Carbon storage trade-offs and invasive species management in baluran national park: an integrated InVEST approach

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Abstract. Ecosystems play a crucial role in carbon storage, with each ecosystem type having a different storage capacity. Baluran National Park comprises several ecosystems, including savannas, coastal, mountainous, mangrove, and evergreen forests invaded by *Acacia nilotica,* all of which impact carbon storage. This study aims to quantify and map the distribution of carbon storage across various land-cover classes in Baluran National Park. The analysis uses a 2024 land-cover map, biogeophysical data (aboveground and belowground biomass, soil organic carbon, deadwood) derived following IPCC and FREL guidelines, and is conducted using the InVEST Carbon Storage and Sequestration model. The results show that secondary forests have the highest carbon storage of 8,86 x 10^5 tC, primarily in aboveground biomass due to tall stands and dense canopies. Among non-forest classes, *A.nilotica* stands have the highest carbon storage at 1,28 x 10^5 tC dominated by belowground biomass because this leguminous species develops a large root system. Despite its contribution to carbon stocks, A. nilotica litter contains allelopathic compounds that suppress understorey vegetation and disrupt savanna dynamics. These findings highlight a trade-off between maximizing carbon storage and conserving native savanna ecosystems, underscoring the importance of integrating invasive species control into carbon-oriented conservation planning in Baluran National Park.

1 Introduction

Baluran National Park, nicknamed the “Little Africa of Java,” is one of the tropical dry savanna ecosystems in East Java that holds significant ecological importance. The area covers approximately 25,000 hectares, with about 40% consisting of extensive savanna, plantation forests, mangroves, and shrublands, which strongly support biodiversity,

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including the endangered banteng (*Bos javanicus*) [1]. The savanna not only functions as a habitat provider for wildlife, maintaining the hydrological cycle, and supporting primary productivity through the interaction of grasses and scattered trees, but also serves as an important carbon reservoir in climate change mitigation [2]. The savanna in Baluran National Park stores carbon in the form of aboveground biomass (AGB), belowground biomass (BGB), and soil organic carbon (SOC), although its absolute values are relatively lower than those of tropical rainforests [1]. Nevertheless, the savanna contributes significantly to carbon storage due to its large spatial area and its role in stabilizing the carbon cycle through vegetation and soil interactions [3]. Secondary forests scattered across the area have structurally higher carbon storage because of their greater vegetation density [4]. During the rainy season, secondary forests and plantation forests experience a significant increase in primary productivity, thereby contributing more to carbon accumulation compared to the dry season. This ecosystem can function either as a carbon sink or a carbon source, depending on management practices and anthropogenic disturbances, such as fires or invasive species [5]. Mangrove forests are known to store the highest carbon reserves, particularly in the form of soil organic carbon (SOC), which can be 3-5 times greater than terrestrial ecosystems [6]. Land covers such as shrublands, grasslands, and dwarf forests have lower carbon reserves, both in aboveground and belowground biomass. The savanna area in Baluran National Park has the potential to have an important type of black soil because this type of soil is known to store high amounts of soil organic carbon (SOC) [7]. Most of Indonesia's black soil contains 1.53% SOC which is very important in storing carbon [8]. Nonetheless, these ecosystems remain significant in the landscape context, as their large coverage can still contribute to the total carbon storage. The diversity of these land covers is essential to be analyzed spatially, particularly in the context of differences in carbon storage across ecosystems increasingly threatened by invasive species (A. nilotica).

Initially, the Baluran National Park landscape was dominated by savanna, but its composition has shifted due to the introduction of invasive alien plant species, namely *Acacia nilotica*. In 2018, it was recorded that A. nilotica had invaded around 6,000 hectares of savanna in Baluran National Park. This thorny woody legume is well known for its highly invasive characteristics. The invasion has altered the savanna vegetation structure by dominating open areas, thereby reducing native vegetation diversity and disrupting the ecological functions of the savanna. Consequently, A. nilotica is listed as a priority invasive plant species that must be controlled in Baluran National Park. *A. nilotica* is also one of the plant species capable of absorbing and storing carbon, even though it disrupts the savanna ecosystem as an invasive species. Studies on aboveground biomass in savannas have been conducted in Brazil. while research on aboveground carbon storage has been carried out on *A. nilotica* L. (Wild) ex. Del. stands [9]. Research on carbon storage assessment in Baluran National Park that incorporates land cover and considers the invasion of A. nilotica remains limited.

The calculation of carbon storage is a crucial foundation in global climate change mitigation policies, particularly within the REDD+ mechanism (Reducing Emissions from Deforestation and Forest Degradation). REDD+ encourages developing countries to maintain and enhance forest carbon storage by reducing deforestation and promoting sustainable forest management practices. To support this policy, spatial-based technologies such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) are used, as they can integrate land cover data with various carbon pool components, namely aboveground biomass (AGB), belowground biomass (BGB), soil organic carbon (SOC), and deadwood[10]. Through this approach, detailed spatial carbon storage maps are generated, allowing the distribution of carbon across different land cover types to be comprehensively analyzed. The results of this spatial analysis are not only relevant for

conservation planning and ecosystem restoration but also serve as an important instrument to support the implementation of climate mitigation policies such as REDD+, including in strategic conservation areas like Baluran National Park.

2 Research Methods

This study was conducted in Baluran National Park, which is astronomically located between 7°29′10″ - 7°55′55″ S and 114°29′10″ - 114°39′10″ E. Baluran National Park is situated at the eastern tip of Java Island, precisely in Situbondo Regency and Banyuwangi Regency, East Java Province. The park covers an area of approximately 25,000 hectares with diverse land cover compositions, including savanna (about 40% of the total area), secondary forests, plantation forests, mangroves, and shrublands. The data used in this study consisted of: (1) a 2024 land cover map derived from IKONOS imagery and working maps of the Baluran National Park Authority; (2) aboveground biomass (AGB) and belowground biomass (BGB) data estimated using the default values of FREL 2016; (3) soil organic carbon (SOC) data based on IPCC (2006) guidelines; and (4) carbon data from deadwood estimated using IPCC default values for forest and non-forest categories.

Data processing was carried out using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Carbon Storage and Sequestration model, a GIS-based tool designed to assess carbon storage and sequestration. The main inputs included raster land cover data and a biophysical table containing AGB, BGB, SOC, and deadwood values for each land cover class[11]. The land cover classification scheme used in this study included: primary forest, secondary forest, savanna, plantation forest, mangrove, shrubland, acacia-invaded areas, settlements, rice fields, bare land, and water bodies. Biomass analysis per land cover class was conducted to obtain carbon storage density (tC/ha) across four carbon pools: AGB, BGB, deadwood, and SOC. AGB values (t dry matter/ha) were converted to carbon using a carbon fraction (CF) = 0.47. BGB values were derived from AGB using root-to-shoot ratios (R) according to ecosystem type. Deadwood values used different IPCC default parameters for forest versus non-forest. SOC was taken as stock (tC/ha) at 0–30 cm depth based on IPCC guidelines or relevant local datasets/literature. In the FREL 2016 document, forest biomass calculations were conducted using allometric equations for all forest types. FREL 2016 provides carbon storage estimates based on AGB and BGB values for each forest type across Indonesia's major islands. For this study, only data from Java Island were used since Baluran National Park is located in East Java. The carbon storage estimates based on FREL 2016 are presented in Table 1.

Table 1. Estimated Carbon storage of Forest Types Based on FREL 2016

Forest Type	AGB (Mg ha^{-1})		BGB (Mg ha^{-1})		Forest Ecosystem (Mg ha^{-1})	
	Mean	SE	Mean	SE	Mean	SE
Primary Dryland Forest	347.88	51.35	100.89	17.29	448.77	54.19
Secondary Dryland Forest	209.78	13.26	60.84	3.97	270.61	13.84
Primary Swamp Forest	248.80	12.92	54.74	3.20	303.53	13.31
Secondary Swamp Forest	204.61	4.98	45.01	1.23	249.62	5.13
Primary Mangrove Forest	236.17	15.26	73.45	4.66	309.62	15.96
Secondary Mangrove Forest	118.02	15.72	13.57	1.78	131.59	15.82

The estimated carbon storage based on soil organic carbon (SOC) from FREL 2016 for the default values of Java Island is only available for Primary Dryland Forest at 10.38 Mg

ha⁻¹ and Secondary Dryland Forest at 5.52 Mg ha⁻¹. Meanwhile, according to the Tier 1 IPCC 2006 method, it is assumed that forest soil carbon storage do not change with management; therefore, it is unnecessary to calculate changes in soil carbon storage for mineral soils (i.e., changes in forest soil carbon storage are considered zero). The estimated carbon storage based on deadwood from FREL 2016 for the default values of Java Island is only available for Primary Dryland Forest at 62.65 Mg ha⁻¹ and Secondary Dryland Forest at 67.41 Mg ha⁻¹. In contrast, the Tier 1 IPCC 2006 method assumes that carbon storage in deadwood and litter are in equilibrium; thus, changes in carbon storage in deadwood are assumed to be zero. Carbon storage estimates for non-forest land cover based on FREL 2016 are presented in **Table 2**. Carbon storage calculations for non-forest land cover based on FREL 2016 do not include soil organic carbon and deadwood carbon. Meanwhile, the Tier 1 method assumes that soil carbon storage refer to the default value, which for tropical dry regions is 47.

Table 2. Estimated Non-Forest Carbon storage Based on FREL 2016

Non- Forest Type	AGB (Mg ha^{-1})		BGB (Mg ha^{-1})		Forest Ecosystem (Mg ha^{-1})	
	Mean	SE	Mean	SE	Mean	SE
Plantation forest	75.78	7.52	24.63	2.44	100.40	7.91
Dry shrub	60.39	7.22	14.25	1.70	74.64	7.42
Estate crop	48.10	6.90	15.63	2.24	63.74	7.25
Settlement	2.17	1.17	0.63	0.34	2.80	1.21
Bare ground	2.40	1.36	0.57	0.32	2.97	1.39
Savanna and grasses	4.06	1.94	0.96	0.46	5.02	2.00
Open water	0	0	0	0	0	0
Wet shrub	19.34	3.97	4.56	0.94	23.91	4.08
Pure dry agriculture	14.08	7.70	2.82	1.54	16.89	7.85
Mixed dry agriculture	64.64	2.30	12.93	0.46	77.56	2.35
Paddy field	10.00	3.88	2.36	0.92	12.36	3.99
Fish pond/aquaculture	0	0	0	0	0	0
Port and harbour	0	0	0	0	0	0
Transmigration area	14.08	7.70	2.82	1.54	16.89	7.85
Mining areas	0	0	0	0	0	0
Open swamps	0	0	0	0	0	0

In general, carbon storage (C) can be calculated using the formula:

$$C = B \times CF \quad (1)$$

Where:
C = Carbon stock (tC/ha)
B = Biomass (Mg ha-1)
CF = Carbon fraction (default 0.47 according to IPCC, indicating that 47% of dry biomass is carbon).

At the landscape or regional scale, total carbon storage is obtained by multiplying the per-hectare value by the area of land cover (A):

$$C_{total} = B \times CF \times A \quad (2)$$

Thus, the total carbon stock can be calculated as:

$$C_{Total} = C_{AGB} + C_{BGB} + C_{Deadwood} + C_{SOC} \quad (3)$$

This formula provides a more comprehensive understanding of carbon distribution within ecosystems and emphasizes the importance of accounting for all compartments, not only the above-ground biomass.

3 Results and Discussion

3.1 Spatial Analysis of Land Use

Based on the results of the spatial analysis, the total area of the study site reached 25,000 ha with a distribution of various land use types. Land use in Baluran National Park is presented in **Figure 1**. The analysis shows that secondary forest dominates with an area of 6,097.40 ha (24.39%), followed by savanna covering 5,879 ha (23.51%). These two land cover types are the main determinants of the ecosystem characteristics in Baluran National Park. A. nilotica invasion also occupies a considerable area of 4,013.43 ha (16.05%), indicating serious pressure on the original savanna ecosystem. Primary forest still covers the central part of the park with an area of 3,611.98 ha (14.45%), serving as a key conservation zone with high carbon density. Meanwhile, plantation forests occupy 3,184.9 ha (12.03%), consisting mainly of teak production forests.

Other land cover types with smaller proportions include dwarf forest (887.05 ha; 3.55%), shrubland (726.99 ha; 2.91%), and mangroves (324.44 ha; 1.30%), which function as coastal buffers. Rice fields cover 275.97 ha (1.10%), while open land (53.18 ha; 0.21%), settlements (24.03 ha; 0.10%), and water bodies (21.63 ha; 0.09%) occupy very small areas but still exert an important influence on the ecological dynamics of Baluran National Park. Overall, these results show that although forest and savanna ecosystems still dominate, the invasion of *A. nilotica* is a critical threat, as it has the potential to shift the composition of native vegetation and reduce the unique biodiversity of Baluran National Park due to its highly invasive nature.

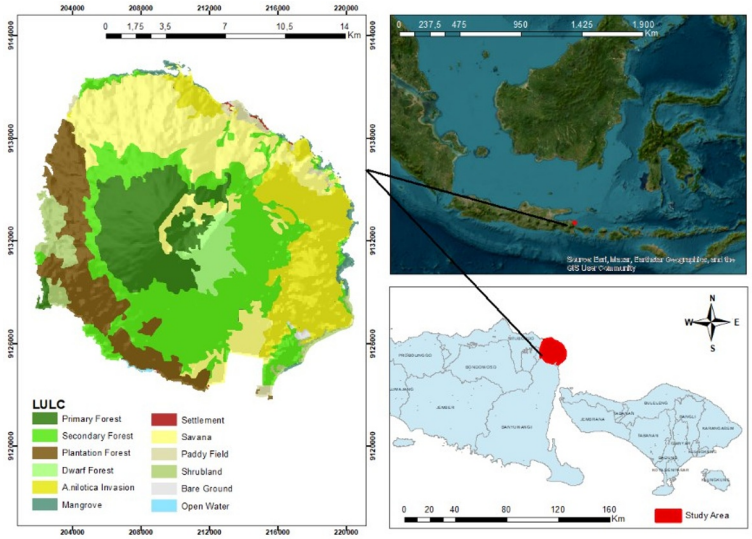

Figure 1. Location and LULC Map of Baluran National Park

In 1969, A. nilotica was introduced to Bekol Savanna with the aim of controlling the spread of natural wildfires that frequently occurred during the dry season. However, within a short period, this species proliferated rapidly and aggressively dominated the savanna, thereby inhibiting the growth of the native dominant grasses [12]. *A. nilotica* releases allelochemical compounds (such as phenolics, tannins, flavonoids), which then trigger the formation of stress proteins (such as Heat Shock Proteins or HSPs) in the target plant cells. These stress proteins are then involved in the process of protein folding, assembly, and translocation, as a failed self-defense effort of the target plant, ultimately leading to death [13]. Over the course of one century, from 2000–2014, the savanna experienced a reduction of approximately 1,361 ha, while areas invaded by A. nilotica increased by as much as 1,886 ha. The spatial distribution of A. nilotica in Baluran National Park shows a clustered pattern. A. nilotica has spread far north and south from its original introduction site, invading not only savannas, but also dry forests in Baluran National Park. These changes highlight that A. nilotica not only invades savanna but also suppresses the regeneration of dwarf forests and shrublands around ecosystem transition boundaries, thereby threatening vegetation diversity and altering the spatial structure of the Baluran landscape. Such land cover changes impact ecological cycles, including wildlife forage availability and carbon storage capacity.

3.2 Carbon Analysis in Each Land Use

Carbon density reflects the concentration of carbon that can be stored in a specific land cover type, while carbon storage represents the total amount of carbon stored across the entire study area [14]. These two are interrelated, as carbon storage is obtained by multiplying carbon density with the extent of land cover. Therefore, even if an ecosystem has high carbon density, its total carbon storage can be lower if the area is small. Conversely, ecosystems with moderate carbon density but covering large areas may contribute significantly to the total carbon storage of the region (**Figure 2**).

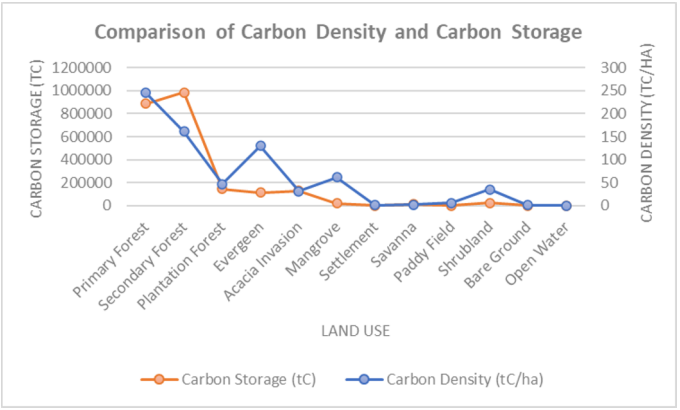

Figure 2. Comparison of Carbon Density and Carbon Storage

Based on the adjusted carbon density for each land use type, aboveground, belowground, soil organic, and deadwood carbon storage was calculated using the InVEST model. We compiled the carbon density levels and calculated the total carbon storage in the study area. As shown in **Figure 3**, the area with the highest carbon density is 245.25 tC/ha, located in the central part of Baluran National Park, where the land use type is primary forest, followed by secondary forest (141.46 tC/ha) and dwarf forest (129.79 tC/ha). In forest ecosystems, the largest contribution to carbon storage generally comes from Aboveground Biomass (AGB), around 6.01×10^5 tC. This is due to stands of large-diameter trees, dense canopies,

and long stand ages, which make aboveground biomass accumulation dominant [15]. The contribution of Belowground Biomass (BGB) is also significant but proportionally smaller compared to AGB. SOC is often relatively high in secondary forests, especially when litter and biomass residues from forest conversion have accumulated. Deadwood contributions are usually lower and only play a role in systems with slow decomposition rates.

Ecosystems dominated by low-structured vegetation such as savanna (2.36 tC/ha), rice fields (9.32 tC/ha), shrublands, and open land (1.40 tC/ha) exhibit very low carbon density. This is related to the dominance of grass cover and the limited presence of woody vegetation capable of storing large amounts of carbon. Mangrove ecosystems (61.85 tC/ha) and shrublands (35.09 tC/ha) occupy a medium position in carbon density. Both ecosystems demonstrate important ecological functions, particularly shrublands, which serve as natural buffers between forests and open land while supporting vegetation regeneration processes. Settlements (1.32 tC/ha) and water bodies (0 tC/ha) practically do not contribute to carbon storage in Baluran National Park.

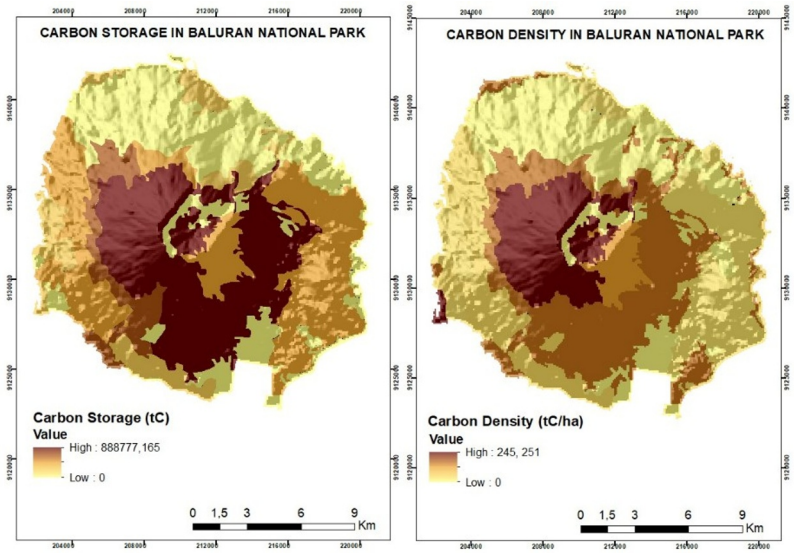

Figure 3. Carbon Storage and Carbon Density in Baluran National Park

Meanwhile, Acacia invasion (31.88 tC/ha), although consisting of woody vegetation, has relatively low carbon density compared to natural forests, highlighting its limitation in carbon storage. The largest contribution lies in Belowground Biomass (BGB) at 1.32×10^4 tC due to its extensive root system. Contributions from AGB, SOC, and deadwood in A. nilotica provide relatively low biomass [9]. SOC under acacia stands tends to be low because acacia releases allelopathic compounds that inhibit decomposition and reduce litter input from other vegetation [13]. Deadwood contribution is nearly insignificant, as acacia stands rarely leave large amounts of deadwood and have a fast turnover rate. Thus, the role of acacia as a carbon sink cannot offset the ecological damage it causes. Acacia invasion leads to the loss of natural land covers such as savanna, shrublands, and grasslands, which are critical habitats for typical Baluran wildlife such as banteng, deer, and various grassland bird species. The dense canopy of acacia suppresses the growth of native grasses, thereby reducing forage availability for herbivores. In addition, the allelopathic nature of acacia leaves can inhibit the regeneration of native vegetation beneath them, accelerate landscape homogenization, and decrease biodiversity (**Figure 4**). If left unmanaged, acacia has the

potential to transform the structure and function of Baluran's ecosystem from open savanna into a homogeneous forest with low species richness.

Figure 4. *A.nilotica* Plants in Baluran National Park

Therefore, although acacia contributes to carbon at a certain level, particularly in BGB, controlling acacia invasion is still necessary. The removal of acacia is not only aimed at restoring the ecological function of natural savannas as biodiversity buffers but also to ensure the long-term sustainability of carbon storage through the dominance of natural forests and native vegetation, which provide a more balanced contribution of AGB, BGB, SOC, and Deadwood. The greatest challenge in controlling A. nilotica lies in its highly persistent seeds in the soil (seed banks can last >20 years) and its rapid regeneration capacity. Thus, continuous, long-term, and integrated management of A. nilotica control is required. The variation in carbon density across different land covers provides an important basis for understanding the contribution of each land cover to carbon accumulation in Baluran National Park. The spatial distribution of total carbon storage in Baluran National Park shows variation influenced by the heterogeneity of land use. Secondary forests contribute the largest carbon storage, totaling 9.85×10^5 tC, followed by primary forests with 8.86×10^5 tC. These two land covers dominate the Baluran landscape and still maintain relatively dense vegetation conditions. Plantation forests (1.46×10^5 tC) and dwarf forests (1.15×10^5 tC) also make significant contributions.

In addition, the extensive acacia invasion stored 1.28×10^5 tC of carbon, indicating that even though it is ecologically considered an invasive species, this vegetation still has a role in contributing to carbon reserves. Other land covers, such as shrublands (2.55×10^4 tC), savannas (1.39×10^4 tC), and mangroves (2.01×10^4 tC), have supplementary roles in maintaining carbon balance, although their contributions are relatively smaller. Settlements (3.16×10^1 tC), rice fields (1.60×10^2 tC), and open land (7.42×10^1 tC) have very low carbon storage due to the limited presence of carbon-absorbing vegetation. Water bodies, on the other hand, have no contribution to carbon storage (0.00×10^0 tC). Spatially, areas with high carbon storage are concentrated in densely forested areas (primary and secondary), while low to very low storage values are distributed in savannas, shrublands, and open lands. These findings reinforce that natural forest cover remains the key factor in maintaining carbon storage capacity in Baluran National Park, while non-forest land covers contribute only minimally.

4 Conclusion

The analysis of carbon storage across different land-use types in Baluran National Park demonstrates that natural forest ecosystems, particularly secondary and primary forests, serve as the main contributors to carbon reserves due to their dense vegetation and balanced contributions from AGB, BGB, SOC, and Deadwood. Plantation forests and dwarf forests also provide notable storage capacity, while savannas, shrublands, mangroves, and other

non-forest covers contribute at smaller scales. Although the invasion of A. nilotica shows measurable carbon storage, primarily in BGB, its ecological disadvantages, such as habitat loss, suppression of native vegetation, and biodiversity decline, outweigh its carbon benefits. This highlights the need for continuous and integrated management to control acacia invasion. Overall, the findings emphasize that conserving and restoring natural forest cover is essential for sustaining long-term carbon storage and ecological balance in Baluran National Park, whereas non-forest land covers play only a complementary role.

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