



HOKKAIDO UNIVERSITY

Title	The interactive effects of human disturbances and biological invasion on tropical moist deciduous forest
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Degree Grantor	北海道大学
Degree Name	博士(環境科学)
Dissertation Number	甲第16572号
Issue Date	2025-09-25
DOI	https://doi.org/10.14943/doctoral.k16572
Doc URL	https://hdl.handle.net/2115/98182
Type	doctoral thesis
File Information	SULTANA_Marzia_abstract.pdf, 論文内容の要旨 https://creativecommons.org/licenses/by/4.0/



学 位 論 文 内 容 の 要 旨/Dissertation Abstract

博士（環境科学）

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学 位 論 文 題 名/Title of Dissertation

The interactive effects of human disturbances and biological invasion on tropical moist deciduous forest

(熱帯湿潤落葉樹林における人為攪乱と生物学的侵入の相互効果)

Invasive alien plant species (IAPs) threat biodiversity through the degradation of habitats and ecosystems. IAPs are species that are introduced to an area outside its natural range and poses a risk of deteriorating natural ecosystems. One of the IAPs, *Acacia auriculiformis* C. Cunn. ex Benth., is widespread throughout Bhawal National Park (50.2 km²) in Bangladesh that has high biodiversity. *A. auriculiformis* is an evergreen species, whereas the native species, particularly the dominant tree, *Shorea robusta* Gaertner f, are deciduous.

Detecting the distribution characteristics of invasive species is a prerequisite for controlling biological invasions. To detect the distribution, firstly, I investigated the effects of disturbances and biological invasion on tropical moist deciduous forests, using satellite imagery and machine learning. The invasive forests were detected by the seasonal variations of vegetation indices (VIs) using multispectral image classification. Using Sentinel-2A (10 m resolution) data across four seasons (winter, summer, monsoon and autumn) in 2022 and 2023, six common VIs were calculated: normalized difference VI (NDVI), enhanced VI (EVI), green chlorophyll index (GCI), green-red VI (GRVI), soil-adjusted VI (SAVI), and atmospherically resistant VI (ARVI). The results indicated that NDVI, GRVI and GCI in winter were effective for extracting *A. auriculiformis*, while ARVI, NDVI and GCI were effective in summer. All VIs for each season were used along with a composited multi-season image to map *A. auriculiformis* forests. Field observations from 2022 were used to train and validate the classification. Binary and multi-class classification applied to multi-season imagery achieved an overall accuracy of 71.1% with a kappa coefficient (κ) of 0.59 and 76.8% with κ of 0.71. The integration of VIs and elevation (DEM, 12.5 m resolution) into the classification process improved performance, yielding an overall accuracy to 90% ($\kappa = 0.88$) in winter and 83% ($\kappa = 0.80$) in multi-season. The observed variations in VIs between invasive and native vegetation classes suggested that integrating multiple VIs with phenology and topography enhanced the efficiency of invasive species detection, particularly when the invasive species exhibited distinct phenological patterns and topographical preferences to native vegetation.

Phenological differences derived from multispectral remotely sensed data were analyzed to map the invasive species distribution. The phenological profiles of three VIs - NDVI, GRVI, and ARVI

were used to examine the spectral response of invasive *A. auriculiformis* forest, dominant native *S. robusta* forest and mixed vegetation using Sentinel-2A images from 2022 to 2023. Analysis of temporal VI curves identified two distinct phenological periods- senescence and green, characterizing plant phenological patterns.

VIs from each phenological period were processed by the median composite method in Google Earth Engine. Phenological spectral features-based VIs were derived from these composited datasets and subsequently used to generate a new feature image encapsulating spectral characteristics from both the green and senescence periods. This facilitated comprehensive spectral differentiation of *A. auriculiformis* from native vegetation. Images generated by phenological spectral features-based VIs were incorporated into three classification algorithms - Random Forest, Support Vector Machine and Classification and Regression Tree and their classification effectiveness was compared. The models were trained and validated using reference data collected from field surveys in 2022. Among the classifiers, Random Forest showed the highest overall accuracy (87%) with a κ of 0.83. The results indicated that the composite image incorporating phenological spectral features enhances the spectral separability of invasive species from coexisting vegetation. By capturing spectral reflectance variations, this approach improved classification accuracy. The findings highlighted the importance of integrating phenological spectral features to species detection early to support forest conservation efforts.

MaxEnt was used in conjunction with remote sensing data, environmental parameters and human-influenced variables to identify factors shaping the distribution of *A. auriculiformis*. The incorporation of spectral variables improved model accuracy, with MaxEnt achieving an AUC of 0.936, indicating an expansion in the potential distribution range of the species. The jackknife test showed that human-influenced factors, proximity to human settlements (31.3%), population density (17.2%) and distance from roads (5.7%), were contributors to predicting the distribution range. NDVI in winter played a key role in detecting the presence of *A. auriculiformis*, contributing 24.3%. Additional factors influencing its spread included annual mean precipitation (5.3%) and soil nitrogen (6.2%). An area of 3.6 km² was identified as having high suitability for *A. auriculiformis* distribution. Integrating remotely sensed data into species distribution models facilitates the development of proactive management strategies to detect the early stages of biological invasion.

In conclusion, this study demonstrated that seasonal remote sensing, in combination with VIs and topography, effectively detected *A. auriculiformis*. Seasonal phenological signals provided valuable insights into the presence and growth pattern of *A. auriculiformis*, and ecological traits that give it a competitive advantage over native vegetation. In addition, the application of MaxEnt further supported the identification of ecologically suitable areas for plantation, while also highlighting high-risk zones vulnerable to invasion. The findings emphasize that biological invasion is strongly linked to human-induced disturbances that alter forest structure and disrupt ecological balance. The integration of phenological dynamics, topographic factors and species-environment relationship, this approach improves early detection, risk assessment, and distribution modeling, providing critical insights for effective forest conservation and sustainable ecosystem management.