Research article

Applicability of Estimation Method for Soil Moisture in Mongolian Grasslands using a Pattern Decomposition Method

AYAKO SEKIYAMA*
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan
Email: a3sekiya@nodai.ac.jp

SAWAHIKO SHIMADA
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

MICHINARI YOKOHAMA
Faculty of Bioindustry, Tokyo University of Agriculture, Abashiri, Japan

HIROMICHI TOYODA
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

Received 1 January 2015   Accepted 1 April 2015   (*Corresponding Author)

Abstract The objective of this research is to develop a method that will allow remotely sensed data to be used for estimating soil moisture and distinguishing vegetated and bare ground areas in Mongolia. The study was conducted in central Mongolia, where climate conditions and human impacts are resulting in degradation of grassland and damage to grazing stock. The method employed was a pattern decomposition method using flat pattern model for estimation soil moisture, which is developed by authors. A total of ten survey plots were established in grasslands, and a spectroradiometer was used to measure spectral characteristics of the soil in the visible and near-infrared wavelengths. Spectral reflectance of the soil was measured, and used to derive the pattern decomposition coefficient and estimate soil moisture. These results were then compared to actual field measurements of soil moisture to verify the accuracy of the method. In addition, photographic images were used to estimate the vegetation coverage for each survey plot, and the effects on vegetation on the accuracy of soil moisture were examined. The results showed a strong negative correlation between water content in soil and the pattern decomposition coefficient for flat model, indicating that this method is capable of accurately estimating soil moisture regardless of soil type. A strong correlation was also found between the vegetation coverage and the pattern decomposition coefficient for vegetation, suggesting that the method can be used to estimate vegetation coverage. A high level of accuracy, however, was achieved only for bare ground, indicating that the vegetation reflectance influences the spectral reflectance of the soil, and the current method is thus not applicable to vegetated areas.

Keywords pattern decomposition method, spectroradiometry, visible and near infrared wavelength

INTRODUCTION

In recent years, a winter disaster known as *Dzud*, characterized by heavy snow and low temperatures, has caused widespread freezing and starving damage to livestock in Mongolia. In addition, it has also been suggested that sparse summer precipitation and resultant lack of soil moisture has depressed vegetation growth (Kondoh et al., 2005). This lack of soil moisture leads to grassland degradation, which weakens livestock and makes them more susceptible to damage from the *Dzud*. Therefore it is important that the continuous monitoring for spatial distribution of soil moisture in the summer, and in addition, a method for estimating both soil moisture as well as distinguishing between vegetated and bare areas, is needed for conserving grassland and predicting and preventing livestock damage from the *Dzud*.

Satellite remote sensing is useful for retrieving information regarding surface conditions iteratively and over a wide area. There are many remote sensing studies dealing with vegetated area, such as predicting plant diversity by vegetation condition from MODIS (Ranjeet et al., 2008), the estimation of biomass production using AVHRR-based vegetation health indices (Kogan et al., 2004), and the evaluation of the vegetation phonological pattern using NDVI (Lee et al., 2002). Few studies, however, deal with soil moisture.

For bare soil, many studies estimate soil moisture using microwave remote sensing. This is a useful wavelength that can be employed either day or night, and is not affected by clouds. In recent years, a synthetic aperture radar (SAR) active sensor has been frequently used with space resolution enhancement (Zribi et al., 2010). In conservation of Mongolian grasslands, however, it is also important to distinguish between bare and vegetated areas. Some preliminary research using the microwave method for this purpose has been implemented, but at present the system is still in the developmental stage.

Some studies have also achieved high accuracy in estimating soil moisture using water absorption in the near and mid infrared wavelengths (Ishiyama et al., 1992; Liu et al., 2003). Water absorption bands, however, occur in a narrow width of the near and mid infrared wavelengths, and many satellites do not have sensors that operate in these wavelengths.

To develop a method for estimating soil moisture that is both widely applicable to remotely sensed data and capable of distinguishing between vegetated and bare areas, Sekiyama et al. (2010) conducted an open-air experiment employing a spectroradiometer, and achieved highly accurate estimates of soil moisture using spectral characteristics of the soil in the visible and near-infrared bands. The reflectance in each band was normalized by the sum of the reflectance in four bands: blue, green, red, and near infrared, and an obtained curve of the band reflectances (band reflectance pattern) was utilized. By applying a pattern decomposition method for analyzing mixel decomposition proposed by Fujiwara et al. (1996), Sekiyama et al. (2010) developed a method for using the pattern decomposition coefficient for flat model calculated from the band reflectance pattern as the index of soil moisture. This method is described in detail in the next section.

In this study, we applied the method of estimating soil moisture developed by Sekiyama et al. (2010) to field data acquired by spectrometer in the Mongolian grasslands. We attempted this method's ability to accurately estimate soil moisture and to distinguish between bare and vegetated areas. Furthermore, we verified the upper limit of vegetation coverage at which soil moisture can be accurately measured by this method.

METHODOLOGY

Estimation of Soil Moisture by the Pattern Decomposition Method

The pattern decomposition method is an un-mixed analysis, in which the measured band reflectance pattern is expressed as the linear sum of three typical band reflectance patterns which are water, vegetation and soil. Several studies have applied this method to estimation of vegetation coverage (Zhang et al., 2007a; Muramatsu et al., 2007) and to classification of land cover and land cover changes (Muramatsu et al., 2000). Zhang et al. (2007b) have also applied the method to datasets of various satellite sensors. Until recently, however, there have been no studies that use this method to estimate the soil moisture condition.

Sekiyama et al. (2010) first applied the pattern decomposition method to the soil spectral reflectance obtained by spectroradiometer in open-air experiments. The soil samples were collected from 8 sampling sites in Japan, Mongolia and Malaysia. Reflectance measurements were taken for each sample at 4-8 different values of water content in soil (WC), ranging from 0%-22.9% (N= 53). Four multi-spectral bands of blue (band 1: 470–502 nm), green (band 2: 539–580 nm), red (637–668 nm) and near-infrared (band 4: 802–870 nm) were calculated from the measured hyper-spectral reflectance data, with a view to application in satellite imagery. The measured spectral radiance was calibrated using the spectral radiance of a white calibration board to convert into spectral reflectance. The soil spectral reflectance in each band was normalized by dividing by the sum of the four bands (Ono et al., 2002), thus defining the normalized band reflectance for soil S_i (band number: i = 1 to 4), which has the property that $S_1 + S_2 + S_3 + S_4 = 1$.

Generally, the spectral reflectance of soil in bands 1–3 (visible) and band 4 (near infrared) decreases with increasing soil moisture creating a spectral reflectance that increases with increasing wavelength. The normalized band reflectance for soil, however, decreases slightly in the visible bands with increasing soil moisture, but increases in the near infrared band. The change of reflectance in the near infrared band with increasing soil moisture is large compared to that in the visible bands, and the slope of the band reflectance (i.e., the reflectance pattern) between bands 3 and 4 may thus be used to estimate soil moisture. The slope between bands 3 and 4 is steep when the soil moisture is high, and flattens when the soil moisture is low. In the pattern decomposition method, the flat model pattern P_{fi} (P_{fi} = 0.25) is defined as the pattern that corresponds to completely dried soil, and each normalized band reflectance for soil S_i is the linear sum of two patterns (flat model and soil). Explicitly,

$$S_i = C_{sf} P_{fi} + C_{ss} P_{si}, \qquad (1)$$

where C_{sf} and C_{ss} are the pattern decomposition coefficients, which are the relative weights of the two patterns. The decomposition coefficients are calculated from S_i using the least squares method, the flat model pattern P_{fi}, and the typical soil pattern P_{si}.

In Sekiyama et al. (2010), a negative correlation (r^2= 0.56) was found between WC and C_{sf} (Fig. 1), suggesting that C_{sf} is an effective index for estimating soil moisture.

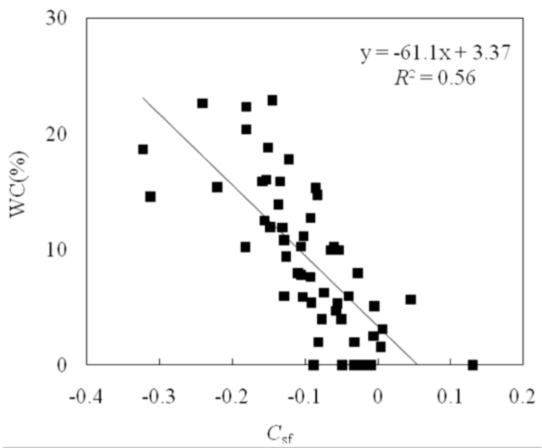

Fig. 1 Relation between water content in soil (WC) and pattern decomposition coefficient for flat model (C_{sf}) (Sekiyama et al., 2010)

Field Survey

Survey area: In this study, ten 40 m × 40 m plots, including pasture and semi-desert areas in three prefectures around the city of Ulan Bator in central Mongolia were investigated (Fig. 2a). The field survey was performed from 9:00 at 12:00 (local time) on August 9 to 16, 2006 and August 8 to 14, 2007, on clear days (Table 1) with sun elevation ranging from 40 to 50 degrees.

The vegetation of Mongolia is predominately grassland. Annual precipitation is below 400 mm, 70% to 80% of which occurs from June to August in central Mongolia. Kondoh et al. (2005) have reported that the growth of plants depends heavily on summer precipitation. Although grassland degradation due to overgrazing and the expansion of cultivated land has become a problem in recent years near Ulan Bator (Yoshihara et al., 2008).

Each plot was taped off into a grid with 10 m intervals (Fig. 2b). At each grid point we measured the spectral radiance of the surface, photographed the surface, and collected soil samples.

The surfaces of all the plots were covered with herbaceous plants. Therefore, the spectral radiance of vegetation and soil both contributed to the measured spectral radiance.

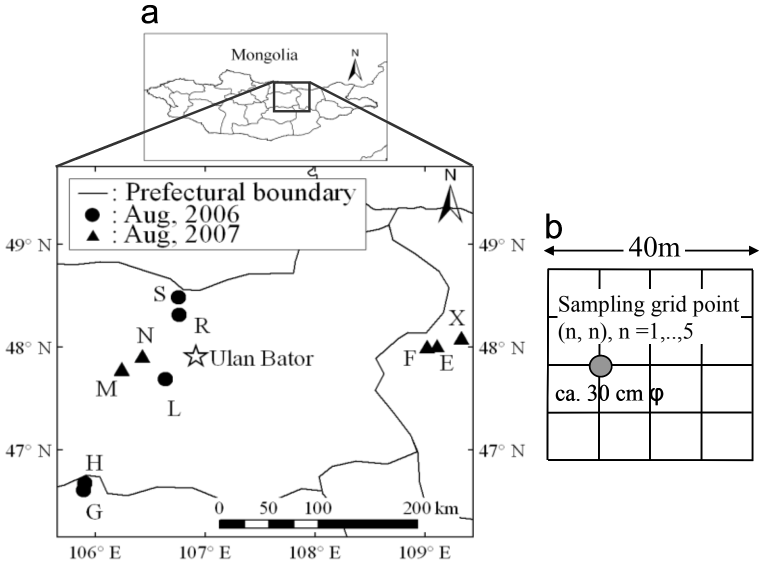

Fig. 2 Map of Mongolia showing the surveyed district (a) and 10 lettered survey plots (b)

Table 1 Location of survey plot and land use

Plot	Latitude (N)	Longitude (E)	Land use	Year
E	48°01’ 04.2”	109°06’ 53.7”	Pasture land	2007
F	48°00’ 09.7”	109°01’ 30.4”	Pasture land	2007
G	46°36’ 28.8”	105°53’ 57.8”	Pasture land	2006
H	46°40’ 39.2”	105°54’ 51.2”	Pasture land	2006
L	47°40’ 59.9”	106°38’ 46.6”	Pasture land	2006
M	47°46’ 59.2”	109°14’ 51.7”	Pasture land	2007
N	47°54’ 55.0”	109°26’ 09.6”	Pasture land	2007
R	48°18’ 41.3”	106°46’ 16.7”	Abandoned farmland	2006
S	48°28’ 42.3”	106°45’ 58.0”	Pasture land	2006
X	48°05’ 16.4”	109°20’ 16.8”	Pasture land	2007

Spectral Radiance Measurement

The spectral radiance of the surface for each grid point (25 samples per plot) was measured using a spectroradiometer (Eko Instruments Co., Ltd, MS-720, with a wavelength range of 350– 1050 nm). The field of view (FOV) of the sensor is 25 degrees, and the measurement was taken at a height of 70 cm above the ground, so the measured area was a 30 cm diameter circle. At each grid point, the spectral radiance was measured three times and the average value was used as the datum for the grid point. The measured spectral radiance was converted into spectral reflectance dividing by the spectral radiance of a white calibration board, and the normalized band reflectance was calculated from the spectral reflectance. The reflectance from a mixed surface of vegetation and soil at each grid point was defined as the normalized mixed-band reflectance M_i. In addition, the sensor FOV was changed to 10 degrees to measure the pure spectral radiance from the bare soil and from the dominant plants (e.g., *Poaceae*, *Rosaceae*, *Fabaceae*, and *Asteraceae*) in each plot. The reflectance values of the bare soil and the vegetation (i.e., the dominant plants) were defined as the normalized band reflectance for soil S_i and the normalized band reflectance for vegetation V_i, respectively, for each plot.

Calculation of Vegetation Coverage and Soil Sampling

Photographs of each plot were taken using a digital camera set at almost the same position as that of the spectral radiance measurement described in the preceding paragraph. The vegetation coverage VC was calculated by extracting pixels of vegetation from the photographic image (*N*= 250).

In 2006, 50 cm^3 of surface soil were taken at each grid point for four plots (25 samples per plot). In 2007, soil samples of the same volume and depth were taken from 15 grid points (column numbers of the grid are 1, 3, and 5) in four different plots. No soil samples were taken in plot E or plot R (Fig. 2). The total number of sampled plots was *N*= 160. The WC for each sample using the oven-dry method, the soil was kept under dry conditions (*WC* = 0 %).

Calculation of Pattern Decomposition Coefficient

The normalized band reflectances for soil S_i and the normalized mixed-band reflectance M_i of all plots were analyzed using the pattern decomposition method. S_i was decomposed using the flat model pattern P_{fi} (= 0.25) and the typical soil pattern P_{si} via Eq. (1), where soil pattern P_{si} is the average value of the S_i (band number: i= 1 to 4) from all plots (P_{s1}, P_{s2}, P_{s3}, P_{s4}: 0.13, 0.19, 0.27, 0.41).

Similarly to S_i, M_i was decomposed using the flat model pattern and the soil pattern. Explicitly,

$$M_i = C_{mf}P_{fi} + C_{ms}P_{si}, \tag{2}$$

where C_{mf} is the pattern decomposition coefficient for flat model and C_{ms} is the pattern decomposition coefficient for soil.

RESULTS AND DISCUSSION

Spectral Reflectance

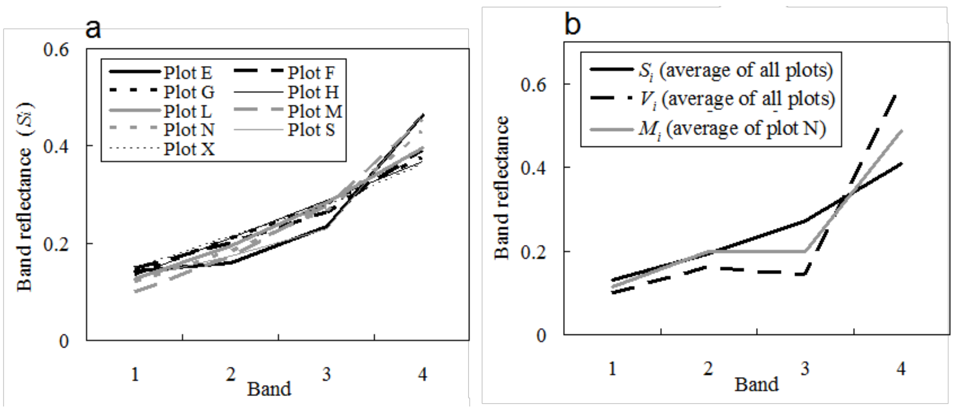

Fig. 3 Soil reflectance pattern (S_i) in each plot (a); and measured reflectance pattern (b)
Reflectance pattern (V_i) of soil and vegetation are average values of all plots, mixed reflectance pattern (M_i) is an average value of all grid points in plot N

The soil reflectance patterns were upward-sloping and linear, and the slopes of the reflectance patterns differed among the plots (Fig. 3a). To indicate the tendency of each reflectance pattern, the soil and vegetation reflectance pattern averaged over all the plots is shown in Fig. 3b. Although vegetation was strongly reflected in bands 2 and 4, absorption in bands 1 and 3 showed the characteristic reflectance pattern of vegetation. M_i was the reflectance from mixed soil and vegetation and was located near the mean value of the reflectance of soil and vegetation in bands 3 and 4. The reflectance patterns for plot N are shown in Fig. 3b, but the same tendencies were observed in the other plots as well.

Vegetation Coverage and Soil Moisture

The average value of vegetation coverage (VC) and water content in soil (WC) in each plot is shown in Table 2. The vegetation coverage was comparatively high for surfaces covered with rich vegetation. In plot M, for example, the surface was bare soil sparsely dotted with *Poaceae*, while in plot X the surface was densely covered by *Poaceae* and *Asteraceae*.

Table 2 Vegetation coverage (VC), water content in soil (WC) (The maximum, minimum and average value) and dry density in each survey plot

	VC (%)			WC (%)			Dry density (g/cm^3)
Plot	Min	Max	Average	Min	Max	Average	
E	18.5	72.5	52.2	—	—	—	—
F	2.0	11.4	6.6	1.6	3.3	2.6	—
G	13.6	47.0	32.3	1.5	3.1	2.3	1.4
H	15.2	69.2	42.0	1.0	1.9	1.3	1.4
L	37.2	94.0	54.5	0.9	4.4	2.9	1.1
M	6.6	51.2	19.4	5.3	15.8	9.7	—
N	5.0	66.3	38.1	5.8	10.8	8.0	—
R	28.5	85.0	54.7	—	—	—	—
S	52.2	93.4	81.6	4.5	20.8	13.4	0.7
X	2.1	32.5	13.9	1.0	23.4	1.5	—

Estimation of Soil Moisture and Effect of Vegetation on Estimation Accuracy

Soil moisture estimation from the pattern decomposition coefficient for flat model: Many studies have been done with visible and near-infrared wavelengths to estimate soil moisture using a soil line. In the scatter diagram of soil spectral reflectance values, where red is plotted on the horizontal axis and the near-infrared on the vertical axis, the data form a straight line (the soil line; Baret et al., 1993). Points on the scatter diagram that correspond to low water content in soil (WC) are located near the origin. However, the soil type must be classified in order to accurately estimate the soil moisture using this method because the slope of the soil line depends on the soil type. The soil line method is thus difficult to apply over a wide area utilizing remotely sensed data.

In contrast, the pattern decomposition method using flat model pattern depends less on the physical characteristics of soils. In our study, the regression analysis between WC and C_{sf} indicated a negative correlation ($WC = -26.6\ C_{sf} + 6.73$, $r^2 = 0.89$) across various soil types (Fig. 4). These results show that the C_{sf} derived from field survey data is also an effective index for soil moisture estimation, and high accuracy can be obtained without needing to classify the soil type.

Relationship between pattern decomposition coefficient and soil moisture: The pattern decomposition coefficient for flat model C_{mf} was calculated from M_i using Eq. (2), and the regression analysis performed using and WC and C_{mf}. No relationship between WC and C_{mf} (r^2 = 0.27) was found. In order to verify whether WC information is included in other coefficients, the following additional pattern decompositions were conducted using patterns of flat model, soil, and vegetation:

$$M_i = C_{ms3}P_{si} + C_{mv3}P_{vi}, \tag{3}$$

$$M_i = C_{mf4}P_{fi} + C_{mv4}P_{vi}, \tag{4}$$

$$M_i = C_{mf5}P_{fi} + C_{ms5}P_{si} + C_{mv5}P_{vi}, \tag{5}$$

where the typical vegetation pattern P_{vi} is the average over all the plots of V_i (band number: i = 1 to 4) from all plots data (P_{v1}, P_{v2}, P_{v3}, P_{v4}: 0.10, 0.16, 0.14, 0.60).

No significant correlation between WC and the pattern decomposition coefficients was found. A strong correlation, however, was found between VC and the pattern decomposition coefficient for vegetation (C_{mv3}, C_{mv4}, and C_{mv5}) (Fig. 5a). Although a correlation between VC and the normalized difference vegetation index: [NDVI, (band 4 − band 3) / (band 3 + band 4)] was noted, (Fig. 5b), the determination coefficients of NDVI were almost the same as that of C_{mv}. These results suggest that C_{mv} is also a valuable index for estimating VC.

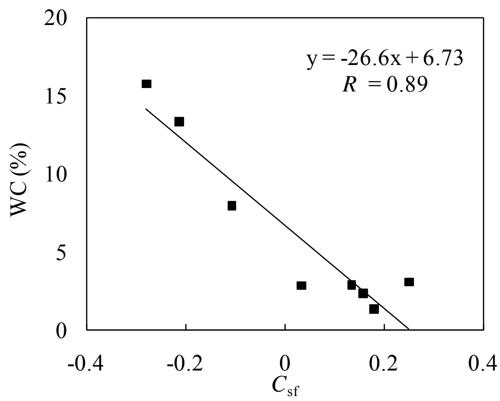

Fig. 4 Relation between water content in soil (WC) and pattern decomposition coefficient for flat model C_{sf}

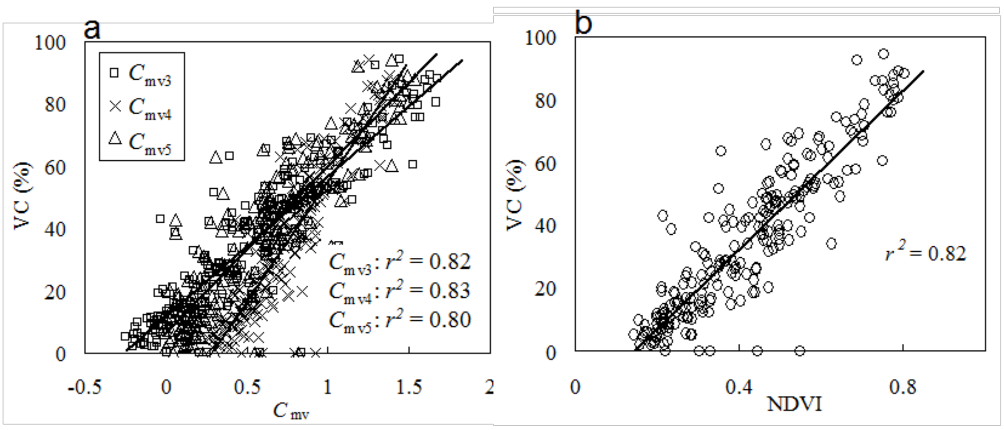

Fig. 5 Relation between vegetation coverage (VC) and pattern decomposition coefficient for vegetation C_{mv} (a)

Three combinations, C_{mv3}, C_{mv4}, and C_{mv5}, are calculated by the pattern decomposition method using soil and vegetation pattern, flat model and vegetation pattern, flat model and soil and vegetation pattern, respectively

Effect of Vegetation on Estimation Accuracy

The upper limit of vegetation coverage at which the pattern decomposition method using flat model pattern is viable was determined. Sekiyama et al. (2010) reported that estimation of soil moisture by this method was not possible when VC was over 50%. In this research, estimations were obtained for VC ranging from 0-50% (Table 3), and regression analysis was conducted using the WC and C_{mf} for each VC class. The results show that accuracy was high in the no-vegetation class (VC = 0%), but lower among the vegetated classes (VC > 0%). This leads to the conclusion that the pattern decomposition method using flat model pattern as developed by Sekiyama et al. (2010) can be effectively used only on bare soil with no vegetation. As a cause of no effectively method for mixed surface of vegetation and soil, it is supposed that physical and chemical characteristics of vegetation to spectrum is too strong compared with soil, and there is also a possibility that this coefficient is not able to estimate the water content because water content information of vegetation and soil is mixed. Thus, this coefficient is an inadequate indicator for water content when samples are contaminated by vegetation signals. Furthermore this method may not have been able to detect soil water content due to slight difference of soil water content in each plot. In fact, soil water content was 3 % or less in almost plots but soil samples were controlled various water content from 0 % to 20% in experiment for developing estimation method of soil content

For VC > 0%, the decomposition of M_i into the flat model pattern was affected by the high reflectance of vegetation in band 4 and the low reflectance in band 3. As a future refinement of this method, a separation (pre-decomposition) of the vegetation reflectance from the mixed data, which may be achieved using the relationship between VC and C_{mv}, is required. Such a refinement would allow the method to accurately extract WC from areas of mixed soil and vegetation.

Table 3 Relation between water content in soil (WC) and the pattern decomposition coefficient for flat model (C_{sf}) at each vegetation coverage (VC)

VC (%)	Estimate accuracy of WC (r^2)	P value
0	0.89	$P < 0.01$
0-5	0.10	$P > 0.05$
5-10	0.29	$P > 0.05$
10-20	0.02	$P > 0.05$
20-30	0.01	$P > 0.05$
30-50	0.006	$P > 0.05$

CONCLUSIONS

In this study, a method for estimating soil moisture developed by Sekiyama et al. (2010) was applied to field data acquired in the Mongolian grasslands. The following conclusions were obtaind:

・The bare soil of the Mongolian grasslands exhibits a negative correlation between water content in soil (WC) and the pattern decomposition coefficient for flat model C_{sf}, which was calculated using the pattern decomposition method modified by Sekiyama et al. (2010). This indicates that C_{sf} is a useful indicator of WC in bare soil.

・A strong correlation was found between the vegetation coverage and the pattern decomposition coefficient for vegetation C_{mv}. This indicates that C_{mv} be used not only to extract bare soil information, but to estimate the vegetation coverage and NDVI as well.

No significant relationship between WC and the pattern decomposition coefficient for flat model C_{mf} was found in the decompositions of the reflectance patterns from vegetated surfaces. This indicates that the method as proposed by Sekiyama et al. (2010) is influenced by vegetation, and is thus capable of accurately estimating soil moisture only on bare soil.

ACKNOWLEDGEMENTS

This research work was supported partly by the Japanese Ministry of Education, Culture, Sports and Science (MEXT) under the Academic Frontier Joint Research Program for Studies on Natural Environment and Culture in Asia of Tokyo University of Information Sciences.

REFERENCES

Baret, F., Jacquemoud, S. and Hanocq, J.F. 1993. The soil line concept in remote sensing. Remote. Sens. Rev. 13 (5), 281-284.

Fujiwara, N., Muramatsu, K., Awa, S., Hazumi, T. and Ochiai, F. 1996. Pattern expand method for satellite data analysis. J. Remote Sens. Soc. Japan. 16 (3), 17-34. (In Japanese with English abstract)

Ishiyama, T., Sugihara, S., Tsuchiya, K., Liu, P.J. and Lu, G.F. 1992. Variation of sand reflectance with moisture content. J. Arid Land Stud. 2, 39-43.

Kogan, F., Stark, R., Gitelson, A., Jargalsaikhan, L., Dugrajav, C. and Tsooja, S. 2004. Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. Int. J. Remote. Sens. 25-14, 2889-2896.

Kondoh, A., Kaihotsu, au-Chavez, L.L., Rober, R.A., Wyatt, H.K., Waddington, M.J., Turetsky, R.M.I., Hirata, M. and Dorgorsuren, A. 2005. Interannual variation of biomass in mongolian herbaceous vegetation. J. Arid Land Stud. 14-4, 209-218. (In Japanese with English abstract).

Lee, R., Yu, K., Price, K.P., Ellis, J. and Shi, P. 2002. Evaluating vegetation phenological patterns in Inner Mongolia using NDVI time-series analysis. Int. J. Remote Sens. 23 (12), 2505-2512.

Liu, W., Baret, F., Gu, X., Zhang, B., Tong Q. and Zheng, L. 2003. Evaluation of methods for soil surface moisture estimation from reflectance data. Int. J. Remote Sens. 24 (10), 2069-2083.

Muramatsu, K., Furumi, S., Fujiwara, N., Hayashi, A., Daigo, M. and Ochiai, F. 2000. Pattern decomposition method in the albedo space for Landsat TM and MSS data analysis. Int. J. Remote Sens. 21 (1), 99-119.

Muramatsu K., Xiong Y., Nakayama S., Furumi S., Ochiai F., Daigo M ., Hirata M., Oishi K., Bolortsetseg B., Oyunbaatar D. and Kaihotsu I. 2007. A new vegetation index derived from the pattern decomposition method applied to Landsat-7/ETM+ images in Mongolia. Int. J. Remote Sens. 28 (16), 3493-3511.

Ono, A., Fujiwara, N. and Ono, A. 2002. Suppression of topographic and atmospheric effects by normalizing the radiation spectrum of Landsat/TM by the sum of each band. J. Remote Sens. Soc. Japan. 22 (3), 318-327. (In Japanese with English abstract)

Ranjeet, J., Chen , J., Lu, N., Guo, K., Liang, C., Wei, Y., Noormets, A., Ma, K. and Han, X. 2008. Predicting plant diversity based on remote sensing products in the semi-arid region of Inner Mongolia. Remote Sens. Environ. 112 (5), 2018–2032.

Sekiyama, A., Shimada, S., Toyoda, H. and Yokohama, M. 2010. Estimation of soil water content using visible and infrared spectral reflectance characteristics. J. Arid Land Stud. 19 (4), 525-535. (In Japanese with abstract)

Yoshihara, Y., Chimeddorj, B., Buuveibaatar, B., Lhagvasuren, B. and Takatsuki, S. 2008. Effects of livestock grazing on pollination on a steppe in eastern Mongolia. Biol. Conserv. 141 (9), 2376-2386.

Zhang, L., Furumi, S., Muramatsu, K., Fujiwara, N. and Daigo M. 2007a. A new vegetation index based on the universal pattern decomposition method. Int. J. Remote Sens. 28 (1), 107-124.

Zhang, L., Fujiwara, N., Furumi, S., Muramatsu, K., Daigo M. and Zhang L. 2007b. Assessment of the universal pattern decomposition method using MODIS and ETM+ data. Int. J. Remote Sens. 28 (1), 125-142.

Zribi, M., Paris, A.T., Duchemin, B., Lili, Z., Wagner, W., Hasenauer, S. and Chehboun, A. 2010. Relationship between soil moisture and vegetation in the Kairouan plain region of Tunisia using low spatial resolution satellite data. Water Resource. Res., 46 (6), 1343-1357.