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Agroforestry Landscape Patterns and Carbon Storage towards Optimal Land Planning and Utilization in Sipolha Horisan Village, Pamatang Sidamanik District, Simalungun Regency

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Abstract: Land conversion due to the increasing population growth rate for various interests has impacted forest land, and deforestation has become a global problem. One step that can be taken in regional planning to utilize and manage forest resources based on the landscape is to develop an agroforestry system. Agroforestry is a method of land management that combines (mixed use) forest plants with agricultural crops or livestock farming within a single area. One area that utilizes land through an agroforestry system is Sipolha Horisan Village, Pamatang Sidamanik District, Simalungun Regency. The purpose of this study was to determine the plant species' composition and agroforestry landscape pattern in Sipolha Horisan Village. The results showed that the agroforestry system practiced by farmers was agrisilvicultural agroforestry, with a random pattern. Carbon storage potential is influenced by plant growth rates. At the tree level, the biomass was 313.18 tons/ha and carbon stocks were 144.06 tons/ha. For understory plants, the biomass was 19.89 tons/ha and carbon stocks were 9.15 tons/ha. The litter produced 39.77 tons/ha of biomass and carbon stocks were 18.29 tons/ha.

Keywords: Agroforestry; Carbon stocks; Land planning; Utilization

Introduction

Land conversion is occurring due to the increasing population growth rate, which is inextricably linked to various interests that impact forest land, leading to deforestation and the destruction of flora and fauna habitats, which threaten the extinction of biodiversity. According to Husain & Korbaffo (2024), continued population growth, while natural resources are limited and damaged by human activities that exploit them, and the conversion of forest land, impact climate change and global warming. Climate change due to global warming has various impacts, such as clean water supply disruptions, species extinction, natural disasters, and so on.

The climate crisis is a global problem that must be addressed collectively by all countries. One step that can be taken in regional planning to utilize and manage forest resources based on the landscape is to develop agroforestry systems. This land management approach, known as landscape agroforestry, combines trees or woody plants with agricultural crops and/or livestock at the landscape level to create a system that is ecologically, economically, and socially productive. Agroforestry is a method of land management that combines (mixed use) forest plants with agricultural crops or livestock farming within a single area. With improved landscape management in the future, small-scale agroforestry systems can also significantly contribute to a region's carbon budget while improving the livelihoods of local residents (Kaswanto & Nakagoshi, 2014).

According to Prihartono & Falatehan (2024) the interaction between heterogeneity in agroforestry landscapes provides landscape services that can enhance resilience to environmental pressures that result in

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changes in land use. Agroforestry systems have been recognized as one of the solutions to reduce greenhouse gas emissions and address climate change. Agroforestry was developed with the aim of improving community welfare, and it is expected to optimize the results of diverse land uses.

According to the WHO (2019), agroforestry has a great ability to absorb carbon dioxide (CO_2) and methane (CH_4) emissions, and to help reduce the rate of deforestation. However, despite its great potential, the application of agroforestry is still limited and not optimal in many countries, including Indonesia. One area that utilizes land with an agroforestry system is Sipolha Horisan Village, Pamatang Sidamanik District, Simalungun Regency. This village is in the Lake Toba area, where land sustainability is highly determined by planning and land use that are in accordance with land capabilities, carrying capacity, and biophysical conditions of the region. Therefore, research on the role of agroforestry in absorbing greenhouse gas emissions is crucial to mitigate the negative impacts of climate change (Wulandari et al., 2020).

Method

The data collection method used was observation, which involved the collection of primary data through direct observation of the research objects in the field. For data collection in this study, a square sample plot was used (Wibowo et al., 2013). The plots were placed in areas where the observed plant species were found. There were 36 plots in plot.

Biomass data (tree species name, height, diameter, and dry and wet litter weight) were collected by measuring the tree species, height, and diameter and analyzed using allometric equations. Litter dry and wet weights were obtained by cutting the stems and leaves. Approximately 100–300 g was weighed to obtain the wet weight, then dried in an oven at 80°C for 48 hours to obtain the dry weight. Litter biomass was analyzed using the Biomass Expansion Factor (BEF) formula (Brown, 1997; Change, 2006).

$$Total\ BK\ (g) = \frac{BK\ sub{-}Example\ (g)}{BB\ sub{-}Example\ (g)} x\ total\ BB \quad (1)$$

To calculate carbon uptake, tree biomass was first calculated using the allometric equation developed by previous researchers (Table 1). Tree diameters measured were >5 cm. Those with a diameter <5 cm were considered seedlings. The carbon concentration in organic matter is typically around 46%, so the estimated amount of carbon stored can be calculated by multiplying the total mass by the carbon concentration in the organic matter as follows:

C = Dry weight of biomass or necromass (kg/ha) x 0.46

To calculate the amount of carbon dioxide (CO_2) uptake, the following formula is used (Ipcc, 2006): CO2 Uptake = Mr. CO_2 / Ar. C or = 3.67 x Carbon Content

The method for processing tree biomass data (Hairiah & Rahayu, 2007) is as follows.

Calculate tree biomass using the allometric equation developed by previous researchers. The measurement begins with felling and weighing several trees.

Table 1. Allometric equation models used

Type of Stand	Allometric Equation (Source)
Mahoni*	BK = $0.902(D^2H)^{0,08}$ (Purwanto et al., 2022)
Sonokeling*	BK = $0.745(D^2H)^{0,64}$ (Purwanto et al., 2022)
Jati*	BK = $0.015(D^2H)^{1,08}$ (Purwanto et al., 2022)
Sengon*	BK = $0.062(D)^{2,47}$ (Rahardjanto et al., 2022)
Pohon-pohon bercabang**	BK = $0.11\rho(D)^{2,62}$ (Ketterings et al., 2001)
Pohon tidak bercabang**	BK = $\pi\ \rho\ D^2\ H / 40$ (Hairiah & Rahayu, 2007)
Kopi**	BK = $0.281(D)^{2,0}$ (Arifin, 2001)
Pinang**	BK = $0.03883(HD^{1,2})$ (Prayogo et al., 2018)
Aren**	BK = $0.077(D)^{2,543}$ (Hossain et al., 2023)
Pisang**	BK = $0.030(D)^{2,13}$ (Arifin, 2001; Noordwijk et al., 2002)
Bambu**	BK = $0.131(D)^{2,28}$ (Priyadarshini et al., 2019)

Total tree biomass and biomass per unit area (tons/ha) are obtained using the Formula 2 and 3 (Ketterings et al., 2001).

$$Total\ tree\ biomass\ (kg) = BK1 + BK2 + + BKn \quad (2)$$

$$Biomass\ per\ unit\ (tons/ha) = \frac{Total\ Biomassa\ (kg)}{Area\ (m^2)} \quad (3)$$

The carbon concentration in organic matter is usually calculated by multiplying the total mass by the carbon concentration in the organic matter as follows Formula 4.

$$C = Dry\ weight\ of\ biomass\ (kg/ha)\ x\ 0.46 \quad (4)$$

To calculate the amount of carbon dioxide (CO2) uptake, the following formula is used (Ipcc, 2006).

$$CO_2\ uptake = \frac{Mr.CO_2}{Ar.C} = 3.67\ x\ Carbon\ Content \quad (5)$$

Note:
Mr = Relative Molecular
Ar = Relative Atomic is approximately 46%

Result and Discussion

Agroforestry Forms and Patterns in Sipolha Horisan Village

Sipolha Horisan Village is a village in Simalungun Regency. One of the unique features of this village is that it is located within the Lake Toba area. It is a beautiful location and is frequently visited by tourists due to its scenic beauty. The land around Lake Toba is generally undulating, so farmers must be wise in selecting the types of crops they grow. Most farmers choose annual crops to grow under tree stands with low canopy density. The most commonly cultivated annual crops are chilies and shallots. Farmers choose annual crops because they have a short harvest period, allowing them to meet daily needs.

Based on field observations, the land use system employed by farmers is agroforestry, specifically agrisilviculture, with a random pattern, as agricultural and forestry crops are planted irregularly. According to Naharuddin (2018), this random pattern arises from a lack of initial planning in plant layout. The placement of woody plants on a plot appears unsystematic. Variations in mixed patterns are found in the types of components, both forestry plants and agricultural plants.

The types of plants grown on community land include various types of plants, including agricultural plants, forestry plants, plantation plants, fruit plants, and vegetable plants. This is supported by the definition of agroforestry stated by Huxley (1999) who stated that agroforestry is a land use system that combines woody plants (trees, bamboo, and others) with non-woody plants such as grass or vegetables. Based on field observations, data on the types of plants grown in the agroforestry system in Sipolha Horisan Village were obtained.

The dominant plantation crop cultivated is coffee (Coffea arabica), which is a source of livelihood for the people of Sipolha Horisan Village. The types of plants include Candlenut (Aleurites moluccanus), Clove (Syzygium aromaticum), Ingul (Toona sureni), Sengon (Albizia chinensis), Jengkol (Archidendron pauciflorum), Durian (Durio zibethinus), Avocado (Persea americana), Mango (Mangifera indica), Petai (Parkia speciose), Guava (Psidium guajava), Coffee (Coffea arabica), Chocolate (Theobroma cacao), Sugar palm (Arenga pinnata), Banana (Musa spp), Areca nut (Areca catechu), Papaya (Carica papaya). Furthermore, the distribution of plants in the agroforestry system in Sipolha Horisan Village can be seen in Figure 1.

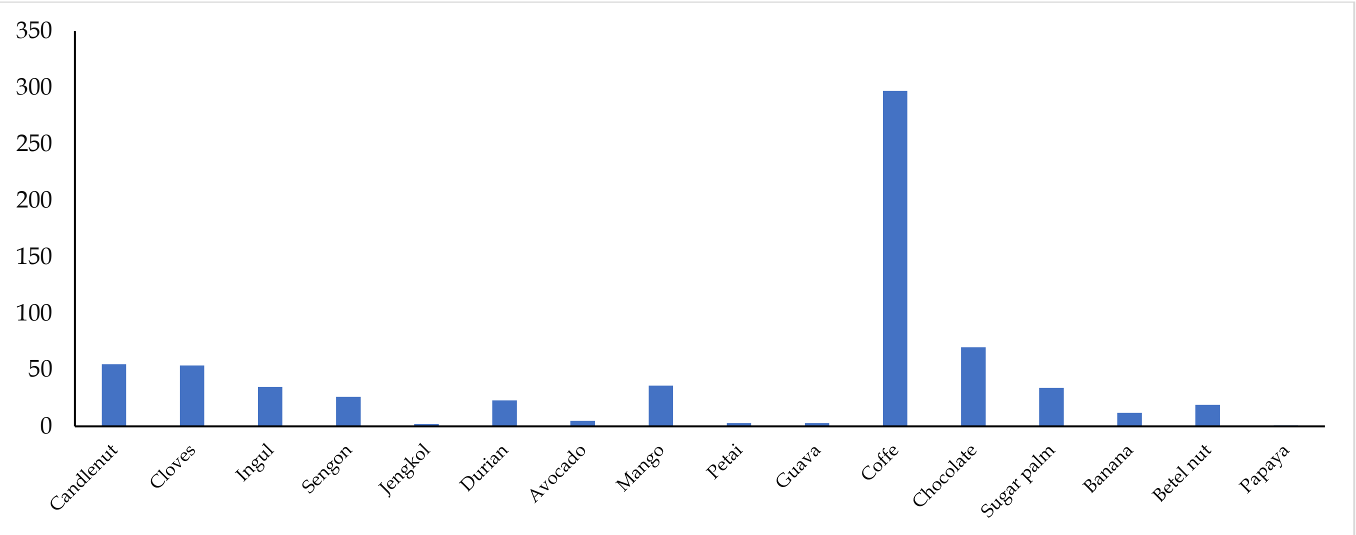

Figure 1. Types of Plants in Agroforestry Distribution Plots

Figure 1 shows that the cultivated crops include candlenut, cloves, sedge, sengon, jengkol, durian, avocado, mango, petai, guava, coffee, chocolate, sugar palm, banana, betel nut, and papaya. These crops are widely cultivated by the community due to their economic and ecological value. Given the undulating biophysical conditions of the land in the Horison Sipolha sub-district, these types of crops are highly suitable for cultivation in the area.

Biomass and Carbon Storage (Carbon Sink) in Sipolha Horisan Sub-district, Simalungun Regency

Biomass and Carbon Storage (Carbon Sink) in Trees: Trees in Sipolha Horisan Sub-district have varying growth rates. Based on their growth rate, trees in Sipolha Horisan Village can be divided into three groups: small plants (dbh 5-20 cm), medium-sized plants (dbh 20-35 cm), and large trees (dbh >35 cm).

Based on field observations, the largest number of small plants (dbh 5-20 cm) was coffee (Coffea arabica) at 296 plants. The fewest small plants were ingul (Toona sureni), areca nut (Areca catechu), sengon (Albizia chinensis), and banana (Musa spp.). The total number of small plants (dbh 5-20 cm) in the agroforestry system in Sipolha Horisan Village was 338. Coffee is abundant in Sipolha Horisan Village under agroforestry systems due to a combination of geographic, climatic, and soil conditions that are highly suitable for cultivating high-quality coffee, and the potential positive impacts, such as economic benefits, on the community. Furthermore, the largest number of medium-sized plants (dbh 20-35 cm) was found in cocoa (Theobroma cacao) with 31 plants. The fewest medium-sized plants were papaya (Carica papaya), petai (Parkia speciosa), avocado (Persea americana), and guava (Psidium guajava) in the Sipolha Horisan Village agroforestry scheme, each with one plant.

The total number of medium-sized plants/poles (dbh 20-35 cm) was 83. The largest number of large-sized plants/trees (dbh >35 cm) was found in candlenut (Aleurites moluccanus) with 52 trees. The fewest large-sized trees/trees were petai (Parkia speciosa) and jengkol (Archidendron pauciflorum) in the Sipolha Horisan Village agroforestry scheme, each with two trees. The total number of large trees (dbh >35 cm) in the agroforestry scheme in Sipolha Horisan Village was 253.

The tree biomass found in the agroforestry scheme in Sipolha Horisan Village can be seen in Table 2. Tree biomass was calculated using an allometric equation developed by previous researchers, beginning with the felling and weighing of several trees. The allometric equation used is shown in Table 1 (the allometric equation model used).

Table 2. Biomass and Carbon Stored in Understory Plants

Hamlet	Dry Weight (g)	Total Biomass (ton/ha)	Carbon of biomass (ton/ha)
I	1585.91	4.69	2.16
II	1414.73	5.18	2.38
III	2195.16	6.62	3.04
IV	1293.22	3.40	1.56
Total	6489.01	19.89	9.15

The total biomass of understory showed different values among the four hamlets of Sipolha Horisan Village, as illustrated in Figure 2.

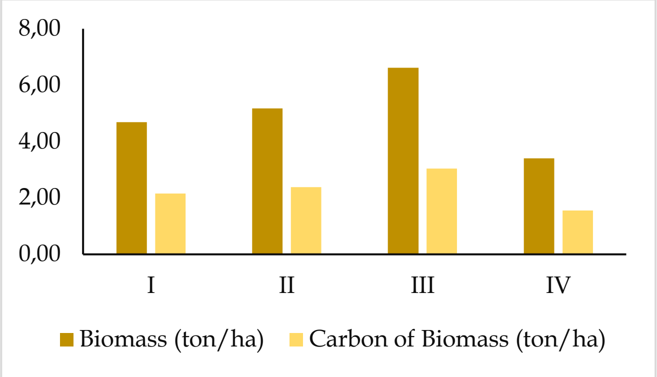

Figure 2. Amount of Understory Plant Biomass and Carbon

The calculation results in the table show that these different biomass values directly reflect the amount and value of carbon obtained. Measurements show that Hamlet IV has the lowest biomass value at 3.40 tons/ha, Hamlet I has a biomass of 4.69 tons/ha, Hamlet II has a biomass of 5.18 tons/ha, and Hamlet III has the highest biomass value at 6.63 tons/ha, resulting in a total biomass value of 19.89 tons/ha for all four hamlets. This difference is attributed to variations in total water content retained in the understory and the total wet weight of each measurement plot.

Based on the calculation of biomass values relative to the total carbon content of the understory, the total carbon (C) value (tons/ha) of the understory in the agroforestry land of Sipolha Horisan Village varies. The measurement results show that Hamlet IV has a low carbon value of 1.56 tons/ha, Hamlet I has a carbon amount of 2.16 tons/ha, Hamlet II has a carbon amount of 2.38 tons/ha, and Hamlet III has the highest carbon value at 3.04 tons/ha. The total carbon content of understory plants in agroforestry land in Sipolha Horisan Village, Simalungun Regency was 9.15 tons/ha. The measurement results show that Hamlet IV has a low litter carbon value of 3.31 tons/ha, Hamlet III has a carbon amount of 4.83 tons/ha, Hamlet II has a carbon amount of 4.96 tons/ha, and Hamlet I has the highest litter carbon value at 5.20 tons/ha. The total litter carbon content in agroforestry land in Sipolha Horisan Village, Simalungun Regency was 18.29 tons/ha. This is because the total water content retained in the litter varies, and the total wet weight varies in each measurement plot. According to Wulandari et al. (2020), the composition of the understory vegetation influences the carbon content and biomass of the understory, including components such as twigs, rotting wood, and leaves above the soil surface.

Biomass and Stored Carbon (Carbon Sink) in Litter

Litter is a component of agroforestry land that can also store carbon. The results of measurements of dead organic matter (litter) in each plot are presented in Table 3 and Figure 3.

Table 3. Biomass and Carbon Stored of Serasah

Hamlet	Dry Weight (g)	Total Biomass (ton/ha)	Carbon of biomass (ton/ha)
I	3699.84	11.30	5.20
II	3005.21	10.78	4.96
III	3530.45	10.50	4.83
IV	2518.17	7.19	3.31
Total	12753.67	39.77	18.29

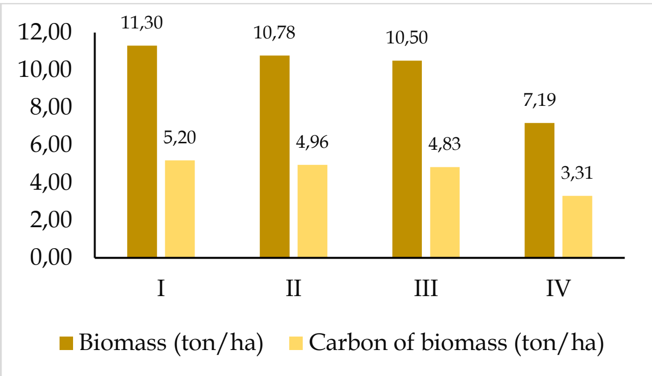

Figure 3. Amount of Biomass and Carbon of Serasah

Total Biomass, Carbon Storage, and Carbon Dioxide Absorption in the Agroforestry Pattern in Sipolha Horison Village

Biomass is the total amount of aboveground living matter in a tree and is expressed in tons of dry weight per unit area (Brown, 1997). The biomass measured includes tree biomass, understory vegetation, and litter in various land-use systems. Biomass is the total amount of aboveground living organic plant matter produced as dry weight of plants per unit area. Total biomass represents the proportion of biomass in plant parts relative to total plant biomass. The results of biomass measurements in the agroforestry system and land use in Sipolha Horisan Village can be seen in Table 4.

Table 4. Total Biomass and Carbon Storage in the Agroforestry Pattern in Sipolha Horison Village

Vegetation Level	Biomass (ton/ha)	Carbon (C) (ton/ha)
Trees	313.18	144.06
Understory	19.89	9.15
Serasah	39.77	18.29
Total	372.24	171.50

Based on Table 4, the measurement results show that understory plants have a lower biomass value of 19.89 tons/ha and a carbon storage of 9.15 tons/ha compared to litter, which has a biomass of 39.77 tons/ha and carbon storage of 18.29 tons/ha. This is because the litter found on the ground surface is a collection of tree parts such as twigs, leaves, stems, fruit seeds and other parts. Meanwhile, understory plants are only dominated by types of herbs and shrubs and low plants that cover the bottom of a forest area. According to Tuah et al. (2017), the high and low biomass and carbon are influenced by the growing location, sunlight, and vegetation that sheds its leaves. This difference in density class is also influenced by vegetation, the environment where it grows, such as humidity, temperature, and land cover type, which can affect the total carbon value of understory plants. At the tree level, the highest biomass value was 313.18 tons/ha with a carbon storage of 144.06 tons/ha.

The high biomass and carbon storage are due to trees having a higher canopy density and greater opportunity to receive sunlight compared to understory plants and litter, thus affecting carbon storage. As explained by Ariani & Wahid (2014), high vegetation density, the overstory plant canopy blocks sunlight from the forest floor, thus inhibiting the photosynthesis process of understory plants. As a result, the carbon content in understory plants and litter is lower than the carbon content in overstory plants. Meanwhile, according to Syam'ani et al. (2012), this is because the photosynthesis process is closely related to the amount of plant biomass. During the photosynthesis process, plants absorb CO_2 from the air and convert it into organic compounds. The results of photosynthesis are used by plants to grow horizontally and vertically, which is indicated by an increase in diameter and height. Overall, the total biomass content in agroforestry land in Sipolha Horisan Village, Simalungun Regency was 372.24 tons/ha and the total carbon storage was 171.5 tons/ha.

The role of trees in agroforestry is considered to have similarities with the potential for carbon absorption in forests through carbon storage sources on the ground surface. The carbon storage of agroforestry is influenced by the composition of large tree stands. A larger average diameter of shade trees will result in greater carbon storage potential (Lestari & Dewi, 2023). Therefore, planning for optimal land use and development is necessary, including selecting tree species with both economic and ecological potential.

Land Use Planning and Village Planning for Agroforestry-Based Land Development in Sipolha Horison Village

In efforts to improve optimal land use based on agroforestry, it is necessary to consider the biophysical conditions of the land, its capability, and it is carrying capacity. Furthermore, it is important to determine which crop types to develop, considering their economic, ecological, and social potential. Research data indicate that the average plant species in Sipolha Horisan Village have varying biomass and carbon storage values. Therefore, planning in selecting species is crucial to increase farmer incomes, contribute to land sustainability, and maintain carbon storage. It is crucial for villages to consider agroforestry planning. According to Septian et al. (2025), agroforestry landscapes are green open spaces capable of storing carbon better than monoculture farming systems. Farmers play a crucial role in increasing carbon storage by selecting the right species for development.

This aligns with the opinion of Arianasari et al. (2021), who stated that farmers can increase their carbon storage value by planting forestry crops and/or using the Integrated Forest Management System (MPTS). This is positively correlated with increased carbon storage and helps enhance the role of community forest farmers in climate change mitigation. Furthermore, Elfis (2024) explains several steps that can be taken in planning and implementing agroforestry-based land use in villages, including: land condition analysis, studying the biophysical aspects of the land, such as topography, soil type, and climate; identification of needs and objectives, adapting the village to farmers' needs, such as food production, timber, or conservation; component selection, selecting the best combination of crops, trees, and livestock; village sketching, drawing the layout, including zoning, planting patterns, and spatial structure; and implementation and monitoring, implementing the village and observing the results to make improvements if necessary.

Furthermore, for land use with an agroforestry system in the Sipolha Horison sub-district, both ecologically and economically, it provides opportunities for optimal land management in developing an agroforestry landscape. The use of agroforestry landscape patterns resulting from land use analysis in the Sipolha Horison sub-district has great potential for increasing and optimizing land productivity and agriculture in a sustainable manner. The importance of selecting tree species as agroforestry components lies in their role in carbon sequestration and in suppressing global warming. Agroforestry can provide opportunities to develop new agricultural landscapes that combine ecosystem services such as carbon mitigation through carbon sequestration and biofuels, biodiversity restoration, and watershed management while maintaining food production (George et al., 2012).

Conclusion

The agroforestry landscape pattern in the Sipolha Horisan sub-district implemented by farmers is an agrisilvicultural agroforestry system, with a random pattern, because agricultural crops and forestry plants are planted irregularly. The potential for carbon storage is influenced by the level of plant growth. At the tree level, the biomass was 313.18 tons/ha and carbon storage was 144.06 tons/ha; for undergrowth, the biomass was 19.89 tons/ha and carbon storage was 9.15 tons/ha; and litter produced a biomass of 39.77 tons/ha and carbon storage of 18.29 tons/ha. In an effort to optimize management and utilization in the Sipolha Horisan sub-district, it is recommended that farmers develop more crop types and local wisdom that have the potential to increase land productivity based on agroforestry landscape patterns and spatial planning, supported by cooperation and collaboration from the government, academics, stakeholders, and farming communities in the implementation and supervision of land management in this area.

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