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Multifunctional Forest Management and Carbon Mapping in Communal Lands: A Sentinel-2 and InVEST-Based Assessment in NW Spain

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Abstract Agroforestry ecosystems combine diverse land uses, enhancing forest multifunctionality and offering effective strategies to address climate change, fire prevention, and biodiversity conservation. This research aims to promote multifunctional forest management by integrating an agroforestry system in the Communal Forest Lands in Joint Ownership of Baroña (CMVMC Galicia, NW Spain), balancing productive, ecological, and social uses. Land uses and covers for 2024 were classified using satellite imagery and field data, achieving a classification accuracy of 89%. Carbon storage was estimated using the InVEST tool, showing that the Coniferous forest class stores the highest carbon stock, with 98,606 tn. The proposed methodology supports territorial planning and sustainable forest management by enabling the quantification of ecosystem services. These results provide a scientific basis for implementing measures to mitigate climate change impacts and improve environmental governance in communal forest systems.

Keywords: ecosystem services, forest carbon storage, remote sensing, land cover change, multifunctionality

1. Introduction

Multifunctional forest management—combining diverse uses within the same forest system—is increasingly seen as a key strategy to address challenges like climate change, biodiversity loss, and wildfires. Climate change disrupts forest ecosystems and services, while the spread of monocultures has intensified soil degradation, altered hydrological cycles, and increased fire risk. Despite this context, the potential of multifunctional forest management remains underutilized. Activities such as beekeeping, mycological harvesting, grazing, or resin collection are seldom integrated in forest planning, despite offering ecological and socio-economic benefits. A multifunctional approach allows for more resilient and productive landscapes. In parallel, geospatial assessment of carbon storage is increasingly important for quantifying ecosystem services like climate regulation (García-Ontiyuelo et al., 2024). Forests, grasslands, and shrublands store more carbon than the atmosphere. Remote sensing, especially Sentinel-2 imagery, offers high-resolution data ideal for monitoring land use changes and carbon dynamics.

In this context, the main objective is to promote multifunctional forest management through integrated planning and ecosystem service valuation. The research focuses on the communal forest lands of Baroña (Galicia, NW Spain), where carbon stocks were estimated using the InVEST tool based on the 2024 land cover classification, including both aboveground and belowground components. This approach supports sustainable forest planning and provides valuable information for decision-making and environmental governance, emphasizing the role of forests as key allies in climate change mitigation.

2. Materials and methods

2.1. Study area

The Community of Communal Forest Lands in Joint Ownership of Baroña (CMVMC) covers 777ha. The area features diverse land uses, dominated by grasslands, scrublands, and forested areas mainly consisting of *Pinus pinaster*, along with native broadleaves such as *Quercus robur* and *Castanea sativa*. Grazing livestock help reduce fire risk by maintaining open areas. The region has a mild Atlantic temperate climate with wet winters and dry summers. Soils are mainly well-drained, nutrient-rich, and developed on granite and schist substrates, supporting a biodiverse forest ecosystem adapted to sustainable management and fire resilience.

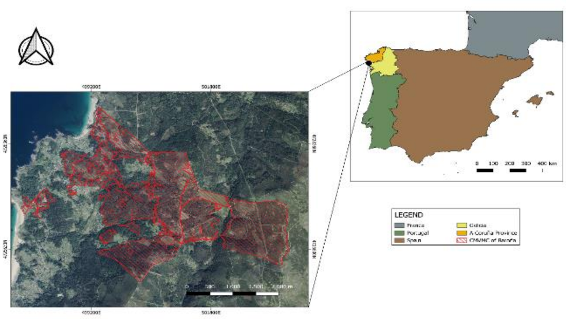

Figure 1. Location of the CMVMC of Baroña in A Coruña province (NW Spain).

2.2. Data Processing and Analysis

This study used Sentinel-2A multispectral images to map land cover and estimate carbon storage in the Baroña CMVMC area. A cloud-free image from spring 2024 was downloaded and atmospherically corrected to Level-2A with Sen2Cor. Using QGIS and the Semi-Automatic Classification Plugin, the image was clipped and processed into a multi-band composite. NDVI was calculated to enhance vegetation discrimination. Image segmentation via Orfeo Toolbox's LargeScaleMeanShift algorithm grouped pixels into polygons classified as coniferous (C), broadleaved (B), eucalyptus (E), and grassland/scrub (G). Classification was refined through spectral band adjustments and validated by photo-interpretation and field visits. A Random Forest algorithm trained on selected polygons performed the final classification. Carbon estimation involved a field inventory of 20 plots measuring tree height and diameter, applying national volume models to estimate biomass volume. Aboveground biomass (AGB) was calculated using volume, wood density, and biomass expansion factors; species-specific carbon content was applied to estimate carbon in aboveground (AGC) and belowground biomass (BGC). Dead biomass carbon (Cd) was estimated considering decay stages. Total carbon stock (Cs) summed aboveground, belowground, dead biomass, and soil carbon. The InVEST model spatially mapped carbon storage using these data.

3. Results and discussion

The land cover classes occupied the following areas: coniferous forests covered 293.47 ha (37.75% of the total area), broadleaf forests 121.40 ha (15.62%), eucalyptus plantations 80.32ha (10.33%), and grasslands/shrublands 282.14 ha (36.30%). The overall classification accuracy for 2024 was 89%, with a Kappa index of 0.85. Based LULC classifications, total carbon stocks were estimated for the Baroña CMVMC area (Table 1). Among the classes, coniferous forests showed the highest carbon storage capacity at 293.47 tn/ha, followed by grassland/shrubland (282.14 tn/ha), broadleaf forests (121.40 tn/ha), and eucalyptus plantations (80.32 tn/ha). When accounting for the total area of each class, conifers stored the most carbon overall (98,606 tn), with grasslands/shrublands second (43,732 tn), broadleafs third (36,177 tn), and eucalyptus last (24,578 tn).

Table 1. Estimation of total carbon stock by land use class in the study area. Values are expressed in tonnes (tn).

LULC	AGB	BGC	Cd	Cs	TC
C	18772	10565	10565	58694	98606
B	2914	1335	1578	30350	36177
E	4177	2008	4337	14056	24578
G	4232	8464	2821	28214	43732
Total	30104	22373	19302	131314	203093

These results highlight the importance of conserving and managing diverse land uses, especially mixed and conifer-dominated forests, to maximize carbon storage potential. These findings support previous studies showing conifers' greater carbon assimilation, thanks to their year-round foliage and longer growing season (Sohrabi et al., 2016). *Eucalyptus,* while storing less carbon long-term, contributes notably to short-term sequestration due to its rapid early growth and high photosynthetic efficiency (Silva et al., 2022). (Silva et al., 2022).

4. Conclusions

This study highlights the innovative use of Sentinel-2 imagery and field data to map land cover and estimate carbon storage in 2024, with an accuracy of 89% and a Kappa of 0.85. Coniferous forests stored the most carbon (336 t/ha across 293.47 ha). Combining open-access geospatial tools with InVEST offers a cost-effective, replicable method for multifunctional forest management and climate mitigation, providing a solid basis for science-driven planning in communal forests.

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