論文の内容の要旨

論文題名　Multi-sensor Remote Sensing Techniques to Manage Cambodian Forests for Implementation of REDD+ policies

（REDD＋政策実行のためのマルチセンサ・リモートセンシング技術の森林管理への適用 :カンボジアを事例として）

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With an increasing role of tropical forests in supporting a range of ecosystem services, such as biodiversity conservation, water regulation, soil conservation, timber, non-timber forest products, carbon sequestration, and climate change mitigation, the importance of forest resources management has become very crucial. The tropical forests of Indo-China countries are rich in biodiversity and carbon density, and thus are significant from social, ecological, political and economic stand points. These forests provide essential livelihoods to the local and indigenous people. However, rapid economic growth, agriculture expansion, illegal logging, population growth, and urbanization have been reported as major contributors to the deforestation. Due to these rapid developments forest resources are at a greater risk. A recent FRA (2010) report shows that deforestation caused a loss of about 13 million hectares of tropical forests per year between the years 2000 to 2010. Therefore, there is an urgent need for better management of these resources. This research work has been carried out in order to partially contribute towards climate change mitigation by studying remote sensing for implementing the reducing emissions from deforestation and forest degradation plus (REDD+) policies.

To mitigate climate change, most of the present studies are concentrated on afforestation, reforestation and reducing deforestation and degradation. This study focuses on the application of multi-sensor remote sensing techniques to manage Cambodian forests for the effective implementation of REDD+ policies. In this context, it is important to obtain reliable and consistent information of (a) forest cover, (b) deforestation, and (c) forest biomass to estimate CO_2 emissions for the improvement of national carbon accounting as well as for the development of Measurement Reporting and Verification (MRV) system and for sustainable forest management.

The first research question that has been dealt in this thesis is: how the forest cover

classification can be improved in tropical countries like Cambodia, where optical sensor data is not suitable due to cloud cover during the rainy season, and defoliation of deciduous forests in the dry season. This thesis has proposed a new method to use Phased Array type L-band Synthetic Aperture Radar (PALSAR) full polarimetric data to classify forests with high accuracy using polarimetric decomposition theorem. The comparison among the classification results derived from Cloude-Pottier H/A/a, Freeman-Durden three component decomposition and Yamaguchi four component decomposition shows that Yamaguchi four component decomposition has the highest overall accuracy, whereas, Freeman-Durden three component based classification shows overestimation in the volume scattering for evergreen forests.

The second research question is: how deforestation and forests types can be characterized based on polarimetric parameters of full polarimetric PALSAR data. In order to evaluate this, the capability of full polarimetric PALSAR data is demonstrated for the characterization of forests and deforestation. Various polarimetric parameters such as backscattering coefficient (σ^o), entropy (H), alpha angle (a), anisotropy (A), pedestal height (PH), Radar Vegetation Index (RVI), Freeman-Durden three-component and Yamaguchi four component based decomposition parameters have been studied. Results show that σ^oHV, cross-polarization ratio (HH/HV), entropy, RVI, PH and Yamaguchi four component based decomposition provide the best outcome among other parameters. This study concluded that the PALSAR full polarimetric data is useful for forests and deforestation characterization.

The third research question is about the use of different Digital Elevation Models (DEMs) data for estimation of height of deforested areas. In order to demonstrate this, Ice Cloud and land Elevation Satellite Geoscience Laser Altimeter System (ICESat-GLAS), Panchromatic Remote sensing Instrument for Stereo Mapping Digital Surface Model (PRISM-DSM), Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER-GDEM), and Shuttle Radar Topographic Mission Digital Elevation Model (STRM DEM) data have been used. The height of the deforested area has been estimated from PRISM-DSM and SRTM-DEM data after offset correction with ICESat-GLAS data. This study is useful for the calculation of carbon emissions due to deforestation as well as 3-D forest information in a cost effective way. This study has some limitations such as: (a) Ineffectiveness of PRISM-DSM data during cloudy days, (b) lack of date of acquisition information of ASTER GDEM data generation, (c) limited GLAS shots in the study area and (d) detection of height of deforested area with a size less than 3x3 pixels of SRTM data, which are beyond this methodology.

The fourth research question that posed in this thesis is: how effective is the PALSAR data to monitor growth stages of cashew plants. This study demonstrates the relationship between backscattering properties (σ^o) of PALSAR dual polarimetric data with the biophysical parameters (height, age, crown diameter, diameter at breast height (DBH), basal area, tree density and biomass) of the cashew plants. The value of σ^o increases with the age of cashew plants. At the young stage, the cashew plants show a higher rate of increase in σ^o compared to that at the mature stage. The σ^o HV shows higher sensitivity to the plant's growth than σ^o HH. High backscattering and low variations have been observed at the mature stage (8-12 years) of cashew plants. Saturation in backscattering has occurred at the age of about 13 years. The validation results indicate strong coefficient of determination (R^2 = 0.86 and 0.88) for PALSAR predicted age and biomass of cashew plants with RMSE = 1.8 years and 16.3 t/ha, respectively.

This study has demonstrated that, PALSAR data is effective for monitoring various growth stages of cashew plants and its dependency on biophysical parameters of plants until the saturation of the PALSAR signal.

The fifth research question answered in this thesis is: how effective is the plantation based biomass estimation for natural forests. The backscattering properties of the PALSAR data was investigated in cashew and rubber plantation areas of Cambodia. The result shows that the PALSAR backscattering coefficient (σ^o) has different responses for both plantation types because of the differences in their biophysical parameters. The PALSAR σ^o indicates a high correlation and a less saturation in cashew plants than rubber plants. Cashew plants-based Multi-linear regression (MLR) model shows a better result than those of rubber and mixture of cashew and rubber based models. Cashew plants based model shows saturation at about 100 t/ha in natural forests area. In high biomass regions such as dense evergreen forests, this model becomes saturated because of the saturation of PALSAR signals. This methodology can provide a general idea about biomass distribution in a time and cost effective way, because collection of inventory data in plantation area is less time and labour intensive compared to natural forests.

The sixth research question responded through this thesis is: how to generate a national level biomass map from remote sensing techniques. Potential of PALSAR dual polarimetric 50m mosaic data to estimate above ground biomass in Cambodia has been investigated. The relationship between PALSAR σ^o HV and HH/HV with field based biomass shows a good correlation with R^2 = 0.67 and 0.56, respectively. PALSAR-estimated biomass map shows good results in flat area forests as compared to mountainous area forests. The validation result shows a high coefficient of determination R^2 = 0.61 with RMSE = 21 t/ha using values up to 200 t/ha biomass. This study demonstrates that PALSAR 50m mosaic data is effective for national level biomass monitoring using non-destructive techniques in a cost-effective way. Use of multi-temporal PALSAR 50m mosaic data will be useful for the assessment of carbon sequestration in the forest ecosystem, and will contribute to better understanding of the global carbon budget and its change over the years.

The seventh research question that has been addressed through this thesis is: how to use updated forest cover and biomass map for implementation of sustainable forest management plans. In this study, the importance of updated information of forest cover and forest biomass is investigated for selecting the sites for planned thinning, reforestation, community forestry, and concession land, which will eventually help to control the deforestation rate in Cambodia. Controlling the deforestation rate is needed for an effective implementation of REDD+ policies. An integrated approach of remote sensing and community forestry is useful for management of forest resources to support sustainable forest management plans.

Based on these results and findings the aforementioned methodologies would be useful for the development of an MRV system for the effective implementation of REDD+ policies in Cambodia, wherein, about 75% of forests are present in flat areas. Hence, SAR data can be applied without limitations of topography as compared to other tropical countries. Application of this methodology to other regions may differ because of tree species, canopy structure and environmental parameters. Therefore it needs to modify the methodology accordingly.