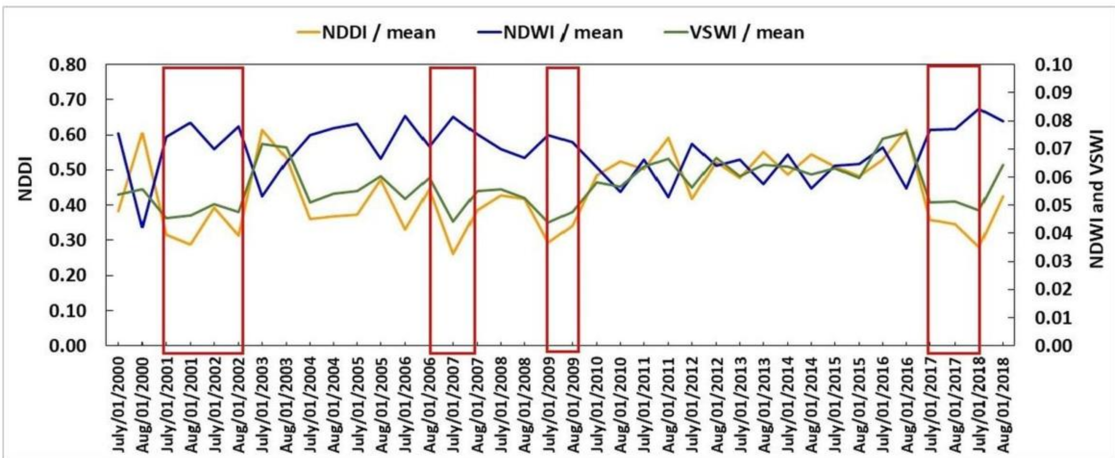


Figure 8. Time series of spatially averaged July and August NDDI, NDWI, and VSWI drought indices from 2000 to 2018. The drought years are highlighted by red columns.

The severity of the drought (moderate, severe, and extreme droughts) for different drought periods is shown in Figure 9. We see a large variability in the changes in drought intensity. The heaviest drought event in the Bayankhongor Province was observed in 2001 when 50.28 % of the total area was identified as an area with moderate drought and 22% of the region was quantified as abnormally dry.

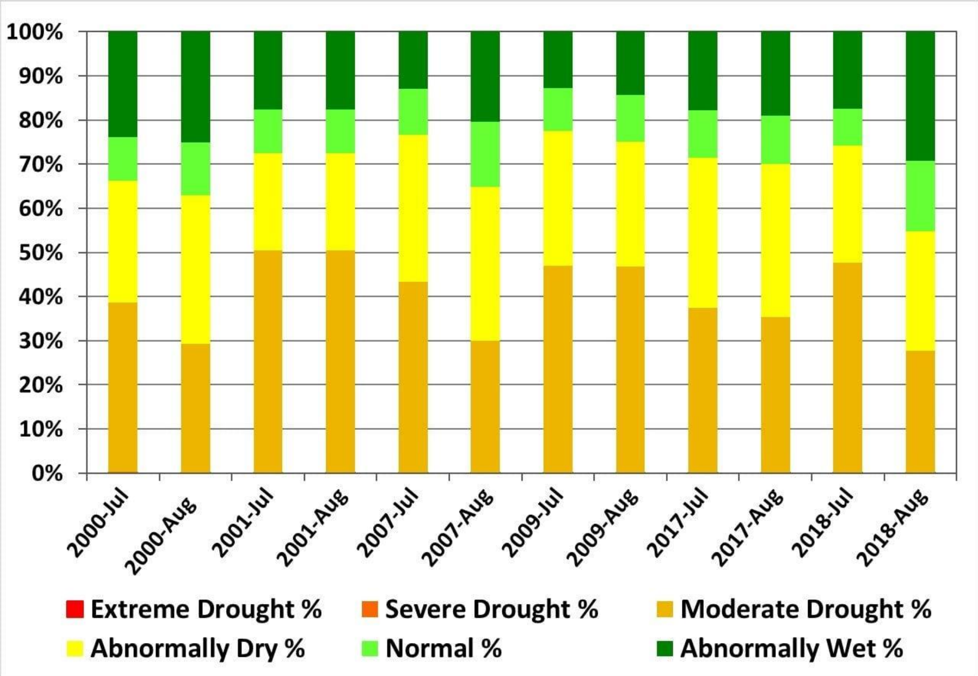


Figure 9. GDI changes in drought intensity (in % of the Province area). Percent of the grassland drought areas are shown as moderate (orange) abnormal dry (yellow), normal (light green), and wet (dark green). Prominent drought years were 2000, 2001, 2002, 2007, 2009, 2017, and 2018.

Conclusion

The multiple linear regression analysis was used to develop Gobi soil moisture index GI, derived from SMOS and MODIS satellite images. Our results provide experimental evidence about the usefulness of the integrated GI for drought monitoring in semi-arid regions. The integrated GI can incorporate both, the meteorological and soil moisture drought patterns and sufficiently well represent overall drought conditions in the arid lands. The GI assessment based on the SMOS SM product presented in this study is one of the first such assessments conducted in Mongolia at the regional level. We tested which drought index has a high relationship with the integrated GI and validated it with the in-situ SM observations. Strong correlations of monthly GI with VSWI, NDDI, NDWI, and in situ SM demonstrate the effectiveness of GI in drought monitoring in semi-arid lands. Comparison of these drought indices with the GI allowed assessing the drought coincidence in time from several angles and quantified better their intensity. The integrated GI was able to detect the drought events in Southwestern Mongolia. In addition, integrated GI is an important source of information to assess grassland drought conditions that are typically quantified using climate indices on the regional scale. The GI can be used as an extra tool for rangeland managers, who are developing a local monitoring system, as well as for researchers in countries with similar climates and ecosystems. Future application of the GI can be extended to monitor potential impacts on water resources and agriculture in Mongolia, which have been impacted by long periods of drought. However, the multiple linear regression model of the new proposed drought index should be enhanced and adjusted in different ecological and climate regions.

REFERENCES

Vova O, Kappas M, Renchin T, and Fassnacht S 2020 Extreme Climate Event and Its Impact on Landscape Resilience in the Gobi Region of Mongolia *Remote Sensing* **12** 2881

Batjargal Z 2018 *THIRD NATIONAL COMMUNICATION OF MONGOLIA Under the United Nations Framework Convention on Climate Change,* the Ministry of Environment and Tourism, Ulaanbaatar*,* Mongolia

Satellite-based system to monitor droughts/droughts handed over to Mongolia 2018 https://www.un-spider.org/news-and-events/news/satellite-based-system-monitor-droughtsdzuds-handed-over-mongolia

Honeychurch W and Honeychurch W 2015 The Heartland of Inner Asia: Mongolia and Steppe Pastoral Nomadism *Inner Asia and the Spatial Politics of Empire* (Springer New York), pp. 79-108

Martnez-Fernández J, González-Zamora A, Sánchez N, Gumuzzio A and Herrero-Jiménez C M 2016 Satellite soil moisture for agricultural drought monitoring: Evaluation Evaluation of the Remote Sensing of Environment SMOS derived from the Soil Water Deficit Index **177** 277–86

Hilker T, Natsagdorj E, Waring R H, Lyapustin A, and Wang Y 2014 Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing *Global Change Biology* **20** 418–28

Chang, S., Wu, B. Yan, N., Davdai, B. and Nasanbat, E. 2017 Suitability Assessment of Satellite-Derived Satellite Drought Indices for Mongolian Grassland *Remote Sensing* **9** 650

Wang L and Qu J J 2007 NMDI: A Normalized Multiband Drought Index for Monitoring Soil and Vegetation Moisture with Satellite Remote Sensing *Geophysical Research Letters* **34**

Martnez-Fernández J, González-Zamora A,, Sánchez N, Gumuzzio A and Herrero-Jiménez C M 2016 Satellite soil moisture for agricultural drought monitoring: Evaluation Evaluation of the Remote Sensing of Environment SMOS derived from the Soil Water Deficit Index **177** 277–86

Remote sensing product 2021 National Remote Sensing Center of Mongolia, http://www.icc.mn/index.php?menuitem=5&datatype=mdro