論　文　の　内　容　の　要　旨

生物・環境工学　専攻
平成 20 年度博士課程　進学
氏　名 パリナズ　ラヒムザデ　バジギラン
指導教官名　大政　謙次

論文題目　**Remotely sensed vegetation and thermal indices for soil/vegetation water stress detection in semi arid regions**
（リモートセンシングによる半乾燥地域での土壌・植生の水ストレス検知のための植生・温度指標）

Arid and semiarid areas account for one third of the earth's land surface area and comprise more than 80% of Iran. Therefore, vegetation and soil water stress is a major widespread problem in the country and drought is a common natural disaster, requiring actions to monitor and detect ecosystem's water stress to mitigate its negative impacts on human life as well as wildlife and plant communities. Water content in soil and vegetation can be estimated by 1) field measurements, 2) meteorological data and 3) remote sensing. Although field measurements are the most accurate methods for estimating soil and vegetation water contents, they are costly and time consuming especially for mountainous and remote areas. On the other hand, climatic and hydrological drought indices which are based on meteorological data have poor spatial resolution. These data are also insufficient and not available for timely drought detection. Therefore, using Remote Sensing (RS) methods allows us to detect drought at higher temporal and spatial resolutions with lower cost and time. RS is a strong methodology in the study of terrestrial ecosystems from a site scale to a regional or global one. Since 1980s a number of remote sensing indices and methodologies have been developed to investigate vegetation condition and amount or soil moisture and drought monitoring. Normalized Difference Vegetation Index (NDVI) using the reflectance of near infrared and red bands is one of the most popular indices used for vegetation monitoring and drought detection in different ecosystems. RS Land Surface Temperature (LST) using thermal infrared bands, is also one of the important indices used successfully for soil moisture estimation and drought monitoring. Vegetation Water Indices (VWIs) calculated using wavelengths around 1240 nm, 1640 nm or 2100 nm in combination with near infrared have been applied as independent vegetation measures for retrieving canopy water contents instead of chlorophyll amount and studies have shown that they can provide us with valuable information on vegetation and/or soil water stress and drought status detection.

However RS indices developed for drought monitoring or detecting vegetation/soil water stress in the ecosystems, are not perfect. On the contrary, they need continual improvements and must be checked or validated for different ecosystems. Also, in Iran very few studies have been conducted and well documented regarding the application of RS indices for drought monitoring and soil/vegetation water stress. Even some indices such as VWIs and LST have not yet been used for the mentioned applications in the country. Recently, high-frequency temporal data of Moderate Resolution Image Spectrometer (MODIS) instrument having three appropriate water absorption channels for retrieving canopy water contents, besides thermal and reflective bands have offered a great opportunity to evaluate the application of vegetation indices and both VWIs and LST for ecosystem water detection at regional and global scales simultaneously. Therefore, the current study aims at evaluation and development of methods which can be used to estimate the spatial distribution and temporal variation of soil and vegetation water status and drought using MODIS data. This research focuses on the application of methods which are more appropriate for semi-arid regions. In this study firstly, NDVI and two VWIs time series were studied. Although the application of vegetation indices such as NDVI and VWIs has proved to be a great tool for detecting vegetation amount, soil/vegetation water content and drought, due to the complexity of each ecosystem, the relationship between vegetation activity and water content in various land cover types in relation to climate variation is different and must be studied. Long term analysis of the vegetation indices is an indispensable requirement to provide better insight into vegetation indices response to climate variations. Therefore, in the first study in this research, in order to evaluate how vegetation indices are affected by climatic patterns and to assess the relationships between them in semi-arid ecosystems of Iran, a six year (2000-2005) MODIS data (MODIS-Terra 8-day 500-meter atmospheric corrected reflectance products (MOD09A1) over a six month growing season was used for retrieving NDVI and two Normalized Difference Infrared Indices (NDII6 and NDII7 using band 6 and 7 MODIS data, respectively) used as VWIs. Daily and monthly precipitation data for 30 meteorological stations covering the years 2000-2005 were collected. Precipitation maps were produced using Inverse Distance Weighted (IDW) Interpolation. The study was carried out in dry farming and rangeland (plain rangeland and mountainous rangeland) areas located in the northwestern part of the country. Vegetation indices dynamics and relationships as well as their response to precipitation were studied. The results revealed the high dependence of temporal dynamics of MODIS vegetation indices on precipitation, promising the capability to differentiate drought and normal conditions in different land cover types. Chlorophyll amount (as depicted by NDVI) and vegetation water content (as depicted by VWIs) were found to be strongly related. In all cases, the relationships between NDII7 and NDVI were both more significant and steeper than those between NDII6 and NDVI (dry farming (R^2: 0.79), mountainous rangeland (R^2: 0.76) and plain rangeland (R^2: 0.73). Different precipitation scheme maps (weekly to cumulative three month) were produced to study the VWIs and NDVI response to rainfall. Among all precipitation schemes, monthly and two-month cumulative precipitation patterns had better relationships with vegetation indices where two-month cumulative precipitation was found to have the best relationship. NDVI, NDII7 and NDII6 from mountainous rangeland showed good correlation with two-month cumulative precipitation (R: 0.81 and 0.77, 0.74), respectively. Among all indices, NDVI was found to be the best index to be used for drought detection for it had better relationship with precipitation (mountainous rangeland (R: 0.81), dry farming (R: 0.73) and plain rangeland (R: 0.69)). However, NDVI has two main limitations for drought monitoring; first the apparent time lag between rainfall and NDVI response and second, little influence of significant precipitation events later in the growing season (plant seed production period) on NDVI. Therefore, the second research was aimed at developing appropriate methods to determine water stress in the semi-arid ecosystems in a timely manner. To do this, a modified approach towards Temperature Vegetation Dryness Index (TVDI) concept incorporating air temperature (Ta) and Digital Elevation Model (DEM) to develop the improved TVDI (iTVDI) is introduced. iTVDI is based on the combination of NDVI and LST (or Ts) and air temperature. ΔT (Ts-Ta) is linearly related to Vapor Pressure Deficit and can be used to estimate evapotranspiration (using surface energy balance equation) in ΔT vs. NDVI space. Vegetation Dryness Index (VDI) concept, originally developed for forest fire detection, was also applied for vegetation/soil water stress. VDI is also based on the combination of NDVI and NDII (in this research NDII7) and has proved to be able to estimate Fuel Moisture Content (FMC) in NDVI vs. VWI space. In this research, MOD09A1 and MOD11A2 were used to calculate vegetation indices and LST (or Ts), respectively. Ambient air temperature data collected from meteorological stations for years 2000 to 2005 were used for retrieving Ts-Ta (ΔT) maps. Temperature data were interpolated using smart interpolation method using Radar Topography Mission (SRTM) Digital elevation model images. As considering the general value of lapse rate (0.6 °C/100 m) is inaccurate and may differ in different places and different months, in this research, environmental lapse rates were calculated using linear regression between air temperature and elevation in each month for available meteorological stations. For conducting this part of the research (especially for retrieving VDI and extracting data from different land covers), a fine resolution land cover map of the study area was needed. Because land cover data of the study area were available at the coarse resolution (the map used in Chapter 3), for the purpose of this research, an accurate land cover map of the study area was produced using ETM+ data. Training data were collected using field survey data (conducted in August 2008), ETM+/NDVI map and ETM+ spectral scatter plots. Maximum likelihood classifications method was used to classify the data. Maximum overall accuracy obtained was 85.05% with a Kappa Coefficient of 0.76. Finally, iTVDI and VDI were retrieved using NDVI/ΔT and NDVI/NdII7 space, respectively for years 2000-2005 during summer time. Then temporal and spatial variations of iTVDI and VDI in four different land cover types (dry farming, plain rangeland, mountainous rangeland and rangeland and shrubs) were studied and finally iTVDI and VDI approaches were validated using precipitation data (precipitation maps were produced using the IDW interpolation method) and surface soil moisture data (retrieved during field survey in August 2008). Results indicated that iTVDI values and spatial/temporal variations were in close relationship with land cover types. Statistically significant relationships found between iTVDI and recent precipitation in the four land cover types (Dry farming ($R=0.84$, P value=0.0002), Plain rangeland ($R=0.77$, P value=0.0013), Mountainous rangeland ($R=0.70$, P value=0.006), Rangeland and shrubs ($R=0.56$, P value=0.03)) or soil moisture ($R=0.80$, P value<0.001) in the study area indicated that iTVDI is highly influenced by recent precipitation during summer time and can therefore estimate water status. It is concluded that iTVDI can be successfully used for vegetation/soil water stress monitoring in the semi-arid ecosystems of Iran Evaluation of VDI in the study area revealed that there was no clear relationship between VDI values and land cover types. Also no significant relationship between VDI values and precipitation or soil moisture was observed. Therefore, VDI does not seem to be applicable to semi-arid heterogeneous ecosystems. As in both VDI and iTVDI definitions, NDVI is coupled with the other variable (NDII7 and ΔT, respectively), the main reason for their different response to actual water status can be attributed to the y axis response to precipitation. Theoretically, both iTVDI and VDI are expected to give similar results. However, such a behavior was not observed in the present study. Although both ΔT and NDII7 represent water content in the ecosystem, their behaviors are not identical. ΔT variations are a function of irradiation and climatic conditions and are mainly influenced by recent precipitation whereas NDII7, similar to NDVI, has seasonal variations making it less responsive to precipitation in the late growing season. On the other hand, NDII7 is characteristic to each ecosystem, and each land cover has its own NDII7 values. Although NDII7 variation is more uniform in higher vegetation covers, in lower vegetation covers (NDVI<0.4) NDII7 values are highly variable in each land cover type with the same NDVI values. Thus, in the two dimensional space of NDVI and NDII7 as presented in VDI definition, NDII7 does not behave as expected for low to moderate heterogeneous vegetation covers. Therefore using ΔT and NDII7 for ecosystem water stress detection will provide different information on water status (ΔT for instantaneous water stress level and NDII7 for annual and seasonal dynamics of water status) and both provide valuable information for the environment. NDII7 can differentiate wet and dry years in semi arid ecosystems and its application in these areas would be beneficial. However should NDII7 be used to determine water status over a time period, it should be incorporated into an index which compares its values with the best conditions at the same pixel level.

In conclusion, MODIS NDVI, NDII6, NDII7 and iTVDI can be used for drought monitoring and water stress detection because all provide valuable information for the environment. Vegetation indices (NDVI, NDII6 and NDII7) have a great potential for long term environmental monitoring and changes in semi-arid regions and time series of theses indices should be applied to provide information on seasonal and annual dynamics of vegetation water content/amount and drought history. On the other hand iTVDI can be used as an index to timely evaluate soil/vegetation water stress status in the semi arid ecosystems.