



Enhancing Regenerative Agriculture Systems in Karst Landscape Based on Biophysical Properties and Farmers' Practices

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Abstract

Conventional farming practices can lead to soil degradation and a decline in productivity. In the era of the climate change, regenerative agriculture (RA) is considered one of the the solutions to these issues. This research aimed to investigate the the potential of RA implementation in areas of Karst in Pacarejo, Semanu, Gunungkidul, Yogyakarta,, based on the existing land characteristicscharacteristics and farmers' practices in the area. Some investigations were conducted through characterisation and observation of biophysical aspects, including soil, vegetation, and water resources,resources, as well as socioeconomicsocial-economic conditions. Some soil physical and chemical properties, vegetative growth of teak trees, and litter accumulation at three different locations in variably sloping lands in the Teak Plantation Station UPN "Veteran" Yogyakarta were investigated. The social and economic conditions of the local farmers were described based on direct discussions and questionnaires handed to 10 farmers. Collected data showed that most soils were generally thin, with similar physical and chemicalchemical properties, and low fertilityfertility, especially in N, P, and K nutrients, and resulting in relatively low growth of the teak trees. However, the living teak plantation and terraces support soil conservation. Farming activities mostly occur during the rainy season and with a limited number of crops to grow. Currently, farmers have been well aware of the need to balance both organic and inorganic fertilizers. In conclusion, these areas can be potentially used for developing regenerative agriculture systems.

Keywords *renewable agriculture, karst ecosystems, thin soils, low nutrient soil, annual crops*

INTRODUCTION

Karst terrain is a crucial landscape for millions of people worldwide, including those in Indonesia. Karst terrain in Indonesia is predicted to cover 154,000 km², or 8% of Indonesia's terrain, which spans thoroughly throughout the country (Haryono et al., 2009; Rahman, 2024).

Karst is a unique ecosystem and extremely fragile (Avrilan et al., 2022). Karst areas have hydrological characteristics characterized by a complex subsurface, natural caves, and high porosity of rock, resulting in high water infiltration. Karst area often functions as a water reservoir for the surrounding community. The karst environment promotes high and unique biodiversity, including endemic flora and fauna that are adapted to the surroundings. Fragile characteristics form karst formations and are associated with hilly and irregular topography, characterized by rocky, shallow, and unworkable conditions, high erosion, restricted plant roots, and infertile soils (Nugroho et al., 2020). These lands are susceptible to a variety of natural and anthropogenic hazards. However, they represent a remarkable natural heritage, and due to the widespread occurrence of carbonate rocks worldwide, they have high economic importance.

As in other countries, most karst areas in Indonesia have long been cultivated as agricultural lands and settlements. Gunungkidul Regency, Yogyakarta Special Regency, is one of the widely known areas, constituting 53% of the total land as karst areas, including the Gunungsewu karst areas. Although there are marginally suitable and unsuitable classes, the entire karst area of Gunungsewu has been cultivated. The lands have very shallow soils, low water-holding capacity,

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and a lack of plant nutrition, resulting in low agricultural productivity ([Avianto et al., 2024](#)). Even farmers extend their cultivated land up to the hill tops. To cope with shallow soils or bedrock, farmers trap the sediments/soils transported by runoff during the rainy season by establishing terraces on the hill slopes; therefore, farmers get more areas of soil-covered land. In this case, crops are grown in soil that is already trapped in terraces.

In the karst area, agricultural activities primarily occur during the rainy season ([Khatimah et al., 2020](#)), with the planting of annual crops such as rice, peanuts, green beans, chilli, and cassava. During the dry season, there are limited perennial trees, such as teak and acacia, or even a complete absence of agricultural activities. Therefore, farmers have to work in non-agricultural sectors, such as industrial sectors in the surrounding cities. [Farikha et al. \(2025\)](#) generally stated that agricultural productivity in the karst area has been very low. Therefore, it is necessary to find suitable agricultural technology to increase food productivity while also protecting the fragile karst terrain from the ongoing effects of global warming.

Based on the descriptions of the natures of karst ecosystems and the agricultural potential of the karst area, it seems that a generative agriculture system can offer safe agricultural activities in the karst area and promote sustainable, higher crop yields. Combinations of annual and perennial crops with livestock in various agroforestry forms can promote better soil quality and its productivity. This small-scale research investigated the biophysical properties of the area and described the traditional farming habits of local farmers, employing regenerative principles of agricultural practices to protect lands in the fragile karst terrains, as well as to promote sustainable productivity.

LITERATURE REVIEW

Characteristics of Karst Lands

Karst is a unique ecosystem and extremely fragile ([Avrilan et al., 2022](#)). Karst areas have hydrological characteristics with a complex subsurface underground, natural caves, and high porosity of rock, which causes high water infiltration. Karst areas often function as water reservoirs for the surrounding community. The karst environment promotes high and unique biodiversity, including endemic flora and fauna that are adapted to the surroundings. Fragile characteristics from karst formation and from hilly and irregular topography with rocky, shallow, and unworkable, high erosion, restricted plant roots, and infertile soils ([Nugroho et al., 2020](#)).

Karst terrains form from the dissolution of carbonate rocks, particularly limestone and dolomite, dissolved by carbonic acid water. This process results in notable landforms such as caves, uvala, ponor, and an underground drainage system. Hydrologically, karst areas have unique drainage patterns with rapid infiltration, causing most water to run through channels and cracks, forming underground rivers. Besides geomorphology and hydrology, karst areas also have specific soils. Soils in the karst area formed from carbonate rock are called Mediterranean or Terra Rossa, characterized by reddish or brownish hues with lower nutrient content. Therefore, soils in karst areas tend to be less fertile for agriculture without appropriate cultivation. Karst forms from the combination of intensive limestone dissolution and high porosity, resulting in high water flow through the ground. Therefore, the underground terrains of the ecosystems have significant water sources, whereas water sources on the surface soils are generally limited; consequently, the surface of the karst is dry and critical. During the rainy seasons, rain drains down through channels or cracks in rocks and accumulates in underground aquifers or rivers. Even in areas with a high amount of rainfall intensity (1875-2125 mm/year), the rainwater cannot be stored or held by soils in hilly terrains.

Karst areas in Indonesia are crucial ecosystems for millions of people, the agricultural sector, settlements, and tourist development. However, these activities also increase environmental

pressure on the karst ecosystem, particularly as noted by [Aprilia et al. \(2021\)](#), higher pollution and pressure increases are occurring in Gunungsewu, Yogyakarta. The dynamics of ecosystems and organisms are closely related to land use and ground cover—for example, in tourist areas with facilities, access roads, buildings, parking spaces, and restaurants. In the agricultural and forestry sectors, the community modifies the karst ecosystem in response to economic and social needs, as well as the preservation of highly valuable vegetation.

Besides their economic, social, and cultural aspects, karst ecosystems offer two important ecological benefits: climate change mitigation and water conservation ([Farikha et al., 2025](#)). Karst ecosystems can trap CO₂ from the atmosphere during karstification processes (karst formation). Absorption of CO₂ from the atmosphere by dissolved atmospheric CO₂ in rainfall by forming bicarbonate acid (H₂CO₃) in water. Acidic water then decomposes limestone into Ca²⁺ and HCO₃⁻ ions. Furthermore, forest vegetation or other crops in karst areas absorb CO₂ during photosynthetic processes. According to [Chen et al. \(2023\)](#), these processes demonstrate carbon sink potential in the short term within the carbon cycle. Therefore, these processes in karst ecosystems are important for controlling global warming.

Another ecological function of the karst ecosystem is water conservation ([Farikha et al., 2025](#)). Although rainwater and surface water in karst cannot be stored in the soil, most of the water drains down into the underground aquifer. It is stored as underground water (aquifer) or flows through a network of underground rivers at various depths, ranging from 77 m to 148 m ([Nugroho et al., 2020](#)). Another ecological function of the karst ecosystem is as a habitat for important natural flora and fauna. The biodiversity of karst areas is unique, particularly in caves, which serve as habitats for several faunas, including bats, crickets, and birds, as well as flora such as species of Asteraceae and Poaceae ([Aprilia et al., 2021](#)). Due to the importance of karst ecosystems for humans and the environment, while they are fragile, the use of karst ecosystems must be carefully managed to protect the entire karst terrain from degradation.

Agricultural Practices in Karst Terrain.

Agriculture is a crucial activity in karst, alongside other human needs, such as settlements, clean water sources, and tourist areas ([Bakri et al., 2023](#)). Most soils in karst areas are generally thin, lying on rocky layers, except those that occupy the bottom of closed depressions or valleys ([Haryono, 2011](#)). Therefore, most karst landscapes are not suitable for any annual crops, and some are marginally suitable for perennial or woody trees. The limited availability of surface water exacerbates these conditions, leading farmers to adopt rain-fed agricultural systems ([Pranata et al., 2023](#); [Farikha et al., 2025](#)).

There are several annual crop species planted during the rainy season, such as rice (*Oryza sativa*), red rice (*Oryza rufipogon* L), groundnut (*Arachis hypogaeae*, L), corn (*Zea mays* L), cassava (*M. esculenta*), chili (*Capsicum frutescens*, L), and sweet potato (*Ipomoea batatas* (L) Lam) in karst areas in Wonogiri ([Farikha et al., 2025](#)). These can be cultivated during the rainy season, but not due to the absence of water ([Pranata et al., 2023](#)). Some perennial crops or tree crops can be grown relatively better in the gardens in both rainy and dry seasons, such as coconut (*Cocos nucifera*), teak (*Tectona grandis*), petai (*Parkia speciosa* Hassk), and acacia (*Acacia auriculiformis*). Some multiple-purpose tree species (MPTS), such as lamtoro (*Leucaena leucocephala* Lam. de Wit) and gliriseda (*Gliricidia sepium* (Jacq. Kunth ex Walp.) were also grown as hedges (fences) in the garden or borders surrounding fields, as for livestock feed ([Farikha et al., 2025](#)). Farmers in the karst area in Wonogiri have practices to avoid harvest failures, particularly by intercroppings, planting several crop species in the same field, such as rice, maize, cassava, and sweet potatoes during the rainy season, while during the dry season they can grow relatively drought-tolerant crops such as peanuts, *C. frutescens*, petai (*P. speciosa*), and *C. longa*.

Based on the above descriptions, it can be concluded that farmers in the karst landscape face similar problems, with most unsuitable lands or marginally suitable for crops being found, particularly due to the natural characteristics of the karst landscape, resulting in low agricultural productivity and consequently low food security in the area. Current and future climate change phenomena may exacerbate these consequences. Therefore, agricultural technology that is suitable for the characteristics of the karst area and can adapt to global warming or climate change is necessary.

RESEARCH METHOD

This research was conducted in a Teak Plantation Located in the karst landscape area with sloping lands belonging to UPN "Veteran" Yogyakarta in Pacarejo Village, Semanu District, Gunungkidul Regency, Special Province of Yogyakarta, Indonesia, from April to August 2025. The sloping lands were divided into three locations based on their altitudes, ranging from 171 to 180 m, 161 to 170 m, and 151 to 160 m above sea level. Biophysical characterization of the area was based on these three locations, while the socioeconomic situations of the farmers were obtained through direct discussions and questionnaires. Coordinates of the sampling locations of the study are presented in Table 1.

Biophysical Aspects

The biophysical aspects characterized in the study comprised soil physical, chemical, and biological properties, vegetative growth of teak trees, litter falls, and local water resources. Three 10-m long & 5-m wide quadrants were systematically established in each location on the sloping karst lands (151-160, 161-170, and 170-181 m above sea level) to calculate the number of teak trees, to measure the diameter of breast height (DBH) of the teak trees, to collect the litter falls on the ground, to take composite soil samples, and to calculate the depths of the soils in the area. Water resource availability was recorded. The teak trees in a quadrant were calculated to obtain the number of trees in a unit area. The amount of litter falling on the soil surface was measured using a 1 m x 1 m frame by cutting all litter fall and lower vegetation and collecting them in a paper bag. Disturbed soil samples were taken using a soil core at a depth of 20 cm, and their soil depths were measured using a soil core until the hardpans within the soil parent materials were reached. Meanwhile, undisturbed soil samples were collected using ring samplers, primarily for bulk density (BD) measurements. The rates of water infiltration of the soils were measured at all three locations.

All composite soil samples were analyzed for soil texture, porosity, permeability, particle density, organic carbon, total and available nutrients (N, P, and K), and pH.

Table 1. Sampling locations in a sloping karst land in Teak Plantation of UPNV in Pacarejo, Semanu, Gunungkidul, Yogyakarta

Land Location (m asl)	Name of the Sample	X Coordinate	Y Coordinate
151 – 160	Sample 1(TS1)	458146,0793	9111862,545
	Sample 2 (TS2)	457938,3173	9111861,529
	Sample 3 (TS3)	458029,7746	9111794,286
161 -170	Sample 4 (TS4)	458055,9214	9111705,271
	Sample 5 (TS5)	457877,4563	9111771,71

Land Location (m asl)	Name of the Sample	X Coordinate	Y Coordinate
171-180	Sample 6 (TS6)	457875,2961	9111618,339
	Sample 7 (TS7)	458031,2111	9111630,898
	Sample 8 (TS8)	457968,583	9111672,778
	Sample 9 (TS9)	457920,2273	9111542,302

Social and Economic of Local Farmers

Social and economic data of the farmers surrounding the Teak Plantation UPN “Veteran” Yogyakarta were obtained from direct interviews and discussions. Fifteen farmers were met and invited to participate in open discussions guided by written questionnaires. The questioners covered following aspects, (i) time to start soil cultivation and how to till the soil, (ii) types of crops to grow and how to obtain seeds or seedlings, (iii) planting patterns, (iv) types of maintenance growing crops and weeding, (v) types and doses of fertilizers, (vi) irrigation types and how to obtain the water, (vii) labor availability, (viii) harvest and postharvest technology of the products, and (ix) net income from the farming.

FINDINGS AND DISCUSSION

Approximately 11 hectares of the Teak Plantation Station UPN “Veteran” Yogyakarta (UPNV) are situated in the karst landscape of the southern part of the Gunung Sewu area. The topography of most areas is complex, with multiple irregularly sloping landscapes, and some small areas are relatively flat or gently sloping. Most of the land area of the station has long been planted with teak trees, and only small parts have been cleared for occasional activities, such as planting experiments, soil science education, and the construction of limited infrastructures and supporting facilities, including water irrigation storage.

Since it was acquired by UPNVY in 2014, this station has been used very little. Therefore, this small research was intended to initiate more valuable and sustainable activities by developing a long-term study on regenerative agriculture systems and their implementation, particularly in the karst landscape ecosystems. For the long term, it can be one of the centers of excellence of the UPNVY. To achieve this idea, a step was taken to characterize the biophysical properties of the land and to partially describe the social and economic aspects of the local farmers who have been living in the environment for years.

Biophysical Properties

The data on some physical properties of the soil are presented in Table 2. Soils in the two upper locations of the sloping lands (161-170 m asl and 171-180 m asl) had the same texture (clay), while in the lowest part had a texture of clay loam. A similar pattern of soil porosity in the two upper parts was slightly better (45.59% and 44.68%) compared to the lowest part of the sloping area, which had good porosity (51.33%). These data showed that soils in the lower parts of the sloping lands had changed due to the accumulation of transported materials from the upper locations. The rate of infiltration was in all locations in the sloping lands.

Table 2. Soil texture, soil depth, soil bulk density (BD), soil particle density (PD), soil porosity, and infiltration in all locations in Teak Plantation UPNVY in Pacarejo, Semanu, Gunungkidul, Yogyakarta.

Land Location (m asl)	Name of the Sample	Texture Class	Soil Depth (cm)	BD (g/cm ³)	PD (g/cm ³)	Porosity (%)	Infiltration rate (m/hr)
151 – 160	TS 1	Loam	>40				
	TS 2	Clay	25				
	TS 3	Clay	27				
		Loam					
Average		Clay Loam	30.67	1.17	2.41	51.33 G	6.26 M
161 – 170	TS 4	Clay	26				
	TS 5	Clay	20				
	TS 6	Clay	20				
Average		Clay	22	1.35	2.48	45.49 SG	5.61 M
171 – 180	TS 7	Clay	10				
	TS 8	Clay	21				
	TS 9	Clay	27.5				
Average		Clay	19.50	1.42	2.57	44.68 SG	3.6 M

Criteria= G=Good, SG=Slightly, Good, M=Medium

The concentrations of the primary nutrients (N, P, and K) availability were the same in all locations in sloping lands in the Teak Plantation UPNVY (Table 3), but in general, soil N availability in all locations was better than P and K availability. Among these nutrients, N is more mobile and can have multiple sources in nature, such as organic matter and various fixation processes. In contrast, P and K primarily come from minerals in the soil. In the karts ecosystem development, the addition of these nutrients from natural minerals did not occur significantly; therefore, in contrast, the loss of these nutrients might have been possible during the karts' dynamics.

Table 3. Macronutrients (N, P, and K) Availability In All Locations In The Teak Plantation UPNVY in Pacarejo, Semanu, Gunungkidul, Yogyakarta

Land Location (m asl)	Name of the Sample	Available N (%)	Available P (ppm)	Available K (me/100g)
151 – 160	TS 1	0.05 L	1.05 L	0.26 L
	TS 2	0.07 M	2.90 L	0.18 L
	TS 3	0.06 M	2.90 L	0.39 L
Average		0.06 M	2.28 L	0.27 L
161 – 170	TS 4	0.06 M	2.25 L	0.19 L
	TS 5	0.06 M	1.01 L	0.26 L
	TS 6	0.07 M	1.01 L	0.22 L
Average		0.63 M	1.42 L	0.22 L
171 – 180	TS 7	0.08 M	1.59 L	0.27 L

Land Location (m asl)	Name of the Sample	Available N (%)	Available P (ppm)	Available K (me/100g)
	TS 8	0.08 M	1.92 L	0.21 L
	TS 9	0.06 M	1.81 L	0.33 L
Average		0.07 M	1.77 L	0.27 L

Criteria: L=Low, M=Moderate

Chemical properties, as presented in Table 4, indicate that the soil pH at all locations on sloping land tended to be similar and neutral. It appears that the acidity of the soil was influenced by the development of the karst ecosystem, also known as karstification, where the accumulation of dissolved carbonate material resulted in a higher pH or a slightly lower one. The soil organic matter content in locations was similar to the texture development discussed above, with more dynamics in the lower parts of the location than in the upper parts of the sloping land. Cation exchange capacity (CEC) tended to be similar, although the upper part of the land was generally higher than the lower parts. While the exchangeable Ca concentrations at all locations were similar, this may have been a continuous result of carification.

Table 4. Soil pH, soil organic carbon (Org-C), soil cation exchange capacity (CEC), and soil exchangeable calcium (ex-Ca) in all locations in the Teak Plantation in Pacarejo, Semanu, Gunungkidul, Yogyakarta

Land Location (m asl)	Name of the Sample	pH	Org-C (%)	CEC (me/100g)	Ex-Ca (me/100g)
151 – 160	TS 1	6.76 N	1.23 L	23.20 M	2.78 L
	TS 2	6.37 SA	0.83 VL	22.00 M	4.23 L
	TS 3	7.37 N	0.57 VL	20.00 M	2.89 L
Average		6.83 N	0.88 VL	21.73 M	3.3 L
161 – 170	TS 4	7.27 N	1.56 L	25.60 H	4.25 L
	TS 5	7.70 SA	1.09 L	24.80 M	3.77 L
	TS 6	7.28 N	0.99 L	22.40 M	1.69 VL
Average		7.42 N	1.21 L	24.27 M	3.24 L
171 – 180	TS 7	7.04 N	1.57 L	26.80 H	2.32 L
	TS 8	7.11 N	1.31 L	26.00 H	2.79 L
	TS 9	7.62 SA	1.16 L	25.60 H	1.09 VL
Average		7.26 N	1.35 L	26.13 H	2.07 L

Criteria: N=neutral, SA=slightly alkaline, L=low, VL=very low, M=medium

Source: Balai Penelitian Tanah, (2009)

From Table 5, it can be seen that teak vegetation exhibited better growth (in terms of a higher number of living plants, larger diameter, and accumulated litter on the surface soil) in the lower parts of sloping land. This might have been associated with better soil properties and better accumulation of organic matter in lower parts, resulting in better growth of teak trees.

Table 5. Number of teak tree, tree diameter, and dry litter fall in all locations in the Teak Plantation UPNVY in Pacarejo, Semanu, Gunungkidul, Yogyakarta

Land Location (m asl)	Name of the Sample	Number of Tree	Tree Diameter (cm)	Litter Fall (ton/ha)
151 – 160	TS 1	16	14,53	1,92
	TS 2	17	14,32	2,23
	TS 3	32	12,58	2,27
Average		21,67	13,81	2,14
161 – 170	TS 4	2	4,14	0,91
	TS 5	11	11,15	1,01
	TS 6	28	27,57	1,77
Average		13,67	14,29	1,23
171 – 180	TS 7	6	8,4	1,43
	TS 8	3	20,6	1,47
	TS 9	2	6,6	1,11
Average		3,67	11,87	1,33

Social-Economic of Farmers

Based on the social economy of the local farmers, it can be seen that they tend to work hard, although with some limitations. The most important limiting factors in farming have been a lack of water, particularly during the dry season. During the rainy season, they can cultivate a greater number of crops, and during the dry season, they sometimes can not grow any crops at all. Farmers have been using both organic and inorganic fertilizers.

CONCLUSIONS

In general, the biophysical properties of the karst landscapes were variably sloping lands with relatively stable conditions. The physical and chemical properties of the soils were relatively similar, with some changes in the lighter textural class, lower organic C concentration, and cation exchange capacity (CEC) in the lower parts of the land. The lower parts of the land were more conducive to the growth of teak trees and the accumulation of litter on the soil surface. Due to the minimal water availability in this karst landscape, farming activities were restricted to only the rainy season. Most crops grown in the area were relatively drought-tolerant species, including rain-fed crops such as rice, maize, peanut, soybean, and cassava. Most farmers have been using both inorganic fertilizers and organic fertilizers; however, they have a better understanding of the needs of organic fertilizers, as they promote soil health and productivity. Based on these biophysical conditions of the land and farming practices by local farmers, regenerative agriculture systems can be gradually adopted by manipulating the biophysical characteristics of the soils in the karst landscapes and improving the capacity of local farmers in the area.

LIMITATIONS & FURTHER RESEARCH

The research limitations in this project were the lack of responses to the questionnaires handed to local farmers and the absence of members of this research team with an agribusiness background. Further study is necessary to improve questionnaires by pre-testing before being handed to farmers and guided by more qualified members of the research team.

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