Exploring EnMAP hyperspectral images and a novel ensemble deep learning model for classifying forest land-cover types in Brazil

DecisionES: Symposium on Ecosystem Services, Forest Management and Decision Making

Matheus Pinheiro Ferreira *et al.*

Department of Forest Sciences, "Luiz de Queiroz" College of Agriculture, University of São Paulo (USP/ESALQ)

July 1, 2025

Introduction

Importance of Forest Land-Cover Mapping

Spatially explicit information on forest land-cover types is critical for:

- Effective management of forest ecosystems
- Conservation of biodiversity
- Monitoring restoration initiatives
- Carbon sequestration assessment

Challenges in Tropical Forest Classification

Tropical forests present specific challenges:

- High species diversity
- Complex structural characteristics
- Spectral variability
- Mixed pixels in moderate-resolution images

Advanced Remote Sensing Techniques

The Environmental Mapping and Analysis Program (EnMAP) satellite offers:

- High spectral resolution (224 bands)
- Ability to detect chemical characteristics
- Continuous coverage of the electromagnetic spectrum
- Potential for discrimination of forest types

Research Questions

1. **Model Comparison:**

   How does the classification accuracy of an ensemble of pixel-wise deep learning methods compare to individual deep learning models and traditional machine learning techniques in differentiating forest land-cover types?

2. **Spectral Resolution:**

   How does spectral resolution influence the classification accuracy of forest land-cover types when comparing hyperspectral data to simulated multispectral data?

3. **Band Selection:**

   Does band selection improve the performance of deep learning models for hyperspectral forest classification?

4. **Spectral Characteristics:**

   What are the specific spectral and chemical characteristics of forest land-cover types that account for their discriminative properties and classification accuracy?

Study area

São Paulo State, Brazil

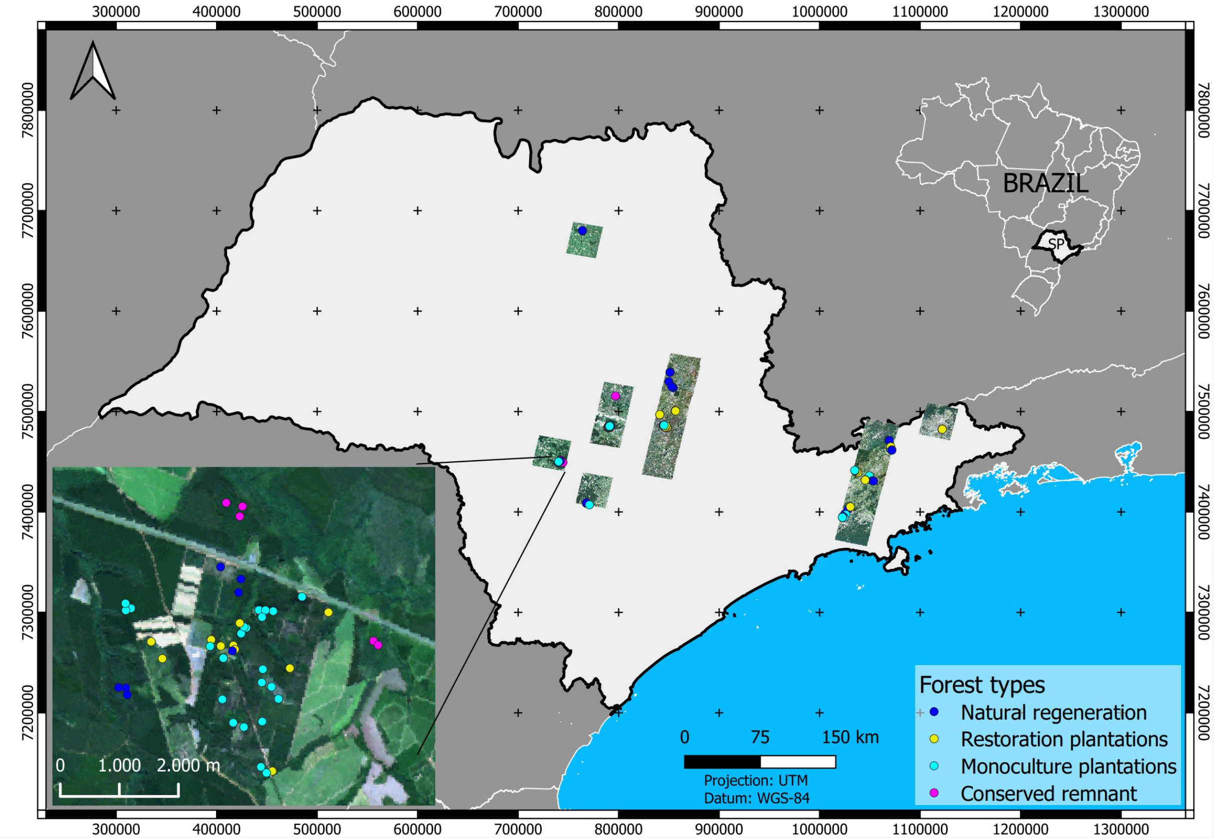
Broad biophysical and restoration gradients that favor developing and testing new remote sensing approaches to classify forest land-cover types.

Biomes

- Atlantic Forest (coastal region)
- Cerrado (inland region)

Ecological Diversity

- Rich mosaic of forest formations
- High level of endemism and biodiversity
- Diverse climatic, topographic, and soil conditions
- Various restoration techniques employed



Forest land-cover types

Conserved remnants

Native forest fragments in an advanced stage of conservation, with structure and composition close to the original forests.

Key Characteristics:

- High species diversity
- Complex vertical structure
- Higher pigment concentration
- Closed and continuous canopy
- Mature trees with large diameters

Natural regeneration

Areas in the process of spontaneous recovery after disturbances, without direct human intervention for species planting.

Key Characteristics:

- Variable species diversity
- Developing structure
- Greater spectral heterogeneity
- Presence of gaps and different successional stages
- Pioneer and early secondary species dominance

Forest land-cover types

Restoration plantations

Reforested areas through active planting of native species, with direct human intervention to accelerate recovery.

Key Characteristics:

- Planned species composition
- More regular planting pattern
- More homogeneous structure
- Different ages and development stages
- Mix of pioneer and non-pioneer species

Monocultures

Commercial plantations of eucalyptus mainly for pulp production

Key Characteristics:

- Low diversity (one dominant species)
- Regular planting pattern
- High spectral homogeneity
- Uniform canopy height and structure

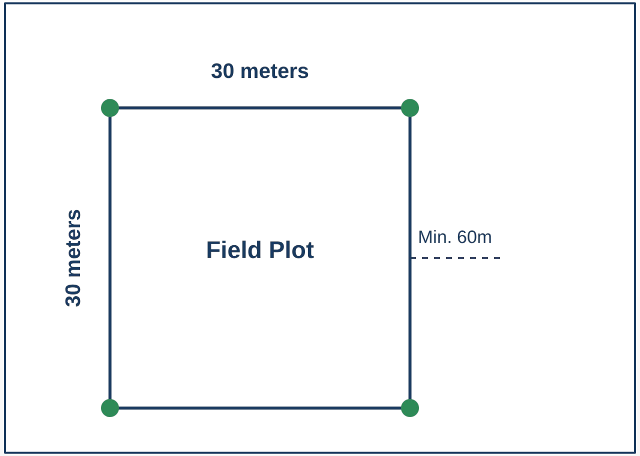
Field data collection

Plot Establishment

30×30 m plots (matching EnMAP pixel size)
Minimum distance of 60 meters between plots
Minimum distance of 30 meters from forest edges
Exclusion of areas smaller than one hectare

Data Collection Methods

High-precision Global Navigation Satellite System (GNSS) for plot corners
Field observations to identify forest types
Interviews with local managers to differentiate between natural regeneration and restoration plantations
Post-processing of GNSS data to ensure accurate geolocation



EnMAP hyperspectral data

EnMAP characteristics

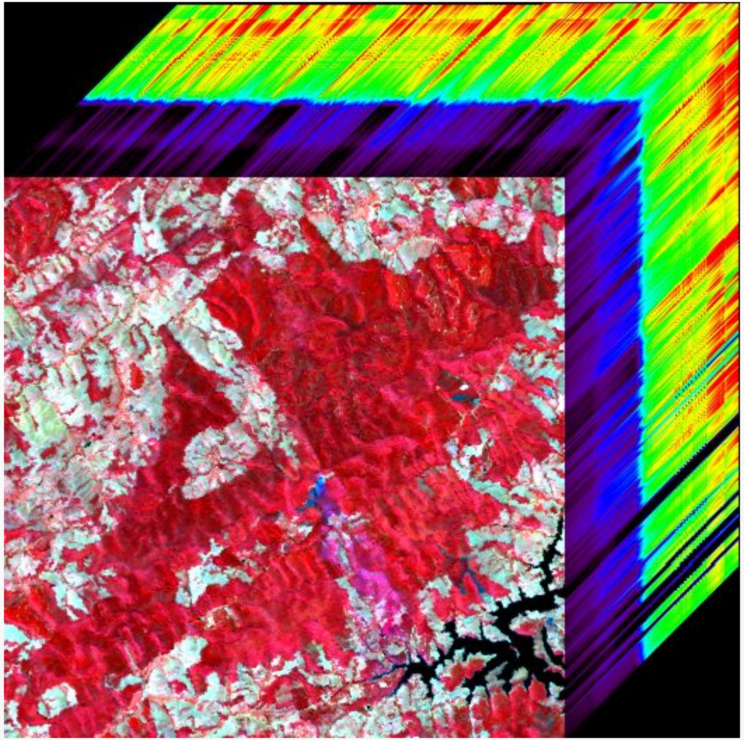
German hyperspectral satellite mission (launched 2022)
Sun-synchronous orbit at 653 km altitude
Swath width: 30 km
Revisit time: 4 days (with pointing capability)

Sensor specifications

VNIR: 420-1000 nm (88 bands)
SWIR: 900-2450 nm (136 bands)
Total: 224 spectral bands
Spectral sampling: 6.5-10 nm
Spatial resolution: 30 m

Study area

16 EnMAP scenes over São Paulo state
Level 2A data (atmospherically corrected)
Acquisition period: 2022-2023



False color composition of an EnMAP scene

Deep Learning Models

1D Convolutional Neural Network

A specialized neural network architecture designed to process one-dimensional sequential data, such as spectral signatures in hyperspectral imagery.

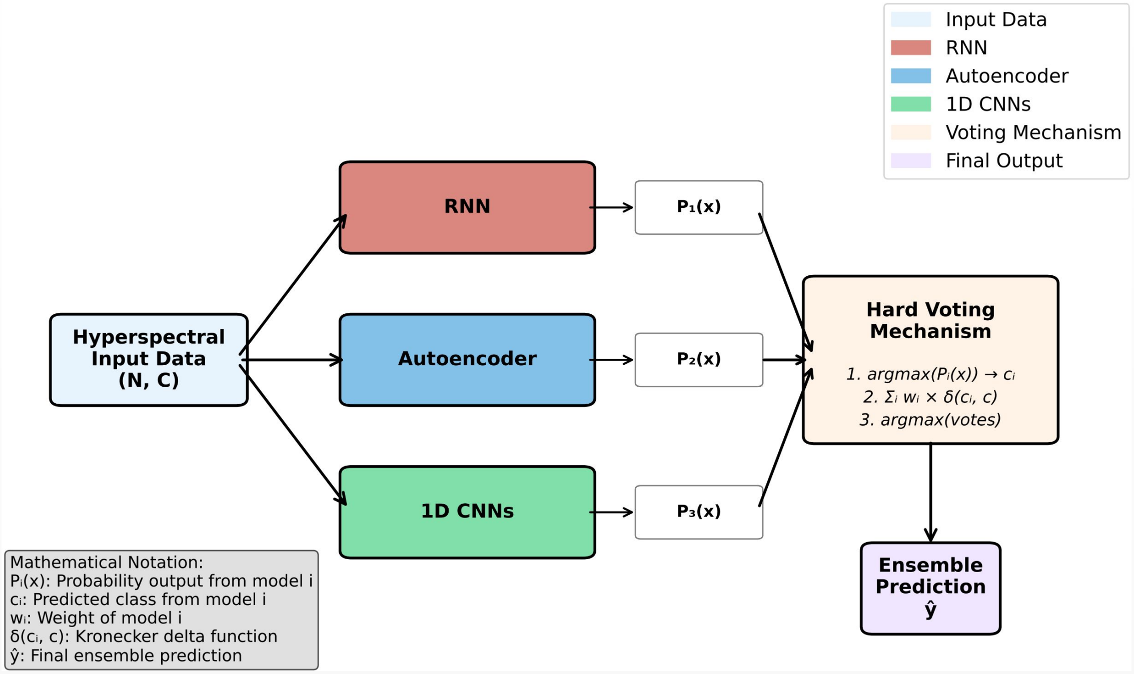
Autoencoder Neural Network

A type of neural network designed to learn efficient data encodings in an unsupervised manner, with applications in dimensionality reduction and feature learning.

Recurrent Neural Network

A class of neural networks designed to recognize patterns in sequential data by maintaining a memory of previous inputs through recurrent connections.

Ensemble Model Architecture



Ensemble approach

Integration of three distinct deep learning models to leverage their complementary strengths for improved forest type classification.

Model Contributions

1D CNN

Local spectral patterns

Adjacent band relationships

Autoencoder

Non-linear dimensionality reduction

Latent feature extraction

RNN

Sequential spectral patterns

Experimental Setup

Dataset division

Training set: 80% of the data
Testing set: 20% of the data
Preservation of plot identity during division
100 iterations with different random splits
Results reported as mean and standard deviation

Experimental scenarios

Scenario 1: Individual models vs. ensemble model
Scenario 2: Hyperspectral vs. simulated multispectral data
Scenario 3: All bands vs. selected bands
Scenario 4: Analysis of spectral and chemical properties

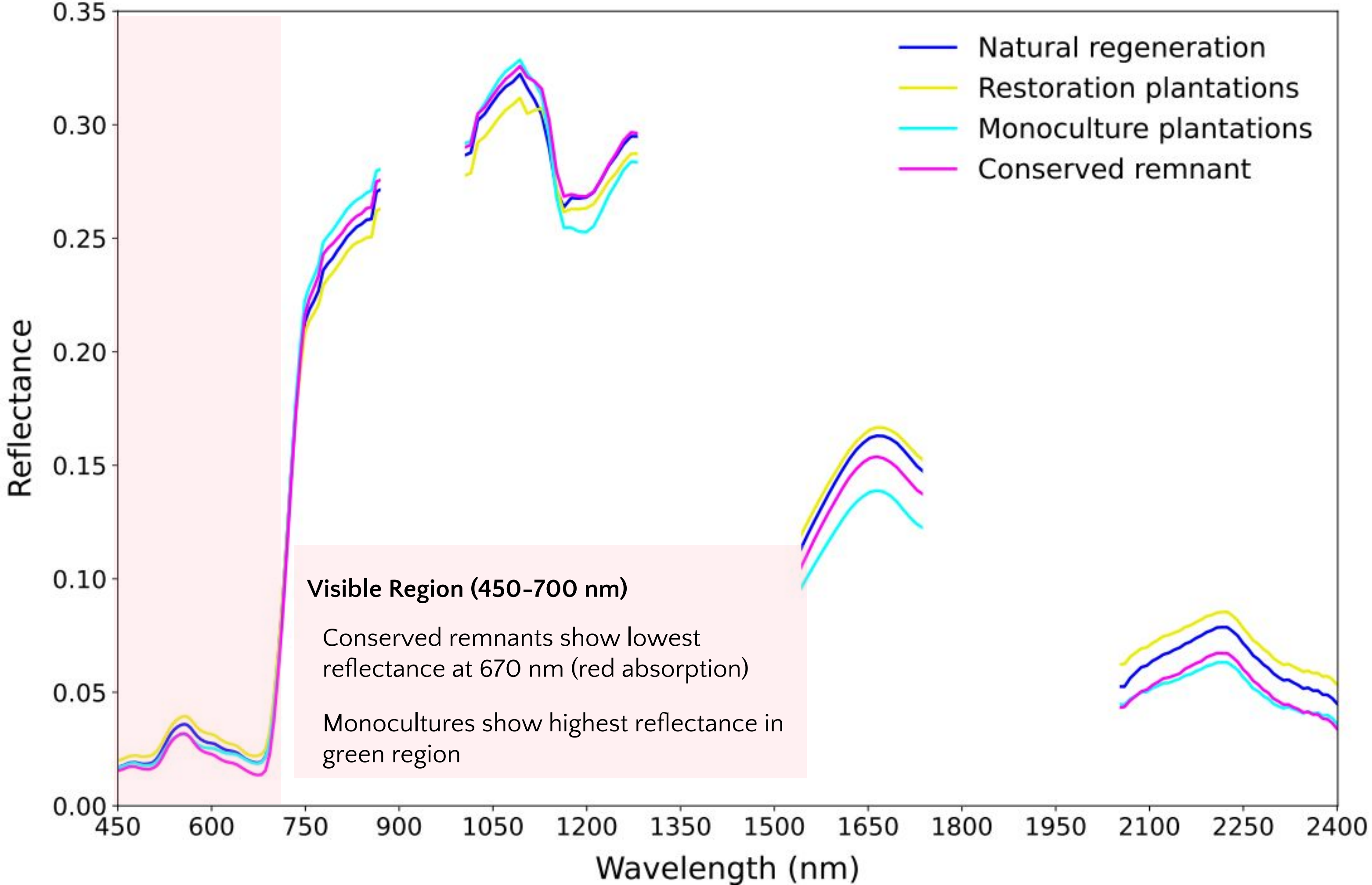
Evaluation metrics

F1-Score (macro-averaged)
Confusion Matrix

Training parameters

Parameter	Value
Optimizer	Adam
Learning Rate	0.0001
Epochs	5000
Batch Size	512
Early Stopping	Patience = 100 epochs
Loss Function	Categorical Cross-Entropy

Spectral properties of forest land-cover types

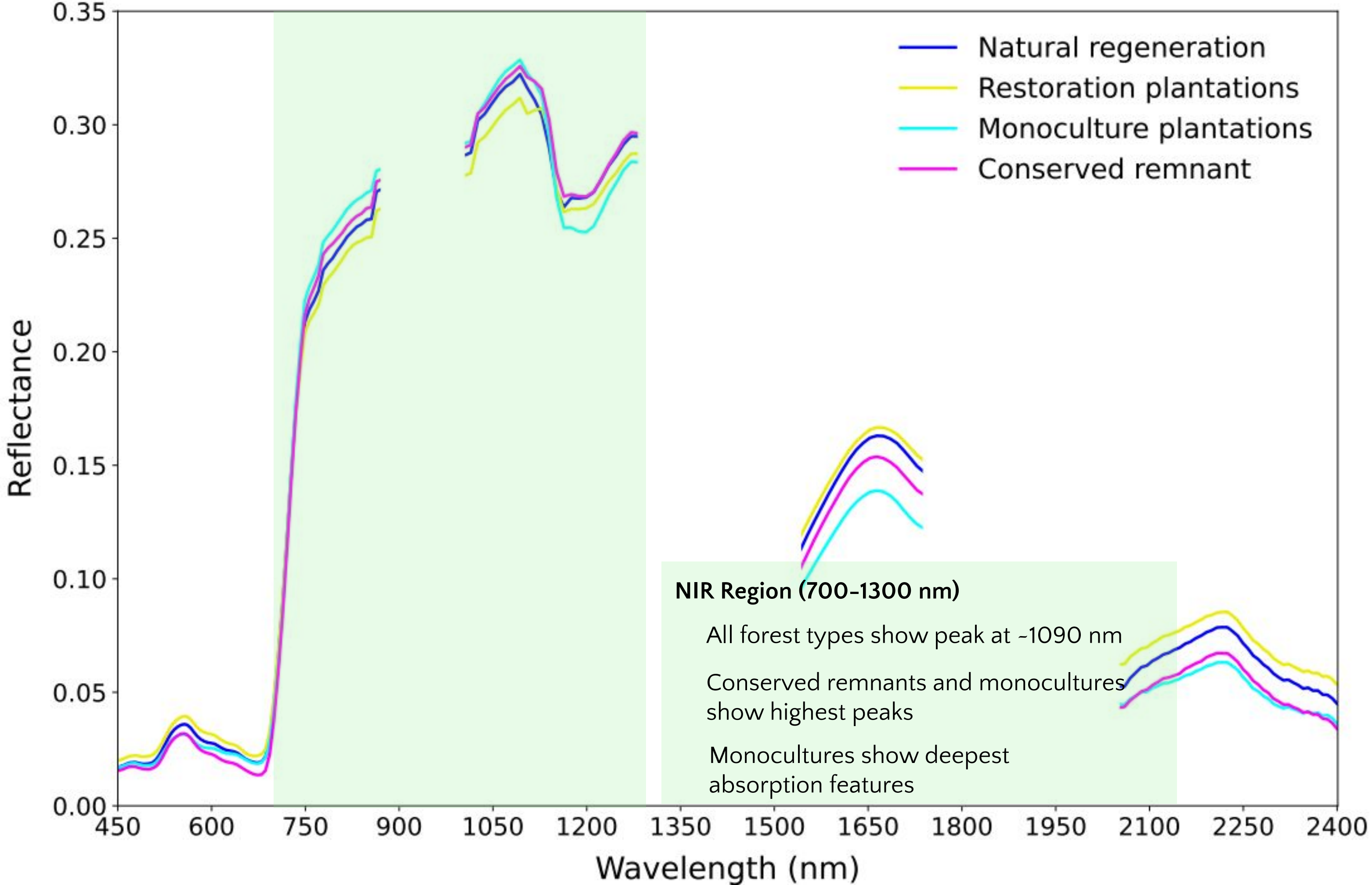


Visible Region (450–700 nm)

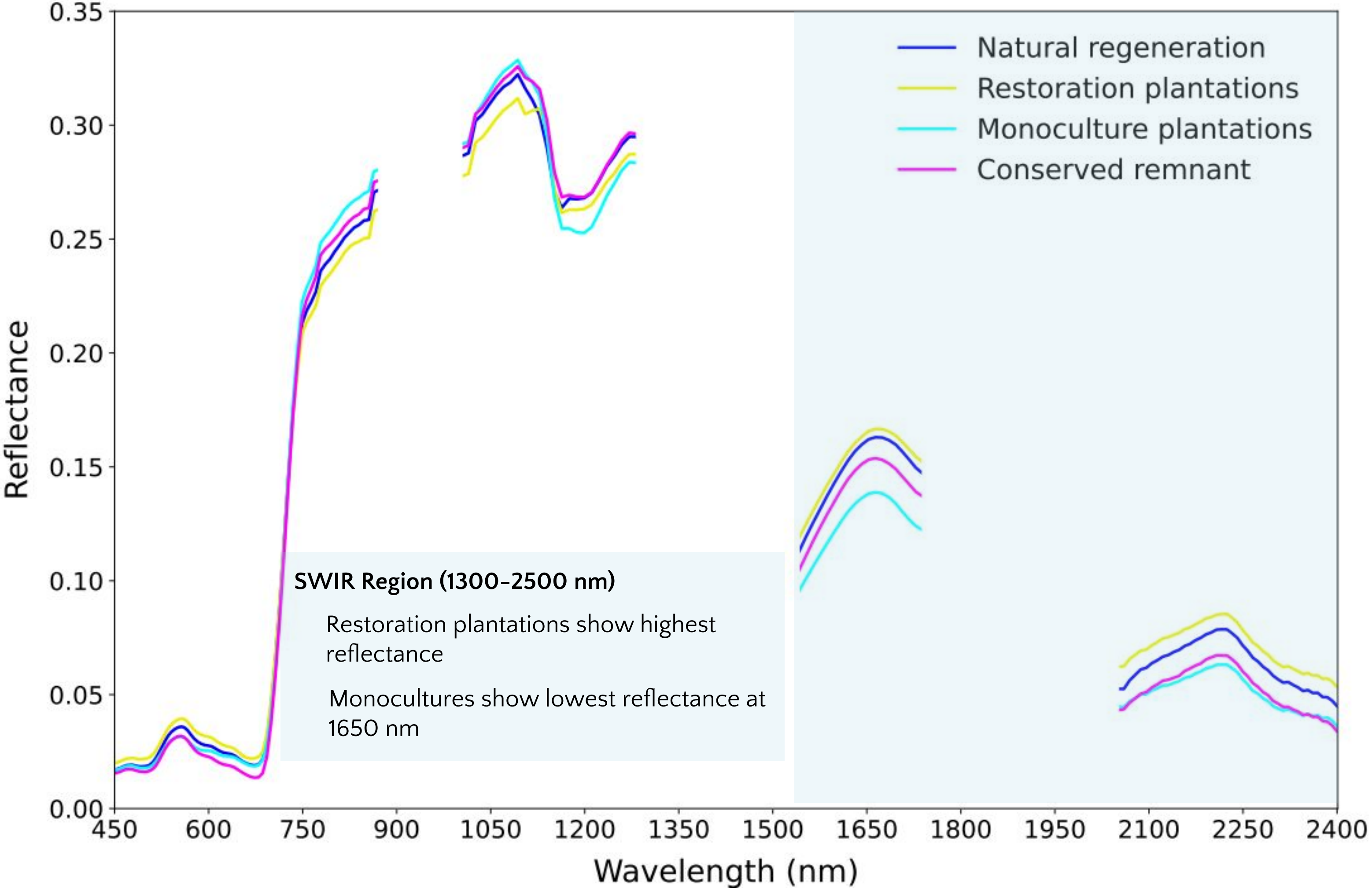
Conserved remnants show lowest reflectance at 670 nm (red absorption)

Monocultures show highest reflectance in green region

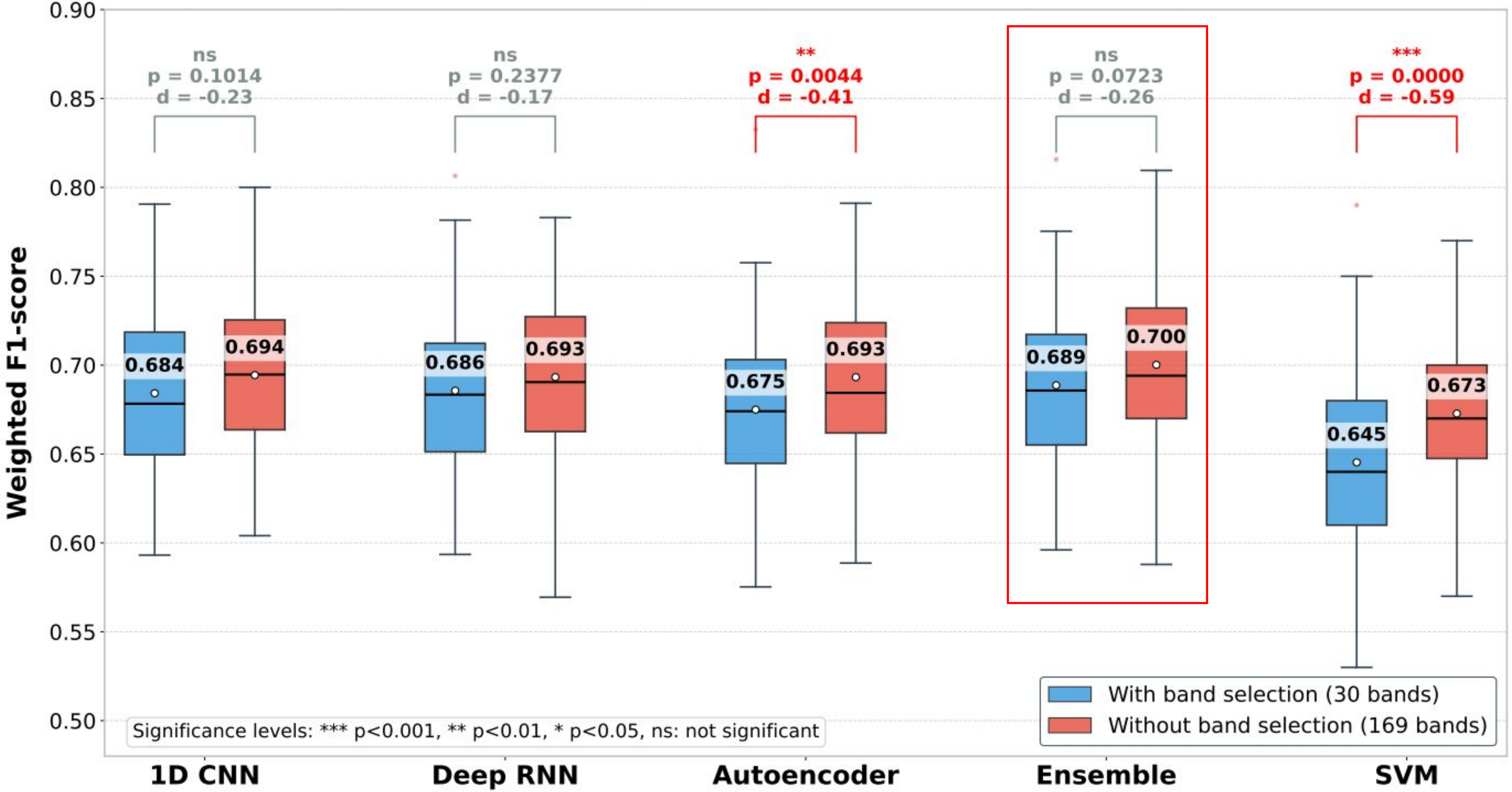
Spectral properties of forest land-cover types

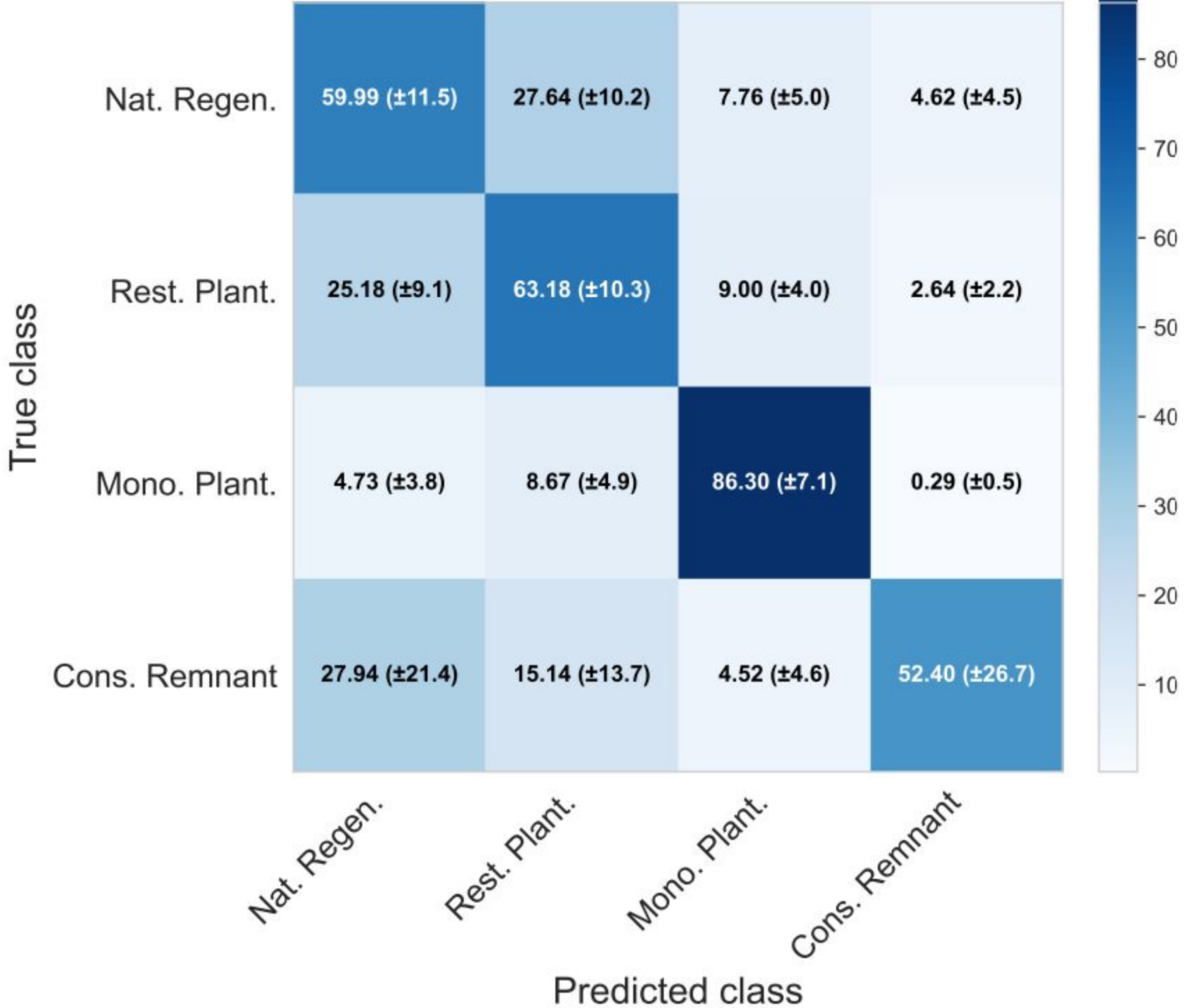


Spectral properties of forest land-cover types

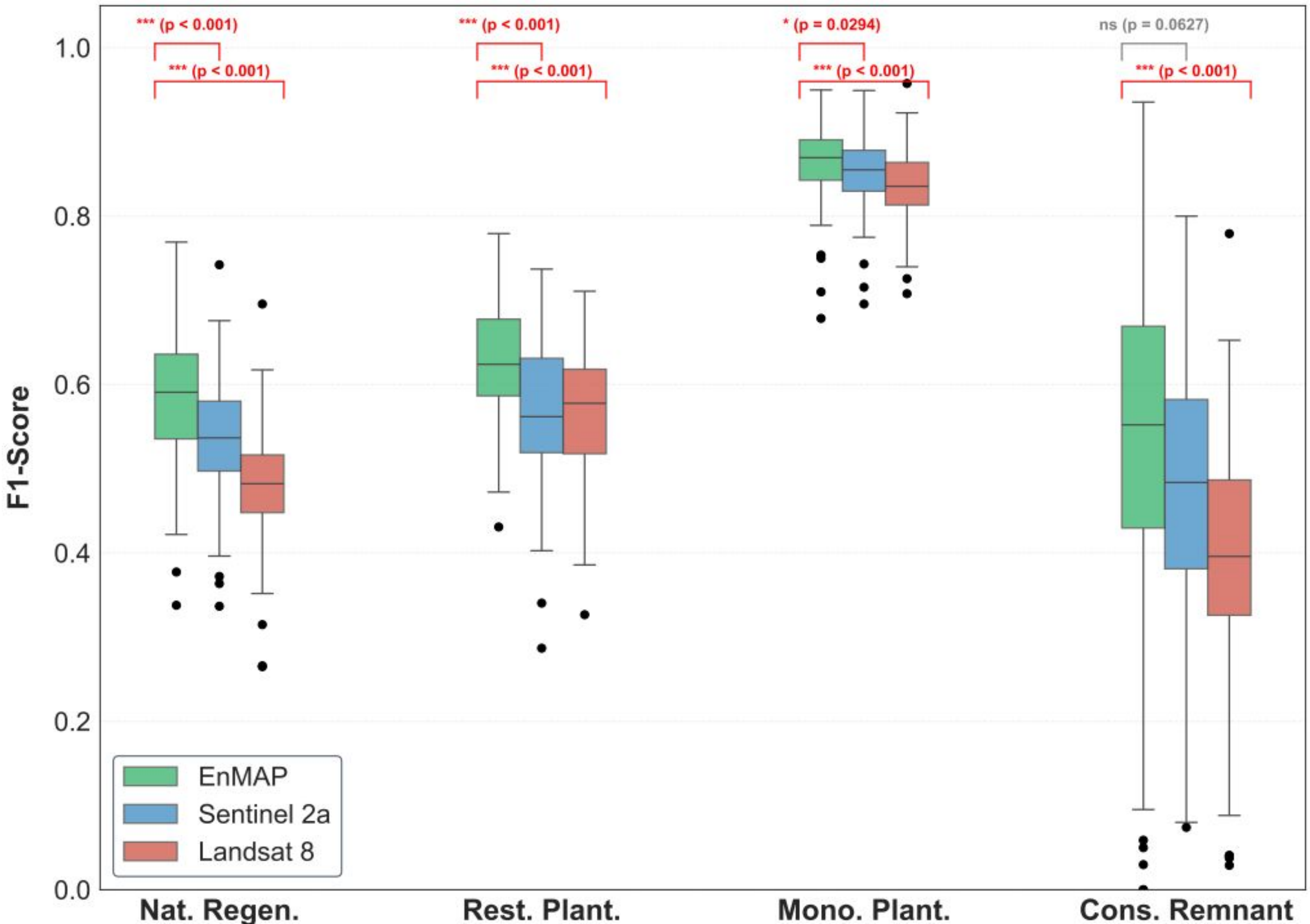


Classification results

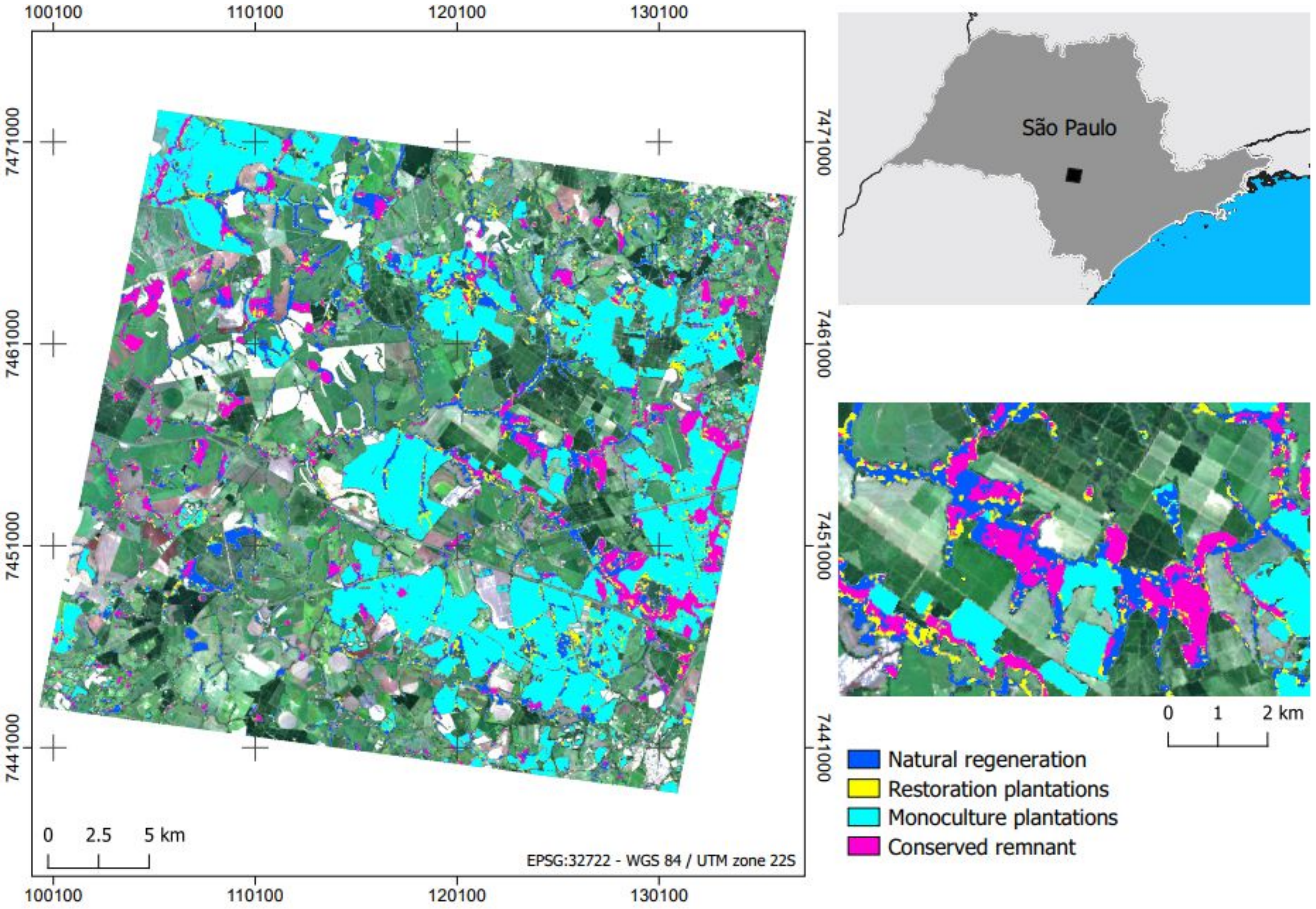




True class
Nat. Regen.
Rest. Plant.
Mono. Plant.
Cons. Remnant
59.99 (±11.5)
27.64 (±10.2)
7.76 (±5.0)
4.62 (±4.5)
25.18 (±9.1)
63.18 (±10.3)
9.00 (±4.0)
2.64 (±2.2)
4.73 (±3.8)
8.67 (±4.9)
86.30 (±7.1)
0.29 (±0.5)
27.94 (±21.4)
15.14 (±13.7)
4.52 (±4.6)
52.40 (±26.7)
Predicted class
80
70
60
50
40
30
20
10



*** (p < 0.001)
*** (p < 0.001)
*** (p < 0.001)
*** (p < 0.001)
* (p = 0.0294)
*** (p < 0.001)
ns (p = 0.0627)
*** (p < 0.001)
F1-Score
0.0
0.2
0.4
0.6
0.8
1.0
Nat. Regen.
Rest. Plant.
Mono. Plant.
Cons. Remnant
EnMAP
Sentinel 2a
Landsat 8


100100
110100
120100
130100
7471000
7461000
7451000
7441000
0
2.5
5 km
EPSG:32722 - WGS 84 / UTM zone 22S
São Paulo
0
1
2 km
Natural regeneration
Restoration plantations
Monoculture plantations
Conserved remnant

Conclusions and Future Directions

Main Contribution

Novel ensemble deep learning approach for forest type classification using hyperspectral data

Practical Applications

Improved monitoring of forest resources

Accurate mapping of planted and natural forests

Future Research Directions

Integration of multi-temporal EnMAP data to capture seasonal dynamics

Fusion of hyperspectral and LiDAR data for improved structural information

Forest Conservation

Restoration Monitoring

Carbon Sequestration

Contact: Matheus Pinheiro Ferreira | **mpferreira@usp.br** | Department of Forest Sciences, ESALQ/USP