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RESEARCH PAPER

Calculation of the biophysical parameters of vegetation in an arid area of south-eastern Kazakhstan using the normalized difference moisture index (NDMI)

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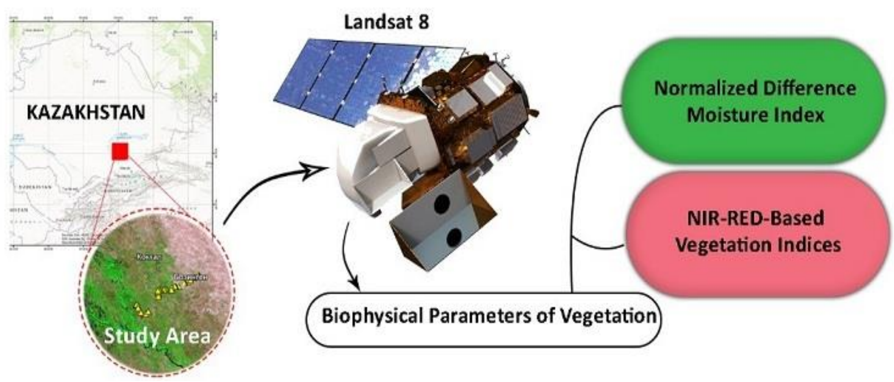
Highlights

- Grassland ecosystems represent a widespread type of terrestrial ecosystem.
- The study aims to compare the accuracy of NIR-RED-based indices with transformed NDMI.
- NDMI is more sensitive than traditional NIR-RED-based vegetation indices.

Graphical Abstract



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Abstract

A comparative analysis was carried out on the accuracy of vegetation indices and NDMI (Normalized Difference Moisture Index) based on Landsat-8 data. The paper describes the peculiarities and the effectiveness of different spectral indices in recognizing sparse desert vegetation and calculating the basic biophysical parameters of vegetation. The theoretical and technical limitations and advantages of different approaches and the application of vegetation indices to different types of vegetation cover are discussed. The original narrow-band water content in the green biomass broadband index was calculated from Landsat-8 data. NDMI was comparatively tested with a number of vegetation indices, based on red and near-infrared bands of satellite imagery. Pearson's correlation coefficients were considered, calculated for three basic vegetation biophysical parameters and spectral indices. The transformed NDMI demonstrates a higher correlation with all the basic biophysical variables of vegetation (grass cover, biomass, and productivity) compared to NIR-RED-based vegetation indices for the intrazonal vegetation of the desert and semi-desert territory of Kazakhstan. NDMI appears to be a promising approach in studies based on the remote detection of non-homogenous vegetation cover in arid areas.

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1. Introduction

Grassland ecosystems represent a very important and widespread type of terrestrial ecosystem across the planet (Holifield et al., 2003). Grasslands are important in soil and water conservation and prevent sand fixation; wind erosion and air purification. Moreover, grassland ecosystems play a key role in livestock production. Therefore, it is essential to design an accurate and rapid method for the estimation of grassland biomass.

Biomass is an important characteristic of grassland, as it closely relates to grassland productivity. Productivity refers to the amount of organic matter produced by plants in a certain area within a certain time. Traditional methods applied to grassland biomass measurement were time-consuming and expensive. Reliable field estimations, based upon traditional methods, are restricted to the local scale only; whereas it is often necessary (and more informative) to obtain such information on the scale of the landscape. Remote sensing is a major source of information for the study of landscapes and estimating biomass over large areas (Wulder et al., 2004; Wulder et al., 2010). One of the vegetation indices most in use for the estimation of vegetation parameters is the Normalized Difference Vegetation Index (NDVI) proposed by (Rouse et al., 1973). NDVI operates with the Red (circa 0.6 μm) and Near-Infrared (circa 0.8 μm) bands of satellite imagery. NDVI and its derivatives, calculated for the NIR and RED bands, called NIR-RED-based indices. Estimation of biomass was done using NIR-RED-based vegetation indices for broadband sensors with spatial resolutions of 30 m to 1 km. Results indicated a wide range of accuracies and precision (Jin et al., 2014; Malakhov, Islamgulova, 2014; Psomas et al., 2011).

Many papers are concerned with the application of NDVI–like vegetation indices and their effectiveness in various landscapes and climatic conditions (Liu et al, 2004; Zhao et al., 2014., Jin et al., 2014; Psomas et al., 2011; Karnielia et al., 2013). Some of the NIR-RED-based indices have more or less significant limitations when determining the quantitative parameters of green vegetation. It has been shown that several environmental factors can affect the NDVI value: atmospheric aerosols, cloud cover, soil saturation, and the structural features of a given sensor (Huete A. et al., 1999). All the factors mentioned indicating constraints and precautions with the use of NDVI, especially when quantitative analysis is requested as a specific part of a given study. Over the decades, there have been many attempts to develop a vegetation index that could minimize one or a few environmental impact-factors. When calculating SAVI, the reflectance of RED and NIR significantly changes within an area of sparse vegetation (grass cover less than 40%) and bare soils (Huete, 1988). Such changes affect the value of vegetation indices in a way that becomes especially discernible when analyzing satellite images of different soil types areas. SAVI could provide the most precise results in areas with predominantly woody vegetation, compared to other soil-adjusted indices. The same results were obtained during a study of OSAVI, which also provided good results for woody vegetation (Kasawani I., et al., 2010). The application of OSAVI in areas of steppe grasslands and desert vegetation areas requires detailed study. Similar limitations in the case of most of the known NIR-RED-based indices make the use of NDMI very appropriate when studying desert and sparse vegetation.

Vegetation Water Content (VWC) is another important characteristic that could be of use in estimating biophysical vegetation parameters (Penuelas et al., 1993). Shortwave infrared reflectance (SWIR) is negatively related to the leaf-water content due to the large absorption of water by the leaf (Yilmaz et al., 2008). B. Gao (1995) proposed a narrow-band index, describing the water concentration in green biomass, as a tool for estimating vegetation status:

$$NDWI = \frac{(\rho_{857} - \rho_{1241})}{(\rho_{857} + \rho_{1241})}, \quad (1)$$

Where ρ857 and ρ1241 represent the reflectance value in the corresponding band of the satellite image (Gao, 1995). It is noticeable that the index operates with only the infrared spectrum, unlike NIR-RED-based indices. The application of NDWI and the high value of its correlations with biophysical vegetation variables explain the physiology of different types of desert vegetation in a better way than NIR-RED-based vegetation indices. The idea of this index is based on the fact, that in the 1.5-2.5 μm area (short-wave infrared, SWIR), Liquid water absorption for green vegetation is significantly higher than that of the 0.9-1.3 μm (near-infrared, NIR) region (Gao, 1995).

Variable indices were considered in the estimate of water content in vegetation and soil. The term Normalized Difference Water Index was introduced to discriminate open waters and to estimate wetland soil moisture (McFeeters, 1996). NDWI by McFeeters, based on the GREEN and NIR bands, was designed to: a) maximize water reflectance by using the green band; b) minimize the low NIR reflectance by water features; and c) take advantage of the high NIR reflectance by vegetation and soil features. Han-Qiu (2005) proposed a modified McFeeters NDWI that is based at the GREEN and MIR bands (Han-Qiu, 2005). MNDWI demonstrated enhanced open-water discrimination while soil and vegetation show negative values yet. Neither McFeetrs' NDWI nor Xu's MNDWI is concerned with VWC estimation. The spectral index was developed, based on the NIR and SWIR bands, which is aimed at VWC and termed it the "Normalized Difference Vegetation Index – NDWI (Gao, 1995). Also, another name Normalized Difference Moisture Index has recently been proposed (Wilson and Sader, 2002) for the index, which has a band composition identical to Gao's index. Such a situation may lead to misunderstanding or even confusion when scientists use the wrong definition of these indices. In another study, rightly pointed out that "NDWI Gao and NDMI Wilson are both used to detect vegetative water in plants and are different from NDWI McFeeters" and was suggested a common name for the Gao and Wilson indices as NDMI (Yilmaz et al., 2008). In the current study, this NDMI name was accepted for purposes.

NDMI and its modifications have been successfully used in different aspects of vegetation study and classification (Alves et al., 2016; Zhao et al., 2014; Zarco-Tejada et al., 2003; Serrano et al., 2000; Numata et al., 2007; Khanna et al., 2013).

The goal of the current study is to compare the accuracy of NIR-RED-based indices, with specific reference to the amount of chlorophyll and the accuracy of the index related to water concentration in green vegetation for the non-homogeneous vegetation conditions of an intrazonal arid area.

2. Materials and Methods

2.1. Study area

The study area is located in the Ili River delta, close to Balkhash Lake in Kazakhstan (Fig. 1). The Ile River forms a branched delta with many channels both functioning and dried-up. The area mainly includes uniform valleys, featuring a minimally altered landscape with a combination of different vegetation types, including tugai (the local name for intrazonal forests), shrubs, meadow grasslands, etc., often located within a small area. Recently, significant transformations in the ecosystem have been observed in the region of the deltaic plains and the lower portion of the Ile River floodplain. The transformations are due to overregulation of the river flow and a total decrease in water discharge. Obvious symptoms of water imbalance in the Ile River delta are the groundwater level, an increase of the mineralization of groundwater, drying, and degradation of hydromorphic soils, the widespread degradation of meadows, the shrinking of tree-and-shrub communities, etc. The study area (about 30000 km^2) represents a part of the Zhideli channel (the most prominent armlet of the Ile River in its delta section) close to Bozingen Village (Fig. 1).

This region is categorized as part of the desert zone and consists of plains with low hills and salty marshes. This territory is currently designated part of Karaoy Nature Wildlife Sanctuary to protect the valuable and rare species of fauna. The eastern border of the study area runs along the sand of the ancient Ily River delta, while the Zhideli channel forms the southern border of the study area.

A significant part of the study area consists of meadow and marshy ecosystems, associated with numerous channels and small lakes in the deltaic portion of the Ile River. The meadows of the desert zone are characterized by intrazonality and mono dominance (they are composed of mostly one plant species). Monodominant meadows of reed (*Phragmites australis*), Calamagrostis (*Calamagrostis epigeios*), bluegrass

(*Elytrigia repens*), wild rye (*Leymus multicaulis*), and licorice (*Glycyrrhiza uralensis*) were previously widely distributed within the Ile River Delta.

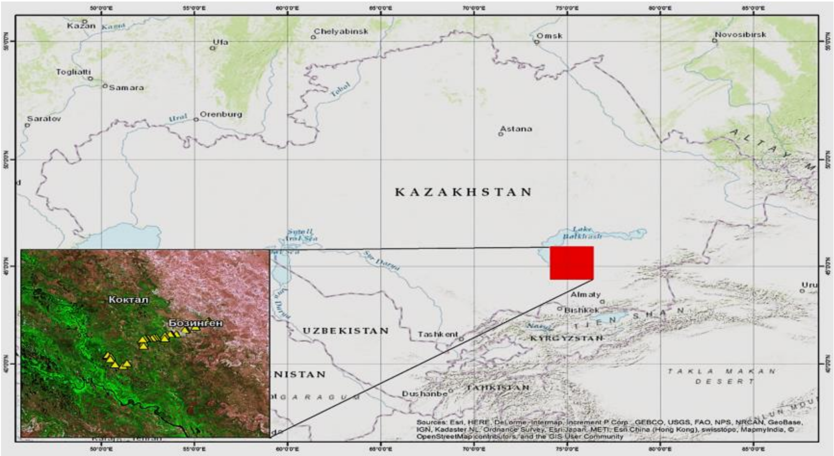

Fig. 1. Location of the study area, yellow triangles depict the sites of field measurements.

Table 1. List of indices examined.

Index	Equation	Reference
NDVI	$NDVI = \frac{NIR - RED}{NIR + RED}$	Rouse et al., 1973
RDVI	$RDVI = \frac{NIR - RED}{\sqrt{NIR + RED}}$	Roujean and Breon, 1995
SAVI	$SAVI = \frac{1.5*(NIR - RED)}{NIR + RED + 0.5}$	Huete, 1988
OSAVI	$OSAVI = \frac{1.5*(NIR - RED)}{NIR + RED + 0.16}$	Rondeaux et al., 1996
MNLI	$MNLI = \frac{(NIR^2 - RED)*(1+L)}{NIR^2 + RED + L}$ L=0.5	Goel and Qin, 1994
EVI	$EVI = \frac{NIR - RED}{NIR + (6*RED - 7.5*BLUE + 1)*2.5}$	Huete et al., 2002; Liu and Huete, 1995
NDMI	$NDMI = \frac{NIR - SWIR}{NIR + SWIR}$	Gao, 1995
DVI	$DVI = NIR - RED$	Tucker, 1979
GEMI	$GEMI = \frac{eta(1 - 0.25eta) - (RED - 0.125)}{1 - RED}$ where $eta = \frac{2(NIR^2 - RED^2) + 1.5*NIR + 0.5*RED}{NIR + RED + 0.5}$	Pinty and Verstraete, 1992
Green ARVI	$GARVI = \frac{NIR - (GREEN - \gamma*(BLUE - RED)}{NIR + (GREEN - \gamma*(BLUE - RED)}$ γ=1.7	Gitelson et al., 1996
Green DVI	$GDVI = NIR - GREEN$	Sripada et al. 2006
Green NDVI	$GNDVI = \frac{NIR - GREEN}{NIR + GREEN}$	Gitelson and Merzlyak, 1998
Green RVI	$GRVI = \frac{NIR}{GREEN}$	Sripada, et al. 2006
IPVI	$IPVI = \frac{NIR}{NIR + RED}$	Crippen, 1990
LAI	$LAI = 3.618*EVI - 0.118$	Boegh et al., 2002
ARVI	$ARVI = \frac{NIR - (RED - \gamma(BLUE - RED)}{NIR + (RED - \gamma(BLUE - RED)}$	Kaufman and Tanre, 1992

Recently, the study area has become more of a refugium for meadow-plant communities. It should also be noted that deltaic meadows of the above-mentioned types are also known as a resort of many relicts, rare or disappearing plant species (Plissak, 1981; Plissak et al., 1991). Another part of the study area is composed of sandy dunes and characterized by semi-desert psammophyllous vegetation, growing in depressions between sandy dunes. The study area combines species of vegetation very different in composition and density, such a diverse species composition characterizes the intrazonal type of ecosystems.

The field vegetation study assumed both traditional geobotanical methods (Bykov, 1978) and new methodical approaches (Rachkovskaya et al., 2000). The precise estimation of the grass cover was performed by the line-cross method. This method uses a randomly selected point in the area as a coordinate centre. From that point, four rays (as in a compass) run to North, West, South, and East. The length of each ray (made of rope) is ten meters. The length of each plant fragment traversed by the rope was measured and then all the measurements were summarized for all four directions. Dividing the total length of the cross-sections by 10 returns the grass cover value as a percentage. The estimation of biomass with living grass and shrubs comprises two field procedures: plants trimmed to a height of 2-3 cm above soil level, and the immediate weighing of the cut vegetation. This operation was performed over an area of 10 square meters for each of the types of plant communities within the study area. This method of biomass calculation appears to be the most appropriate for shrubs, semi shrubs, and mixed pasture (Larin et al., 1975). Also, spectral signatures for different vegetation types and density were obtained with a Field Spec4 spectrometer.

Landsat-8 (OLI) image (LC81510282015190LGN00), was used synchronously to the field measurements. The image was pre-processed with radiometric and atmospheric correction using the standard procedure with Hexagon ERDAS Imagine software. The calculation of the correlation between the basic biophysical variables of intrazonal mixed vegetation with water concentration index and vegetation indices is the subject of the current study. Table 1 comprises the list of indices studied. All selected indices form three basic groups. The first group is NDVI and the other simple ratios (DVI, RDVI) that measure, in different ways, the Red and Infrared bands only as a means of estimating the amount of chlorophyll. The second group of indices applies additional bands of satellite imagery along with more complicated equations to reduce the soil impact (SAVI, OSAVI, and MNLI, etc.), and atmospheric effects (EVI, ARVI, GARVI, etc.). The third group is the NDMI itself, which refers to water concentration in vegetation rather than chlorophyll concentration.

3. Results and Discussion

Stat Soft Statistical 12 was used with default settings to estimate the correlations between the spectral indices and the biophysical vegetation parameters, with significant correlations (r) marked at $P< 0.05$. Table 2 represents the correlations of analyzed indices with the biophysical parameters of vegetation, defined in the field. NDMI, related to water content in green biomass, demonstrated the best results, as it has the highest and most significant correlations with all of the biophysical parameters tested for the mixed vegetation in the study area. No other indices revealed such a high correlation to the biophysical variables of the mixed intrazonal vegetation.

Previously, different NIR-RED-based vegetation indices were used to estimate the major vegetation biophysical variables in the desert zone. Our previous studies, performed on homogenous desert-vegetation cover, revealed good correlations of SAVI and EVI to biomass and grass cover (Malakhov and Islamgulova, 2014). However, in the case of the heterogeneous intrazonal vegetation (current study) the accuracy of NIR-RED-based indices decreases (Table 2). Advanced NIR-RED-based indices, which count soil and atmospheric impacts, function properly if the vegetation is homogenous, regardless of the density of the vegetation cover. However, the accuracy of the advanced NIR-RED-based indices in the case of heterogeneous vegetation is not as high, as quantified analysis of the satellite imagery is necessary. Another factor that makes the application of NIR-RED-based indices questionable in heterogeneous vegetation is the presence of a considerable amount of dried plants and plant debris. The presence of litter and gaps in the vegetation canopy is detected as background information and may serve as an obstacle to the performance of the traditional indices.

Table 2. Correlations (Pearson coefficient) of vegetation parameters and spectral indices.

Index	Grass cover correlation	Biomass correlation	Harvest correlation
NDMI (Gao's NDWI)	0.78	0.76	0.73
NDVI	0.64	0.28	0.25
RDVI	0.6	0.15	0.12
SAVI	0.55	0.05	0.03
OSAVI	0.56	0.08	0.05
MNLI	0.66	0.47	0.43
EVI	0.55	0.05	0.03
DVI	0.54	0.04	0.02
GEMI	-0.02	-0.4	-0.4
Green ARVI	0.7	0.47	0.43
Green DVI	0.42	-0.13	-0.15
Green NDVI	0.55	0.04	0.007
Green RVI	0.56	0.02	-0.002
LAI	0.56	0.03	0.01
IPVI	0.64	0.28	0.25
ARVI	0.7	0.5	0.47

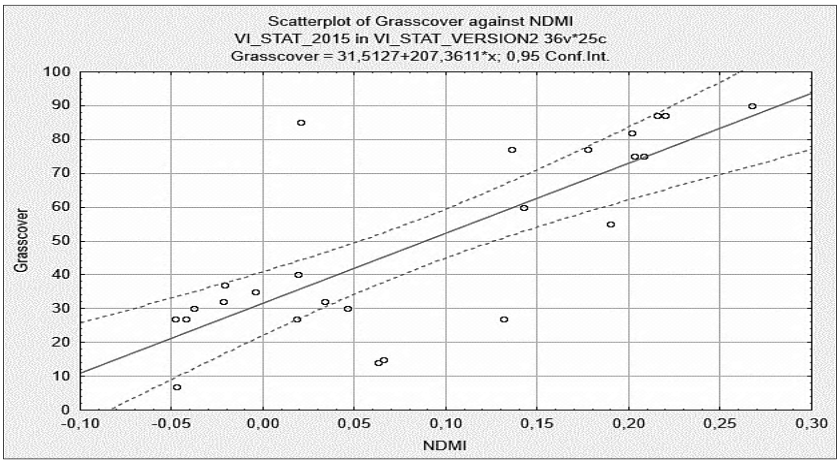

Fig. 2. Correlation scatterplots of NDMI and Grass cover.

A high concentration of dead and litter material in the substrate reduces the detected photosynthesis rate. Chlorophyll reflectance in the NIR band is not prominent with sparse vegetation; and the red reflectance of bare soils and plant debris delivers a kind of red-edge effect-masking, leading to inaccurate measurements with remotely sensed data (Figs. 3A and B). At the same time, NIR and SWIR reflectance remained stable and high when the vegetation cover was sparse, so the VWC index should perform better (Roujean and Breon, 1995).

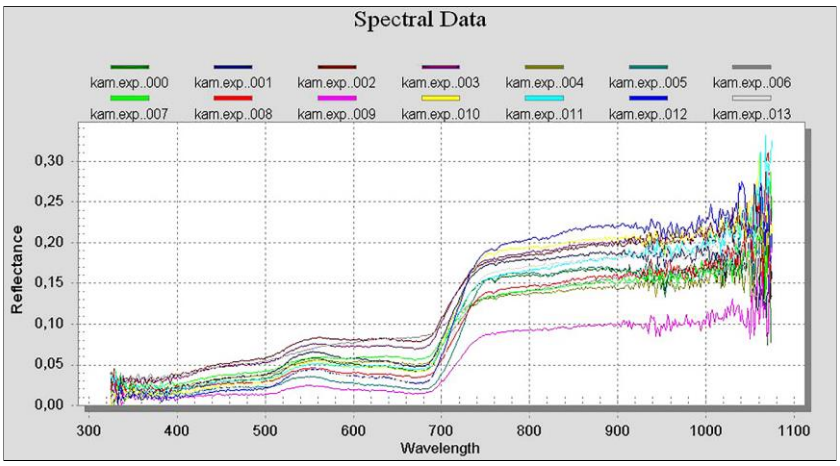

Fig. 3 A. Dense vegetation: RED and NIR reflections markedly differ.

It is obvious (though the special measurements were not done) that meadow vegetation possesses more liquid water within its tissues than desert shrubs and grass, and this fact makes the infrared index theoretically more sensitive to different types of desert vegetation than NIR-RED-based indices. Its applicability is also related to the index mechanism: Although the NIR channel was observed eight leaf layers, the red channel sees one leaf layer or less due to strong chlorophyll absorption in red channels. This sensitivity is an advantage of NDMI. At the same time, this index is observed to negate the soil brightness that usually has the effect of saturating NIR-RED-based indices. Negative NDWIs was reported in more than 98% of soils (Gao, 1995). Finally, due to its ability to recognize more details in multi-layered vegetation, the infrared index has more detailed spatial distribution: spatial variation of NDVI image over green vegetation is small, while the spatial variation of NDWI over the same area is large, as many points of NDWI values between 0.0 and 0.15 have similar NDVI values (approximately 0.63) (Gao, 1995).

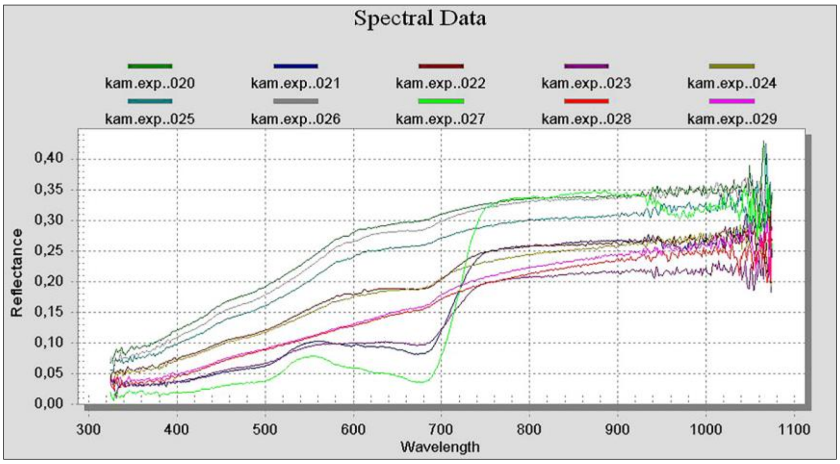

Fig. 3 B. Sparse vegetation: RED reflectance oversaturates NIR reflectance.

In terms of broadband indices, NDMI, as applied in this study, does not correspond exactly to the NDWI index, since the 6th band of Landsat OLI does not exactly correspond to the 1.241μm band of NOAA (Gao, 1995). However, this ratio could be of use in separating desert vegetation of a mixed nature. In describing the peculiarities of water absorption in infrared bands, was showed that petty transmittance in thick leaves with, the difference between reflectance of TM5 (band 6 of Landsat OLI) in a dry, fresh leaf should be equal to the absorption by water in that leaf (Hunt et al., 1987). Therefore, in dry leaves reflectance of TM5 is almost exactly equal to the reflectance of TM4 (band 5 of Landsat OLI). On this basis, the difference between the reflectance of TM4 and TM5 for the fresh leaf should also be equal to the water absorption in that leaf. As a result, plant water stress augmented the reflectance of TM5 and TM7 (band 7 of Landsat OLI) in leaves and the intact plant.

4. Conclusion

For the current study, the correlation of NIR-RED-based indices was examined to the biophysical parameters of vegetation alongside that of NDMI, calculating water absorption in intact plants with NIR and SWIR bands rather than chlorophyll concentration. NDMI appears to be more relevant and sensitive than traditional NIR-RED-based vegetation indices when calculating biophysical parameters of vegetation in the conditions of heterogeneous desert vegetation in Southern Kazakhstan. This index is more sensitive to the depth of a canopy. The index can recognize water content in many layers of green vegetation (up to eight leaf layers instead of the single uppermost leaf layer that is recognizable by NIR-RED-based vegetation indices). NDMI may successfully be adopted for those satellite platforms possessing appropriate spectral bands. NDMI looks promising and has the potential for further study and implementation in a variety of agricultural and ecological applications. However, it is now clear that the NDMI application, either alone or with traditional indices makes the picture of vegetation that one can obtain from satellite imagery more detailed and nuanced.

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