博 士 論 文 の 要 約

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学 位 論 文 題 名

Linking Solar-Induced Chlorophyll Fluorescence to Gross Primary Productivity Across Terrestrial Ecosystems

（陸域生態系における太陽光誘起クロロフィル蛍光と総一次生産量の関係の解明）

1. Background and Objectives

Terrestrial ecosystem photosynthesis plays an essential role in the global carbon cycle because it represents the largest biological sink of atmospheric carbon dioxide (CO_2). Variations in photosynthetic activity directly affect ecosystem productivity and the exchange of carbon between land and the atmosphere. For this reason, accurate estimation of gross primary productivity (GPP) is fundamental for understanding ecosystem functioning and carbon dynamics.

Solar-induced chlorophyll fluorescence (SIF) is emitted by chlorophyll during the process of photosynthesis and has gained attention as a proxy for photosynthetic activity. Unlike reflectance-based vegetation indices, SIF is directly linked to photosynthetic processes at the leaf level. Previous studies using satellite observations have shown strong correlations between SIF and GPP at regional and global scales. However, satellite-derived SIF has limitations due to its coarse spatial resolution and limited temporal coverage, which restrict its ability to capture short-term variability and ecosystem-specific processes.

In addition, the interpretation of SIF signals is influenced by canopy structure, vertical heterogeneity, and environmental conditions. Factors such as leaf area distribution, chlorophyll reabsorption, and multiple scattering within the canopy can modify the observable SIF signal. The main objective of this thesis is to evaluate how effectively SIF can track and predict GPP across terrestrial ecosystems with different levels of canopy structural complexity, using ground-based SIF observations combined with eddy covariance measurements.

2. Study Sites and Ecosystem Characteristics

This study was conducted in three contrasting terrestrial ecosystems in Japan, selected to represent a gradient of canopy structure and environmental conditions.

The first site is a rice paddy ecosystem characterized by a simple and homogeneous canopy structure. Rice plants form a relatively uniform canopy with limited vertical variation, which allows SIF emitted from leaves to be observed with minimal interference from canopy structure.

The second site is a cool-temperate bog ecosystem. Vegetation at this site is low in stature and the canopy structure is relatively simple. However, photosynthetic activity in this ecosystem is strongly controlled by environmental factors, particularly water availability and radiation conditions.

The third site is a mixed larch–Sasa sparse forest composed of a deciduous larch overstory and an evergreen Sasa bamboo understory. This ecosystem has a vertically heterogeneous, multi-layer canopy structure. Overstory and understory vegetation differ in phenology and photosynthetic activity, providing a suitable system for examining how vertical canopy structure influences SIF–GPP relationships.

3. Data and Methodology

Ground-based SIF measurements were carried out using high-resolution spectroradiometers capable of detecting both red SIF (F687) and far-red SIF (F760). Measurements were conducted at high temporal resolution, allowing detailed examination of diurnal and seasonal patterns. Data quality control procedures were applied to remove periods affected by low radiation, unfavorable measurement conditions, or instrumental instability.

Ecosystem-scale GPP was independently estimated using eddy covariance observations, which provide continuous measurements of carbon dioxide exchange between ecosystems and the atmosphere. To enable direct comparison, SIF data were temporally aggregated to match the time scale of GPP estimates.

Analyses were performed at diurnal, seasonal, and phenological scales. Seasonal changes were examined by dividing the observation period according to crop growth stages in the rice paddy, hydrological conditions in the bog, and leaf development and senescence phases in the forest ecosystem. In addition, vegetation indices and meteorological variables were used to support the interpretation of SIF–GPP relationships.

In the mixed larch–Sasa forest, particular attention was given to canopy vertical structure. Differences in contributions from overstory and understory vegetation were examined to better understand how SIF signals relate to the spatial distribution of photosynthetically active foliage within the canopy.

4. Results

Distinct patterns in the relationships between SIF and GPP were observed across the three study ecosystems, reflecting differences in canopy structure, vertical heterogeneity, and environmental regulation.

4.1 Rice paddy ecosystem

In the rice paddy ecosystem, SIF exhibited strong and consistent relationships with ecosystem-scale GPP throughout the growing season. F687 closely tracked both diurnal and seasonal variations in GPP. During periods of high radiation and active crop growth, increases in F687 corresponded directly with increases in GPP. Conversely, decreases in photosynthetic activity during cloudy conditions or toward the late growing season were accompanied by clear reductions in F687.

The relationship between F687 and GPP remained stable across phenological stages, indicating that the homogeneous canopy structure of the rice paddy allows fluorescence emitted from leaves to reach the sensor with minimal interference. This result suggests that, under simple canopy conditions, red SIF provides a reliable indicator of ecosystem photosynthetic activity.

F760 also showed a positive relationship with GPP in the rice paddy ecosystem; however, the correlation was generally weaker than that observed for F687. This difference indicates that, in ecosystems with limited chlorophyll reabsorption and scattering effects, red SIF is more sensitive to changes in photosynthesis than far-red SIF.

4.2 Cool-temperate bog ecosystem

In the cool-temperate bog ecosystem, SIF–GPP relationships were more variable than in the rice paddy ecosystem. Both F687 and F760 exhibited meaningful relationships with GPP, but the strength of these relationships changed depending on environmental conditions.

During periods of sufficient radiation and favorable moisture conditions, increases in SIF were accompanied by increases in GPP, indicating active photosynthesis. However, under conditions of reduced radiation or environmental stress, the correspondence between SIF and GPP weakened. Seasonal analyses revealed that fluctuations in water availability and radiation strongly influenced photosynthetic activity, leading to greater variability in SIF–GPP relationships compared to the rice paddy ecosystem.

Incorporating environmental variables, particularly incoming radiation and moisture-related factors, improved the ability of SIF to represent GPP in the bog ecosystem. These results indicate that, although canopy structure is relatively simple, environmental controls play a dominant role in regulating photosynthesis and SIF emission in wetland ecosystems.

4.3 Mixed larch–Sasa sparse forest

The mixed larch–Sasa forest exhibited the most complex SIF–GPP relationships among the three ecosystems. Seasonal patterns in GPP were primarily driven by the phenology of the deciduous larch overstory, with high GPP during the leaf-on period and reduced GPP during leaf senescence. In contrast, the evergreen Sasa understory maintained photosynthetic activity for a longer portion of the year, contributing to ecosystem GPP during transitional seasons.

F687 showed weaker and more variable relationships with GPP in the forest ecosystem compared to the other two ecosystems. The strength of the F687–GPP relationship decreased during periods of increased foliage density, suggesting enhanced chlorophyll reabsorption and multiple scattering within the canopy. As a result, red fluorescence emitted from lower canopy layers was less effectively detected by the sensor.

F760, in contrast, exhibited a stronger and more stable relationship with GPP across seasons. The reduced sensitivity of F760 to chlorophyll reabsorption allowed it to better represent integrated canopy-scale photosynthesis in this vertically heterogeneous ecosystem. These results indicate that far-red SIF is more suitable than red SIF for tracking GPP in forest ecosystems with complex canopy structures.

4.4 Comparison across ecosystems

Comparisons among the three ecosystems revealed clear differences in the performance of red and far-red SIF as proxies for GPP. In the rice paddy ecosystem, F687 provided the strongest relationship with GPP due to the simple and homogeneous canopy structure. In the bog ecosystem, both F687 and F760 were influenced by environmental variability, and their performance improved when environmental factors were considered. In the forest ecosystem, F760 consistently outperformed F687, reflecting the effects of vertical canopy structure on fluorescence propagation.

These cross-ecosystem comparisons demonstrate that the optimal use of SIF for estimating GPP depends strongly on ecosystem characteristics. While red SIF is effective in simple canopies, far-red SIF becomes increasingly important as canopy complexity and vertical heterogeneity increase.

4.5 Summary of results

Overall, the results show that SIF can track ecosystem-scale GPP across diverse terrestrial ecosystems, but the strength and stability of SIF–GPP relationships vary with canopy structure and environmental conditions. Red SIF performs well in structurally simple ecosystems, whereas far-red SIF provides a more reliable indicator of photosynthesis in ecosystems with complex, multi-layer canopies.

5. Discussion

The results demonstrate that canopy structure strongly influences the relationship between SIF and ecosystem-scale photosynthesis. In ecosystems with simple canopy structures, such as rice paddies, SIF signals can be directly linked to changes in GPP. Under these conditions, red SIF provides a reliable indicator of photosynthetic activity. In ecosystems where environmental stress plays a major role, such as bogs, SIF–GPP relationships are influenced not only by canopy structure but also by radiation and moisture conditions. This explains why the inclusion of environmental variables improves GPP estimation in wetland ecosystems.

In contrast, forest ecosystems with vertically complex canopies present additional challenges. Red SIF emitted from lower canopy layers is more strongly reabsorbed by chlorophyll in upper leaves before reaching the sensor. Far-red SIF is less affected by this process and therefore better represents integrated canopy-scale photosynthesis. These findings indicate that differences between red and far-red SIF arise not only from physiological processes but also from canopy radiative transfer effects.

6. Conclusions and Implications

This thesis demonstrates that SIF can be used to track ecosystem-scale GPP across a range of terrestrial ecosystems, but its interpretation depends strongly on canopy structure and environmental conditions. Red SIF is most effective in ecosystems with simple canopy structures, while far-red SIF provides more reliable information in structurally complex forest ecosystems.

By clarifying how canopy structure influences SIF–GPP relationships, this study contributes to improving the application of ground-based and satellite-derived SIF observations for estimating terrestrial ecosystem productivity. The results provide useful insights for future studies aiming to monitor ecosystem photosynthesis and carbon cycling under changing environmental conditions.