



Blue carbon dynamics and mangrove extent: a case study from the Indonesia–Timor Leste Coastal ecosystem

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ABSTRACT

Around 20% of mangrove forests in Indonesia are in a degraded condition, which has a negative impact on the potential for blue carbon storage. When mangroves are damaged or degraded, carbon stored in the soil and vegetation can be released back into the atmosphere as CO₂, ultimately increasing greenhouse gas emissions and exacerbating climate change. Mangrove forests can store up to four times more carbon per hectare, around 800–1,200 tons per hectare, than terrestrial tropical forests. This research was conducted in the Wini mangrove forest area, North Central Timor, East Nusa Tenggara (NTT) which directly borders Timor Leste. The determination of the location of the observation station was based on a map of changes in mangrove forest land use obtained from the Geospatial Information Agency. The parameters measured included organic carbon, mangrove area and sediment type. Organic carbon was analyzed using the Loss on Ignition (LOI) method, and sediment grain size was measured using a particle size analyzer. The results of the study showed that the average organic carbon stock in mangrove forests reached 570,600–843,600 tons per hectare, with an average change in the area of mangrove forests from 2013 to 2023 of 181.29 hectares and the type of sediment dominated by sandy mud. This change in area is caused by the conversion of mangrove land into ponds, rice fields, and settlements.

Introduction

Mangrove is one type of coastal ecosystem that functions as a blue carbon absorber which plays an important role in mitigating climate change. Changes in the area of mangroves in Indonesia in recent years have decreased significantly, this is influenced by human intervention and climate change (Cameron *et al.*, 2018; Alongi, 2021). Purnabasuki, (2012) stated that the mangrove forest ecosystem is able to store carbon per hectare up to four times greater than other terrestrial tropical forests. The process of carbon absorption by mangroves occurs through photosynthesis, where carbon dioxide from the

atmosphere is converted into organic matter stored in tree trunks, leaves, and roots (Mcleod *et al.*, 2011; Kauffman and Donato, 2012; Alongi, 2012).

Globally, mangrove loss is estimated to result in significant annual carbon emissions, equivalent to those released by approximately 19 million motor vehicles (Mcleod *et al.*, 2011). Mangroves in coastal Indonesia have a large area and are one of the main contributors to global blue carbon stocks. Donato *et al.* (2011) stated that mangrove blue carbon stocks can reach more than 1,000 tons of carbon per hectare.

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The East Nusa Tenggara region has a very significant rate of mangrove forest destruction seen per year in the last decade. The decline in mangrove forest areas is due to land changes, logging, and conversion of mangrove forests into ponds, rice fields, and settlements (Rudianto *et al.*, 2020). Mangrove forests in the East Nusa Tenggara region are still relatively natural. The conversion of mangrove forests into fish ponds has caused a significant reduction in carbon stocks and has an impact on reducing the productivity of fishery ecosystems that depend on mangroves as habitats for fish and crabs (Kusmana, 2018).

The coastal area of Indonesia-Timor Leste has unique conditions that allow for the study of blue carbon dynamics and mangrove distribution in the context of global climate change and the impacts of human activities. In the border area of Indonesia-Timor Leste, mangrove ecosystems also act as ecological boundaries that support biodiversity, climate change mitigation, and the welfare of coastal communities that depend on coastal natural resources (Namazi *et al.*, 2019). This research was conducted on the coast of Wini, North Central Timor Regency. Geographically, this research area is located between 9°01'06"–9°39'41" South Latitude and between 124°05'36"–124°51'14" East Longitude. In this research area, the conversion of mangrove forests into ponds, rice fields, and settlements has resulted in the release of carbon that has accumulated over the years. Mangroves not only function as carbon sequestration, but also as habitat providers for various marine species and natural buffers against storms and abrasion. In the long term, these land changes have the potential to weaken the carbon mitigation function and regeneration capacity of mangroves in coastal areas and eliminate the livelihoods of fishermen who depend on the coast for their livelihood.

Research on changes in mangrove area has been conducted by Danoedoro (2019) in Segara Anakan, Cilacap, Andy *et al.* (2022) in Teluk Pandan, Lampung, Febrianto *et al.* (2022) in Kalimantan, Aritonang *et al.* (2022) in Tangkolak Barat, Karawang and carbon content in mangroves has also been conducted including Khoirunisa *et al.* (2024) in LSA, Hapsari *et al.* (2022) on Bintan Island and Hickmah *et al.* (2021) in Karimunjawa. This study aims to analyze changes in the area of mangrove forests during 2013, 2018 and 2023 and to analyze the organic carbon content accumulated in sediments in the Wini Indonesia-Timor Leste Border Area. Analysis of changes in the area and dynamics of carbon stocks in mangrove forests is still focused on the islands of

Java, Bali and Sumatra. It is very rare to find an analysis of the area and dynamics of mangrove forest carbon stocks in the Palau Timor region, East Nusa Tenggara. It is hoped that data on changes in area and estimates of carbon absorbed can be used as basic data in future policies for climate change mitigation, especially the mangrove ecosystem in Wini, North Central Timor, East Nusa Tenggara because the Wini Indonesia-Timor Leste border area mangrove ecosystem also plays a role as an ecological border that supports biodiversity, climate change mitigation, and the welfare of coastal communities.

Materials and Methods

Location and time of research

This research was conducted in the coastal area of Wini, the border of Indonesia and Timor Leste as shown in Figure 1. This study used a purposive sampling method and with primary and secondary data. Primary data is the carbon content in sediment and secondary data uses mangrove area data in 2015, 2018 and 2023. The tools used in this study were a Canon camera, a roll meter to measure mangrove transects.

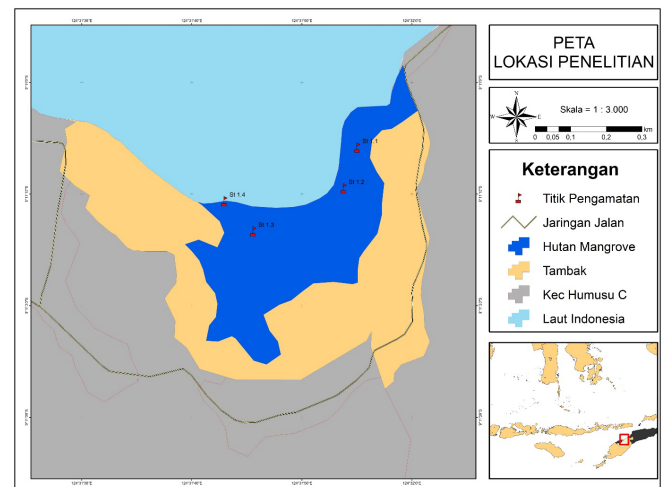


Figure 1. The Research Site in Wini. East Nusa Tenggara, Indonesia

Sediment Sampling Method

Samples were taken using modified core sediment with PVC pipe with a depth of 30 cm with a diameter of 5 cm which was inserted vertically and rotated into the sediment. After the modified core entered the soil as deep as 30 cm, the modified core was pulled. Then the sediment was measured by dividing it using intervals of 0-10 cm, 10-20 cm and 20-30 cm in the three classes and 4 station points, then the sample was inserted into the sample plastic.

Sediment Sample Processing Methods

Sediment sampling was carried out at each point using a modified sediment core with a 50 cm PVC

pipe and a diameter of 5 cm. Analysis of soil organic carbon content used the Loss On Ignition (LOI) method. Sediment samples were placed in an aluminum cup, then placed in an oven at a temperature of 60°C for 48 hours. After drying, the sample was ground with a mortar to make it homogeneous before being burned. Each subsample that had been ground was placed in a zipper bag (plastic clip bag). The sample was weighed ± 2 grams, then placed in a porcelain crucible. Then the sample was put into a furnace and burned at a temperature of 450°C for 4 hours, then weighed again.

Measurement of organic sediment material was carried out using the LOI (Loss on Ignition) method in the following manner:

$$\text{Bahan Organik} = \frac{(Wt-C)-(Wa-C)}{Wt-C} \times 100\%$$

Information :

Wt: Total weight of crucible and sample before drying

C: Weight of empty crucible

Wow: Total weight of crucible and sample after drying

The data calculated are the volume of sediment samples, bulk density and the percentage of organic carbon in the sediment. The calculations used in the data analysis according to are: Soil bulk density is the weight of particles per unit volume of soil and its pores. The formula used to calculate bulk density (BD) is

$$\text{Soil bulk density (g)} = \frac{B \text{ Dry (g)}}{B \text{ Wet (cm}^3)}$$

Carbon (C) density is calculated using the equation:

$$\text{Soil C density (gcm}^{-3}) = \%C \times BD$$

The carbon content in soil is estimated using the equation:

$$\text{Soil C (Mgha}^{-1}) = BD \times SDI \text{ (Soil Depth Interval)} \times \%C$$

If the analysis only produces organic matter content (for example with the LOI method). Then the soil Corg content is assumed to be 1/1.724 of the soil organic matter content. If the type of substrate has an organic matter content of 98% then Corg = 98% / 1.724. The results of the soil carbon calculation are then converted into tons/ha by multiplying by 100 (conversion factor from g/cm³ to tons/ha).

Sediment grain size analysis was conducted to determine the type of sediment in the waters. Sediment grain size is classified based on the United States Department of Agriculture (USDA) soil grain size classification and the USDA soil triangle (Boyd et al., 2002).

Mangrove area data processing method

Processing mangrove area data using ArcGIS, namely with maps obtained from the Geospatial Information Agency in 2013, 2018 and 2023. Classifying supervised or unsupervised to identify mangrove areas. Creating a special class for mangroves so that it can be distinguished from other classes such as open land, water, or settlements. Then analyzing changes in the area of mangrove forests during the period 2013, 2018 and 2023

Results and Discussion

Organic carbon in mangrove sediments

The organic carbon content in sediment is the amount of carbon that can be absorbed and stored by sediment in the form of organic matter that is input into the soil structure and utilized as energy for soil organisms (Aldiano et al. 2022). The carbon storage value per station ranges from 348,608-615,680 tons/ha and the highest is found at stations 1.3 and 1.4 with a total of 1,058,080 tons/ha and the lowest is found at stations 1.1 and 1.2 with a total of 739,958 tons/ha. This number is obtained from the sum of each station. These results are supported by Donato et al. (2011) who stated that the blue carbon stock of mangroves can reach more than 1,000 tons of carbon per hectare. The fluctuation pattern of carbon storage per station and per layer is presented in Table 2. In this case, the sediment grain size is dominated by sand (0.05-2mm) and silt (0.001-0.05mm). At stations 1.1 and 1.2, the sediment type is dominated by fine sand with a grain size of 0.1-0.27 mm. At stations 1.3 and 1.4, the sediment type is dominated by very fine sand with a grain size of 0.05-0.1 mm, thus the sediment texture at the Wini research station on the Indonesia-Timor Leste border is dominated by silty loam, loamy sand, and sandy loam.

Mangrove forest ecosystem can prevent abrasion, inhibit sedimentation rate and as a place for fish spawning, fish growth and feeding place for fish such as grouper, snapper and other types of crustaceans (Majid et al., 2016). The type of tide in Wini, the border of Indonesia - Timor Leste, is a mixed tidal type with a double daily tendency where in one day there are two high tides and two low tides with different height variations. The highest tide at the research location reached 2.97 m and at the lowest ebb condition it was 0.52 m with an MSL of 1.8 m. Furthermore, the results of the tidal analysis are in the range of 1.69-2.93 m. This tide has a significant effect on the mangrove ecosystem in Wini. The tide helps spread mangrove seeds and nutrients and

provides habitat for many coastal biota. Significant tidal variations can help maintain soil fertility because the dynamics of organic carbon accumulated in sediments become new nutrients for mangrove growth and the humidity level around the mangrove forest so that the carbon contained in the mangroves is not directly released but is deposited.

Kusumaningtyas et al. (2019) explained that variations in organic carbon content in mangrove ecosystems are influenced by geographical conditions, such as differences in environmental types, river dominance, tidal dominance. These processes affect the accumulation, storage, and composition of organic matter in sediments.

Table 1. Organic Carbon Content in Sediment

St	Interval (cm)	S-OCS ($\frac{ton}{ha}$)	Total S-OCS ($\frac{ton}{ha}$)	Average S-OCS Per Class ($\frac{ton}{ha}$)	St	Interval (cm)	S-OCS ($\frac{ton}{ha}$)	Total S-OCS ($\frac{ton}{ha}$)	Average S-OCS Per Class ($\frac{ton}{ha}$)
1.1	0-10	115.40	348,608	739,958	1.3	0-10	116.48	442,400	1,058,080
	10-20	116.43				127.43			
	20-30	116.45				198.49			
1.2	0-10	96.45	391,350		1.4	0-10	159.70	615,680	
	10-20	109.44				197.50			
	20-30	185.46				258.48			

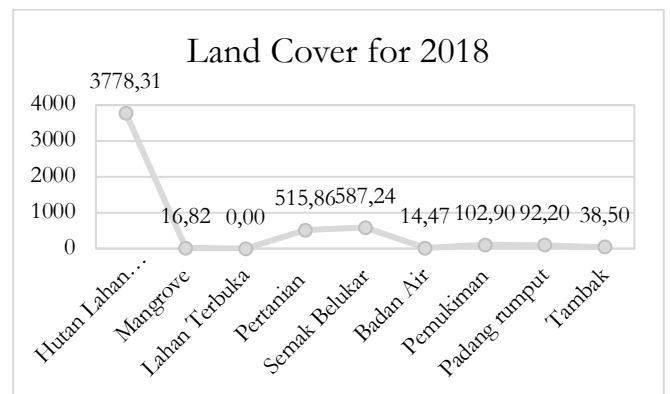
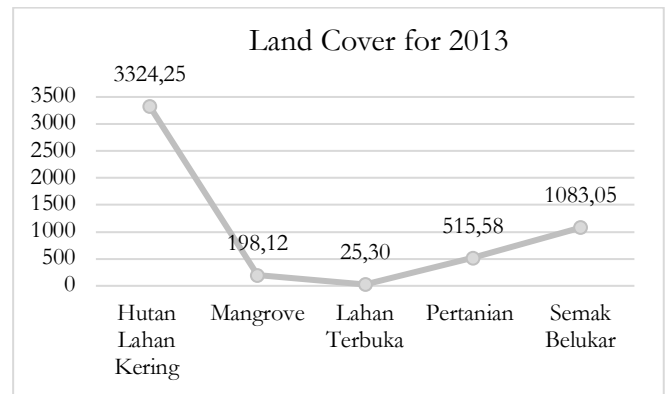
Table 2. Family, species and mangrove name (Indonesian and local)

No	Family	Species	Indonesia name	Local Name
1	<i>Rhizophoraceae</i>	<i>Rhizophora apiculata</i>	Bakau	Mangi-
		<i>Rhizophora mucronata</i>	Bakau hitam	Mangi
2	<i>Sonneratiaceae</i>	<i>Sonneratia alba</i>	Pedada	Soki-Soki

There are types of mangroves found in the research area dominated by three types of mangrove species, namely *Rhizophora apiculata*, *Rhizophora mucronata* and *Sonneratia alba*. In the front part of the sea is dominated by *Sonneratia alba* followed by *Rhizophora apiculata* and *Rhizophora mucronata*. The type of sediment in the mangrove species *Sonneratia alba* is dominated by very fine sand with a grain size of 0.05-0.1mm.

Wini mangrove forest area

Mangrove forests in Wini have been converted into ponds, plantations, rice fields, or settlements. This conversion is one of the main causes of the decline in mangrove area, especially in coastal areas that are densely populated or have high economic pressure.



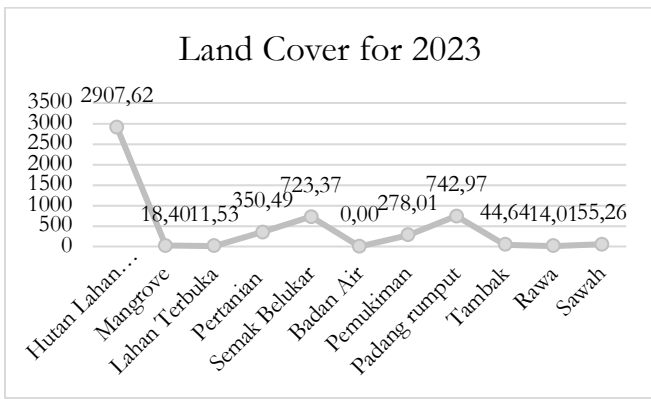


Figure 2. Land Cover from 2013, 2018 and 2023

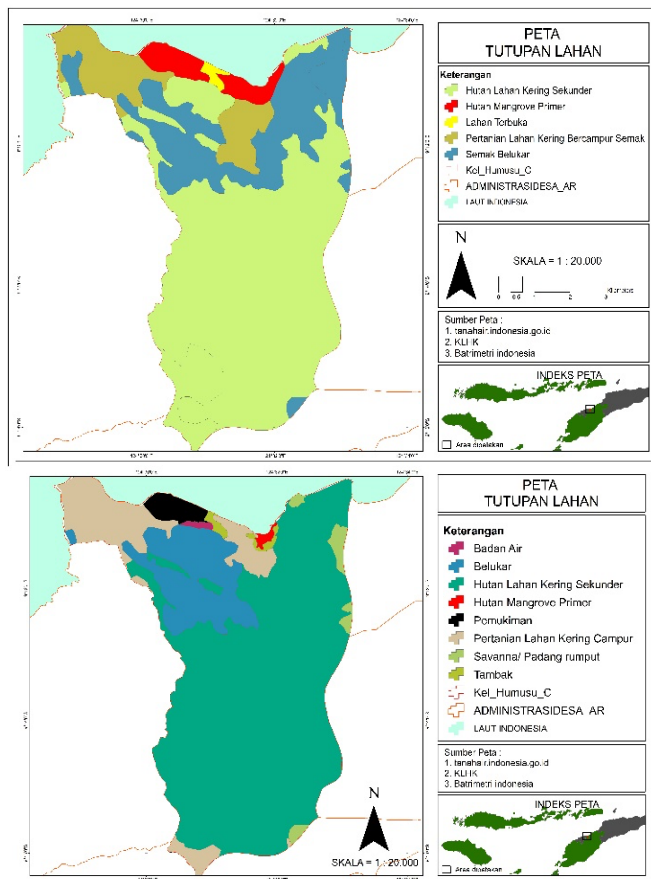
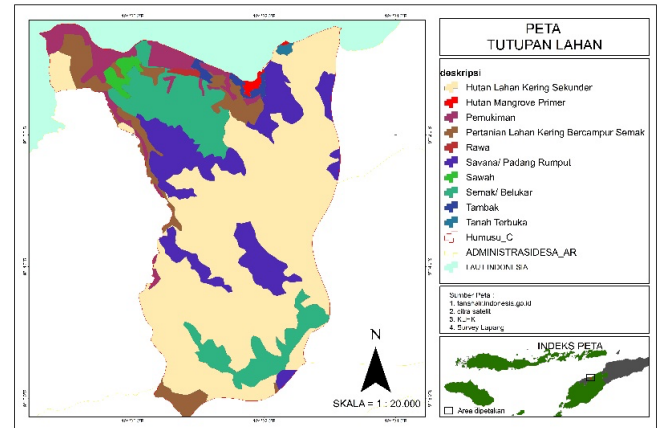


Figure 3. Land Cover Maps 2013, 2018 and 2023

Mangrove density

The change in area is very significant from 2013 to 2023, with clear trends of deforestation, mangrove loss, and land conversion to agricultural areas and fish ponds. These dynamics can have environmental impacts, such as reduced biodiversity, increased carbon emissions, and potential impacts on local livelihoods. It is clear that in 2013, land cover in the Wini Coastal Area on the Indonesia-Timor Leste Border was dominated by dry land forests (3324.25 ha) in light green on the map, mangroves (198.12 ha) in red on the map, open land (25.30) in yellow on the map, agriculture (515.58 ha) in light brown on the map and shrubs (1083.05 ha) in light blue on the map

with a total area of 5146.30 ha in figures 2 and 3. In 2018, land cover was dominated by dry land to 3778.31 ha in dark green on the map, mangroves decreased drastically by around 181.29 ha to 16.82 ha in red on the map. The mangrove forest cover has decreased due to settlements (102.90 ha) in black on the map and ponds (38.50 ha) in light green on the map from previously not existing in figures 2 and 3. In 2023, mangroves increased by around 2 ha to 18.40 ha, but the areas of settlements, ponds and rice fields increased in area in Figures 2 and 3.



Discussion

Mangrove forests, which are categorized as wetland ecosystems, can store carbon reaching 800-1,200 tons per hectare. The release of emissions into the air in mangrove forests is smaller than forests on land, this is because the decomposition of aquatic plant litter does not release carbon into the air. The Mangrove Ecosystem is currently facing threats such as land conversion, deforestation and the impacts of climate change, namely rising sea levels (Wahyuningsi, 2021). The carbon storage value per station ranges from 348,608-615,680 tons/ha and the highest is found at stations 1.3 and 1.4 with a total of 1,058,080 tons/ha and the lowest is found at stations 1.1 and 1.2 with a total of 739,958 tons/ha. These results prove that mangroves are very effective in absorbing and storing carbon in sediment. The main challenge in maintaining mangrove forests in the border area between Indonesia and Timor Leste is the regulation needed to convince the community not to damage mangrove forests in the border area because this area has strategic potential in maintaining and becoming the coastal boundary between Indonesia and Timor Leste. This statement is supported by Spalding et al. (2014), who stated that effective mangrove management policies can help reduce the rate of mangrove degradation in coastal areas. Educating and assisting coastal communities to maintain the sustainability of mangroves. Replanting

damaged mangrove forest areas with *Rhizophora apikulta*, *Rhizophora mucronate* and *Sonneratia alba* mangrove species which are generally found in abundance.

Clay and Silt sediments have a large specific surface area, allowing for the adsorption of more organic matter on sediment particles. This process increases the retention of organic carbon. Alongi (2012) stated that mangroves with dominant mud sediments (clay and silt) have organic carbon reaching 1,023 tons/ha, much higher than mangrove areas with sand substrates. Fine sediments support an anaerobic environment, which slows down the decomposition of organic matter so that carbon can be stored longer because it tends to be stable in coastal environments such as mangroves, preventing carbon from being carried away by currents or waves. While coarse sediment types in the form of sand and gravel have large pores that allow water and oxygen to enter, increasing the rate of decomposition of organic matter, as a result, carbon tends to be released back into the atmosphere or sea. The surface area of coarse sediment particles is smaller, so the ability to bind organic matter is lower than fine sediment. Mcleod *et al.* (2011) stated that mud substrates in coastal areas show higher carbon storage efficiency due to the low rate of decomposition in anaerobic environments. Areas dominated by sand show faster carbon release due to high oxidation of organic matter.

Land conversion into ponds, plantations, and settlements are the main causes of mangrove loss in various coastal areas. According to research by Giri *et al.* (2010), increasing population and land needs often become pressures that significantly reduce the area of mangroves in coastal areas of Southeast Asia, including Indonesia. Exploitation of mangrove wood for fuel and construction is a significant threat. The use of this wood is often carried out without regard to sustainability, thus accelerating the rate of mangrove deforestation, this is what affects the area of mangrove forests which are decreasing very significantly in 2018 in Wini on the Indonesia-Timor Leste border.

Mangroves store large amounts of carbon, both in the form of biomass and sediment. Loss of mangrove area means a decrease in carbon storage capacity, which in turn contributes to climate change. Donato *et al.* (2011) showed that mangroves have a very high carbon stock compared to other terrestrial ecosystems, so the loss of mangroves will increase carbon emissions and reduce the habitat area of coastal ecosystems such as fish and crustaceans. In this case, to reduce repeated destruction of mangrove

forests, strict regulations, public awareness, and monitoring of changes in mangrove land are needed. According to Spalding *et al.* (2014), effective mangrove management policies can help reduce the rate of mangrove degradation in coastal areas.

Conclusion

The dynamics of changes in mangrove forest areas are very significant throughout 2013-2023 where the changes that occurred from 2013-2018 were around 181.29 ha. In 5 years, this change greatly affected the carbon content in mangrove forests where this change affected climate change and sea level rise. Changes in the mangrove forest area are influenced by settlements, ponds and rice fields. This factor causes significant changes in the area of mangrove forests. The carbon storage value per station ranges from 348,608-615,680 tons/ha and the highest was found at stations 1.3 and 1.4 with a total of 1,058,080 tons/ha and the lowest was found at stations 1.1 and 1.2 with a total of 739,958 tons/ha. Thus, mangrove forests play a very important role in reducing global warming and also as an ecological boundary in the Indonesia-Timor Leste region that supports biodiversity, climate change mitigation, and the welfare of coastal communities that depend on coastal natural resources.

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