学位論文内容の要旨

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学位論文題名

Characterizing typhoon-disturbed biomass dynamics using multitemporal airborne laser scanning and imagery, and deep learning in cool-temperate forest of northern Japan

（北日本の冷温帯林における複数時期の航空レーザ計測・写真と深層学習を用いた台風攪乱後バイオマス動態の解明）

Temperate forests are major carbon sinks, but post-disturbance biomass recovery is still difficult to quantify consistently at high spatial and temporal resolution. In northern Japan, Typhoon Songda (2004) caused extensive windthrow in the Tomakomai Experimental Forest and created a long-term need to separate immediate damage effects from delayed regrowth dynamics. This dissertation addresses that need by integrating field inventory data and multi-temporal remote sensing within one harmonized cross-year framework, so that interannual comparisons are not confounded by inconsistent processing scales.

Three LiDAR datasets (2004, 2014, and 2022) were compiled and harmonized to 2 m canopy height models (CHMs) across the overlapping 2,516 ha analysis domain after denoising and point-density normalization. Plot data from 2002, 2004, 2013, 2014, 2020, and 2021 were used to estimate biomass and calibrate a CHM-AGB allometric relationship, with each CHM year matched to temporally corresponding field observations. This calibrated relationship was then applied to each year's harmonized CHM to generate year-specific AGB maps at 2 m grid-cell resolution. Disturbed versus undisturbed areas were identified from 2004 color-infrared aerial imagery using deep learning (overall accuracy 99.6%; balanced accuracy 98.4%), while needleleaf versus broadleaf crown types were classified from 6 cm UAV RGB imagery (overall accuracy 95.4%; balanced accuracy 95.3%). In 2022, broadleaf forest occupied 93.3% of the mapped area and needleleaf forest occupied 6.7%, enabling explicit type-specific growth comparisons under both disturbed and undisturbed conditions.

Across 2004-2022, mean growth rates were 0.13 m yr^{-1} for CHM and 1.30 Mg ha^{-1} yr^{-1} for AGB. Disturbed stands showed faster AGB increase than undisturbed stands (1.64 vs. 1.29 Mg ha^{-1} yr^{-1}). Within disturbed stands, AGB growth accelerated from 0.97 Mg

ha^{-1} yr^{-1} in 2004-2014 to 2.48 Mg ha^{-1} yr^{-1} in 2014-2022, indicating a delayed but substantial recovery phase rather than an immediate post-typhoon rebound. At the whole-forest scale, mean CHM increased from 12.46 m to 14.86 m and mean AGB increased from 130.3 Mg ha^{-1} to 153.7 Mg ha^{-1} between 2004 and 2022. Growth-rate distributions also differed between disturbance classes and between needleleaf and broadleaf stands, showing persistent spatial heterogeneity in recovery pathways.

These results provide landscape-scale evidence that carbon recovery in cool-temperate forests after severe wind disturbance is significant but time-lagged. Methodologically, the study provides a practical workflow linking field plots, harmonized LiDAR structure, and image-based disturbance mapping for restoration planning and carbon accounting. The framework is transferable to disturbance-affected forests where repeated LiDAR and inventory data are available. Remaining uncertainty is mainly associated with CHM-AGB model formulation, attribution of localized negative growth patches, and inter-year data heterogeneity. Future work should incorporate independent validation datasets, uncertainty diagnostics, and management-history information to improve process attribution and further strengthen long-term recovery assessment. The same framework can support periodic updates as new LiDAR acquisitions become available, enabling consistent monitoring of recovery trajectories beyond the current 18-year window.