Global J. Environ. Sci. Manage. 10(1): 267-286, Winter 2024, Serial #37

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Root growth and arbuscular mycorrhizal fungi on woody plants for vegetative stabilization of tropical slopes

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ARTICLE INFO

Article History:
Received 08 January 2023
Revised 13 March 2023
Accepted 18 May 2023

Keywords:
Arbuscular Mycorrhizal Fungi
Bamboo
Nutrient uptake
Root direction
Tree-root growth
Woody plants

DOI: 10.22034/gjesm.2024.01.17

ABSTRACT

BACKGROUND AND OBJECTIVES: Arbuscular mycorrhizal fungi improve plant growth but have not been studied for slope stabilization. Inoculation of these fungi and bamboo intervention can enhance root growth toward the slip plane. The study tests tree roots' responses to seeding in bamboo tubes and the fungi consortium.
METHODS: The growth of three fast-growing native Indonesian woody plants: *Paraserianthes falcataria*, *Acacia mangium*, and *Gmelina arborea*, was monitored in a screen house. These plants were seeded in bamboo tubes containing soil from Jati Radio and Citatah. The tubes were placed on an inclined plane resembling a 20o slope. Arbuscular mycorrhizal fungi were added in three doses and controlled by the plots without mycorrhiza and bamboo.
FINDINGS: The results showed that bamboo could direct root growth toward the slip plane. The best arbuscular mycorrhizal fungi inoculation results were obtained in Gmelina arborea with a treatment dose of M3 or 30 grams on Jati Radio and Citatah soils. Both treatments did not show significant differences in both locations.
CONCLUSION: *Gmelina arborea* has the highest phosphorus absorption at 80 percent and the highest biomass weight at 660 grams with M3 dose in Citatah, and 71 percent with 330 g at the same dose in Jati Radio, which is related to the optimal level of arbuscular mycorrhizal fungi inoculation. Therefore, this species provides the best option for implementing biotechnological strategies to stabilize slopes in areas prone to landslides. Combining bamboo with arbuscular mycorrhizal fungi can direct and accelerate root growth, with the goal of crossing landslide slip planes.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
57	9	5

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Note: Discussion period for this manuscript open until April 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Climate-related disasters are expected to become more common in the coming years due to climate change. Climate change is expected to increase the frequency and intensity of extreme precipitation, resulting in landslide occurrence (Lin *et al.*, 2020). Shifts in precipitation patterns caused by climate change contribute to an increase in the frequency of shallow landslides (Guo *et al.*, 2023). Soil conditions, morphology, vegetation cover, and land use, all contribute to the site conditions that cause shallow landslides (Masi *et al.*, 2023). In Indonesia, from 1815 to 2019, disaster events were dominated by climate-related disasters, comprising floods with 10.438 events, landslides with 6.050 events, droughts with 2.124 events, and forest fires with 1.914 events (Yulianto *et al.*, 2021). Mitigation of landslide hazards depends on understanding the causes and triggering processes, which depend directly on soil properties, land use, and changes over time (Fiolleau *et al.*, 2023). Slopes are the main topographic drivers for landslides, soil erosion, and nutrient loss (Abdalla *et al.*, 2020). Vegetation stabilizes steep slopes, especially by increasing soil cohesion (Phillips *et al.*, 2021). However, vegetation cover changes over time due to natural processes and land management practices or disturbances such as forest fires (Rengers *et al.*, 2020). Vegetation restoration can reduce runoff and soil loss and increase solid organic carbon content (Yang *et al.*, 2023). Deep-rooted vegetative cover is a potential solution to stabilize newly constructed slopes or repair shallow landslides (Asima *et al.*, 2022). Plants, soil physical properties, thickness, and lithology stratigraphy are critical components. The aboveground parts of plants may limit erosion by intercepting raindrops and retarding surface runoff. Roots may help stabilize soil while reducing its water content through absorption and transpiration. However, it is not easy to improve slope stability through the growth of plants without detailed and in-depth knowledge of slope movements, soil properties, and the plants themselves. This study describes the experimental manipulation of the tree-root growth of three woody plant species native and economically beneficial to Indonesia, *Paraserianthes falcataria, Acacia mangium, and Gmelina arborea,* as a strategy for reducing shallow landslide hazards. Using arbuscular mycorrhizal fungi (AMF) and bamboo, were encouraged roots to grow downward across imaginary slip planes, and were induced roots to increase the overall shear strength of the soil. A study on plant manipulation using these methods for landslide mitigation has not been performed elsewhere. In this study, AMF was intended to trigger and accelerate the growth of roots and plants. AMF is the most common fungus in the terrestrial ecosystem and forms a symbiotic relationship with the plant roots belonging to Glomeromycota (Thiergart *et al.*, 2019). AMF infects the host plant's root system to produce external hyphae tissue that grows expansively and penetrates the subsoil layer, thereby increasing root capacity in nutrient and water absorption (Fattahi *et al.*, 2021). The role of AMF in increasing the availability and absorption of P and other nutrients through the following process mechanisms: 1) chemical modification by mycorrhiza in the process of soil P solubility so that plants exudate organic acids and acid phosphatase enzymes which accelerate the process of P mineralization. Root exudation occurs as a response of plants to P-deficient soil conditions, which affects the chemistry of the rhizosphere; 2) the diffusion distance of the phosphate ions can be shortened by the external hyphae of AMF, which can also function as phosphate absorbing and translocation tools; 3) P absorption still occurs in mycorrhizal plants even though it is below the minimum concentration where the roots are no longer able to absorb P and other nutrients. This process occurs due to higher external hyphae affinity or increased attraction of phosphate ions which causes faster P movement into the AMF hyphae (Bahadur *et al.*, 2019). The role of AMF affects soil health and nutrient cycling in tropical slope environments. AMF plays an essential role in the conservation of nutrient cycles, helps to improve the soil structure (Fall *et al.*, 2022), transports carbon in the root system (Busso and Busso, 2022), overcomes the degradation of soil fertility (Sekar *et al.*, 2019), and protects plants from disease (Hou *et al.*, 2022). AMF is a group of fungi belonging to the phylum Glomeromycota, which live in symbiosis with plant roots (Husna *et al.*, 2022). Root infection obtained the best results in infecting roots when the plants began to adapt to the growing media because the roots in the soil have started to grow a lot or evenly in the roots so that AMF can infect more effectively. The optimal dose of AMF for woody plants is 20 g/plant containing approximately 200–250 spores (Rini *et al.*, 2021). The optimal time of inoculation and dose of AMF accelerated plant growth. Research by Khan *et al*. (2021) explained that AMF inoculation in the form of root pieces could increase the dry weight of shoots of signal grass by 0.15 gram (g) and the root dry weight by 0.06 g compared to plants without AMF. *Gmelina arborea*, *Acacia mangium*, and *Paraserianthes falcataria* are fast-growing, adaptable, and versatile plants that have invaded beyond their native areas (Koutika and Richardson, 2019). Taproots in woody plants grow downward parallel to plant growth. New lateral roots can be produced by the parent root at any stage of development, at any location along the parent root axis, and whenever necessary to modify the architecture of the root system in response to environmental stimuli (Montagnoli, 2019). The state of the art of root growth direction modification was performed using bamboo pots placed on a simulated inclined plane resembling a 20° slope. The bamboo pot method is combined with AMF to stimulate root growth. The bamboo is installed not in the form of a tube but in bamboo sticks which are placed around the tree in a certain diameter. For example, the estimated diameter is 0.5–1 m and the depth is adjusted to the depth of the slip plane at the site. Around the plants bordered by bamboo, soil is added with compost and AMF, which acts as a biological fertilizer. Thus, to a depth of more than 30–45 centimete (cm), nutrients are still used for growth until the time limit for root growth to come out of the bamboo circle and penetrate into the slip plane. Planting trees will have a good reinforcement effect on 20° and 35° slopes (Lan *et al.,* 2020). The proposed combined methods are breakthroughs in slope reinforcement and can be applied to prevent landslides. The growth of the root system is usually very plastic and acclimatized in response to specific stresses, for example, physical, soil chemical, or mechanical. Roots can respond to mechanics of varying strength. On steep slopes, the source of root strength is primarily located in the lower slope quadrant and is followed by the wind direction quadrant. The cross-sectional area of the roots at the point of attachment of the lateral roots to the taproot is more comprehensive in the lower slope quadrant. The critical role of roots is anchoring trees to the soil where they grow (Montagnoli, 2019). Roots can change the direction of growth in response to mechanical forces and other environmental influences (Bujoczek *et al.*, 2021). The direction of root growth was modified using a bamboo tube placed on an inclined plane. Landslides on unstable slopes greater than 30° require appropriate bio and eco engineering techniques (Lan *et al*., 2020). AMF has been widely used to enhance plant growth but is not intended for slope stabilization. Research on AMF inoculation for the improvement of lemongrass plants has been carried out by De Souza *et al.*, (2022). Combining bamboo tubes with AMF to stimulate root growth and direction provides a new technique for further landslide disaster mitigation that can be used on slopes to prevent landslides. Planting on sloping land has been conducted using various techniques, for example, palisades, brush layering, bamboo fences, and grass planting (Suresh and Dwivedi, 2022). However, this technique has a weakness: the direction of root growth does not reach deep; thus, the lower soil is easily eroded by water, and the plants fall easily. The technology of using bamboo to direct root growth and stimulate root growth with AMF is a breakthrough and a novelty of this study. There is currently no literature on these methods in other publications. Furthermore, because the plants have spread globally, the findings of this study have the potential to be widely used. Some fungi are infectious diseases if they penetrate cells (Jangjou, *et al*., 2019), but AMF benefits plant growth. Concerning fungi, AMF has also been widely used in improving nutrient crisis land (Asmelash *et al*.,2016). One of the causes of landslide-prone soil is in terms of the physical and chemical conditions of the soil so that plants do not thrive. Conditions like this can be corrected in advance with biochar. Biochar is a black carbon sorbent that can stabilize organic substances in soil (Yavari *et al*., 2022a). Biochar, a carbon-rich bio-sorbent, has shown its ability to stabilize organic substances in soils and, therefore, potentially can reduce their leaching (Yavari *et al*., 2022b). The experimental set-up in this study emulated conditions in slide-prone areas in Indonesia, where landslides and debris flows compose large proportions of the yearly disasters. The experiment replicated the slide-prone areas of Jati Radio (JR) and Citatah (CT) in West Java, where both regions have experienced landslides. This study aimed to test the effectiveness of several AMF doses, determine the appropriate dose to increase root growth and use bamboo tubes to modify the root growth direction. The most significant results are the correct dose of AMF and the environmentally friendly technique to modify the direction of root growth for further plantings on a slope to mitigate landslide disasters. This study was conducted in JR and CT, West Java, Indonesia in 2021.

MATERIALS AND METHODS

Field landslide observations

Field observations for this study were performed in two Indonesian areas where shallow landslides had occurred: Citatah Town, Cipatat District, and Jati RadioTown, Cililin District. Both are located in the West Bandung Regency of West Java Province, Indonesia. The observations in the field were focused on the geology of landslides. A simple geological model of the landslides was developed based on the observations. The model guided experiments in a screened house.

Artificial plant-root growth and growing media

The experiment was conducted in a screen house of plastic-screened bamboo with a 65 percent (%) paranet shade. The screen house was first designed and constructed to resemble the conditions of the two landslide models, CT and JR. A split plot design was used in a randomized block design, with three replications for each treatment. One plot was designed for the slope movement model for CT, and the other for JR. The CT plot was filled with bentonite clay, corresponding to the slip plane lithology in CT. The JR plot, by contrast, was filled with igneous rock clasts in the form of gravel with a small amount of sand as the slip plane in Jati Radio. The identification of mycorrhiza spores was performed in the laboratory. In this study, soil for growing media was collected from the two landslide areas, CT, and JR. The growing medium used was a 3:1 mixture of soil and compost. This medium was placed inside bamboo tubes. The bamboo's bottom was slanted, mimicking the slope in the field with a slope angle of 20°. The tube was 25 cm long on the short side and 30 cm long on the long side, with diameters ranging from 8 to 9 cm, allowing root growth to be directed vertically during the early stages of development. The plants were growing vertically as normal. In the experiments, the base of the bamboo was inclined to replicate the slope in the field. This is due to the slope which is a factor that influences the asymmetrical belowground development of the root (Wang *et al*., 2023). For 4 months, all seedlings were enclosed in a screen house. The control plots refer to plots without AMF and not using bamboo tubes but polybags.

Plant species

Three species of woody plants were used in this study: *Paraserianthes falcataria*, *Gmelina arborea*, and *Acacia mangium*. The plant seeds used were seedlings measuring 20 cm in height. These plants can be found in CT and JR. These fast-growing plants are essential for protecting against landslides as they can mitigate the risk faster. In addition, these trees offer economic benefits to the local community.

Inoculum

Endogenous mycorrhiza, also known as AMF, was used in this study. The number of spores per 100 g of mycorrhiza consortium contained in the packaging was *Glomus* sp., 766 spores; *Glomus moseae,* 168 spores; *Scutellospora* sp., 29 spores; *Acaulospora* sp., 23 spores; *Gigaspora* sp., 11 spores; and *Gigaspora margarita,* 9 spores. The following four dosages were prepared: M0 = without mycorrhiza, M1 = 10 g containing ± 100 spores, M2 = 20 g containing ± 200 spores, and M3 = 30 g having ± 300 spores. M0 refers to the control plot without mycorrhiza. The dose determination for this experiment was based on the results of a previous study in which the best dose was micro aggregates (200–250 spores), equivalent to 20 g/plant (Rini *et al*., 2021). The dose is given once at the beginning of planting woody plant seeds.

Plant height and biomass weight observations

Plant height was measured on all plots to monitor plant growth. Measurements began at the start and continued every 2 weeks until the experiment concluded at week 16. The length was measured from the stem's base to the growing shoots' tip. Root growth was not observed every 2 weeks because removing the plants from the medium and replanting them caused them to wither and even die. Root length measurements were taken at the beginning and end of the experiment. At the end of the observation, plant biomass, including roots, shoots, and leaves, was measured by cutting plant samples.

Root observation

Fresh roots were cut into 1 cm fragments, washed, and cleaned in 10% KOH at 90°C for 2 h. The segments were acidified with 5% lactic acid for 20 min, stained with 0.05% weight per volume (w/v) Trypan blue for 30 min at 90°C, and then microscopically observed for root mycorrhiza colonization. The frequency of fungal structures in the root fragments (F%) and the intensity of the mycorrhiza colonization (M%) were evaluated in 20 randomly chosen root fragments (1 cm length) per glass slide, repeated five times for each sample. Mycorrhiza parameters (F% and M%) were calculated according to Alhadidi *et al*. (2021). The root growth direction was observed at the end of the experiment, on the 16th week after planting. The comparison was observed between plots using bamboo and those without bamboo.

Percentage of nutrient uptake (%)

The percentage of nutrient uptake was calculated based on the analysis of the initial and final soil samples. The nutrient parameters analyzed were mainly nitrogen (N), phosphorus (P), and kalium (K). The difference in the nutrient content in the initial soil samples and at the end of the experiment was the value of nutrients absorbed by plants.

Experimental design and data analysis

Subplots were designed for the two main plots of JR and CT, and each main plot received four doses of mycorrhiza (M0, M1, M2, and M3). In the two main plots, 12 treatment combinations were used, consisting of 4 doses of AMF and 3 species of woody plants. Each treatment was repeated three times for 36 plants observed. The SAS 9.4 variance program was used to analyze the results. The analysis results were then used Duncan Multiple Range Test at 5% to perform if the treatment was significantly affected. Numbers followed by the same letter on the row show no significant difference at the level of F 5%. The F test is a test that measures the magnitude of the difference in variance between the two groups, namely the CT and JR soils, which received the addition of AMF treatment.

RESULTS AND DISCUSSION

Citatah landslide

The landslide in CT, according to Johnson *et al.* (2023) classification, corresponds to a complex type, changing from a debris slide to earth flow. The slope is quite steep, measuring around 35° on the uphill side, 23° in the middle, and 10° on the foothill side. The lithology is layered sedimentary rock consisting of sandstone, siltstone, claystone, and sedimentary breccia. The thickness of the soil ranges from approximately 3–5 m. The soil was formed by the weathering of these underlying rocks and by amendments from landslides. The degree of weathering can be seen in the field, with the weathering level being completely weathered near the ground surface and slightly weathered in the depth. The landslides event was triggered by rainfall and the conversion of vegetation cover from forest to mixed plantation, shrub, and bushes. The CT landslide can be described as a debris slide to earthflow or a sand/silt/debris flowslide. Sedimentary rock, primarily siltstone and claystone, exists at the bottom of the landslide, and moderately to completely weathered rock or soil with a 3–5 m thickness lies above it. The slip plane is claystone, and siltstone lies at the boundary between weathered and slightly weathered rock. The CT landslide can be seen in Fig. 1a.

Jati Radio landslide

The landslide in JR was triggered by rainfall and was likely promoted by the human removal of vegetation. The landslide was additionally controlled by hydrogeological conditions, in which the bottom topography of the land that slide is a channel like structure. The slope exceeds a 40° height on the slope and diminishes downward to approximately 20° at the foot of the slope. The hill is composed of andesitic rock that is both jointed and weathered. The upper reaches have in situ soil, whereas the lower reaches have much soil transported by slopewash and slope failure. The soil thickness in the upper and middle hills ranges from a few tens of centimeter to 2 m, while, at the bottom of the hill, the thickness of the soil reaches more than 5 m. The slip plane is underlain by fresh or unweathered to slightly weathered andesite, and is overlain by slightly to completely weathered rock or soil above it. The vegetation covering the area is a mixed forest interspersed with seasonal crops planted by people. The simple model of the JR landslide can be described as earthflow or sand/silt/debris flowslide. Andesitic rock forms the foundation, and moderately to completely weathered rock or soil lies above it, with a thickness of up to around 2 m. The slip plane is the boundary between slightly weathered rock and soil. The JR landslide can be seen in Fig. 1b.

(a) (b)

Fig. 1: Landslides in Citatah (a) and Jati Radio (b) with the crowns on top

Table 1: Results of analysis of CT and JR soils

Parameter	CT		JR	
	Results of analyses	Criteria	Results of analyses	Criteria
pH H_2O (1:5)	5.9	acid	5.3–6.8	Acid-neutral
C organic (%)	2.98	low	1.17–1.72	Low
N total (%)	0.28	low	0.11–0.19	Low
C/N ratio	11	low	9	Low
P_2O_5 (ppm)	7–7.2	low	6.6–11	Low
K_2O (ppm)	430	high	348	High
Grain size: (%)				
Gravel	0–0.59		0.41–0.50	
Sand	7.46–14.91	Clayey silt	9.86–11.95	Sandy silt
Silt	67.59–72.95		76.14–80.63	
Clay	17.5–19		9–11.5	

Growing media

According to the soil analysis results (Table 1), the CT and JT fertility level and C/N (carbon per nitrogen) ratio are low to moderate. Soils' C/N ratios should be increased so plants can absorb nutrients directly. This was accomplished by adding compost at a 3:1 soil-to-compost ratio. Compost can also help to improve the structure of soil media. Grain size analyses revealed that the JR soil was coarser than the CT soil. Soil observations in the field also demonstrated by the grain size macroscopically.

The results of CT and JR soil analysis showed that both soils were acid-neutral with a pH between 5.3 and 6.8. While organic C, total N, C/N ratio and P_2O_5 showed low values. Conversely, K_2O shows a high value. Grain size based on gravel, sand, silt, and clay criteria indicated clayey silt on CT and sandy silt on JR.

Paraserianthes falcataria *Acacia mangium* *Gmelina arborea*

Fig. 2: Physical growth of *Paraserianthes falcataria, Acacia mangium, and Gmelina arborea* at the end of the experiment, namely in the 16th week after planting

Plant growth and height observations

The physical characteristics of *Paraserianthes falcataria*, *Acacia mangium*, and *Gmelina arborea* were observed regularly every 2 weeks. The physical growth of the plants exhibited a positive response, appeared to grow well and showed no plant nutrient deficiency (Fig. 2). An increase in plant height is markedly correlated with an increased number of leaves that grow on each stem. Root growth is also strongly correlated with the development of plant height. The growth of stunted plants is also correlated with the slow growth of roots; vice versa, the growth of fertile plants also shows the development of abundant roots. Cao *et al.* (2020) also discovered that the root growth rate is strongly related to the number and area of leaves, demonstrating that these plant organs are interconnected in photosynthesis. Trees continuously adapt the spatial distribution of the roots in response to environmental conditions through new lateral roots, changes in the growth direction, and wood production reactions (Montagnoli, 2019). In this study, the mycorrhiza showed a positive effect on plant growth. Plants have grown significantly as a result of the optimal mycorrhiza doses. Fig. 3 depicts the plant height growth trends up to 16 weeks. Pearson's correlation revealed a similar trendline in all CT and JR plots.

The variance analysis showed that treatments mycorrhiza doses of *Paraserianthes falcataria* were not significantly different in both main plots of JR and CT, and the best dose was M3. Similarly, *Gmelina arborea* treatments were not significantly different in the two locations, and the best dosage was also M3. However, for *Acacia mangium*, neither area was significantly different, and all doses had a positive effect.

Biomass weight analysis

Wet biomass weight was measured to determine the effect of the mycorrhiza intervention on root growth 16 weeks after planting. The results of the analysis are presented in Table 3. The table shows the wet weight of the biomass of *Paraserianthes falcataria* and *Gmelina arborea* showed extreme growth with the best mycorrhiza dose, M3, except for *Acacia mangium*, which showed the best mycorrhiza dose, M1. The wet weight of the root biomass from these three woody plants was compared to that of the control. The table shows that plants infected by mycorrhiza had a higher wet biomass than controls.

The plots in a polybag (C) and bamboo (M0), both without AMF, at the two sample locations (JR and CT), showed no significant difference in biomass weight. Only *Acacia mangium* planted in CT soil was better in bamboo than polybag plots.

The abundance of mycorrhiza species

The positive effect of the mycorrhiza intervention on root and plant growth was also shown by the infection of the three woody plant species. At the end of the experiment, 16 weeks after planting, samples were taken from the two main plots, the CT and JR plots, by choosing the best-growing plants. The results obtained from laboratory observations

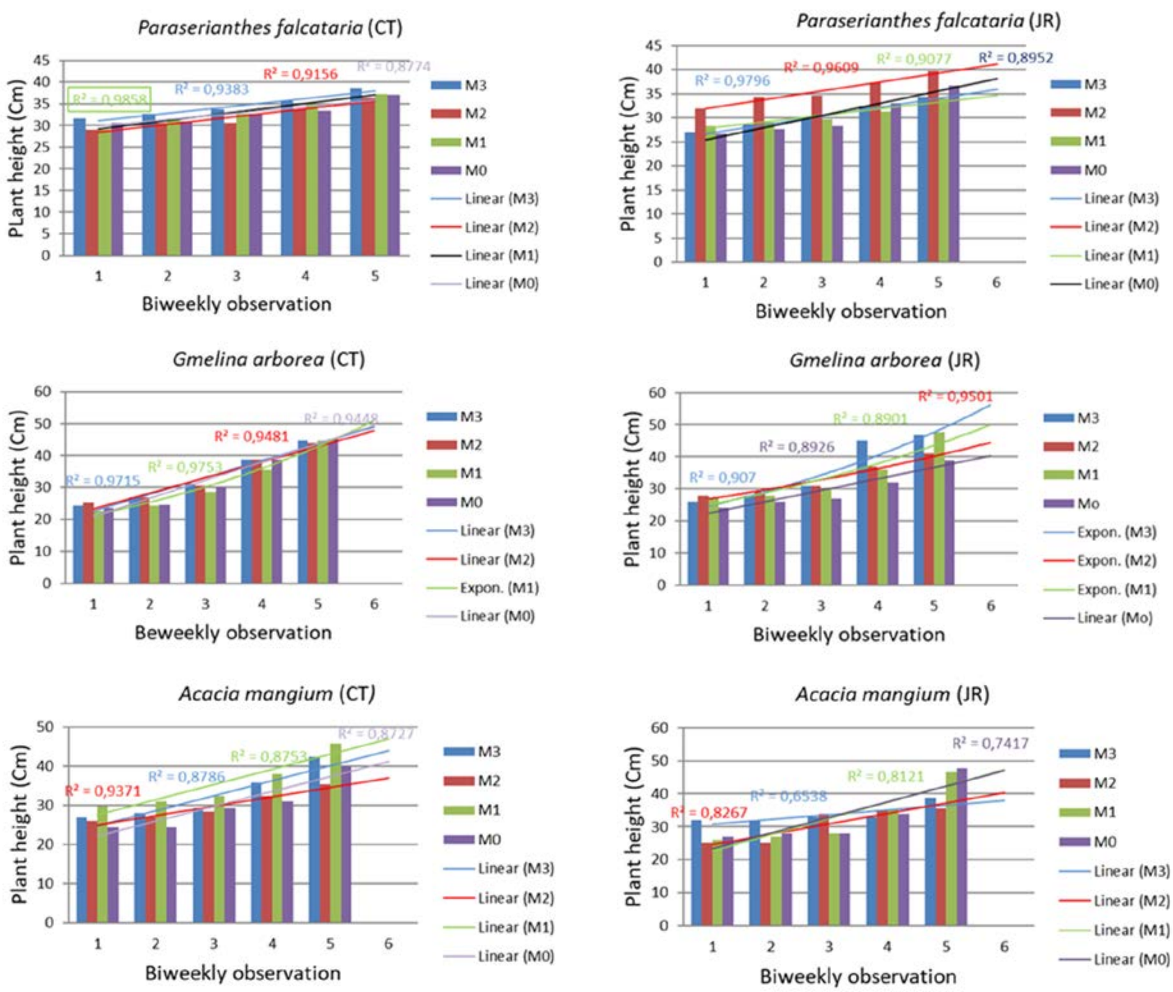

Fig. 3: Effect of mycorrhiza doses on plant growth with height characteristics of *Paraserianthes falcataria*, *Acacia mangium*, and *Gmelina arborea* in CT and JR plots.

Table 2: Effect of mycorrhiza doses on the average plant height of the woody plants.

Locality	Plant species	Mycorrhiza doses			
		M0	M1	M2	M3
CT	*Paraserianthes falcataria*	70.33 c	63.33 c	87.66 b	95.66 a
	Gmelina arborea	95.66 a	97.33 a	71.66 b	100.33 a
	Acacia mangium	8.66 a	88.33 a	73 b	84.66 a
JR	*Paraserianthes falcataria*	68 b	71.33 a	65 b	76.66 a
	Gmelina arborea	55.66 c	97.66 a	85.66 b	94.33 a
	Acacia mangium	81.66 a	79.66 a	56.66 b	63 b

Note: Numbers followed by the same letter on the same row show no significant difference at the level of F 5%.

are shown in Table 3. The highest level of mycorrhiza infection occurred in the roots of *Gmelina arborea* with the treatment level of M3 mycorrhiza in CT two plots, which reached 67.4%, with the highest wet biomass weight of 660 g. However, it was not significantly different from the M3 treatment in JR plots. The predominant mycorrhiza in both locations' soil samples were *Glomus* sp. and *Gigaspora* sp. The diversity of mycorrhiza species affects nutrient uptake, increasing the growth rate. Table 4 shows that the number of mycorrhiza species *Glomus* sp. and *Gigaspora* sp. in the soil of both locations (CT and JR) planted with *Acacia mangium* was significantly lower than that of *Gmelina arborea* and *Paraserianthes falcataria*. The low number of *Glomus* sp. and *Gigaspora* sp. spores led to the slow growth of *Acacia mangium* (Table 4), which was also indicated by the weight of the biomass at the end of the experiment (Table 3). The macroscopic observations and laboratory tests showed that JR soil is coarser than CT soil (Table 1). The coarser grain is why *Glomus* sp. *and Gigaspora* sp. develop healthily, because their hyphae can spread more widely. AMF's ability to absorb water from soil pores is due to the smaller and more delicately branching mycorrhiza hyphae outside the roots, with a diameter of approximately 2 µm.

Table 3: Biomass weights of the three plants species

No.	Locality	Plant species	Control (Plot without AMF)		AMF dose (Plot with bamboo)			
			Media code	Wet weight (g)	Media code	Wet weight (g)	Media code	Wet weight (g)
1	Citatah	*Paraserianthes falcataria*	C	105b	M0	153b	M3	205a
		Gmelina arborea	C	205b	M0	396b	M3	660a
		Acacia mangium	C	80b	M0	82a	M3	80b
2	Jati Radio	*Paraserianthes falcataria*	C	65b	M0	76b	M3	105a
		Gmelina arborea	C	310b	M0	316b	M3	330a
		Acacia mangium	C	105b	M0	164a	M1	165a

Table 4: Number of mycorrhiza spores in the roots of the three plant species in CT and JR soils

CT			JR		
Sample code	Species	Number of spores	Sample code	Species	Number of spores
Pf-M3	*Glomus* sp.	598a	Pf-M3	*Glomus* sp.	698a
	Gigaspora sp.	102a		*Gigaspora* sp.	72a
	Scutellospora sp.	15b		*Scutellospora* sp.	11a
	Acaulospora sp.	21a		*Acaulospora* sp.	13a
Am-M1	*Glomus* sp.	458b	Am-M3	*Glomus* sp.	646b
	Gigaspora sp.	98b		*Gigaspora* sp.	66b
	Scutellospora sp.	26a		*Scutellospora* sp.	10b
	Acaulospora sp.	22a		*Acaulospora* sp.	9b
Ga-M3	*Glomus* sp.	589a	Ga-M3	*Glomus* sp.	708a
	Gigaspora sp.	112a		*Gigaspora* sp.	74a
	Scutellospora sp.	18b		*Scutellospora* sp.	12a
	Acaulospora sp.	20b		*Acaulospora* sp.	14a

Note: Numbers followed by the same letter on the same column show no significant difference at the level of F 5%.

Root growth direction

At the end of the experiment, 16 weeks after planting, observations were made in the direction of root growth for all plants. The bamboo tube intervention on the root growth direction was intended to direct roots downward across the imaginary slip plane and anchor the plants in the underlying rock. The experimental results showed that the roots of *Paraserianthes falcataria, Acacia mangium,* and *Gmelina arborea* followed the bamboo shape to grow in a vertical direction downwards (Figs. 4, 5, and 6). The directed growth occurred in all plots with bamboo tubes but did not occur in the control plot without the bamboo intervention. Roots change growth direction due to mechanical forces (Montagnoli, 2019).

Nutrient uptake

The calculation results for the nutrient uptake percentage were obtained from the best-growing plants. The symbiotic responses of AMF and suspected plants showed differences in nutrient uptake. Results of Duncan's analysis showed a significant difference between *Gmelina arborea* and the two other plants, *Paraserianthes falcataria* and *Acacia mangium*. *Gmelina arborea* showed the best response in CT and

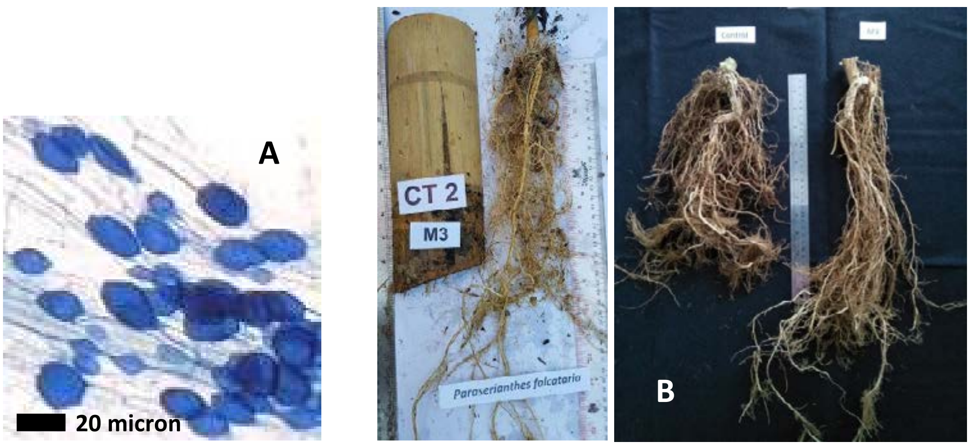

Fig. 4: (A) Mycorrhizal infections in *Paraserianthes falcataria* roots (M3). (B) AMF (M3) and *Paraserianthes falcataria* symbiosis planted in CT soil with a bamboo tube at 16 weeks old. The bamboo modified the root growth and grew longer than the control

Fig. 5: (A) Mycorrhizal infections in *Acacia mangium* roots (M3). (B) AMF (M3) and *Acacia mangium* symbiosis planted in CT soil with a bamboo tube at 16 weeks old. Bamboo strongly affected root growth. Roots grown without bamboo tubes grew heavier than those grown with bamboo tubes.

Fig. 6: (A) Mycorrhizal infections (M3) in the roots of *Gmelina arborea* plant. (B) The symbiosis of AMF (M3) and *Gmelina arborea* planted in JR soil with a bamboo tube at 16 weeks old. The bamboo-modified roots grew longer and more extensively than those without bamboo

Table 5: Percentage of nutrient uptake in an AMF-woody plant symbiosis.

Nutrient	Woody plant species	Soil before experiment		Soil after experiment		Nutrient uptake (%)	
		CT	JR	CT	JR	CT	JR
Phosphate	*Paraserianthes falcataria*	611.3	519	509.9	267	17 a	48 a
	Acacia mangium	611.3	519	416.6	221	31 a	57 a
	Gmelina arborea	611.3	519	120.4	146	80 b	71 b
Nitrogen	*Paraserianthes falcataria*	0.51	0.59	0.33	0.4	35 a	32 a
	Acacia mangium	0.51	0.59	0.39	0.24	23 a	59 b
	Gmelina arborea	0.51	0.59	0.25	0.19	50 b	67 b
Kalium	*Paraserianthes falcataria*	907	1582	890	609	21 a	61 a
	Acacia mangium	907	1582	704	644	22 b	59 a
	Gmelina arborea	907	1582	736	559	18 b	64 b

Note : Numbers followed by the same letter on the row show no significant difference at the level of F 5%.

JR soils (Table 5). The highest nutrient absorption in P was good for *Gmelina arborea*, at approximately 80% in CT soil and 71% in JR soil. In contrast, the two other plants yielded values of 17% and 31% in CT soil and 48% and 57% in JR soil.

Effect of mycorrhiza on plant growth

In this experiment, the effect of mycorrhiza on plant growth could be observed from the plant height (Table 2) and biomass weight (Table 3). All plants could grow from CT and JR on both soil media. It could be observed that there were differences in the plant responses to AMF doses. In CT plots, the chosen amounts of M0 and M1 were beneficial for the growth of *Gmelina arborea* and *Acacia mangium,* whereas M3 was suitable for all plants. For JR plots, the M1 dose was suitable for the growth of the three types of plants. The M3 dose was only beneficial for *Paraserianthes falcataria* and *Gmelina arborea*. An interesting result is that *Acacia mangium* had the best growth on M0, both in CT and JR. Therefore, *Acacia mangium* grows well without mycorrhiza application. The result also indicates that the AMF consortium is incompatible with *Acacia mangium.* Doses of M1 and M3 showed growth effects at both locations for *Paraserianthes falcataria* and *Gmelina arborea*. Therefore, the M1 dose is the best dose considering economical mycorrhiza application. The dose of M3 showed the best plant height growth in line with a high biomass weight at both test sites (CT and JR) for *Gmelina arborea*, followed by *Paraserianthes falcataria* and *Acacia mangium*, respectively (Table 3). The dose of M3 (30 g/plot) was the best dose for *Paraserianthes falcataria,* which was also shown by the fact that doses of 15, 20, and 25 g appeared to cause the best growth and results were not significantly different between the three doses (Listiani and Yuniati, 2021). Mycorrhiza inoculation at 20 g/plot in *Gmelina arborea* increased growth to 2.4 times the biomass weight compared to the case without mycorrhizae (Akhabue *et al*., 2020). The application of rhizobium and mycorrhizae on *Acacia crassicarpa* caused variations in growth parameters. The highest growth rate and increase in dry weight indicated symbiotic compatibility between rhizobium strains and mycorrhizal species (Liu *et al*., 2020). This study used AMF containing various types of spora and found promising results for both soil types (CT and JR) and all woody plants tested, even at the lowest dose (M1).

Effects of mycorrhiza on nutrient uptake

In the results, the effectiveness of AMF was indicated by the increase in nutrient uptake, which impacted the increase in root length. Modification of the root growth direction was achieved using bamboo. This was seen in *Paraserianthes falcataria* and *Gmelina arborea* (Figs. 4 and 6). *Acacia mangium* in the control (C) was denser. Still, root growth in bamboo was longer (Fig. 5). AMF inoculation increases the growth of woody plants such as teak, cocoa, and coffee (Bezza Beyene *et al.*, 2022). Through symbiosis with the AMF, the host plant obtains nutrients from the fungus, while the AMF receives carbohydrates from the host plant (Wira Yuwati *et al*., 2020). For host plants, AMF is very beneficial in the absorption of nutrients and water, tolerance to drought, the inhibition of infection by disease organisms (Tao *et al*., 2022), increasing seedling growth, tree height, and crop yield (Umer *et al*., 2021), improving soil aggregation (Fall *et al.*, 2022) addressing non-biological and biological stresses in plants, and increasing ecosystem productivity (Xiao *et al.*, 2023). Mycorrhiza can generally increase plant tolerance to abiotic conditions (Begum *et al*., 2019). Plant growth indicates effective P absorption. At the end of the experiment, wet biomass data for the three woody plant species revealed that *Gmelina arborea* had the most significant biomass weight, as shown in Table 3. AMF mainly leads to plants' increased uptake of nutrients, particularly phosphate (Zai *et al*., 2021). Much progress has been made in research on P-deficiency-induced root architecture remodeling, and several reports suggest that the root tip is a useful site for locally sensing the status of P deficiency (Bi *et al*., 2023). Functional analyses of the different

Fig. 7:

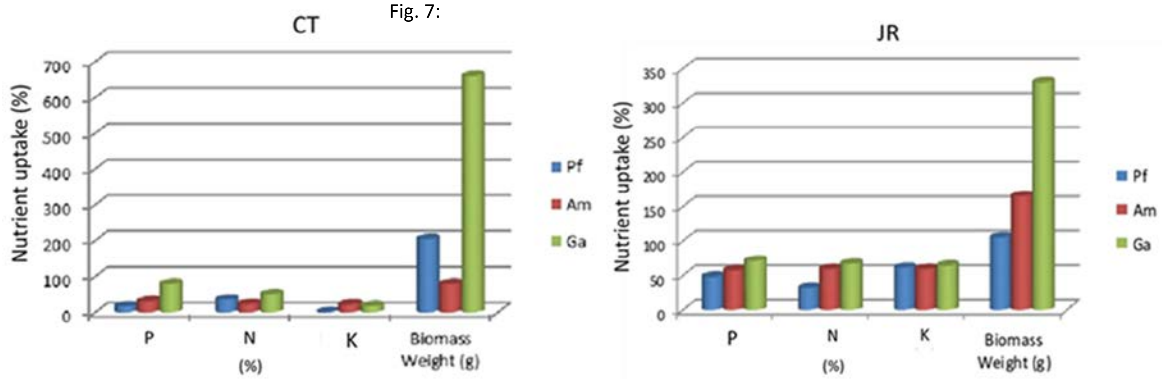

Fig. 7: Percentage of nutrient uptake (N, P, and K) in symbiosis between AMF and woody plants is compared with biomass weight (g) in Citatah and Jati Radio soil.

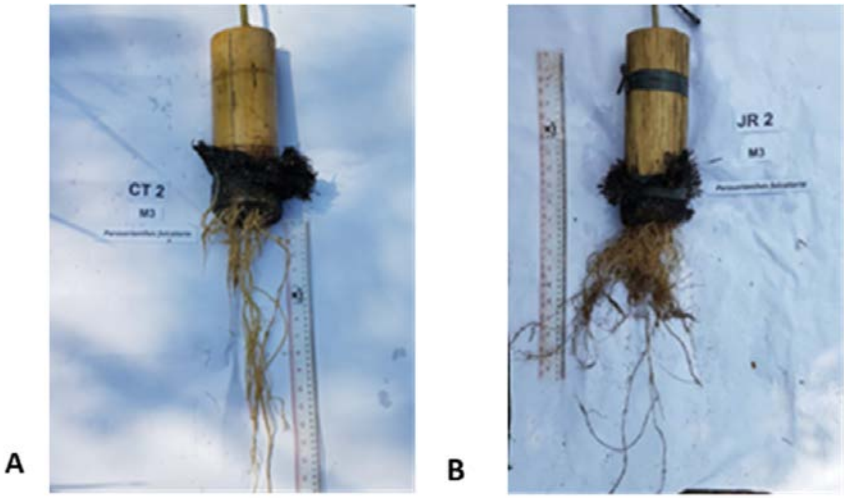

Fig. 8: Root growth of *Paraserianthes falcataria* in JR soil media (A) and CT soil media (B)

root tissues of the root tip are required to identify the early steps of P starvation responses. Several phytohormones, particularly auxins, are involved in the modulation of root architecture adaptation (Dixit *et al*., 2022). The nutrients N, P, and K absorbed by the three tested woody plants showing AMF activity are presented in Fig. 7. The best nutrient uptake measured by the wet biomass weight parameter was shown by *Gmelina arborea* grown on both test soils, namely CT and JR.

Effect of bamboo on root growth direction

Three types of plants were planted in bamboo tubes filled with planting medium on a 20^o slope, and inhibited growth was observed at the roots, which normally grow laterally. Taproots appear to be longer than lateral roots. Because of its role as an anchor, the longer taproot can theoretically strengthen plant growth by penetrating deeper into the ground. Taproots that are longer than lateral roots will also protect the plant from the wind so that it is more stable and can grow on slopes (Dumroese *et al*., 2019). The downslope quadrant gets the greatest quantity of root resources on steep slopes, followed by the wind direction quadrant. The larger cross-sectional area at the point of attachment of the lateral root to the taproot in the downslope quadrant indicates the shallow roots play an essential role in tree anchorage. Roots change growth direction due to mechanical forces (Montagnoli, 2019). The root growth direction can be modified using bamboo tubes and AMF, which has been proven in this study (Figs. 4, 5 and 6). The results of this study showed that, in general, in CT and JR soil media, bamboo intervention can force root growth in the vertical direction, different from the growth in the control plant (Figs. 3b, 4b, and 5b). The roots can penetrate the bamboo base and grow into the slip plane medium. Roots are expected to penetrate the actual slip planes for future applications, and rock crevices and roots can strengthen the grip on the soil. This follows Zhang *et al*. (2020) statement that deepening roots into soil layers provide good shear strength and bending effects. This will undoubtedly provide support for the above soil layer and be effective in controlling shallow landslides. The extent to which plant roots penetrate the bamboo appears to be dependent on the grain size of the soil medium. For example, the difference in root growth of *Paraserianthes falcataria* in JR and CT soil media, demonstrates this. In JR, roots can penetrate the bamboo base more quickly than in CT (Fig. 8). JR soil media (sandy silt) is porous in comparison to CT soil media (clayey silt). This is consistent with the results of research by Biehl *et al.* (2023) on the growth and root morphology of *Picea abies* seedlings, and soil strength due to the hydrogels effect. Their results showed that the compaction of clay soil caused the total length of primary and lateral roots to decrease, but root growth was stronger. Furthermore, Xiong *et al*., (2022) described that, in

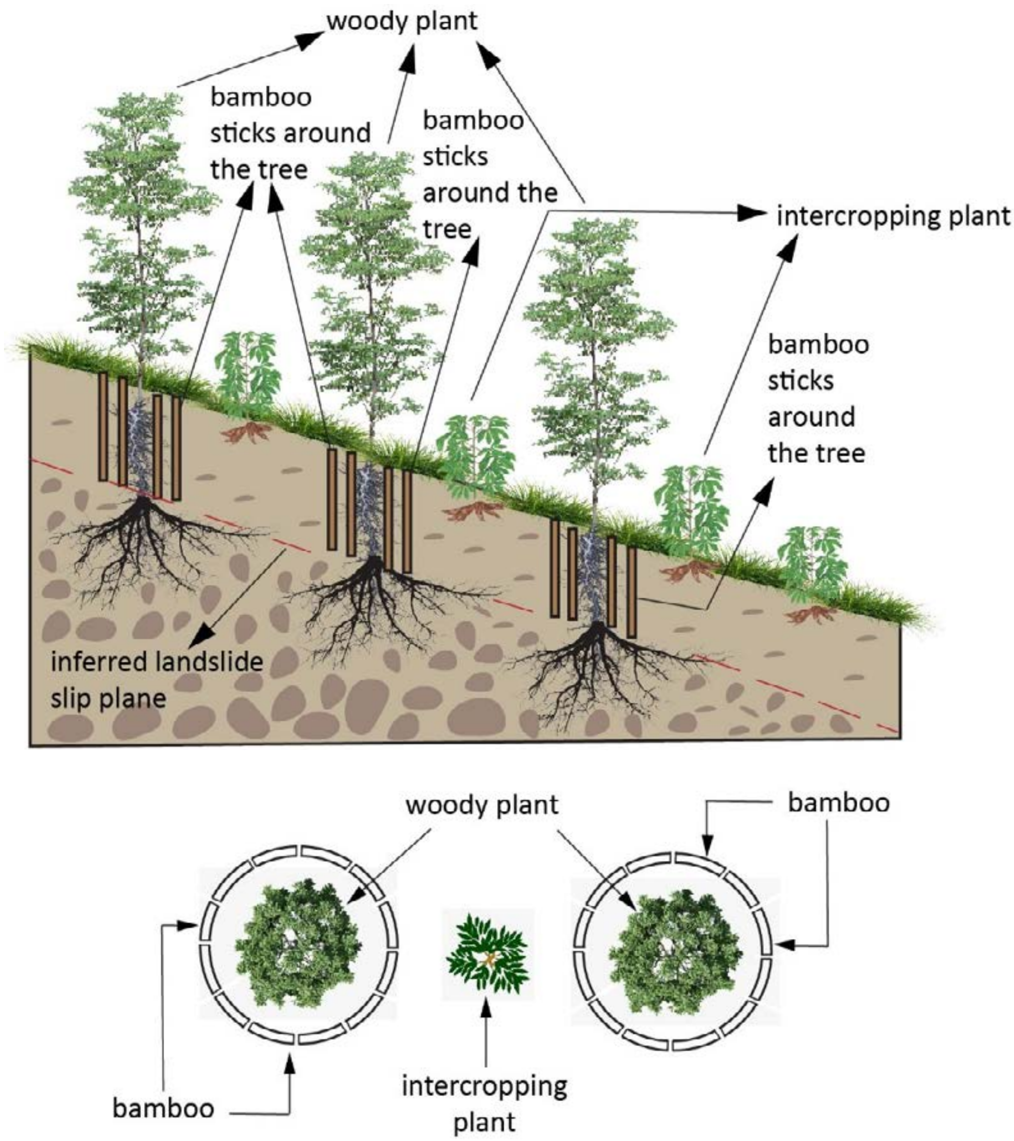

Fig. 9: Illustration of the use of bamboo sticks in conjunction with AMF interventions in tree planting on a slope to stabilize the slope. The figure depicts a cross-section on top and a plane section on the bottom.

uncompacted soil, the number of biopores crossed by roots was much greater than in compacted soil.

Effects of arbuscular mycorrhizal fungi on soil shape

Mycorrhiza significantly increased root growth in the woody plants tested in the experiment. The study also revealed that the roots spread into the soil beneath the bamboo tubes, resulting in more stable soil. The growth and decomposition of roots and mycorrhizal hyphae control the soil macroaggregates' stability. AMF appears to be the most important mediator of soil aggregation (Carrara *et al*., 2023). As a helpful resource in AMF associations, the external hyphae provide a direct physical link between the host plant and soil. External hyphae of AMF can bind the small soil debris into micro aggregates by generating a glycoprotein (glomalin), accounting for 30%–60% of C in undisturbed soils (Villa-Rivera *et al*., 2021). The entanglement of macroaggregates results in a stepped-forward shape and soil aggregation balance. The results suggest that inoculating seedlings with AMF and supplementing with P should be a management strategy, especially for the best species, *Gmelina arborea*. These results are similar for pioneer woody plant species when revegetating riparian areas or for late secondary species when planting secondary forests for enrichment (Ishad *et al*., 2021; Araiza-Aguilar *et al.,* 2020). In ecosystems, mycorrhizae play a role in cycling and conserving nutrients through soil mycelia, is a food source for numerous soil fauna, improve soil structure, play a role in carbon transport from plant roots in other soil organisms, and act as a bioindicator environmental quality in terms of fungal diversity (Muhammad *et al*., 2021). In nature, temperature and humidity regimes are intimately connected, and temperature may be a more significant driver for the success of mycorrhiza types than previously assumed. The poorer performance of AMF in low-temperature and drought conditions may reflect stress avoidance rather than stress tolerance by AMF (Kilpeleainen *et al*., 2020). Applying mycorrhizae, cow dung, and biochar improved the sandy soil characteristics (Herawati *et al.*, 2021).

CONCLUSION

The soil thickness of the landslide areas in CT and JR is approximately 2–5 m, with the slip plane at the boundary between the weathered and slightly weathered rock. This setting is suitable for applying the proper vegetation to stabilize the slopes. AMF and bamboo interventions can accelerate plant growth and change the direction of root growth. Plants on the slopes can grow faster with these interventions. The plant's root system acts as an anchor, increasing the slope's stability. The grain size of JR soil is coarser than CT soil, and JR soil is more porous than CT soil, causing the taproot to grow and penetrate the bamboo base faster in JR soil than in CT soil. As a result, the potential slip plane in JR soil can be reach and grip more quickly for landslide mitigation than in CT soil. The AMF treatment of *Gmelina arborea* produced the best results in this experiment. The optimal level of AMF is related to *Gmelina arborea's* highest phosphorus absorption at 80% and the highest biomass weight of 660 g with the M3 dose in CT, and 71% with 330 g at the same dose in JR. The high absorption of phosphorus nutrients then affects the increase in root growth and length. The results are not significantly different to those of AMF treated with M1. Consequently, from an economic point of view, M1 doses are recommended and can be used to stimulate tree-root growth in *Gmelina arborea* trees. Based on *Gmelina arborea* distribution and soil characteristics, similar to JR and CT, M1 AMF doses can be applied in other locations. According to the findings of this study, bamboo tubes combined with AMF can stimulate root growth and direction. These provide a new technique for environmentally friendly landslide disaster mitigation and can be used to prevent landslides. Based on the root growth rate and biomass weight, *Gmelina arborea* can be recommended as the best woody plant for stabilizing slopes at the CT and JR test sites. These findings can also be applied in other area which the similar soil characteristics as CT and JR. The symbiotic relationship between AMF and plant roots can enhance nutrient and water absorption, leading to faster and better plant growth. Therefore, excellent and fast plant growth can contribute to faster slope stabilization, essential for landslide protection.

RECOMMENDATION

This study recommends that bamboo and AMF can be used to direct and accelerate the growth of woody tree roots so that they grow lengthwise to reach and grip the slip plane. The area of land between woody trees can be used for intercropping plants, thereby increasing the economic value for the community. This type of ecosystem will eventually give rise to agroforestry, a way of land conservation and a method of landslide protection (Fig. 9).

1. Gmelina arborea is a recommended plant for use in slope stabilization. Adding 10 g or ±100 spores of AMF is sufficient to be given once at the beginning of tree planting growth.

2. The role of bamboo is to direct the growth of vertical roots so that they grow further into the slip plane, allowing the tree to prevent slope movements.

3. In practical application, bamboo can be installed as sticks around the tree instead of bamboo tubes. The recommended diameter for bamboo sticks is 0.5 m with a depth according to the estimated slip plane depth and up to at least 2 m.

4. Intercropping plants such as *Manihot* sp. can be used between the woody trees, adding economic

value to the local people.

Despite the favorable elements of this technology, several restrictions can create hurdles to the beneficial implications of this application, such as the fact that this procedure is partially dependent on the plant's dormant seasons, which is an availability limitation of the site. The application of this technique is prospective in Indonesia, because lots of land is prone to landslides; bamboo is easy to get in any area because it is easy to grow; AMF and woody plant symbiosis is very beneficial because it can restore problematic soil conditions especially the lack of nutrients for plants; the combination of bamboo and AMF is an environmentally friendly and economical technology. The challenge faced in the restoration program using new techniques, namely planting woody plants combined with bamboo and AMF on sloping land, is an approach to empowering the community in terms of participating in caring for plants for rehabilitation so they can grow well. It requires an expert with experience working on restorations with challenging soils, and another with a different perspective and understanding of this kind of complication. The attention and support of the local government significantly contributed to the success of the restoration. The implementation of planting on sloping land before planting is identifying those site factors that inhibit vegetation growth. Identify primary vegetation limiting features: steep slopes, poor nutritional status, unpleasant chemical characteristics, and soil temperature extremes. Forest erosions are closely related to steep slopes, poor texture/compaction, and low nutrient status. Restorative technology that employs AMF is also known as soil bioengineering or biotechnique. This technique is advantageous since it only necessitates a little maintenance after implementation. Because it is relatively inexpensive, this technique can be an excellent tool for mitigating landslides and unstable slopes. Bioengineering systems, like living systems, require little or no maintenance and continue to improve over time. Bioengineering can act as a link between traditional engineering treatments and standard seeding work. Bioengineering can help with the reclamation of forest lands.

AUTHOR CONTRIBUTIONS

I.G. Tejakusuma contributed to the conceptualization, methodology, preparation of photos and figures, and manuscript writing. E.H. Sittadewi, the corresponding author, conducted observations, formal analyses, funding acquisition, project administration, and manuscript writing. T. Handayani performed the methodology, formal analyses, data curation, writing, reviewing, and editing. T. Hernaningsih supported the conception and design of the manuscript, conducted a literature review, and drafted and prepared the manuscript. W. Wisyanto performed data acquisition, analysis, and interpretation and sharpened the background. A. Rifai assisted with experimental and administrative work and provided technical and material assistance. All authors read and approved the final manuscript.

ACKNOWLEDGEMENT

The authors are grateful to the Head of Research Center for Geological Disaster, the Head of Research Center for Sustainable Production System and Life Cycle Assessment, and the Head of Research Center for Environmental and Clean Technology of the National Research and Innovation Agency, Indonesia. The authors thank the editors and anonymous reviewers for their constructive comments.

CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

AMF	Arbuscular mycchorizal fungi
Ac	Acasia mangium
C	Carbon
cm	centimete
C/N Ratio	Carbon/nitrogen ratio
CT	Citatah
F%	Root fragments
Ga	Gmelina arborea
K	Kalium
K_2O	Kalium oxide
KOH	Kalium hydroxide
JR	Jati Radio
M%	Mycorrhiza colonization
Mo	Without *AMF*
M1	*AMF 10 mg*
M2	*AMF* 20 mg
M3	*AMF* 30 mg
P	Phosporus
P_2O_5	Phospore pentoxide
Pf	*Paraserianthes falcataria*

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HOW TO CITE THIS ARTICLE

Tejakusuma, I.G.; Sittadewi, E.H.; Handayani, T., Hernaningsih, T.; Wisyanto, W.; Rifai, A., (2024). Root growth and arbuscular mycorrhizal fungi on woody plants for vegetative stabilization of tropical slopes. Global J. Environ. Sci. Manage., 10(1): 267-286.

DOI: 10.22034/gjesm.2024.01.17

URL: https://www.gjesm.net/article_704899.html