Potential Changes in Climate Regulating Ecosystem Services from Anthropogenic Activities in the Cisadane Watershed, Indonesia

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ABSTRACT

Due to increased anthropogenic activity, critical watersheds that exceed their carrying capacity occur in many world regions. The Cisadane watershed experiences changes in land use/cover (LULC) every year, impacting changes in climate regulation ecosystem services, so assessing it is necessary. This study aims to mapping potential changes in climate regulating ecosystem services (carbon storage and sequestration) in Cisadane watershed from LULC caused by anthropogenic activities. The assessment was carried out by integrating several steps: land demand forecasting using Markov chain analysis, LULC simulation using the Multi-Layer Perceptron-Markov chain (MLP-MC) model, and carbon storage estimation using InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) methods in three scenarios, namely business as usual (BAU), protecting paddy fields (PPF), and protecting forest areas (PFA). The results show that the three scenarios presented have different environmental and socio-economic implications, including potential changes in carbon pool and climate mitigation. From the calculation of net present value (NPV) forests have a positive value, so forest protection measures are needed so that future cash flows will be better. These results demonstrate InVEST's capacity to provide information about carbon stocks and sequences that decision-makers and environmental observers can use to manage watersheds sustainably.

1. INTRODUCTION

A watershed is a complex system because it has several components that interact with each other, both in natural resource systems in ecosystems and socio-economic systems [1]. Watershed-level management is critical because it is the basic unit in natural resource management [2]. The main challenge in mainstreaming ecosystem services in land use planning is due to the overlapping rules between institutions and the understanding of different stakeholders [3]. Anthropogenic activities, including domestic, agricultural, and industrial waste, are important in water pollution and damage to natural watershed ecosystems and human health [4]. Watershed degradation occurs because the management of watershed natural resources is exploitative and aggressive, so it exceeds its carrying capacity [5].

Watershed ecosystems produce ecosystem service products for human welfare, including carbon storage and sequestration, which play a role in climate mitigation actions. The provision of ecosystem services by watersheds is influenced by current land use/ land cover (LULC) and its future trends [6]. Changes in LULC can significantly impact global climate change by either promoting or depleting the regional carbon storage capacity [7]. One of the most vital watersheds in Indonesia for giving ecosystem services and supporting living is the Cisadane watershed, which is one of 15 watersheds in Indonesia that are priority watersheds to be restored immediately [8]. Quantitative evaluation of ecosystem services facilitates ecosystem management and sustainable development of an area [9].

The current existing methods for evaluating the implications of LULC to carbon storage primarily include field investigation, remote sensing inversion, and model simulation [10]. Carbon modeling generally uses Principal Component Analysis (PCA) with dynamic models [11]

Some methods for estimating carbon storage and sequestration, such as the gross primary productivity (GPP) as the photosynthetic input and the ecosystem respiration as the output (RECO) are the two major fluxes that determine the carbon balance at the ecosystem level. The net ecosystem production (NEP) is also used to determine the value related to climate policy [12]. High carbon storage is the ultimate result of maximizing net primary production (NPP), which is equal to plant growth, according to some studies [13][14].

Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) is a spatially integrated tool that can measure ecosystem services [15]. The InVEST model has demonstrated low application cost, high accuracy, and strong spatial analysis capacity when compared to other models, such as Artificial Intelligence for Ecosystem Services [16]. InVEST's Carbon Storage/Sequestration module has been implemented in China [17].

The InVEST method, developed by the Natural Capital Project, is one of the functions that assess environmental services for carbon storage and sequestration from all types of carbon storage sources. The application of Geographic Information Systems (GIS)-based methods is very suitable for measuring carbon storage, which is quite extensive. The method applied in measuring carbon stocks in other sources is to extract the correlation value between other carbon sources and aboveground biomass. The InVEST method can calculate a valuation of carbon uptake from land use to gain a better understanding of the contribution of various types of land use to climate change so that appropriate policies and practices can be formulated to reduce carbon emissions and increase carbon uptake to achieve mitigation goals.

Several studies have been conducted worldwide to investigate carbon storage and sequestration. In Morocco, researchers used GIS integration and the InVEST model [18]. In China, the InVEST and PLUS models were integrated using three scenarios to evaluate changes in carbon sequestration services in 2035 [19]. The Ca-Markov/Random Forest and InVEST models were used to investigate carbon storage and sequestration in a eucalyptus productive zone in the Brazilian Cerrado [20]. Carbon storage models have also become the focus of research by several researchers, such as research on predicting carbon absorption in the Shiyang River Basin [21]. The InVEST model can also be used to model blue carbon, as was done in Spain [22].

Studies have been conducted on carbon storage in different ecosystems across Indonesia. In Manado's Kawanua Arboretum BP2LHK, allometric equations were used to calculate carbon storage. The research revealed that Diospyros rumphii plants had the highest carbon storage, amounting to 74.246 tons/ha [23]. Another study used remote sensing in the mangrove area of the Perancak Estuary in Bali, where the total carbon storage was found to be 22.18 ± 11.76 tonC/ha and CO2 sequestration was calculated to be 81.41 ± 43.18 tonC/ha [24]. In the Brantas River basin in East Java, a combination of GIS and the Rapid Carbon Stock Appraisal (RaCSA) method was used to determine carbon storage. The findings showed a decrease in carbon storage due to land use changes [25]

The economic valuation of carbon provides a means for climate change mitigation policy instruments, compares competing environmental initiatives, and motivates public willingness to pay for mitigation activities[26]. Various methods, such as total economic value (TEV), the Kyoto Protocol mechanisms, the carbon market, the carbon stock exchange, and economic cost analysis, are used to estimate carbon prices [27]. The monetary valuation of carbon sequestration is crucial for decision-makers to balance the climate change mitigation benefits of carbon sequestration and local economic development [28].

Various research has been carried out for assessing carbon storage and sequestration in many parts of the world, including Indonesia. However, only a few investigations have been performed in critical humid watersheds. This study aims to mapping potential changes in climate regulating ecosystem services (carbon storage and sequestration) in Cisadane watershed with different scenarios The results are expected to be useful for regional planners, and decision-makers for sustainable watershed management.

2. MATERIALS AND METHODS

2.1. Study area

This research was conducted in the Cisadane watershed in West Java Province and Banten Province, Indonesia. (Fig. 1). Cisadane River is the main river in this watershed, originating from Mount Gede and flowing 126 km into the Java Sea. The Cisadane watershed covers 151,126 ha; the upper part is dominated by mountains with a slope of up to >40%, the middle part is undulating, and a 0–8% slope dominates the lower flat area. The climate belongs to a tropical climate, with a temperature range of 20°C -34°C and annual precipitation of 2000–5000 mm. This watershed acts as a source of fresh water for living around 1,7 million people [29]. It is anticipated that the estimated number will rise along with the advancement of society, which will unavoidably result in changes to the utilization of LULC, as well as the storage of carbon.

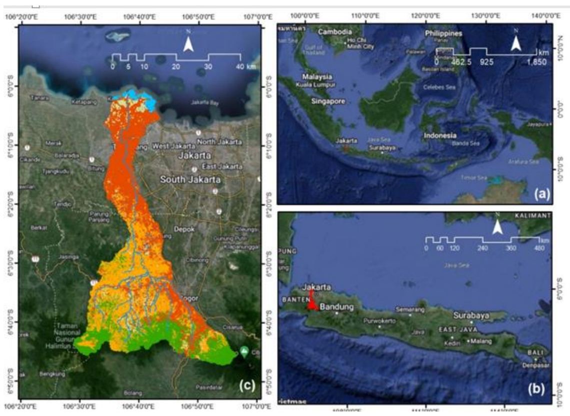


Figure 1. Study area, Cisadane watershed, Indonesia

2.2. Methods

A flowchart of the integrated assessment method was used in this study (Figure 2). The assessment was carried out in two stages: (i) LULC change and prediction by using Land Change Modeler (LCM). This part has been carried out and published [30], and (ii) carbon storage estimation using InVEST statistical methods. This is achieved through interactive analysis between top-down and bottom-up Cellular Automata (CA) system demands integrating self-adaptive inertial mechanisms and competition [31].

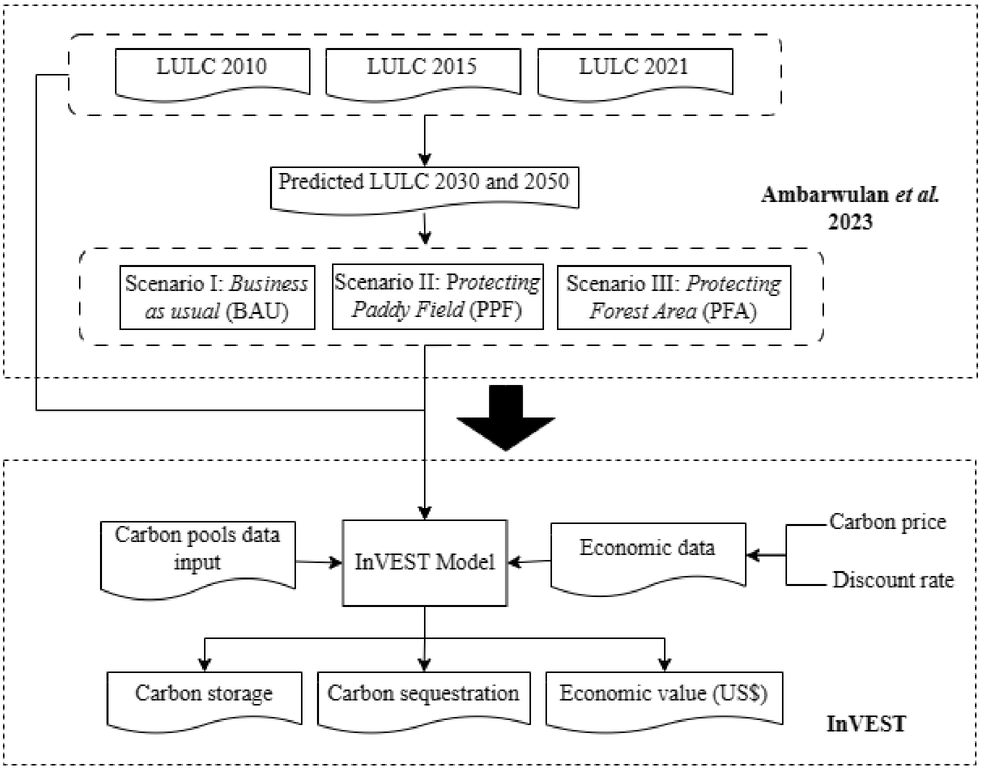


Figure 2. Flowchart of integrated assessment methods

2.2.1. Multi-year LULC map and prediction

The multi years LULC maps was derived from Landsat 5 of 2010, Landsat 8 of 2015 and Sentinel 2 of 2021. The Random Forest (RF) classification have been applied for classifying the LULC maps using Google Eart Engine (GEE) platform. The class for the LULC classification used in this study refers to the National Standardization Agency for Indonesia (2010), although several studies have used the LULC classification standard [30]. The LULC classes were built-up land (BUL), dryland farming (DF), paddy field (PF), plantation (PLT), forest (FRT), pond (PO), and water body (WB). In the accuracy assessment of the LULC maps, the Kappa index value was around 90%, so LCM is applicable for predicting the 2030 and 2050 LULC changes. The multi-year LULC maps of this study have been done by [32].

Spatial models have been developed using the integration of remote sensing (RS) and Geographic Information Systems (GIS) to predict LULC. Various models to predict LULC are available, including the Markov chain (MC) model [33]. Some studies use hybrid models such as the Multi-Layer Perceptron-Markov chain (MLP-MC) model [34], and CA-MC [35] to simulate predictions. [36] and [37] comparing CA-MC to MLP-MC show that MLP-MC provides a better understanding of predicting future LULC. In this study LULC change and prediction have been carried by using Land Change Modeller and have carried by [32].

It is essential to consider the social and economic development and natural conditions of different study areas for specific analysis to simulate future land use spatial changes. Therefore, the simulation needs to be combined with the actual situation of the study area [38]. To develop future land management scenarios, land management policies were generated that considered the implications for deforestation and food security. Three different scenarios were considered: business as usual (BAU), protecting paddy field area (PPF), and protecting forest area (PFA).

Table 1. The three scenarios for predicting LULC 2030 and 2050 [32]

	Scenario	Description
	Business as Usual (BAU)	This scenario assumes that LULC change can occur without limitations and controls; for example, no intervention is carried out. In other words, future land use (2030 and 2050) occurs based on changes in 2010, 2015, and 2021 LULC trends.
[.	Protecting paddy fields (PPF)	This scenario uses the assumption that paddy field areas are maintained without decreasing to ensure the availability of food security in Indonesia following Law no. 41 of 2009 (RI, 2009). PPF scenario is structured to keep these areas, and land-use changes are assumed to occur in other LULC.
I.	Protecting forest areas (PFA)	PFA scenario uses assumptions to conserve forest areas following RI, 1999. It is designed to maintain the ecological function of the Cisadane watershed by making a simulation of maintaining a fixed forest area. In this case, changes will occur in other LULC outside the forest areas.

2.2.2. InVEST carbon model

The InVEST model is commonly used for quantifying regional carbon storage for each land use/cover, as mentioned in [39], [40]. The InVEST model was developed by Stanford University, California, to support environmental decision-making [41]. This model is based on geographic information systems (GIS) and includes algorithms that occur in changing Land Use Land Cover (LULC) patterns to a change in terrestrial carbon storage and other ecosystem service outputs [42]. InVEST software (v3.14.0) measures carbon storage provided by the Cisadane Watershed Ecosystem. Data requirements in carbon storage models can be seen in Table 2 below.

Table 2. InVEST Data Requirements: Carbon Storage and Sequestration [43]

Required	Service	a	Land Use/Land Cover	Look up carbon stock(s) per pixel	Total carbon stock (Mg/pixel)
		b	Carbon in aboveground biomass		
		c	Carbon in belowground biomass		
		d	Carbon-dead organic matter		
		e	Carbon in Soil		
Optional	Service	a	Carbon removed via timber harvest	Calculates carbon stored in harvested wood products per pixel	Total carbon stock, including that in HWP (Mg/pixel)
		b	First year of timber harvest		
		c	Harvest frequency		
		d	Half-life of harvested wood products		
		e	Carbon density in harvested		
		f	Biomass conversion expansion factor		

		g	Future Land Use Land Cover	Calculates the difference between carbon stocks	Carbon sequestration rates (Mg/pixel/yr)
Optional	Value	a	Value Of sequestered carbon	Calculates the value of carbon	Value of sequestration carbon (currency/pixel/yr)
		b	Discount rate		
		c	Timespan		
		d	The annual rate of change in the price of carbon		

The concentration of carbon is determined for each grid cell of a region, taking into account the carbon density pool that includes aboveground carbon concentration ($C_{m,a}$, Mg/km^2), below-ground carbon concentration ($C_{m,b}$, km^2), soil organic carbon ($C_{m,s}$, km^2), and dead organic matter ($C_{m,d}$, km^2)[44]. The formula [1] can be used to calculate the CS density (C) for each land use type in every cell[45].

$$C = \sum_{m=1}^{n} A_m * (C_{m,a} + C_{m,b} + C_{m,s} + C_{m,d}) \quad (1)$$

To calculate the carbon and carbon sequestration for this area, the eq. [2,3] were employed, respectively. CS was denoted as C^{T2} and C^{T1} for the years T2 and T1, respectively. The biophysical data was collected from field surveys and sampling[46]. By analyzing the net change in pixel-by-pixel CS between existing and future LULC maps over the years, a carbon sequestration model was created.

$$C = \sum_{m=1}^{n} C_{m,i,j} \quad (2)$$

$$S = C^{T2} - -C^{T1}, where \ \ T2 > T1 \quad (3)$$

Carbon storage table data obtained through literature studies, 2021 land cover maps, and estimated land cover maps for 2030 and 2050 are then included in the InVEST model so that carbon storage map outputs in each land cover in 2021, 2030, and 2050 in tons/ha, then analyzed into carbon storage maps so that the value of storage and sequestration value in each land cover is obtained.

2.2.3. Economic valuation of carbon

The economic value of carbon in Cisadane Watershed has been calculated based on the current total carbon stock in 2021, as well as the predicted value in 2030 and 2050. This calculation is done under three different scenarios that take into account the different rates of ecosystem area loss. To analyze the economic value of absorbing carbon, the market price of carbon (Rp/tCO2) has been determined. The national carbon price is $2 (IDX Carbon) assuming a constant price in the projection year. For the given land parcel k, one can calculate the NPV for C sequestration over time using the following formula [4,5]. Using the benefit transfer method, the carbon price is set as follows:

$$V = (1 + i)\ P \quad (4)$$

With, V as the carbon value in 2020 (US $), i as the average inflation rate (%), P as the carbon value in 2021 (US $), and t as the period.

$$NPV = V\frac{sk}{yfut-ycur}\sum_{i=0}^{yfut-ycur-1}\left(1+\frac{i}{100}\right)^{-t}\left(1+\frac{c}{100}\right)^{-t} \quad (5)$$

With, V as the monetary value per unit of C; sk as the sequestered carbon in land parcel k; yfut as future year; ycur as current year; i as the discount rate; and c as the annual rate of change in C price.

3. RESULTS

3.1. Carbon storage and sequestration

Anthropogenic activities have an impact on changes in land use and land cover. Anthropogenic Activities. Anthropogenic activities refer to actions and processes driven by human activity that affect the environment. These activities, often linked to industrialization, urbanization, and other forms of human development, can significantly alter natural ecosystems. The scenario created in the previous stage determines land coverage for 2030 and 2050. This condition will certainly also affect changes in carbon storage and sequestration. there are significant discrepancies in the carbon sequestration capacity of different LULC types, and the transformation between LULC types will directly affect the distribution and function of vegetation and soil [47]. In this research stage, the scenarios created will be associated with carbon storage and sequestration.

Figure 3 presents data on carbon storage and sequestration in each land use and land cover from 2010 to 2021. Built-up areas have relatively lower carbon storage compared to forested areas. The carbon content in built-up areas has increased over the years, reflecting the potential for carbon sequestration efforts or changes in land use practices. Dryland agriculture shows a significant increase in carbon storage. Forested areas significantly contribute to carbon sequestration, possibly due to the presence of vegetation in agricultural practices. Water bodies have zero carbon reserves, indicating that these areas do not make a significant contribution to carbon sequestration.

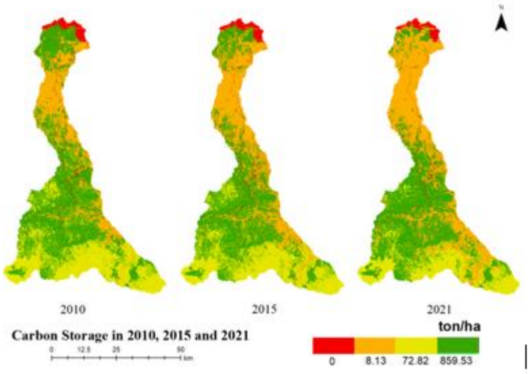


Figure 3. Carbon storage in 2010,2015, and 2021

Forests have a large carbon storage capacity, with a slight decrease in carbon content from 2010 to 2021. This decrease may be due to deforestation or changes in forest management practices. Carbon sequestration in paddy fields has decreased quite drastically, possibly due to extensive land conversion. Plantation areas have shown a relatively insignificant increase in carbon content during the period. Similar to water bodies, ponds also do not contain carbon sources.

Table 3. Carbon storage and sequestration

LULC class	2010		2015		2021	
	Ha	Carbon (ton)	Ha	Carbon (ton)	Ha	Carbon (ton)
BUL	32.624	268.888	45.614	374.053	52.799	450.132
DF	12.153	2.821.447	33.845	3.164.592	39.692	4.012.469
WB	1.812	0	1.812	0	1.812	0
FRT	67.567	3.383.464	42.125	2.999.582	35.519	2.249.277
PF	27.902	2.715.540	19.172	1.678.462	12.469	858.012
PLT	6.189	223.404	6.189	262.853	6.189	371.940
PO	2.879	0	2.798	0	2.646	0

From observing Table 3, several trends are also obtained. Overall trends show increased carbon content in most land-use classes from 2010 to 2021. vegetation areas (DF, FRT, PF) generally exhibit higher carbon pools than other land use classes. Vegetated areas (DF, FRT, PF) play an important role in carbon sequestration, emphasizing the importance of sustainable forestry practices and conservation efforts. Efforts to increase carbon sequestration in non-forest areas, such as built-up areas, can be explored through green infrastructure and urban planning. Ongoing monitoring and assessment of land use change is critical to understanding impacts on carbon dynamics and informing sustainable land management strategies. In general, these tables help analyze the carbon dynamics of different land use classes, helping to guide policies and practices for sustainable land management and climate change mitigation.

Table 4 presents carbon storage and sequestration data in the first scenario, Business as Usual (BAU). In this table, several things can be analyzed. The built-up area shows increased carbon area and content from 2030 to 2050. The carbon pool in the BUL is projected to increase from 563,702.41 tons in 2030 to 702,732.73 tons in 2050. The dryland farming area has decreased in carbon content from 3,354,836 tons in 2030 to 3,017,827 tons in 2050. The decrease in carbon content may be due to changes in land use or management practices. The water bodies and ponds area have a zero-carbon pool. The Forest areas show decreased carbon area and content from 2030 to 2050. The carbon pool in forests is projected to decrease from 2,091,487.98 tons in 2030 to 1,295,070.20 tons in 2050. The paddy fields have decreased in area and carbon content, with carbon pools decreasing from 457,771 tons in 2030 to 231,009 tons in 2050. This decline may be due to land use strategies or management practices changes. The area of the plantation shows an increase in carbon content from 2030 to 2050. The carbon pool in plantations is projected to increase from 380,914 tons in 2030 to 517,699 tons in 2050.

Table 4. Carbon storage and sequestration in the BAU scenario

LULC class	Scenario I : BAU			
	2030		2050	
	Area (ha)	Carbon (ton)	Area (ha)	Carbon (ton)
BUL	61.242	563.702	74.722	702.732
DF	45.447	3.354.836	48.975	3.017.827
WB	1.812	0	1.812	0

FRT	27.463	2.091.487	15.568	1.295.070
PF	6.446	457.771	1.579	231.009
PLT	6.189	380.914	6.189	517.699
PO	2.527	0	2.281	0

The analysis of the first scenario has significant implications to consider. Firstly, the increase in the overall carbon pool for the entire landscape under the BAU scenario is primarily driven by changes in built-up areas and plantations. Secondly, the reduction in carbon pools in FRT and PF highlights the need for sustainable forest management practices that can help maintain or increase carbon sequestration. Continuous monitoring and adaptive management strategies are crucial to assess the impact of land-use change on carbon dynamics and make informed decisions for sustainable land management.

Table 5 presents carbon storage and sequestration data in the second scenario, PFF. In this table, several things can be analyzed. The built-up area shows increased carbon area and content from 2030 to 2050. Carbon ponds in this LULC class are projected to increase from 483,515.41 tons in 2030 to 595,611.85 tons in 2050. The dryland farming area has a decrease in carbon content, with the carbon pool increasing from 2,915,548 tons in 2030 to 2,567,243 tons in 2050. The water bodies and ponds have a zero-carbon pool. The forest area shows decreased carbon area and content from 2030 to 2050. The carbon pool in forest is projected to decrease from 2,090,242.76 tons in 2030 to 1,293,104.06 tons in 2050. The paddy field area has increased in carbon content, with carbon gain increasing from 17,535,858.86 tons in 2030 to 17,617,867.56 tons in 2050. The area of the plantation shows an increase in area and carbon content from 2030 to 2050. The carbon pool in plantation is projected to increase from 373,719 tons in 2030 to 494,566 tons in 2050.

Table 5. Carbon storage and sequestration in the PPF scenario

LULC class	Scenario II : PPF			
	2030		2050	
	Area (ha)	Carbon (ton)	Area (ha)	Carbon (ton)
BUL	57.350	483.515	67.231	595.611
DF	43.280	2.915.548	45.530	2.567.243
WB	1.812	0	1.812	0
FRT	27.463	2.090.242	15.568	1.293.104
PF	12.504	753.585	12.515	761.786
PLT	6.189	373.719	6.189	494.566
PO	2.527	0	2.281	0

The results of implementing the second scenario are shown in Table 5. Based on the projections, the total carbon pool for the entire landscape is expected to increase under PPF, primarily due to changes in built-up areas, paddy fields, and plantations. However, the decrease in carbon pools in forests emphasizes the need for further research on land use and management practices that promote carbon sequestration. To ensure sustainable land management, it is crucial to implement continuous monitoring and adaptive management strategies to evaluate the impact of land-use changes on carbon dynamics. By analyzing potential changes in carbon pools resulting from PPF scenarios, policymakers and practitioners can make informed decisions regarding land-use policies and practices that promote carbon sequestration and mitigate climate change.

Table 6 presents carbon storage and sequestration data in the third scenario, PFA. In this table, several things can be analysed. The BUL area shows increased carbon area and content from 2030 to 2050. Carbon ponds in BU are projected to increase from 487,847.07 tons in 2030 to 556,239.07 tons in 2050. The dryland farming area has experienced a decrease in area and carbon content, with carbon pools decreasing from 3,123,355 tons in 2030 to 2,634,862 tons in 2050. The water bodies and ponds area have a zero-carbon pool. The forest area shows increased carbon area and content from 2030 to 2050. The carbon pool in this class is projected to increase from 3,005,612.00 tons in 2030 to 3,009,544.28 tons in 2050. The paddy field areas have decreased in area and carbon content, with carbon pools decreasing from 450,034 tons in 2030 to 397,165 tons in 2050. This decline may be due to land use strategies or management practices changes. The area of the plantation shows an increase in area and carbon content from 2030 to 2050. The carbon pool in PLT is projected to increase from 343,082 tons in 2030 to 439,094 tons in 2050.

Table 6. Carbon storage and sequestration in the PFA scenario

LULC class	Scenario III : PFA			
	2030		2050	
	Area (ha)	Carbon (ton)	Area (ha)	Carbon (ton)
BUL	59.846	487.847	69.625	556.239
DF	38.823	3.123.355	34.167	2.634.862
WB	1.812	0	1.812	0
FRT	35.519	3.005.612	35.519	3.009.544
PF	6.410	450.034	6.410	397.165
PLT	6.189	343.082	6.189	439.094
PO	2.527	0	2.527	0

The implications of using this third scenario. The overall carbon pool for the entire landscape under PFAs is projected to increase, primarily driven by built-up, forest, and plantation changes. Reducing carbon pools in paddy fields indicates the need for further investigation into land use and management practices to increase carbon sequestration. Continuous monitoring and adaptive management strategies are essential for assessing the impact of land-use change on carbon dynamics and making informed decisions for sustainable land management. Table 6 assists in analyzing potential changes in the carbon pool under PFA scenarios, helping inform land-use policies and practices for carbon sequestration and climate change mitigation.

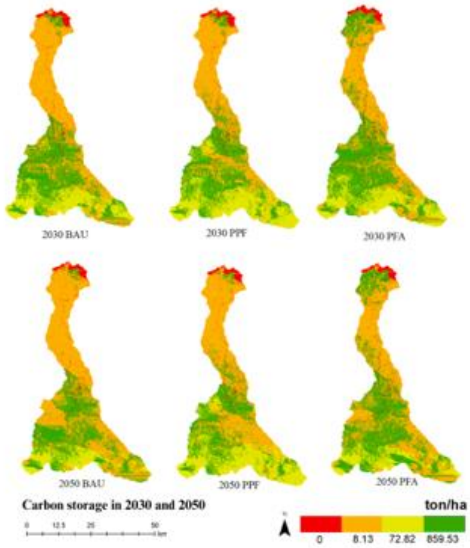
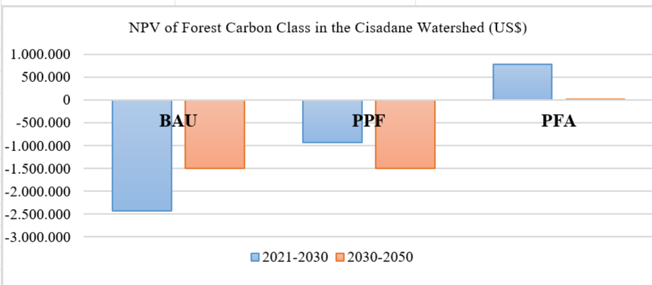


Figure 4. Carbon Storage in 2030 and 2050

3.2. Valuation of carbon sequestration

Valuation of carbon sequestration refers to assessing or determining the economic value of carbon sequestration and storage by various ecosystems. Assigning an economic value to each ton of carbon absorbed or stored by a particular project or activity. This value may change depending on the global carbon market or carbon pricing schemes in force at the national level. In this valuation assessment, we will use national level prices.



Scenario	2021-2030	2030-2050
BAU	-2.428.917	-1.497.265
PPF	-932.953	-1.498.619
PFA	787.943	7.393

Figure 5. NPV of forest class carbon (FRT) under various scenarios (US$)

NPV values are presented for values from 3 different scenarios, namely BAU, PPF, and PFA (Figure 5). The discount rate used is 6% (Bank Indonesia) which will affect the present value of future cash flows. The national carbon price is $2 (IDX Carbon) assuming a constant price in the projection year. A negative NPV value will indicate an economic loss, and conversely, if the NPV value is positive it will indicate a gain in economic value [48].

Based on the BAU and PPF scenarios in the forest class (FRT), the level of loss is not much different, both in 2021-2030 and 2030-2050. The PPF scenario reduces some of the losses in the BAU scenario, which is a scenario that assumes that current land use trends will continue without significant changes in policy or practice. Losses resulting from reduced carbon stocks are a consequence of the continued reduction in projected forest cover and will result in increased costs in the future. PFA's NPV is positive, indicating that there will be an increase in economic value, namely US$ 787,943 in 2021-2030 and US$ 7,393 in 2030-2050. The forest land protection scenario will increase carbon sequestration through sustainable forest management practices or land restoration, carbon storage in forests can increase and create carbon economic value assets.

4. DISCUSSION

This study discusses the dynamics of carbon sequestration and economic assessment in the Cisadane watershed. Watershed ecosystems play a crucial role in both environmental and economic prosperity. Therefore, it is essential to assess carbon sequestration and storage to monitor the ecosystem's health and conduct financial calculations. The Cisadane watershed is particularly vulnerable to changes in land coverage, which can impact various aspects such as climate control, hydrology, soil reformation, and others. Despite the numerous benefits provided by the watershed, land coverage must be managed wisely to avoid conflicting economic and environmental interests [49]. This is because changes in land coverage can affect the uptake of carbon and other vital aspects such as water supply, irrigation, living habitats, flood control, erosion control, tourism, transportation, and livelihoods [50].

The United Nations Framework Convention on Climate Change (UNFCC) and The Kyoto Protocol's emphasis on carbon sequestration in terrestrial ecosystems underscores a critical aspect of mitigating climate change [51]. This has sparked considerable interest among scholars and decision-makers in exploring methods to enhance carbon sequestration as a means to combat the impacts of climate change. Carbon sequestration in terrestrial ecosystems has thus become a focal point in discussions surrounding sustainable development and environmental protection [52], [53], [54]. Central to this discourse is the recognition of the significant role that LULC plays in global carbon storage and sequestration dynamics. Different LULC types exhibit varying capacities for carbon sequestration, thereby influencing the distribution of vegetation and soil carbon levels. [55].

The analysis reveals nuanced variations in carbon storage corresponding to changes in LULC. For instance, stable carbon storage conditions are observed in water bodies and ponds, where carbon density and area exhibit inconspicuous changes. The specific change process was that the increase of LULC type with high-density carbon and the decrease of LULC type with low-density carbon improved regional storage [56], such as the conversion of dryland farms and built-up areas to forests or plantations can enhance regional carbon storage. However, scenarios where LULC types with low-density carbon increase while those with high-density carbon decrease led to reduced carbon storage, exemplified by the decline of forests and the expansion of built-up land. This expansion, often associated with economic and social development, results in a net loss of carbon storage, as evidenced by cases such as Hainan Island which resulted in a loss of carbon storage of 2.95 Tg [57]. This trend is particularly prominent in tropical regions like South America including Colombia and Brazil, where forests are converted into cropland and built-up areas [58], [59]. The InVEST model analysis reveals a decline in carbon storage and density, with urbanization, farmland expansion, and deforestation as the primary causes [60], [61].

The implementation of optimistic scenarios such as the Protecting Forest Areas (PFA), which prioritize forest expansion, consequently, amplifies carbon sequestration potential. Forest ecosystems are pivotal carbon sinks, holding nearly 40% of terrestrial biomass [62]. This significant increase in carbon storage observed in ecological restoration scenarios is also shown in Liaoning Province China, where there is a substantial increase in forest area with values of 2164,4 Tg [63].

Studies affirm that forest has a powerful carbon sink function, and the same as cropland [58]. One of the croplands used to develop scenarios in this research is the paddy field. The Protecting Paddy Field Scenario (PPF) highlights the contribution of expansion paddy fields to carbon sequestration. Cropland such as paddy fields can absorb carbon through crop growth, while farmland soil sequesters carbon, thereby increasing soil carbon storage [64]. However, it is crucial to acknowledge that disturbances, including harvesting and construction activities in vegetated areas, can disrupt carbon sequestration dynamics and ecosystem services. Converting natural forests into managed systems such as paddy fields can upset the carbon balance [65], underscoring the importance of sustainable land management practices to maintain or enhance carbon sequestration potential.

The valuation of carbon sequestration is a complex process that involves multiple factors, such as the market price of carbon, discount rates, and social value. The NPV simulations for carbon ingestion are obtained through the InVEST model, which integrates land use and land cover scenarios. This approach helps to assess the spatial-temporal impact of land use distribution on carbon storage and sequestration at a regional scale from 2021 to 2050. The study used a mix of carbon price differences and discount rates to address future risks and inefficiencies and to explore variations in NPV in response to these scenarios.

This research applied a carbon price of US$2/t C at the country level (IDX bursa carbon). The International Monetary Fund (IMF) proposed a carbon price of US$ 25 per ton of CO2 at the international level, taking into account different stages of economic development to stimulate greater participation in achieving the Paris targets [66]. Furthermore, the research also investigated the correlation between NPV and carbon sequestration and found a high positive linear relationship, indicating that an increase in carbon sequestration would lead to a rise in the economic value of carbon at the discount rate and given carbon price [67].

Few studies have calculated the economic value of carbon absorption for forests separately from other land use and land cover classes. However, a study conducted in Ratezat National Park, Romania, showed an economic gain of US$ 34.12 million through Forest Carbon Sequestration (FCS) with a value of US$ 60 per ton of carbon. In contrast, this study showed an economic loss of around US$ 31 million, raising serious concerns about forest protection in the study area[68].

The rapid destruction and loss of forest cover result from increased extractive pressure [69] and the expansion of agricultural land in the study area. Other studies have also identified agriculture as a key driver of the LULC transition [70]. The economic losses reported in this study for all land use and land cover classes are synchronized with previous findings [71], which have reported economic losses during the PPF scenario of US$ -932.953 in 2021-2030 and US$-1.49 million in 2030-2050. The biggest economic loss happens in the BAU scenario with a value of US$-2.42 million in 2021-2030 and US$-1.49 million in 2030-2050. The PFA achieved positive NPV, indicating that there will be an increase in economic value about US$ 787,943 in 2021-2030 and US$ 7,393 in 2030-2050. This suggests that economic gains in the Cisadane watershed can be realized by adopting intensive forest protection initiatives such as national afforestation programs, forest fire prevention and management schemes, or activities from other countries.

REDD+ (reducing emissions from deforestation and forest degradation) guides sustainable forest management and biodiversity protection while upholding rights for local people and forest products. In addition, REDD+ also provides financial benefits for increased C storage and stabilization in forests [72]. These studies can be very relevant and useful in providing the basic information and assistance needed to successfully implement REDD+ projects. Discrepancies between the current literature show uncertainty in monetary valuations and next-generation preferences for atmospheric C mitigation [73].

The valuation of carbon storage offers critical insights with implications for financial feasibility, management strategies, and policy interventions. Negative NPV outcomes signal insufficient present value of cash flows to cover costs and meet discount rate requirements, necessitating further analysis to understand revenue streams and identify areas for management strategy improvements. Sensitivity analysis incorporating different discount rates and cash flow assumptions provides a nuanced understanding of financial feasibility, accounting for economic risks associated with estimated carbon uptake. This underscores the importance of integrating economic considerations into mitigation strategies, guiding investments in conservation, restoration, and sustainable land use projects to optimize carbon sequestration potential.

5. CONCLUSIONS

The Study conducted a comprehensive evaluation of carbon storage and sequestration in Cisadane watershed using a combination of methods, including CA-Markov and Invest models to quantitatively assess the dynamics of land use and carbon storage in Cisadane Watershed from 2010 to 2021 and predict the LULC and carbon storage for 2030 and 2050 by considering three different development scenarios. The study aimed to investigate the impact of land-use change on CS&S capacity. In addition, the study sought to identify the economic value of losses from the changes in gain and loss. A sensitivity analysis was conducted using three scenarios, which utilized a mix of the social cost of C value and social choice as a discount rate to observe variations in NPV.

The results of the study revealed that the construction land in the Cisadane watershed has increased significantly in the past ten years, and the areas that reduce carbon storage are mainly distributed in the watershed. Due to the loss of forest area and the expansion of built-up areas and agriculture in BAU and PPF scenarios, the results show a decrease in carbon storage and large economic value of losses from 2021 to 2050. However, the scenario of protecting forest areas effectively inhibited the decline in carbon storage, which will achieve positive economic growth.

The study provides valuable insights into the potential of different land use and land cover types for carbon sequestration, the patterns of carbon sequestration for these types, and the amount of carbon loss that occurs over time due to human activities, such as deforestation and agriculture. Future research can address limitations by integrating factors such as watershed ecosystem composition and regeneration patterns, rainfall, and climate change, which will lead to more precise carbon mapping and better inform the success of carbon trading markets. This forward-looking approach emphasizes the importance of ongoing research efforts in understanding and mitigating the impacts of land-use changes on carbon storage and ecosystem services.

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