論 文 の 内 容 の 要 旨

農学国際専攻

平成 29 年度博士課程 入学

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論文題目 **Application of remote sensing and resource assessment techniques for the single-tree management system of high-value hardwood species in northern Japan (高価値広葉樹の単木管理システムにおけるリモートセンシングと資源評価技術の応用)**

High-value timber species play a significant economic role in forest management. In uneven-aged mixed conifer-broadleaf forests in northern Japan, monarch birch (*Betula maximowicziana*), castor aralia (*Kalopanax septemlobus*), and Japanese oak (*Quercus crispula*) are important producers of high commercial value timber. The supply of high-value timber from these species is exclusively dependent on selective harvesting of large-size trees within mixed forests. Single-tree management system has been applied for the management of high-value timber species. Single-tree management is a forest management approach that aims at enhancing selected trees of high timber quality and value in a forest stand. Under single-tree management system, identification and registration of target trees, measurement of their size and assessment of timber quality, and periodic monitoring of selected trees are three most important tasks. To accomplish these important steps, forest managers mostly rely on the extensive field survey. Recently developed remote sensing (RS) technology, such as airborne laser scanning (ALS), unmanned aerial vehicle digital aerial photogrammetry (UAV-DAP) have great potential for acquiring individual tree information of high-value timber species for the purpose of single tree management. The major aim of this study is to examine the potential use of UAV-DAP in combination with long-term forest measurement dataset for single-tree management of high-value timber species. To fulfill the major aim, four specific research questions will need to be addressed: (1) Is UAV-DAP applicable in practical forest measurement of high-value timber species, e.g., tree height? (2) If it is applicable, how do UAV-DAP could be used in single tree identification and estimation the single tree positions and their

tree size? (3) How to assess the resource sustainability of target high-value timber species? and (4) How to estimate the time for a selected tree to reach a desired size?

To apply the RS and resource assessment techniques for practical purposes, the first research question is whether these techniques could be used reliably. The Chapter 2 of the thesis deals with the assessment of accuracy of RS data in practical field application. Since height information can be directly derived from RS data, individual tree height derived from field survey, LiDAR data, and UAV-DAP data were compared. In addition, the accurate measurement of individual tree height is necessary for both practical management and scientific reasons such as estimation of stem volume. The spatial position, tree height, and diameter at breast height (DBH) of 178 field measured trees of monarch birch, castor aralia and Japanese oak were used for the purpose of comparison. Field measured trees were manually digitized with the aid of field recorded tree spatial position and high resolution orthophotographs, and tree height were extracted for these tree crowns. Tree heights from three different sources were cross-compared statistically through paired t-tests, correlation coefficients, and height-diameter models. The results indicated that UAV-DAP derived tree heights were highly correlated with LiDAR tree height and field measured tree height. The performance of individual tree height measurement using traditional field survey is likely to be influenced by individual species. Overall mean height difference between LiDAR and UAV-DAP derived tree height indicates that UAV-DAP could underestimate individual tree height for target high-value timber species. The results of Chapter 2 confirmed the applicability of UAV-DAP for the tree height measurement of large-size high-value timber species.

The Chapter 3 deals with the second research question of how UAV-DAP could be used for the retrieval of individual tree spatial positions and individual tree DBH. High-resolution spectral information of UAV-DAP and LiDAR were applied in this Chapter. Multi-resolution segmentation was employed on UAV-DAP orthophotographs to derived individual tree crown objects. Object-based image analysis with random forest classification was used to classify forest canopy into five categories of three high-value timber species, other broadleaf species, and conifer. UAV-DAP can produce overall accuracy of 73% and 63% for classifying forest canopy into five categories in sub-compartment 36B and 59A, respectively. These results were used to identify the individual tree spatial position of high-value timber species. When estimating DBH, UAV-DAP can produce high-prediction accuracy comparable to field and LiDAR data. The results of Chapter 3 are useful for forest managers for searching of high-value timber trees with their estimated tree size in large area of mixed-wood forests.

Assessment of sustainability was employed in Chapter 4 focusing on the third research question. The sustainability of three high-value timber species were investigated using nearly 50 years of census data in long-term permanent plots. Commonly used variables in forest inventory, such as stocking, demographic parameters, and species proportions of these species were used as measures of sustainability. Results showed that the tree density and basal area of the three high-value timber species increased during the study period. Moreover, the basal area increment (BAI) of these species showed an increasing trend across census periods. However, while no significant differences in the tree mortality of these species were observed, the numbers of in-growth fluctuated across census periods. Increasing trends in species proportions of monarch birch and Japanese oak were observed. Even though there were some fluctuations across census periods, especially in smaller diameter classes, diameter distribution curves of high-value timber species followed a reversed J-shaped pattern. The results revealed that the sustainability measures of high-value timber species can be achieved in forest stands managed under single-tree selection system.

Understanding individual tree growth of these species is important for the simulation and development of forest management options as well as for the purpose of periodic monitoring. In the Chapter 5, individual tree growth models of three high-value timber species were developed using long-term plot measurement data. Linear mixed-effects modelling approach was used to predict the individual tree basal area growth as a function of initial tree size, stand structure, and forest management. Model prediction followed by leave-one-out cross validation revealed a correlation between predicted and observed basal area increments with correlation coefficients of 0.62, 0.73 and 0.70 and root mean square errors values of 10.44, 7.91, and 11.62 cm^2/year for monarch birch, castor aralia, and Japanese oak, respectively. The results of model prediction were used to estimate the time for a certain diameter tree to reach a target diameter using compound interest formula. The results indicated that a 30 cm DBH tree will take 29, 28 and 48 years to reach 50 cm DBH and 48, 46, and 80 years to reach 70 cm DBH for monarch birch, castor aralia, and Japanese oak, respectively.

Overall, the results of this thesis indicated that the use of RS data and resource assessment techniques could facilitate the retrieval of individual tree information of high-value timber species and could support single-tree management systems. The applicability of UAV-DAP data in practical forest measurement of high-value timber species was confirmed. In addition, the results can provide individual tree spatial positions and their tree size which can be used in the practical field survey. Resource assessment techniques could be used for adapting

silvicultural practices and harvesting practices as well as for simulating various silvicultural and management options for managing high-value timber species in a sustainable manner. The development of tree growth model will provide valuable information to estimate the timing of management and for periodic monitoring of economically high-value timber species. The combined use of RS data and long-term forest measurement data in the single-tree management planning of high-value timber species should be analyzed further.