Soil moisture estimation using MODIS and ground measurements in eastern China

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Recent technological advances in remote sensing have shown that soil moisture can be measured by microwave remote sensing under some topographic and vegetation cover conditions. However, current microwave technology limits the spatial resolution of soil moisture data. It has been found that the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) are related to surface soil moisture; therefore, a relationship between ground observed soil moisture and satellite NDVI and LST products can be developed. Three years of 1 km NDVI and LST products from the Moderate Resolution Imaging Spectroradiometer (MODIS) have been combined with ground measured soil moisture to determine regression relationships at a 1 km scale. Results show that MODIS NDVI and LST are strongly correlated with the ground measured soil moisture, and regression relationships are land cover and soil type dependent. These regression relationships can be used to generate soil moisture estimates at moderate resolution for study area.

1. Introduction

Soil moisture is a key variable in controlling the exchange of water and heat energy between the land surface and atmosphere through evaporation and plant transpiration. It plays an important role in the development of weather patterns and the production of precipitation (Clark and Arritt 1995, Fennessey and Shukla 1999). Recent technological advances in remote sensing have shown that soil moisture can be measured by a variety of remote sensing techniques (Engman 1990). Techniques in the optical/IR and microwave regimes have attracted more attention (Chauhan 2003). Optical/IR techniques can provide fine spatial resolution for soil moisture estimation, but it is difficult to decouple signatures of soil type and soil moisture. Microwave technology has demonstrated a quantitative ability to estimate soil moisture physically for most ranges of vegetation cover (Njoku et al. 2002). However, the channel frequencies and the spatial resolution of current satellite microwave radiometers are not optimal for land remote sensing due to practical problems in supporting a large, low frequency antenna in space (Zhan et al. 2002).

Some attempts have been made by combining the strengths of microwave as well as optical/IR remote sensing approaches for soil moisture estimation. The soil
moisture Algorithm Theoretical Basis Document of the Visible Infrared Imager/Radiometer Suite (VIIRS) describes a two-step approach to obtain fine resolution soil moisture by linking microwave derived soil moisture with optical/IR parameters based on the Universal Triangle relationship among soil moisture, land surface temperature (LST) and the Normalized Difference Vegetation Index (NDVI).

The present study is designed to produce a soil moisture estimation algorithm by linking optical/IR measurements to ground measured soil moisture. Three years of 1 km NDVI and LST products from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) have been combined with ground measured soil moisture to determine and validate regression relationships at a 1 km scale. Based on the regression relationships, soil moisture maps at 1 km resolution can be developed over the study area.

2. Methodology

2.1 Algorithm theory

Vegetation and land surface temperature have a complicated dependence on soil moisture. Careful analyses of data by Carlson et al. (1994) and Gillies et al. (1997) showed that there is a unique relationship among soil moisture, NDVI, and LST for a given region. The results were later confirmed by theoretical studies using a soil-vegetation-atmosphere-transfer (SVAT) model.

Figure 1 represents a schematic description of the relationship referred to as the ‘Universal Triangle’. The abscissa and the ordinate are scaled temperature and NDVI, respectively such that:

\[
T^* = \frac{T - T_0}{T_s - T_0},
\]

(1)

\[
NDVI^* = \frac{NDVI - NDVI_0}{NDVI_s - NDVI_0}.
\]

(2)

Figure 1. Universal Triangle Relationship between soil moisture, temperature and NDVI (Chauhan 2003).
Where, $T$ and $NDVI$ are observed LST and NDVI, respectively, and the subscripts $o$ and $s$ stand for minimum and maximum values.

Carlson et al. (1994) found that the relationship between soil moisture $M$, $NDVI^*$, and $T^*$ can be expressed through a regression formula such as:

$$M = \sum_{i=0}^{n} \sum_{j=0}^{n} a_{ij}NDVI^{*i}T^{*j}.$$  \hspace{1cm} (3)

In terms of a second order polynomial, the above equation can be expanded as (Chauhan 2003):

$$M = a_{00} + a_{10}NDVI^* + a_{20}NDVI^{*2}
    + a_{01}T^* + a_{02}T^{*2}
    + a_{11}NDVI^*T^* + a_{22}NDVI^{*2}T^{*2}
    + a_{12}NDVI^*T^{*2} + a_{21}NDVI^{*2}T^*.$$  \hspace{1cm} (4)

Equations (1), (2) and (4) have been employed for the present study. The regression relationships are identified by combining the ground measured soil moisture with MODIS scaled NDVI and LST. By applying these regression relationships to MODIS measurements, soil moisture estimates at MODIS resolution can be obtained. A statistical analysis has been performed to compare soil moisture estimates and ground measurements. Finally, the advantages and limitations of this approach are discussed.

2.2 Study area

The current study is conducted over Shandong Province, situated in the eastern part of China (34.3° N to 38.2° N, 114.7° E to 122.7° E). It has a total area of 156 000 km$^2$, and 65% of its land is plains and low-lying land, while 35% is mountainous or hilly land. The bulk of this region is cropland along with other short vegetation in the agriculture fields.

There are 137 reasonably distributed ground stations over Shandong Province, which collect soil samples to measure soil water content gravimetrically at the top 10 cm layer of soil at 8.00 am on the 6th, 16th, and 26th of each month since the year 2003.

2.3 Data sources

The local overpass time of the satellite Terra almost matches the observation time of ground measurements, so we used Terra MODIS data in this study. Three years (2003–2005) of Terra MODIS data and ground observed soil moisture over the study area were acquired. MODIS data are daily surface reflectance (MOD09) to derive NDVI, and daily surface temperature (MOD11) at 1 km resolution. In order to investigate the dependency of the regression relationships on land cover and soil types, data on land cover and soil types at 1 km resolution of the study area have been collected from the Chinese Academy of Science.
3. Results and discussion

3.1 Algorithm construction

Two years of data (2003 and 2004) were used for algorithm calibration and one year of data (2005) for validation. A system of equations (4) was set up using ground observed soil moisture and MODIS scaled NDVI and LST for all the pixels matching the site of each ground station. The regression coefficients $a_{ij}$ for each station were determined using the least square method. The coefficients of determination, relative errors and standard deviation between the algorithm derived and the ground observed soil moisture were calculated (table 1).

For a total of 93 ground stations with valid data, relative errors approach 0, and the standard errors are less than 0.05; the coefficients of determination for 55 stations are greater than 0.8, 71 stations greater than 0.7 and 82 stations greater than 0.6. The results demonstrated the feasibility of soil moisture estimation using equation (4). For practical use, we investigated the dependency of the regression relationships on land cover and soil types, and calibrated equation (4) for the major land cover and soil types in the study area. Grassland, Cropland, Wooded Grassland, Closed Shrub-Land, and Urban and Built-up are the five main land covers, and Loam, Clay Loam, and Sandy Clay Loam are the three main soil types for the study area. These land cover and soil type based regression relations, in conjunction with MODIS scaled NDVI and LST, were then used to obtain soil moisture. Coefficients of determination and p-values between the regression derived and the ground measured soil moisture show that regression relations are land cover and soil type dependent (table 2). Considering the Cropland and Grassland, which account for more than 85% of the study area (1165 pixels against a total of 1360 pixels), the overall coefficients of determination are greater than 0.4, and the p-values are less than 0.02. The same results can be seen for the most dominant soil type, Loam, which accounts for a total of 767 pixels. In this sense, these regression relations can be applied to estimate the soil moisture over non-ground measurement areas based on land cover and soil type information. Thus the moderate resolution soil moisture maps can be generated over the study area. Figure 2 is the soil moisture map at 1 km resolution on 26 November 2005. The white regions in the map are the areas where soil moisture is not computed because of corrupted data due to clouds. Clearly, the 1 km image shows more detail in the soil moisture quantitative estimates and spatial pattern than the sparse ground measurements.

3.2 Algorithm validation

The ground observed soil moisture and MODIS scaled NDVI and LST for the year 2005 were used to validate the regression algorithms. The maximum standard error is less than 0.07, and the relative errors are around 10% (table 3). So the soil moisture estimation approach using MODIS and ground measurements is feasible.

<table>
<thead>
<tr>
<th>Number of stations</th>
<th>55</th>
<th>71</th>
<th>82</th>
<th>90</th>
<th>93</th>
<th>93</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>&gt;0.8</td>
<td>&gt;0.7</td>
<td>&gt;0.6</td>
<td>&gt;0.5</td>
<td>$&lt;1 \times 10^{-10}$</td>
<td>&lt;0.05</td>
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<tr>
<td>Standard error</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
3.3 Discussion

There are still some limitations to this soil moisture estimation approach. The time difference between the ground measurements and the Terra overpass could impact on the results. In addition, the 10 cm depth layer observation does not actually correspond to the surface parameters. The estimation errors could also come from the fact that the point ground soil samples may not represent the 1 km footprints of MODIS observations. Moreover, for the cloudy worst case, it is difficult to derive soil moisture from MODIS land parameters, which operate in the optical/IR bands. Further study will focus on these aspects.

Table 2. Statistics for land cover and soil type oriented algorithms.

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Soil type</th>
<th>$P$-value</th>
<th>$R^2$</th>
<th>Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooded Grassland</td>
<td>Loam</td>
<td>0.0526</td>
<td>0.5488</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Sandy Clay Loam</td>
<td>0.3047</td>
<td>0.9556</td>
<td>11</td>
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<tr>
<td></td>
<td>Clay Loam</td>
<td>0.1651</td>
<td>0.6340</td>
<td>29</td>
</tr>
<tr>
<td>Closed Shrubland</td>
<td>Loam</td>
<td>0.0440</td>
<td>0.9242</td>
<td>15</td>
</tr>
<tr>
<td>Grassland</td>
<td>Loam</td>
<td>3.40E-14</td>
<td>0.4248</td>
<td>412</td>
</tr>
<tr>
<td></td>
<td>Sandy Clay Loam</td>
<td>0.0256</td>
<td>0.6746</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Clay Loam</td>
<td>0.0003</td>
<td>0.5295</td>
<td>95</td>
</tr>
<tr>
<td>Cropland</td>
<td>Loam</td>
<td>1.50E-09</td>
<td>0.4481</td>
<td>262</td>
</tr>
<tr>
<td></td>
<td>Sandy Clay Loam</td>
<td>0.0040</td>
<td>0.6464</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Clay Loam</td>
<td>3.40E-12</td>
<td>0.4540</td>
<td>313</td>
</tr>
<tr>
<td>Urban and Built-up</td>
<td>Loam</td>
<td>0.0497</td>
<td>0.7036</td>
<td>29</td>
</tr>
<tr>
<td></td>
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<td>0.0031</td>
<td>0.7443</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Clay Loam</td>
<td>0.2738</td>
<td>0.6153</td>
<td>27</td>
</tr>
</tbody>
</table>

Figure 2. Soil moisture map at 1 km resolution over Shandong Province on 26 November 2005.
4. Conclusion

Notwithstanding the limitations just mentioned, the primary conclusions of the present research are clear: (1) the core process to link ground measured soil moisture and MODIS land parameters is the ‘Universal Triangle Relation’, which is reinforced by the application in this paper; (2) the results suggest that soil moisture estimation by combining ground measurements and MODIS land parameters is feasible; (3) compared with the ground measurements, the soil moisture map at 1 km resolution generated by the regression algorithm provides more regional soil moisture details and spatial patterns.

Acknowledgment

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References


<table>
<thead>
<tr>
<th>Land cover</th>
<th>Regression derived and measured soil moisture</th>
<th>Percentage relative error</th>
<th>Standard error</th>
<th>Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooded Grassland</td>
<td></td>
<td>15.01</td>
<td>0.0585</td>
<td>43</td>
</tr>
<tr>
<td>Closed Shrubland</td>
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<td>−9.83</td>
<td>0.1454</td>
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<tr>
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<td>−10.87</td>
<td>0.0497</td>
<td>230</td>
</tr>
<tr>
<td>Cropland</td>
<td></td>
<td>−8.74</td>
<td>0.0481</td>
<td>289</td>
</tr>
<tr>
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<td></td>
<td>11.41</td>
<td>0.0609</td>
<td>31</td>
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