論　文　の　内　容　の　要　旨

生物・環境工学　専攻
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論文題目　**Application of spectral mixture analysis of remote sensing data to soil erosion modeling in Philippine watersheds**

(フィリピンの流域土壌浸食モデルにおけるリモートセンシングデータのミクセル分解の応用)

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Soil erosion models are useful tools to generate quantitative data that are necessary for designing sound conservation measures. However, one of the major problems in soil erosion modeling is how to obtain the necessary information, more especially if the aim is to represent the output information at regional or catchments scale for soil conservation planning. Field surveys are labor intensive and expensive and yield normally only information on very limited geographical unit. For many applications these expenses are not feasible and remote sensing techniques may prove as a useful alternative. In the Philippines, although substantial work has been done to improve the erosion prediction, there has been no or very little work carried out using remote sensing data. With the remote sensing data becoming more available and affordable it is imperative to incorporate this in the soil erosion modeling process.

Relying on recent advances in remote sensing, this study provides a methodology designed to improve both quantitative and qualitative estimates of soil erosion using remotely sensed-derived parameter as input to soil erosion model. Specifically, the point of analysis is the application of linear Spectral Mixture Analysis (SMA) of Landsat ETM data to estimates the vegetation parameter for the Revised Universal Soil Loss Equation (RUSLE). Vegetation cover is one of the most influential factors in determining erosion rates. Vegetation has direct effect on cushioning the impact of rainfall and improves soil properties that inhibit soil erosion. Hence an accurate estimate of vegetative cover is a prerequisite for soil erosion modeling. Traditional method and extraction of vegetation information from remote sensing data such as classification techniques and vegetation indices such as NDVI were found inaccurate. Thus, an alternative approach based on SMA was proposed in this study. Linear SMA is a sub-pixel classification technique, which assumes that the spectral values of an image are produced by the linear mixing of a limited number of surface elements ("endmembers"). A desirable feature of linear SMA models is that it can estimate the fractional abundance of green vegetation and soils simultaneously, appropriate for soil erosion analysis. Linear SMA was also found useful in estimating percent ground cover, which also plays a major role in controlling soil erosion.

This study also tried to extend the use of erosion model from merely soil loss prediction to the assessment of land capability and suitability of a particular land-use system. This objective arise from the fact that the continuing land degradation of many watershed in the Philippines due to soil erosion is accounted from the lack of effective land-use planning and allocation that considers protection from soil erosion and its environmental effects.

The study was carried out in three different phases as follow:

a) Estimation of vegetative cover (C-factor) for RUSLE model using SMA

This study proposed that the fractional abundance of vegetation, ground cover (i.e. cover of soil surface such as litter, dried leaves, rocks or gravel) and bare soil components in a given pixel of Landsat ETM could be used to estimate the C factor. This presumption is based on the fact that the greater the amount of vegetative and ground cover, the lesser the soil erosion, whereas, the more exposed soil or bare soil the higher the soil erosion. Thus by estimating these components in a given pixel using linear SMA, a bare soil/cover ratio could be derived to define the C factor as follow:

$$C = F_{bs}/(1+F_{veg}+F_{npm})$$

where, F_{bs}, F_{veg}, and F_{npm} are the linear SMA-derived fractions of bare soil, vegetation and non-photosynthetic materials, respectively. The equation assumed that soil erosion only occurred when there are exposed soils that are subject to soil detachment by raindrop impact and surface run-off. In densely vegetated areas or no amount of exposed soil, the C value is basically zero. The addition of 1.0 in the denominator limits the C values from 0 to 1 with higher values indicating more exposed soil, and low values corresponding to high abundance of vegetation or groundcover.

Using the above equation, C factor map was generated and validated using the field measured C factor in the study area. NDVI-derived C factor was also presented in this study for comparison with the proposed method.

b) Soil erosion modeling using RUSLE and its validation

Using the results of unmixing as input to RUSLE model, both qualitative and quantitative soil erosion estimations were conducted. The modeling of soil erosion was conducted using a raster-based approach where a square cell of 30 meters was chosen to match with the spatial resolution of Landsat ETM image. Grids of rainfall, soil, elevation, and land cover were created using (ArcInfo) software. The generated thematic maps including the SMA derived C factor map were then multiplied to determine the soil erosion in the study area.

The predicted patterns of erosion and soil loss estimates were validated by comparing the model predictions with catchment's erosion intensity map derived from a combination of very-high resolution imagery and field survey. A comparative analysis of soil erosion using image classification, NDVI and

SMA-derived C factor as inputs to soil erosion model was also conducted and presented in this study.

c) Land suitability and capability assessment

Land suitability is defined as the measurement and rating of the impacts of a land-use on the productivity and stability of an area. Land capability assessment on the other hand, refers to the systematic arrangement of land into various categories according to its capability to sustain particular land-uses without land degradation. The assertion made in this study was that, a given land-use or land cover is suitable when the average annual soil erosion is less than or equal to the permissible level of soil erosion. This level by which soil erosion can be allowed is what commonly termed as tolerance limit (T). Technically T is defined as the maximum long-term average annual erosion rate that a particular soil or area can tolerate without excessive degradation. Thus, if annual soil loss is more than the tolerance limit, then land-use is unsuitable and vise versa.

A suitability rating (SR) was derived for the different land-uses in the study area by dividing the annual soil loss values with the tolerance limits. Such that in areas where SR is equal to 1.0 or less means that the soil erosion in the area is equal to or lesser than the corresponding T values and therefore have suitable land-use. Those areas with SR greater than one have unsuitable land-use because the soil erosion is exceeding to what is sustainable. These results carries an important implications in terms of prioritizing the areas that need to be rehabilitated and where soil conservation practices needs to be immediately implemented. A land capability classification and recommendation of appropriate land-use was then carried out based on erosion index that defines the susceptibility of an area to soil erosion.

The study area from which the above methodology was implemented is the Lamesa watershed located in the northernmost part of Metro Manila, Philippines and lies between 14.70 to 14.77 N latitudes and 120.98 to 121.12 E longitudes. This is a watershed reservation covering an area of about 2, 700 hectares and consists mainly of secondary forests and grasslands. The area experienced high deforestation rates in the past, which resulted to the conversion of large natural forest to grassland. Cultivated lands and abandoned slush and burned areas are found in patches. Soil conservation is of significant concern because this area supports a critically important water resource of Metro Manila.

Results of the study showed that the C factor value estimated using SMA correlated strongly with the values measured in the field. The correlation coefficient (r) obtained was 0.94. In contrast, the correlation between measured C factor values and NDVI was poor ($r = 0.64$) using a quadratic function. A comparative analysis between NDVI- and SMA-derived C factor also showed that the latter produced a more detailed spatial variability. Furthermore, SMA-derived C factor generated more accurate erosion estimates when used as input to RUSLE model. Accuracy assessment using very high resolution QuickBird image and field data indicated that using SMA-derived C factor, an overall accuracy of 70.92% and Kappa coefficient of 0.63 could be achieved in terms of identifying the different erosion classes. This is much higher compared with the overall accuracy of 42.23% and Kappa coefficient of 0.28 using NDVI-derived C factor.

The suitability assessment of the existing land-use system indicated that the total areas with suitable land-use is 1133.2 ha or 54% of the area, while 979.6 ha (46%) has unsuitable land-use. The average annual soil erosion from areas with unsuitable land-use is about 56.5 ton/ha/yr. Maintaining and increasing the density of vegetation in these areas should therefore be encouraged. The capability classification map indicated that these areas should be under forest more especially those that were classified with erosion index (EI) of greater than 10.

The good correlation between linear SMA–derived C factor and values measured in the field can be accounted to good estimates of vegetation canopy and ground cover provided by linear SMA. Since, C factor represents the protection from erosion afforded by vegetation canopy and ground cover, good estimates of these parameters are likely to results to suitable C factor values. One limitation of SMA-derived C factor though, was the assumption that its value is zero under densely vegetated and areas with good ground cover. This assumption implied that the overall soil erosion estimates would be underestimated in these areas. It was reported that even undisturbed forests having complex canopies and full canopy and litter coverage still have slight erosion rates that ranges from 0.07 - 0.11 t ha^{-1} y^{-1}. However, taking into account that the original intent of the USLE and RUSLE was to define long-term erosion risk and the concerns are to identify areas that need immediate rehabilitation for soil conservation purposes, the absolute values of soil erosion are not primarily important in heavy vegetated areas.

The linear SMA method offers a reliable estimate of C factor on a pixel-by-pixel basis that is useful for spatial modeling of soil erosion using the RUSLE model. It should be pointed out, however, that the estimated soil erosion quantities might not be accurate as this is expressed only as the average soil erosion per year. Nevertheless, the results gave qualitative indications of increasing soil loss with decreasing cover and accurately identified erosion areas better than the commonly used method, which is based on NDVI and common classification method. This is a significant result for improving the applicability of RUSLE as soil erosion prediction model at watershed scale.

To achieve a sustainable management of watershed, it is necessary that soil erosion be kept within a certain sustainable limits. For this purpose the concept of soil loss tolerance was adopted, as the maximum soil loss value that can be permitted for a given land without causing degradation of soil. Evaluating and classifying lands and consequently recommending land-use or land cover system on the basis of soil loss tolerance concept is the best way to control soil erosion. The method provides a systematic approach that integrate important biophysical factor influencing soil erosion; thus offer a good criteria for improving the land-use planning and allocation in the Philippines.