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Research Paper

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

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Abstract

Conventional farming practices have led to soil degradation and a decline in productivity. In the era of climate change scenario, a regenerative agriculture (RA) is considered as one of solutions to these issues. This research was intended to investigate potential of RA practices in Karst Landscape in Pacarejo, Semanu, Gunungkidul, Yogyakarta based on the land characteristics and farmers' practices in the area. Characterisation of biophysical aspects, including soil, vegetation, and water availability as well as farming practices in the area. Some soil physical and chemical properties, teak trees growth, and litter biomass on soil surface at three different elevations (151-160, 161-170, and 171-180 m asl) in variably slopping lands in the Teak Plantation Station UPN "Veteran" Yogyakarta in Pacarejo were investigated. The farming practices by the local farmers were described based on direct discussions and questioners handed to 15 local farmers. Collected data showed most soils in all elevations were generally similar in physical and chemically properties, with some changes in lighter textural class, lower organic C concentration, cation exchange capasity (CEC) at lower parts of the lands. Lower parts of lands were more conducive conditions to vegetation growth of teak trees and accumulation of litter falls on the soil surface. Farming activities mostly occur during rainy season with rain-fed commodities, namely maize, peanut, cassava, soybean, and rice. Currently local farmers have been well aware of importance of organic fertilizers to maintain soils quality and intercropping. In conclusions, these areas can be potentially used for developing regenerative agriculture systems.

Keywords *renegerative agrciculture, 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 km^2, 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.

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

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cultivated. The lands have very shallow soils, low water-holding capacity, 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.

Beside economy, social, and cultures, ecosystem karst have two important ecolological benefits, such as climate changes and water conservation (Farikha et al., 2025). Karst ecosystems can trap CO_2 from the atmosphere during karstification processes (karst formation). Absorption of CO_2 from the atmosphere by dissolved atmospheric CO_2 in rainfall by forming bicarbonate acid (H_2CO_3) in water. Acidic water then decomposes limestone into Ca^{2+} and $HCO3^-$ ions. Furthermore, forest vegetation or other crops in karst areas absorb CO_2 during photosynthetic processes. According to Chen et al. (2023), in short terms, in carbon cycle these processes show carbon sink potential. Therefore, these processes in the karst ecosystems are important to control 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 karts 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 in an important activities in karst, along with other human needs, such as settelements, clean water source, 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 karts 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 hypogeae*, 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, most unsuitable lands or marginally suitable to agricultural crops to grown particularly due to natural characteritics of the karst landscape, resulting in low agricultural productivity and consequently low food security in the area. These consequnces may will be exaggerated by current and future phenomenon of climatic changes. 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.

Table 1. Sampling locations in three elevation on the slopping karst land in Teak Plantation Station UPNVY in Pacarejo, Semanu, Gunungkidul, Yogyakarta

No.	Elevation (m asl)	Replication*)	X Coordinate	Y Coordinate
1	151 – 160	Sample 1(TS1)	458146,0793	9111862,545
2		Sample 2 (TS2)	457938,3173	9111861,529
3		Sample 3 (TS3)	458029,7746	9111794,286
4	161 -170	Sample 4 (TS4)	458055,9214	9111705,271
5		Sample 5 (TS5)	457877,4563	9111771,71
6		Sample 6 (TS6)	457875,2961	9111618,339
7	171-180	Sample 7 (TS7)	458031,2111	9111630,898
8		Sample 8 (TS8)	457968,583	9111672,778
9		Sample 9 (TS9)	457920,2273	9111542,302

*) Three replications in each elevation

Biophysical Aspects

The biophysical aspects characterized in this study comprised soil physical & chemical properties, teak tree growth, litter falls on soil surface, and water resource availability. Three 10-m long & 5-m wide of quadrants were systematically plotted in each elevation on the variably slopping karst lands (151-160, 161-170, and 1701-181 m asl) 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 surface soil, 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 falls on the soil surface was measured using a 1 m x 1 m wood frame by cuting all litter fall and other lower vegetations and collecting them in a paper bag. Disturbed composite soil samples were taken using a soil core at of 0-20 cm depth, while measuring the soil depths. All composite soil samples were analyzed for soil texture, soil porosity, soil permeability, soil particle density (PD), soil organic C content, and the soil pH, and concentrations of available primary nutrients (N, P, and K). Some undisturbed soil samples were taken using ring samplers especially for bulk density (BD) and soil permeability measurements. Infiltration rates of the soils were measured at all three locations using a double ring infiltrometer method.

Farming Practices

Farming practices data were collected from local farmers living in the immediate areas of the Teak Plantation Station UPN "Veteran" Yogyakarta. There were 15 farmers were met and invited to have open discussions with surveyors guided by written questioners. The questioners covered following aspects, (i) time to start field cultivation (farming activities) and how to till the soils, (ii) types of crops to grow and how to obtain seeds or seedlings, (iii) planting and cropping patterns during a year, (iv) means of maintenance crops such as weeding and pest control, (v) types of fertilizers and their application, (vi) irrigation types and how to obtain the water, (vii) labor availability, and (viii) harvest and postharvest technology.

FINDINGS AND DISCUSSION

About 11 ha area of the Teak Plantation Station UPN "Veteran" Yogyakarta (UPNV) lies in the karst landscape of southern part of Gunung Sewu area, specifically in Pacarejo Village, Semanu, Gunungkidul, Yogyakarta. Topography of most area are complex with multiple irreguler slopping landscapes, with very small area are relatively flat to gentle (4%) and most of the lands area (more than 63%) are steep. Most lands had been planted long with teak trees, and only small parts had been cleared for some occasional activities such as planting experiments, soil science education, and some limited infrastructures such as rest area and water installation.

Practically since it has been belong to UPNVY in 2014, activities in this station have been very limited. Therefore this research was intended to initiate useful and sustainable activites through developing a long-term study on regenerative agriculture systems in the karst landscape ecosystems. For longer purposes, this station and combined with immediate lands can become one of the centers of excellence of the UPNVY. To achieve this idea, this research was as an initial step to characterize biophysical properties of the lands and to partly understand farming practices conducted by local farmers who have been living years in this area.

Biophysical Properties

Soil Physical Properties

The data of some physical properties of the soil are presented in Table 2. Soils in the two upper elevations of the slopping lands (161-170 m asl and 171-180 m asl) had same texture (clay), while soil in the lowest part had texture of clay loam. Soil depths generally increased with lower elevation, due to higher accumulation of transported particles on this area from the upper elevations. Similar patterns of the soil porosity of the two upper parts were slightly good porosity (45.59 % and 44.68%) compared to that of the lower parts of slopping lands good porosity (51.33%). These data showed that soils in the lower parts of the slopping lands had been changed due to accumulation of transported finer materials from the upper elevations. The rate infiltration rates of soil in all location were medium and same all elevations in the slopping 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.

No	Elevation (m asl)	Replication	Texture Class	Soil Depth (cm)	BD (g/cm^3)	PD (g/cm^3)	Porosity (%)	Infiltration Rate (m/hr)
1	151–160	TS 1	Loam	>40	1.17	2.41	51.33 G	6.26 M
2		TS 2	Clay	25				
3		TS 3	Clay Loam	27				
		Clay Loam		30.67				
4	161–170	TS 4	Clay	26	1.35	2.48	45.49 SG	5.61 M
5		TS 5	Clay	20				
6		TS 6	Clay	20				
		Average	Clay	22				
7	171–180	TS 7	Clay	10	1.42	2.57	44.68 SG	3.60 M
8		TS 8	Clay	21				
9		TS 9	Clay	27.5				
		Average	Clay	19.50				

Criteria: G=Good, SG=Slightly Good, M=Medium; BD and PD measured once in all location
^ =Only one measurement; *= Calculated based on BD and PD values,

Soil Chemical Properties

Some chemical properties of the soils at all alevations are presented in Table 3. This table shows that soil pH all elevations in slopping lands tended to be similar, neutral or close to pH 7. It seems that acidity of the soil was affected by processes of the karst ecosystem development or karsification, where accumulation of dissolved carbonate materials had resulted in higher soil pH. Soil organic C contents in all elevations were similar to the textural development as discussed above, where more dynamics in lower parts of elevations occurred than that of the upper parts of the slopping lands, resulting in very low organic C. The CEC tended to be similarly lower at the two lower parts of the slopping lands than the upper parts, and apparently correlated to lower concentration of soil organic C in lower parts of the soils. While the exchangeable Ca concentrations generally low at all locations, 2.07 to 3.24 me/100 g. This might have been due to highly-karsification procceses in this old karst ecosystem.

Table 3. 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

No	Elevation (m asl)	Replication	pH	Org-C (%)	CEC (me/100g)	Ex-Ca (me/100g)
1	151 – 160	TS 1	6.76 N	1.23 L	23.20 M	2.78 L
2		TS 2	6.37 SA	0.83 VL	22.00 M	4.23 L
3		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
4	161 – 170	TS 4	7.27 N	1.56 L	25.60 H	4.25 L
5		TS 5	7.70 SA	1.09 L	24.80 M	3.77 L
6		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
7	171 – 180	TS 7	7.04 N	1.57 L	26.80 H	2.32 L
8		TS 8	7.11 N	1.31 L	26.00 H	2.79 L

No	Elevation (m asl)	Replication	pH	Org-C (%)	CEC (me/100g)	Ex-Ca (me/100g)
9		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=sligtly alkaline, L=low, VL=very low, M=medium (Balai Penelitian Tanah, 2009)

Nutrient Availability

The concentrations of the primary macronutrients (N, P, and K) availability were the same in all elevations on slopping lands in the Teak Plantation UPNVY (Table 4). However, in general soil N availability were classified better (medium) than P and K availability (low) in the all levations of the lands. Among these nutrients, in minerals soils N is generally from various sources, such as organic matter decomposition and different N fixation processes in natures through microbial symbioses or non-sysmbioses. Because of no fertilization activities in the teak plantation, P and K nutrient in the soils could be primarily from minerals in the soil. In this karst ecosystem, the mineral-containing P as well as K sources might be very low or even absence. Contrary, most of these nutrients may have had lost and leached from the soils.

Table 4. Macronutrients (N, P, and K) avalaibility in all elevations in the Teak Plantation UPNVY in Pacarejo, Semanu, Gunungkidul, Yogyakarta

No	Elevation (m asl)	Replication	Availailable N (%)	Available P (ppm)	Available K (me/100g)
1	151 – 160	TS 1	0.05 L	1.05 L	0.26 L
2		TS 2	0.07 M	2.90 L	0.18 L
3		TS 3	0.06 M	2.90 L	0.39 L
	Average		0.060 M	2.28 L	0.27 L
4	161 – 170	TS 4	0.06 M	2.25 L	0.19 L
5		TS 5	0.06 M	1.01 L	0.26 L
6		TS 6	0.07 M	1.01 L	0.22 L
	Average		0.063 M	1.42 L	0.22 L
7	171 – 180	TS 7	0.08 M	1.59 L	0.27 L
8		TS 8	0.08 M	1.92 L	0.21 L
9		TS 9	0.06 M	1.81 L	0.33 L
	Average		0.073 M	1.77 L	0.27 L

Criteria: L=Low, M=Moderate

Vegetative Data

From Table 5, it can been that teak vegetation had better growth (better number of living plants, bigger stem diamater, and more litter accumulation on the surface soil) at lower parts of the slopping land. This might have been associated with better soil physical properties such as textural class of clay loam and good porosity in lower parts of slopping lands, resulting better growth teak trees and more accumulated litter fall on the surface soil.

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

Farming Practices

Based on the collected data from questioners and discussions with local farmers, it could be sumarized that within a year farmers in this area grew several annual crops, particularly rice, maize, peanut, soybean, and cassava. The field activities were usually started from late dry season by preparing land and further during the rainy season the lands were cultivated intensively. Most farmers worked in a field manually and only some farmers used a hand tractor to till the fields. Generally the cropping patterns involved rice, maize, peanut, soybean, and cassava. Usually rice was grown monoculturally in the early rainy season, while the following vegetables were grown using multiple cropping patterns, by planting more crops within the same land. Rice seeds were usually bought from market, while some vegetable crops could be self-sustained from previous season. One of the particular important inputs of the farming practice was fertilizers. Most farmers have been using inorganic fertlizers such as urea, NPK, KCl, ZA, TSP, and phonska. Nevertheless most farmers also usually organic fertilizers such as compost and green manure, coming from livestock. All farming activities in the area involved all family members; and therefore they did not account the expentitures for labor for farming activites. Water availability in this karst landscape has been a long-limiting factor for agricultural activity, therefore farming parctices depend largely on the rainfall during the rainy season. Actually a potential water resource had been identified and found in the lowest elevation of the karst land in the Teak Plantation UPNVY called Luweng, a geological object as a part of underground water drainage systems (Ediyanto et al., 2021).

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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