（ 続紙 1 ）

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論文題目	Application of satellite remote sensing techniques to detect spatial and temporal patterns of fire and other deforestation drivers in NW Madagascar マダガスカル北西部における火災およびその他の森林減少要因の空間的・時間的パターンへの衛星リモートセンシング技術の応用		

（論文内容の要旨）

This doctoral thesis examines the Northwestern dry forests of Madagascar, an ecologically significant biome increasingly affected by human activities, focusing on fire as a primary deforestation driver, alongside other climate-related disturbances. It investigates spatial and temporal patterns of fire and its role in forest loss, degradation, and regeneration with extensive use of satellite remote sensing techniques. In this context, the research evaluates the effectiveness of these remote sensing methods in monitoring forest recovery and the broader impact of disturbances on forest health and structure. The thesis is structured to address six major research questions, each contributing to a comprehensive understanding of deforestation drivers in Northwestern Madagascar.

Chapter 2, “Northwestern Madagascar’s tropical dry forests: rapid loss under increasing disturbances,” reports the primary drivers affecting forest dynamics, particularly those leading to forest loss and degradation. It identifies four primary drivers: anthropogenic disturbances (such as land clearing for agriculture, village expansion, and resource acquisition), fire, cyclones, and climate forcings. A significant aspect of this chapter is the update of forest cover and loss maps, which reveal an additional 9.73 million hectares lost over a recent 9-year period (2014-2023). This finding indicates that over 55% of Madagascar’s forest cover has been lost since 1953, with the Northwestern dry forest region experiencing the most significant loss—about 80% of its 1953 cover. The alarming increase in forest loss rates over the last decade, coupled with more frequent fires and rapid population growth, highlights the urgent need for research into the ecological effects of these disturbances and the development of effective protection and management strategies.

Chapters 3 and 4, titled “A validation of GEDI-derived forest structural metrics in a semideciduous seasonally dry forest in Northwestern Madagascar” and “Integrating single-epoch GEDI lidar and landcover time series data for analysis of forest structure post disturbance,” respectively, evaluate the use of GEDI (Global Ecosystem Dynamics Investigation) lidar data to study the effects of disturbance on forest loss and recovery. In Chapter 3, GEDI forest structural metrics are assessed and validated using data collected from field surveys. The work reported in this chapter is the first of its kind in Madagascar, and it provides essential baseline information on forest structure and the available remotely sensed lidar data from GEDI. In Chapter 4, a novel methodology is introduced to (1) map the detailed fire record of the region and (2) study recovery over time using single-epoch GEDI data. This approach helps to develop a comprehensive understanding of forest ecosystem recovery post-disturbance. The findings indicate that GEDI metrics provide an accurate depiction of forest structure (%RMSE within 20%). Furthermore, the successful combination of single-epoch GEDI footprints with continuous land cover datasets, like Landsat, proves effective in monitoring and assessing post-disturbance recovery. However, the sensitivity of GEDI data to lower-level algorithm parameters requires careful consideration during waveform processing.

Chapter 5, “Long-term water availability and fire drive disturbance patterns and forest dynamics in Northwestern Madagascar,” explores the hierarchy of importance among the drivers of forest loss, degradation, and regeneration identified in Chapter 2. Using robust statistical methods and machine learning algorithms, the study reveals that fire and long-term drought predominantly influence these processes. The analysis highlights a marked increase in

forest degradation over the past two decades, with an acceleration in the last ten years. This period also coincided with a decline in vegetation regeneration rates. Applying the forest recovery analysis methodology developed in Chapter 4, the research suggests that these forests are likely more adapted to short-term drought stressors rather than fire, with the latter having a more enduring impact on the landscape.

The specific impacts of fire on forest structure and the long-term effects of repeated fires in the dry forests are investigated in Chapter 6: "Non fire-adapted dry forest of northwestern Madagascar: escalating and devastating trends revealed by Landsat timeseries and GEDI lidar data". The study provides evidence that even a single fire can significantly disrupt the forest ecosystem and fire regime. In these forests, a single fire event results in considerable detrimental effects on forest structure, notably reducing plant area index (PAI), canopy cover (CC), and canopy height (CH), with minimal signs of recovery over time. Subsequent fires tend to occur more frequently and with higher intensity, as indicated by an observed average return rate within two years. During the 37-year study period, no fires were recorded at the study site from 1985 to 2014. However, once a forest experiences a fire, it becomes highly susceptible to further burning, with each subsequent fire causing increased intensity and more significant losses in PAI, CC, and CH.

Chapter 7, "The role of Ankarafantsika National Park in promoting forest recovery and resilience," addresses the efficacy of Ankarafantsika National Park in protecting forests against loss and fostering resilience amidst disturbances. This chapter extends to evaluating the park's management strategy, particularly the implementation of conservation management zones. The findings suggest that while the national park has the potential to protect and promote resilience, its effectiveness is somewhat diminished, largely due to increased anthropogenic pressures. The impact of the park's zoning strategy, although discernible, appears to be modest. This limited effectiveness is likely attributed to inadequate enforcement of protection and zoning regulations, combined with a general lack of awareness and education about park conservation among local communities.

In summary, this thesis makes significant contributions to the understanding of forest lo ss and forest dynamics in northwestern Madagascar. It advances the applications of rem ote sensing techniques, particularly through the innovative application of fire history ma pping, as well as the use of GEDI lidar observations in conjunction with land cover ti meseries and GEDI data validation. The thesis also offers a thorough analysis of defore station drivers, including human activities and natural disturbances, and provides insight s into the resilience of Madagascar's dry semi-deciduous forests against disturbances, es pecially fire. Furthermore, it evaluates the conservation strategies and management pract ices of Ankarafantsika National Park, highlighting the importance of enhanced conservat ion efforts for the protection and ecological integrity of these forests. The findings of t his research offer essential guidance for conservation practitioners and policymakers, aid ing informed decision-making for the protection and sustainable management of these cr itical ecosystems.

注)論文内容の要旨と論文審査の結果の要旨は１頁を３８字×３６行で作成し、合わせて、３，０００字を標準とすること。
論文内容の要旨を英語で記入する場合は、４００～１，１００wordsで作成し
審査結果の要旨は日本語５００～２，０００字程度で作成すること。

（続紙 ２ ）

（論文審査の結果の要旨）

森林保全は気候変動緩和と適応に重要な課題であると認識されながらも、人口増加と食料不足が深刻なアフリカでは、非持続的な焼畑などに駆動されて、森林の劣化・消失が急速に進行している。本研究は、アフリカ諸国の中でも固有の動植物に富むマダガスカルにおいて、その北西部に位置するアンカラファンツィカ国立公園とその周辺の季節的半落葉林に注目し、火災をはじめとする森林消失の駆動要因を複数のタイプの衛星写真データとGIS統計手法を組み合わせて解析した。評価すべき点は以下の４点にまとめられる。

1. 近年NASAが公開した衛星LIDARデータ (Global Ecosystem Dynamics Investigation, 通称GEDI) を、当該地域での火災による森林劣化・消失・回復のモニタリングに活用するための解析技術の基盤を確立した。またプログラム言語Pythonによるデータ解析ツールも複数開発した。
2. 解像度や観測期間の異なる複数のオープンデータソース（LANDSAT, MODIS, GEDI, PlanetScope）を組み合わせて解析することで、マダガスカル北西部全域の1953-2022にかけての森林消失率の変遷を明らかにした。また、人口、雨量の変動、火災などとも関連して解析し、究極要因としての人口増加が火災頻度を通して森林消失を引き起こしている状況を定量的に示した。
3. 国立公園内の約3000ha において、過去40年において、森林火災が起き始めたのは、2017年以降に限られ、一回の火災が次の火災を促すという負の連鎖を通して、急速な砂漠化が進む状況を定量的に明らかにした。
4. 国立公園の存在が火災による森林消失を抑制しているが十分ではない現状から、より良い森林とその生物多様性保全に向けての提言を行った。

以上のように、本研究は、GISを駆使した解析手法を前進させ、また、森林火災による森林消失という世界各地で見られる環境問題に応用することで、複数の重要な知見を得ており、熱帯林環境学、生態系生態学、地球環境科学の発展に寄与するところが大きい。よって、本論文は博士（農学）の学位論文として価値あるものと認める。

なお、令和6年2月15日、論文並びにそれに関連した分野にわたり試問した結果、博士（農学）の学位を授与される学力が十分あるものと認めた。

また、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。