論 文 の 内 容 の 要 旨

農学国際専攻

平成 27 年度博士課程 進学

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論文題目 **Applicability of unmanned aerial vehicles (UAVs) for uneven–aged forest management planning: A study in a mixed conifer–broadleaf forest in Northern Japan**

（異齢林管理計画への無人航空機（UAV）の利用可能性：北日本の針広混交林を対象として）

Conventional remote sensing (RS) techniques such as satellite RS, airborne laser surveying (ALS), synthetic aperture radar (SAR) and interferometric SAR (InSAR) have limited applicability in operational forest management at local scale because they often require trade–offs between resolution, scale, frequency and cost. By addressing the limitations of conventional remote sensing platforms, fixed–wing unmanned aerial vehicles (UAVs) may bridge the gap between the need for an effective method for data acquisitions and the efforts associated with ground surveys. Previous studies have shown that digital photogrammetric techniques such as structure from motion (SfM) are capable of successfully reconstructing three–dimensional (3D) forest canopy using fixed–wing UAV imagery over even–aged plantations, and forest types with simple structural arrangements, e.g., boreal forests, and woodlands. Although fixed–wing UAV photogrammetry has great potential in forestry applications, its applicability in uneven–aged forest management planning has not been studied intensively. Thus, the aim of this study is to explore how fixed–wing UAV photogrammetry can be incorporated into uneven–aged forest management planning in mixed conifer–broadleaf forests. This thesis comprises seven Chapters including four main Chapters to address four research questions.

Three forest management Compartments (43, 45 and 48) that are located in the University of Tokyo Hokkiado Forest (UTHF) were chosen as the area of interest (AOI). These Compartments comprised forest areas with varying levels of forest structural and spatial complexity. High resolution RGB aerial imagery were acquired over the AOI using a Trimble UX5 fixed–wing UAV platform. These imagery were subjected to a

photogrammetric processing using a digital photogrammetric software package to build 3D point clouds and orthomosaics. Then commonly used canopy models, e.g., canopy height models (CHMs), and structural metrics, e.g., height, density, and height variation metrics, were derived using 3D point cloud data. Also, an image metric that explains the broadleaf vegetation cover percentage was calculated using the spectral information contained in the orthomosaics.

The first research question, i.e., how accurate the UAV–photogrammetric products are?, was addressed in Chapter 3 using UAV, ALS and field data from Compartment 43 and 48. The accuracy of UAV–SfM products, i.e., 3D point clouds, CHMs, and structural metrics were evaluated by comparing them to ALS derived 3D point clouds, CHMs and structural metrics, respectively. Then the utility of UAV–SfM structural metrics for estimating forest structural attributes, e.g., dominant height (hdom), basal area (BA), quadratic mean diameter at breast height (Dq), and stem density (N), was examined by employing generalized linear modelling (GLM). Also, the impact of terrain conditions, e.g., altitude, slope, aspect, and forest structural complexity e.g., as explained by canopy height, roughness, and cover, on the performance of the UAV–SfM CHM was explored using GLM. The results demonstrated that apart from the poorly reconstructed small canopy gaps, UAV–SfM point clouds, CHMs, and structural metrics have a comparable accuracy to ALS observations. Also, UAV–SfM data provided similar results to ALS in terms of the area–based estimations of the commonly used forest structural attributes. Relative root mean squared error (%RMSE) values of UAV–SfM estimated hdom, BA, Dq, and N were 7.4%, 18.7%, 12.1%, and 22.7%, respectively. Further, the terrain condition did not show statistically significant association with the performance of the UAV–SfM CHM whereas forest structural attributes that explained the vertical and horizontal variations of the forest canopy were significantly associated with the performance of the UAV–SfM CHM, e.g., canopy height and roughness showed positive coefficient while canopy cover showed a negative coefficient. In Chapter 3 of this thesis, it was demonstrated that although there are differences between ALS and UAV–photogrammetry technique, fixed–wing UAV–photogrammetric products developed over uneven–aged mixed conifer–broadleaf forests perform well in reconstructing forest canopy structure and predicting forest structural attributes that are commonly used in forestry applications. Nevertheless, the performance of UAV–SfM CHM is likely to be influenced by the structural complexity of the forest canopy.

The second research question, i.e., what type of quantitative forest information can be retrieved using UAV photogrammetric products?, was addressed in the Chapters 4. First, the utility of fixed–wing UAV–photogrammetry in estimating widely used forest resource information, e.g., merchantable volume (V) and carbon stock in living biomass (CST), was tested using regression modelling of field measurements, and UAV–SfM structural and image metrics calculated at plot–level. Also, the spatial distributions of UAV–SfM estimated V and CST were mapped over Compartment 43 and 48. UAV–SfM results, e.g., plot–level estimates and spatial distribution maps of V and CST, were then compared to ALS results to get better understanding on the accuracy of the UAV–SfM estimations. Plot–level validation of UAV–SfM estimated V revealed a RMSE of 39.8 m3 ha–1 and a %RMSE of 16.7%, whereas the RMSE and %RMSE vales for UAV–SfM estimated CST were 14.3 Mg C ha–1 and 17.4%, respectively. The image metric (broadleaf vegetation cover percentage) that was included in the regression analysis showed a statistically significant association with both V and CST, and provided an additional explanatory power. Nevertheless, RMSE values did not significantly change after adding the image metric into the regression analysis, e.g., %RMSE was reduced by 1.9% for V estimation, and 1.5% for CST estimation. Furthermore, the obtained UAV–SfM estimates were comparable to ALS estimates (relative RMSE of ALS estimations were 16.4% and 16.7% for V and CST, respectively). The spatial distributions of V and CST could be successfully mapped using UAV–SfM data and their stand– and landscape–level variations could be identified with a comparable accuracy to ALS observations. Therefore, the potential of fixed–wing UAV–photogrammetry to capture the fine scale spatial variation of V and CST in uneven–aged forests that are subjected to silvicultural practices and natural disturbances over time was further confirmed in the Chapter 4 of this thesis.

The utility of UAV photogrammetry to characterize forest canopy structure was examined in Chapter 5 to answer the third research question, i.e., how UAV–photogrammetric products can be used to characterize forest canopy structure and vegetation types?. Seven structural metrics derived from UAV–SfM data, e.g., 95th percentile of canopy height (P95), mean canopy height (MeanH), standard deviation of canopy height (SDH), coefficient of variation of canopy height, surface area ratio (SR), canopy cover > 2 m height (CC), and canopy cover > mean height (CCmean), were compared to field measurements, e.g., hdom, BA, Dq, standard deviation of diameter at breast height, CST, N, and proportion of broadleaf stem density, using univariate (Pearson correlation coefficients) and multivariate analyses (Principal component analysis–PCA). Then twelve subsets (each including three UAV–SfM metrics, i.e., a metrics that explained height measurement, a metric that explained height variation and a metric that explained canopy cover) were defined and PCA ordinations were produced. These twelve PCA ordinations were compared to the PCA ordinations of four base combinations, i.e., all the field metrics, all the UAV–SfM structural metrics, all the field and UAV–SfM metrics, and all the ALS metrics, to examine if a subsect of UAV–SfM structural metrics is capable of capturing the vertical and horizontal variations of the uneven–aged forest canopy structure as explained by all the field and ALS structural metrics. After identifying the appropriate subsect of UAV–SfM structural metrics through PCA ordination comparison, the subsect of UAV–SfM structural metrics was coupled with the broadleaf vegetation cover percentage metric to classify the predominant forest structure types in Compartment 43 and 48. Unsupervised k–means clustering algorithm was used for the classification. Lastly, the spatial distribution of the identified forest structure types were mapped. The results demonstrated that all the chosen UAV–SfM structural metrics have significant correlations with at least one field measurement of forest canopy structure. Also, all the PCA ordinations of the UAV–SfM metric subsets were correlated to the PCA ordinations of the base combinations. Subset that comprised MeanH, SDH, and CC showed the strongest correlations with the PCA ordinations of all the base combinations, suggesting that this particular subset is capable of characterizing the vertical and horizontal variations of the forest canopy structure at the AOI. Forest canopy structure classification identified five predominant forest structure types: short, open canopy, conifer dominating structures; short, dense canopy, broadleaf dominating structures; tall, close canopy, broadleaf dominating structures; very tall, close canopy, conifer dominating structures with relatively high variation of canopy height; and very tall, close canopy, conifer dominating structures with relatively low variation of canopy height. Results also revealed that the remotely sensed forest structure types have relationship to the conventional forest stand classification maps. In Chapter 5, it is concluded that the structural and spectral information retrieved from fixed–wing UAV–photogrammetric products are capable of characterizing the vertical and horizontal variations of the forest canopy structure, discriminating broadleaf and conifer vegetation types, and identifying predominant forest canopy structure types in uneven–aged mixed conifer–broadleaf forests without ground sampling data.

Several major limitations, i.e., bias, resource intensiveness and lack of spatially explicit data, are often associated with the conventional ground data acquisition and uneven–aged forest management planning. Thus, in Chapter 6 of this thesis, it is discussed how the fixed–wing UAV platforms can be used to overcome major limitations of the conventional data collection method and support uneven–age forest management planning. This was demonstrated by conducting a case study in the UTHF, particularly by providing empirical evidences for the forest management Compartment 45 which is scheduled to be managed in 2018. Detailed investigation revealed several stages in the forest management planning process of UTHF that can benefit from fixed–wing UAV–photogrammetry, e.g., forest stand classification, forest inventorying, harvesting and restoration planning, and carbon management. First, the utility of UAV–SfM data for forest stand classification of Compartment 45 was tested and the UAV results were compared with the conventional stand classification map (prepared using ground based observations). Then the utility of UAV–SfM derived structural metrics for forest inventorying, e.g., to estimate BA, Dq, V, and CST, was examined for Compartment 45 using the regression equations developed in Chapter 3 and 4 of this thesis. Finally, the potential of V and CST information of Compartment 45 in the harvesting decision making processes were examined. The results revealed that UAV–SfM data are promising to discriminate broadleaf dominating mixed stands, young broadleaf stands, and sparse forest stands. However, misclassifications were often occurred when classifying conifer dominating mixed stands, conifer dominating mixed stands with poor regeneration, and reserve forest area as their delineations are not solely based on the forest canopy vegetation structure. Regression equations developed using the UAV–SfM and field data of Compartment 43 and 48 performed well in terms of area–based estimation of forest structural attributes of Compartment 45, e.g., %RMSE values were 15.0%, 12.3%, 12.9%, and 12.6% for BA, Dq, V, and CST, respectively. Also, the spatial distributions of V and CST could be accurately mapped over Compartment 45 using UAV–SfM data. UAV–SfM estimated V had a good potential to be used in the forest harvesting decision making in uneven–aged forest management planning. In this thesis, CST which has huge importance at local–, national–, regional– and global–level is proposed as a new indicator to be incorporated into future management planning for identification of restoration sites, and for carbon management at forest enterprise level because UAV–SfM estimated CST information at local–level has huge potential to contribute to national–level carbon management and reporting. Chapter 6 of this thesis showed that fixed–wing UAV data is capable of minimizing efforts and time spent for convention data collection methods by providing detailed and accurate complementary data source that can be utilized in important stages of the forest management planning of the UTHF.

Overall, the results of this thesis demonstrated that fixed–wing UAVs are an efficient data collection method in forestry applications, hence capable of supporting precision forestry at local–level. Particularly, they can contribute to the existing data collection and management planning processes by providing detailed, accurate and spatially explicit forest information, e.g., stand delineation, forest inventory, and forest canopy structural complexity. Nevertheless, the conventional method cannot be replaced by UAV photogrammetric data due to some limitations of photogrammetry, e.g., poor penetration ability into the canopy, and lack of information about understorey and regeneration that also play an important role in forest management decision making. Therefore, it is concluded that fixed–wing UAV–photogrammetry has a good potential in uneven–aged forest management planning as a complementary data source to improve efficiency, minimize resource requirement, and enhance precision of the data. Future research should target to explore how the limitations of fixed–wing UAV–photogrammetry can be overcome, e.g., if the limitations could be overcome when fixed–wing UAV–photogrammetry is combined with other data sources such as terrestrial laser scanning (TLS), and if results can be improved when UAV platforms are used with other sensor types such as LiDAR.