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EFFECT OF TEAK (*TECTONA GRANDIS*) PLANTATIONS ON HYDRAULIC CONDUCTIVITY AND POROSITY OF ALFISOLS IN COSTA RICA

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FERNÁNDEZ-MOYA J, ALVARADO A, FORSYTHE W & MARCHAMALO-SACRISTÁN M. 2013. Effect of teak (*Tectona grandis*) plantations on hydraulic conductivity and porosity on Alfisols in Costa Rica. Afforestation is thought to improve soil hydraulic properties and recover hydrological services linked to forest systems. However, some researchers do not consider teak plantations as producing environmental services. The influence of teak plantations on hydraulic properties of Alfisols in a moist tropical region (North Pacific coast of Costa Rica) was studied. Saturated hydraulic conductivity (Ksat), porosity and macroporosity were measured at five landuses: secondary forests, grasslands, mature teak (about. 20 years), young cloned teak (2 years) and young coppiced teak (2 years). Three plots were sampled for each landuse and six samples were taken at each plot: three between 0–10 cm deep and three between 50–60 cm. Topsoil (0–10 cm) hydraulic properties varied between the landuses. Ksat: forest > grazed land ≈ coppiced > mature teak ≈ cloned. Porosity: forest > mature teak ≈ coppiced > grazed land ≈ cloned. Macroporosity: forest ≈ coppiced > mature teak ≈ grazed land ≈ cloned. Effects of teak plantations on some soil hydraulic properties depended on the age and management of the plantations. The study found no negative impact of wood extraction on soil hydraulic properties.

Keywords: Forest soils, forest hydrology, soil physics, afforestation, macroporosity, tropical soils

FERNÁNDEZ-MOYA J, ALVARADO A, FORSYTHE W & MARCHAMALO-SACRISTÁN M. 2013. Kesan ladang pokok jati (*Tectona grandis*) terhadap kekonduksian hidraulik dan keliangan tanah jenis Alfisols di Costa Rica. Penghutanan dianggap dapat menambah baik ciri hidraulik tanah dan memulihkan khidmat hidrologi yang berkaitan dengan sistem hutan. Namun, sebilangan penyelidik tidak menganggap ladang pokok jati sebagai menawarkan khidmat persekitaran. Kesan ladang pokok jati terhadap ciri hidraulik tanah Alfisols di kawasan tropika yang lembap (pantai Pasifik Utara Costa Rica) dikaji. Kekonduksian hidraulik tepu (Ksat), keliangan dan keliangan makro disukat di lima jenis penggunaan tanah: hutan sekunder, padang rumput, ladang pokok jati matang (kira-kira 20 tahun), ladang pokok jati muda daripada klon (2 tahun) dan ladang pokok jati muda daripada kopis (2 tahun). Tiga plot disampel daripada setiap jenis penggunaan tanah dan enam sampel diambil daripada setiap plot: tiga sampel antara kedalaman 0 cm–10 cm dan tiga sampel antara 50 cm–60 cm. Ciri hidraulik tanah atas (0 cm–10 cm) berbeza antara jenis penggunaan tanah. Ksat: hutan > padang ragut ≈ ladang pokok jati kopis > ladang pokok jati matang ≈ ladang pokok jati klon. Keliangan: hutan > ladang pokok jati matang ≈ ladang pokok jati kopis > padang ragut ≈ ladang pokok jati klon. Keliangan makro: hutan ≈ ladang pokok jati kopis > ladang pokok jati matang ≈ padang ragut ≈ ladang pokok jati klon. Kesan ladang pokok jati terhadap beberapa ciri hidraulik tanah bergantung pada usia dan pengurusan ladang. Kajian mendapati pembalakan tidak memberi kesan negatif terhadap ciri hidraulik tanah.

INTRODUCTION

Environmental degradation and the increase in human population and water requirements are causing shortage of water resources (Hoff 2010). Hence, many national and international water policies as well as tools are being implemented such as programmes of hydrological payments for environmental services (PESs) (Brauman et

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al. 2007). Forest plantations, in addition to being socio-economically productive, provide hydrological environmental services, as they affect the way water moves across the landscape in the water cycle (Brauman et al. 2007). Further research is needed to evaluate the hydrological behaviour of different plantation species growing at different locations, especially for exotic and fast-growing species, since every forest plantation cannot be considered as environmentally positive (Brauman et al. 2007, Carle et al. 2009). The evaluation and quantification of the environmental services are especially necessary when PES programmes are applied.

Afforestation can protect and even restore degraded soils and their hydrological functions in the water cycle (Bruijnzeel 2004, Brauman et al. 2007, van Dijk & Keenan 2007). Tree cover also controls peak flows and landslides caused by moderate rainfall events, even though it cannot control extreme events of large catchment areas (Bruijnzeel 2004, van Dijk & Keenan 2007). However, forests and forest plantations consume more water than other non-forested land (particularly those used in agriculture or animal husbandry), and they are assumed to yield less water flows (Bruijnzeel 2004, van Dijk & Keenan 2007). The balance between water use of forests and forest plantations as well as their hydrological environmental service values has been polemical for various decades (Bruijnzeel 2004, Jackson et al. 2005). Van Dijk and Keenan (2007) summarised the major arguments pointing out that in most cases forests are the original ecosystems and therefore a forested catchment will be closer to the natural state ecosystem. Although deforested catchments are thought to produce more water as the surface water flow increases, this is normally caused by lowering of soil infiltration which also causes a diminished aquifer recharge and water storage (Brauman et al. 2007). Van Dijk and Keenan (2007) consider that forest plantations can generate an increase of dry season stream-flow when (1) they restore the soil hydrological properties of degraded soils, (2) as a consequence, more water infiltrates into the soil instead of running-off and (3) the groundwater response time is such that the additional infiltrated water is released during the dry season low flow period.

Infiltration, porosity, macroporosity and hydraulic conductivity or permeability are important hydraulic soil properties which affect groundwater recharge and erosion (Ilstedt et al. 2007, Bonell et al. 2010, Hassler et al. 2011). These soil properties are assumed to show higher values in forested systems compared with other systems such as agricultural ones (Brauman et al. 2007, Ilstedt et al. 2007, Hassler et al. 2011). There is shortage of experimental studies concerning the effect of afforestation on infiltration, hydraulic conductivity or permeability in the tropics (Ilstedt et al. 2007).

Teak (*Tectona grandis*) has been extensively used in productive planted forests in Central America. Costa Rica and Panama accounted for about 40,000 ha in 2002, while the area planted increased (up to 140,000 ha) in Guatemala, El Salvador and Nicaragua (FAO 2002). In Central America, the species is intensively managed in 20–25-year rotations and yields approximately 10 m^3 ha^{-1} $year^{-1}$ of commercial industrial volume (FAO 2002). Higher soil hydraulic properties were reported under teak reforestation compared with degraded grassland where teak was planted (Mapa 1995). However, some authors do not consider teak reforestation as producing hydrological services (Carle et al. 2009). In fact, high erosion rates and soil degradation under teak plantations are a common myth in tropical forest science (Healey & Gara 2003, Boley et al. 2009, Carle et al. 2009). This paper analyses the influence of teak plantations on soil hydraulic properties of Alfisols in a tropical region (Guanacaste, Costa Rica) focusing on: (1) the influence of teak plantations on soil hydraulic conductivity, porosity and macroporosity compared with secondary forests and grasslands, (2) the effect of plantation age and establishment procedure on soil hydraulic properties and (3) the relation between soil hydraulic properties such as hydraulic conductivity, porosity and macroporosity and other soil properties such as root density. Our main hypothesis was to demonstrate the lack of legitimacy of the myth of soil degradation under teak plantations in order to analyse if these ecosystems were providing equivalent hydrological services than afforestation with other species.

MATERIALS AND METHODS

Study area

The study area is located in the North Pacific coast of Costa Rica (Guanacaste) (Figure 1) in a 1500 ha property of Panamerican Woods Company with 1100 ha covered by planted teak. The climate is classified as tropical moist according to Holdridge's life zones, with annual average precipitation of 2500 mm and four to six dry months. Soils are fertile reddish clayey, described as Typic Rhodustalfs mixed with Typic Dystrustepts and small clusters of other soils derived from sedimentary limestones and basalt parent material (Thiele 2008).

The plantation was established from 1985 till 1991 on grazed land. At present, the area is a mosaic of teak plantations of different ages, cultivated under various management practices, surrounded by small grazed patches, small villages and secondary forests close to streams. The actual young plantations (1–5 years) were established in harvested areas after the first rotation. They were established following different methods depending on the site: (1) clones were planted in the most productive sites and were managed intensively using herbicide for weed control and (2) the coppice method was used in less productive sites where weed control was done manually and only around trees that would remain until the final cut (low intense management).

Field sampling design and variables analysed

The experimental design included five treatments: (1) secondary forests (F), (2) grazed land (G), (3) mature plantation (approximately 20 years) (M), (4) young plantation (2 years) from clones (Cl) and (5) young plantation (2 years) from coppice (Co). Mature plantations have a tree density of 150–200 trees ha^{-1} while young plantations, 800 trees ha^{-1}. Three points were sampled in each treatment (total 15 sampling points, Figure 1), placed between tree rows in the plantation treatments. All sampling points were located in 30–60% slopes, taking care of selecting similar areas (at the same position within the slopes—middle) and soil was classified as Typic Rhodustalfs. A 60-cm deep soil pit was dug in each sampling point and six undisturbed soil samples were taken: three at the soil surface (0–10 cm) and three at 50–60 cm depth. Undisturbed soil samples were collected with metallic cylinders (7.5 cm height × 4.5 cm diameter). The resulting 90 soil samples were taken during the rainy season (28–30 July 2010) assuming water content as field capacity. Soil samples were analysed at

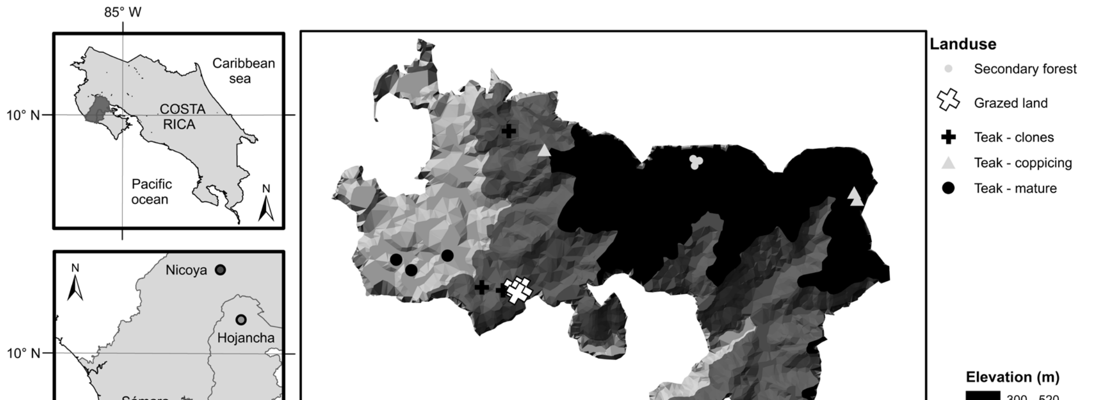

Figure 1 Study area at Panamerican Woods 'Carrillo' plantation in Guanacaste region, Costa Rica; symbols represent the location of sampling points

the Centro de Investigaciones Agronómicas, University of Costa Rica.

The field water content of undisturbed soil core samples were analysed for hydraulic conductivity, water content (mass and volume), bulk density, soil particle density, porosity and air space using the methodology described in Forsythe (1975). For measurement of saturated hydraulic conductivity (Ksat), a constant water head (7.5 cm) was applied and the water flow through the soil cylinder per time unit was recorded. After a constant flow rate had been established, the percolated water volume per time unit was measured and the Ksat was calculated using Darcy's equation for saturated conditions. Bulk density was estimated using oven-dried weight and volume of the undisturbed soil samples. Water content (mass) was estimated by comparing the wet weight of undisturbed soil samples with the oven-dry weight. Water content (volume) is water content (mass) multiplied by bulk density. Soil particle density was calculated using a 40-g soil subsample and measuring the solid phase volume by evaluating the mass and density of distilled water displaced by it after being gently boiled to remove air bubbles. Porosity was calculated using the estimated values of bulk density and soil particle density. Air space at field capacity (As) or macroporosity was estimated as As = porosity – water content (volume), i.e. the percentage of porosity not occupied by water in the field-capacity soil samples. Root density (roots) was measured by weighing the oven-dried root mass contained in the volume of undisturbed soil samples; roots present in the soil sampled were visually identified and manually extracted. Once the three samples per treatment and horizon were analysed, they were mixed and evaluated for texture (Table 1) following a modified hydrometer method (Forsythe 1975).

Statistical analysis

The study variables followed a log normal distribution, as expected (Bonell et al. 2010) and log 10 transformation was used. The temporal variation of the variables was minimised by taking 90 samples within a 3-day period, so was the spatial variation by taking three samples per sampling point as repetitions. An ANOVA test was used to evaluate the effect of landuse on the study variables (F, G, M, Cl and Co). Tukey's test was used to analyse differences between means. A Pearson test was done to evaluate the correlation between the study variables. All statistical analyses were done using SAS 9.0 (SAS Institute Inc. 2002). Statistical tests were considered significant at $\alpha = 0.05$.

RESULTS

The different landuses had statistically significant effect on hydraulic conductivity, porosity, root density and macroporosity of the topsoil (Tables 2 and 3). Mean topsoil hydraulic conductivity was higher in secondary forests (3.76 cm hour^{-1}) than other landuses. The lowest hydraulic conductivity values were found in young cloned teak plantations (0.70 cm hour^{-1}) and mature teak plantations (0.53 cm hour^{-1}). Mean topsoil porosity was also higher in secondary forests (69.37%) than in the other landuses. The lowest porosity values were found in the young cloned teak plantations (57.68%) and grazed land (57.66%). Mean topsoil root density was higher in secondary forests (4.78 mg mL^{-1}) and mature teak plantations (3.12 mg mL^{-1}) compared with other landuses. The lowest roots were found in the young cloned teak plantation (0.45 mg mL^{-1}). Mean topsoil macroporosity was slightly higher in secondary forests (19.98%) and young coppiced teak plantations (21.56%) compared with other landuses, although not significant.

At 50–60 cm depth, hydraulic conductivity and porosity were affected by landuses but not root density and macroporosity (Tables 2 and 3). Mean subsoil hydraulic conductivity was higher in secondary forests (0.68 cm hour^{-1}) and grazed land (1.12 cm hour^{-1}) than in other landuses. Mean subsoil porosity was higher in secondary forests (61.44%), mature teak plantations (59.65%) and young cloned teak (59.12%) than other landuses.

Table 4 shows that porosity is correlated with hydraulic conductivity, root density and macroporosity. Macroporosity was also correlated with root density. Soil samples at 50–60 cm depth showed no correlation between variables (result not shown).

Table 1 Soil particle size and textural class of experimental sites

Site	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class
F1	0–10	18	29	53	Clay
	50–60	0	26	74	Clay
F2	0–10	28	26	46	Clay
	50–60	12	29	59	Clay
F3	0–10	22	32	46	Clay
	50–60	22	29	49	Clay
G1	0–10	7	44	49	Silty clay
	50–60	8	35	57	Clay
G2	0–10	7	41	52	Silty clay
	50–60	8	40	52	Silty clay
G3	0–10	8	40	52	Silty clay
	50–60	3	30	67	Clay
M1	0–10	21	36	44	Clay
	50–60	23	31	46	Clay
M2	0–10	26	36	38	Clay loam
	50–60	47	24	28	Sandy clay loam
M3	0–10	13	36	51	Clay
	50–60	5	29	66	Clay
Cl1	0–10	6	44	51	Silty clay
	50–60	3	34	63	Clay
Cl2	0–10	3	29	68	Clay
	50–60	1	21	78	Clay
Cl3	0–10	21	46	33	Clay loam
	50–60	5	31	63	Clay
Co1	0–10	15	29	56	Clay
	50–60	5	22	73	Clay
Co2	0–10	18	29	53	Clay
	50–60	3	22	75	Clay
Co3	0–10	3	29	68	Clay
	50–60	8	52	40	Silty clay

F = secondary forest, G = grazed land, M = mature teak plantation, Cl = young (2 years, second rotation) cloned teak plantation, Co = young (2 years, second rotation) coppiced teak plantation

Table 2 Analysis of variance to evaluate the effect of landuse over study variables using $\log_{10}$ transformations

Soil depth (cm)	Variable	F value	p value
0–10	Ksat	3.54	0.0146 *
	Porosity	14.32	< 0.0001 *
	Roots	4.75	0.0034 *
	As	3.76	0.0115 *
50–60	Ksat	11.47	< 0.0001 *
	Porosity	4.07	0.0073 *
	Roots	–	–
	As	0.85	0.5025

Ksat = hydraulic conductivity, roots = root density, As = air space; *statistically significant ($\alpha = 0.05$)

DISCUSSION

Landuse changes in tropical areas, especially afforestation, affected soil hydraulic conductivity, porosity, infiltration and macroporosity (Table 2), as had been reported (Zimmermann et al. 2006, Listo 2009, Bonell et al. 2010). However, high variability was found between results reported by different authors (e.g. Bruijnzeel 2004, Brauman et al. 2007, van Dijk & Keenan 2007, Ilstedt et al. 2007).

Soil hydraulic properties, including hydraulic conductivity (or permeability), are related to soil structure (Baver et al. 1972). The loss of soil structure is one of the consequences of denaturalisation of ecosystem

Table 3 Means of study variables for the different landuses (n = 9)

Soil depth (cm)	Landuse	Ksat (cm hour^{-1})	Porosity (%)	Roots (mg mL^{-1})	Macroporosity (%)
0–10	F	3.76 a (3.22)	69.37 a (4.36)	4.78 a (3.85)	19.98 a (7.05)
	G	1.12 ab (1.56)	57.66 b (3.08)	1.55 ab (1.34)	6.61 a (4.80)
	M	0.53 b (1.35)	60.67 ab (3.20)	3.12 a (3.49)	5.67 a (4.84)
	Cl	0.70 b (1.45)	57.68 b (2.92)	0.45 b (0.60)	9.04 a (6.56)
	Co	7.72 ab (12.47)	65.62 ab (6.18)	2.13 ab (1.83)	21.56 a (12.04)
50–60	F	0.68 a (1.09)	61.44 a (5.31)	0.18 (0.18)	10.39 (3.22)
	G	1.12 a (1.50)	51.35 b (5.75)	0.00 (0.00)	10.75 (7.32)
	M	0.08 b (0.11)	59.65 a (2.50)	0.19 (0.23)	8.82 (7.31)
	Cl	0.03 b (0.01)	59.12 a (3.89)	0.01 (0.02)	13.17 (4.54)
	Co	0.05 b (0.04)	57.93 ab (8.12)	0.47 (1.08)	10.10 (5.36)

F = secondary forest, G = grazed land, M = mature teak, Cl = young cloned teak plantation, Co = young coppiced teak plantation; Ksat = hydraulic conductivity, roots = root density; means with different letters are statistically significant (α = 0.05) using Tukey's test for $\log_{10}$ mean difference analysis, roots and As at 50–60 soil depth were not analysed using Tukey's test because analysis of variance was not significant (Table 2); values in parentheses are standard deviations

Table 4 Pearson's correlation matrix between $\log_{10}$ transformed topsoil study variables

Variable	Log_{10} porosity	Log_{10} roots	Log_{10} As
Log_{10} Ksat	0.41513 (0.0046) *	0.22474 (0.1525)	0.22172 (0.1582)
Log_{10} porosity		0.62153 (< 0.0001) *	0.56264 (< 0.0001) *
Log_{10} roots			0.35534 (0.0264) *

Ksat = hydraulic conductivity, roots = root density, As = air space, *significant (α=0.05); values in parenthese are p values

that can reduce soil hydraulic properties. The results in Table 3 validated this since secondary forests had higher hydraulic conductivity, porosity and macroporosity in the topsoil than other landuses. Higher hydraulic conductivity and porosity were observed at 60 cm depth. Similar findings have been found in Alfisols and Ultisols from India and Brazil (Zimmermann et al. 2006, Bonell et al. 2010). The effect of forest at 60 cm depth on hydraulic conductivity was negligible, with similar values to grazed land. At the same soil depth, porosity under the forest cover was not significantly higher than that found under mature or young cloned teak plantations. The diminished effect of landuse over soil hydraulic properties at 60 cm depth might be due to the general decrease of these properties with soil depth (Bonell et al. 2010). However, Bonell et al. (2010) found higher soil hydraulic conductivity at 1.5 m under forests compared with degraded forests and *Acacia auriculiformis* plantations. This suggests that the lack of effect in our study at 60 cm depth can be caused by: (1) a low number of soil samples (9 per treatment and deepness), (2) different sampling techniques or (3) laboratory analysis methodologies.

This study showed differences between mature and young teak plantations, and also between cloned and coppiced plantations (Table 3). Young coppiced plantations had higher hydraulic conductivity and macroporosity values at the soil surface than mature or young cloned teak plantations. However, porosity did not vary between young coppiced and mature plantations but higher than young clones. The differences point out that the analysis of the effects of landuse and afforestation over soil hydraulic properties should take into account the local landuse history of areas as well as age, establishment method and management of the planted forest.

The low values of soil hydraulic properties in young cloned plantations (second rotation) compared with the high values of young coppiced plantations reflect the negative impact of clone establishment and intensive management on soil hydrological properties. Intense weed control using herbicide, mechanical or manual means or light competition is common in most productive teak plantations (Pandey & Brown 2000) and it is considered to be the cause of soil remaining unprotected, causing erosion and diminishing soil hydraulic properties (Bruijnzeeel 2004, van Dijk & Keenan 2007, Boley et al. 2009, Bonell et al. 2010). The intense weed control may cause reduction of understorey non-extractable biomass and, as a consequence, reduced soil organic matter (Balagopalan et al. 2005, Boley et al. 2009). Low values of soil organic matter are recognised as a consequence of soil degradation and have been considered as a cause of deterioration of soil hydraulic properties in teak plantations (Mapa 1995).

Harvesting and wood extraction from productive planted forests are assumed to have negative impact on soil hydraulic properties (Bruijnzeeel 2004, van Dijk & Keenan 2007, Durán & Rodríguez 2008). However, the results shown in Table 3 disagreed with the hypothesis as young coppiced plantations had higher soil hydraulic properties than mature plantations just 2 years after extraction and re-establishment. The different results may be due to the cable timber extraction technology applied by the company, indicating that forest extraction can be done without negative impacts on soil hydraulic properties (Worrel & Hampson 1997). Cable extraction is based on manual felling where a modified tractor (with a tower) is placed on a forest road on the perimeter of the stand. A cable is set up to another extreme of the stand. Felled stems are attached to the cable which will lift them up to the forest road; hence, no machinery works within the stand, minimising soil disturbance. Bruijnzeel (1997) also considered a 2-year period as necessary time for the newly established forest plantations to recover soil hydraulic properties after degradation suffered during wood extraction.

Contrary to other findings, the effect of grazing land did not show lower hydraulic conductivity values than those found under teak plantations (Mapa 1995, Zimmermann et al. 2006), although values in grazed lands had lower porosity. This could be partially explained by (1) a decrease in livestock pressure in the region in recent years, decreasing the animal density and consequently soil compaction, (2) a relatively high root density at soil surface which could enhance soil hydraulic properties and (3) a difference in textural class (Table 1).

Porosity was highly related to all the other studied soil hydraulic properties at the surface horizon (Table 4). However, this variable is not commonly used in other similar studies in spite of its simplicity and low cost of its field measurement. The relation between porosity and root density is explained by the pores created by the roots after they die and decompose, improving the soil structure (Durán & Rodríguez 2008, Bonell et al. 2010). The relation between porosity and air space is direct as it is calculated as the percentage of porosity occupied by air at a given water content, in this case considered to be field capacity. Mapa (1995) considered air space at field capacity or macroporosity as one of the variables most related to soil water movement. It is also explained by Darcy's law (Baver et al. 1972) as hydraulic conductivity is directly related to porosity and pore size.

CONCLUSIONS

Landuse and forest management affect soil hydrological properties, modifying its role in the water cycle and, consequently, they should be taken into account in water resource management plans in areas where future water supplies are questionable. Tropical secondary moist forests in Alfisols showed higher values of topsoil hydraulic conductivity, porosity and macroporosity than grazed land or teak productive planted forests. Young (2 years, second rotation) coppiced teak plantations showed high hydraulic properties.

This study showed differences in the effect of teak plantations on some soil hydraulic properties depending on the age and management of the plantation. No negative impact was observed on soil hydraulic properties due to wood extraction at the end of the rotation, probably because of the cable extraction technique. Porosity showed high correlation with all soil hydraulic properties at the topsoil. Given the simplicity and low cost of the estimation method, it can be used efficiently in future studies on hydrological variables.

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