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Soil Water Conditions According to Landscape Position and Aboveground Vegetation in an *Acacia mangium* Plantation in Sabah, Malaysia

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Abstract

We studied the soil water dynamics of the humid tropics at a 1.6-ha *Acacia mangium* stand in Sabah State, northern Borneo, to quantify the effect of landscape position and vegetation on soil water conditions. We monitored the volumetric soil water content (VSW) at a depth of 30 cm at 12 locations in the research plot, every 30 min for 1 year using ADR theta probes. To analyze the drying process, twelve events were selected in the course of the research period when comparatively long intervals without rainfall occurred. The decline in soil water during the drying periods fit linear regressions well when we excluded the data from the first 24 h after the last rain event. The absolute value of the slope of the regression was termed the drying rate (DR). Topographic index, described as $\ln(\alpha/\tan\beta)$ (α = upslope contributing area per unit contour; $\tan\beta$ = local slope angle) was also determined. The range of the VSW in bottomland was smaller than for other landscape positions, but no significant relationship was observed between the topographic index and the VSW. The median DR was significantly correlated with tree density, and with the topographic index. During a drying period, evapotranspiration was the major factor controlling the soil water regime in this stand. The normalized DR according to tree density was significantly lower in the bottomlands, and described the wet gleyic characteristics of the bottomland well. The DR appeared to be a good indicator for detecting the effects of vegetation and topography on soil water conditions in the humid tropics.

Discipline: Forestry and forest products
Additional key words: humid tropics, slope position, soil drying rate, soil moisture, tree density

Introduction

Water and nutrients are major factors limiting plant growth. In humid tropical regions, nutrients are considered the most important factor for growth due to low-activity clay and low soil organic matter[9]. Although the soil water condition has not received as much attention as nutrients, short- and long-term drought can occur even in the humid tropics[19] and affect tree growth because some fast-growing forest plantation species are thought to consume more water than others. For example, *Acacia mangium* is characterized as having a high net photosynthetic rate under good site conditions[11,12], a high transpiration rate[11], low water-use efficiency[7,10,12], and a high moisture content in the stem[22]. A risk of water shortage can occur in this region in some cases such as ENSO[1,13,15], and overall, such fast-growing plantation forests are at greater risk of suffering drought stress.

Landscape position and vegetation conditions have crucial effects on soil water. Soil water dynamics with respect to topography have been studied mostly in drier regions[3,6,16,20,21], however detailed information on the change in soil water condition with topography is still limited in the humid tropics. Bruijnzeel summarized the effects of vegetation status on the water yield in the tropics well, although the effects differed in each case and were contradictory[5]. To obtain a better understanding of

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the soil water conditions, we need to examine each regulating factor such as vegetation, topography and soil moisture status.

In this study, we investigated how the landscape position and tree density affect the soil water in a humid tropical tree plantation by analyzing the soil water content and its drying processes.

Materials and methods

1. Experimental stand

The study was conducted at the Kolapis A Station in the Lungmanis Forest Reserve, located about 60 km west of the city of Sandakan, Sabah, Malaysia (5º54'N and 118º04'E; Fig. 1). The mean annual rainfall from 1961 to 1990 at Sandakan was 3,087 mm[14]. The climate of this region is humid tropical without a distinct dry season based on long-term meteorological data. The soils are classified as Profondic Alisols[8]. The physical properties of the topsoil in the stand are shown in Table 1. The experimental stand comprised about 1.6 ha of *Acacia mangium* Willd. plantation; the 14-year-old trees were originally planted in 30 quadrats with 5 rows and 6 columns, each containing 7 × 7 trees, with 3 × 3 m spacing (Fig. 2). Several trees had already died or been removed due to damage resulting from light depression. The dead trees near each site are shown in Fig. 2. Line thinning was conducted for an agroforestry intercropping trial in April 2002. The intercropping of mixed local species began from February 2003. The eastern two rows of quadrats were thinned by one or two lines in an east to west direction. The western two rows were also thinned by one or two lines from north to south. Thinning by one line is equal to removing 33% of the stand, and thinning by two lines is equal to removing 66%. The center row of quadrats was left as a control.

2. Measuring soil water content

Twelve ADR sensors (ML2x; Delta-T, Cambridge, U.K.) were installed at a depth of 30 cm, at which most of the fine roots (< 2 mm in diameter) of the upper trees were distributed above this depth in the experimental stand in May 2002 (Fig. 2) and the volumetric soil water content (VSW) was measured every 30 min for 1 year. The effect of intercropping was negligible, because it started at almost the end of the measurement. Single channel preheat type loggers (UIZ3635; UIZIN, Tokyo, Japan) were used to record continuous measurements. The locations of the measurement sites are shown in Fig. 2. For the measurement sites, the landscape positions of sites 2 and 3 correspond to a crest, sites 1 and 4–9 to a slope, and sites 10–12 to the bottomland. Rainfall was measured in the nearest open area every 30 min using a 0.5-mm tipping-bucket rain gauge with a pulse logger. The output voltage of the sensor was calibrated with the soil of each site as outlined in the ADR sensor's manual[2].

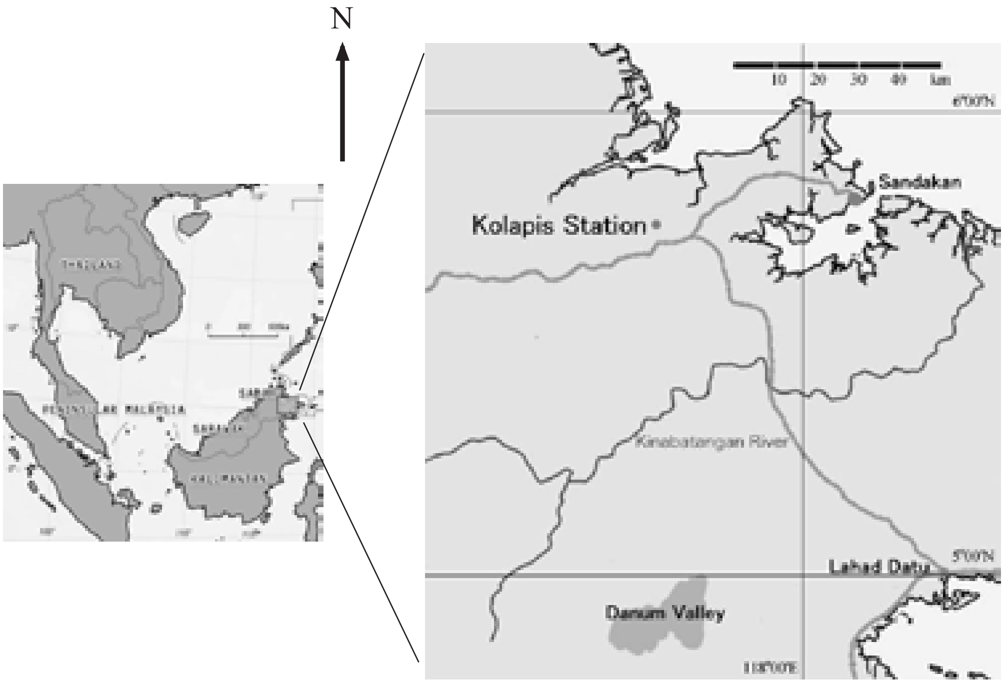

Fig. 1. Location of the experimental stand

Table 1. Topographic, soil, and stand density characteristics at each measurement site

Site no.	Slope (degree)	Topographic index	Landscape position	Tree density (per 314 m^2)	Thinning	Bulk Density (Mg/m^3)	Soil texture (%)		
							clay	silt	sand
1	12.9	3.47	Slope	6	Yes (East to West)	1.58	35.3	17.3	47.4
2	6.9	3.57	Crest	10	Yes (East to West)	1.44	54.0	25.6	20.4
3	7.0	4.79	Crest	8	Yes (East to West)	1.44	37.1	15.5	47.4
4	13.8	4.56	Slope	6	Yes (East to West)	1.27	47.2	24.1	28.7
5	13.9	4.81	Slope	12	No	1.34	38.6	25.6	35.8
6	11.9	4.91	Slope	11	No	1.29	39.7	18.3	42.0
7	9.3	5.26	Slope	15	No	1.48	38.9	24.6	36.5
8	13.3	4.10	Slope	11	No	1.41	44.8	21.2	34.1
9	9.9	4.68	Slope	9	Yes (North to South)	1.41	43.5	30.5	26.0
10	1.5	9.34	Bottomland	6	Yes (North to South)	1.46	29.9	25.0	45.1
11	6.4	5.43	Bottomland	5	Yes (North to South)	1.40	44.5	29.6	26.0
12	1.5	7.04	Bottomland	6	Yes (North to South)	1.49	36.1	31.6	32.2

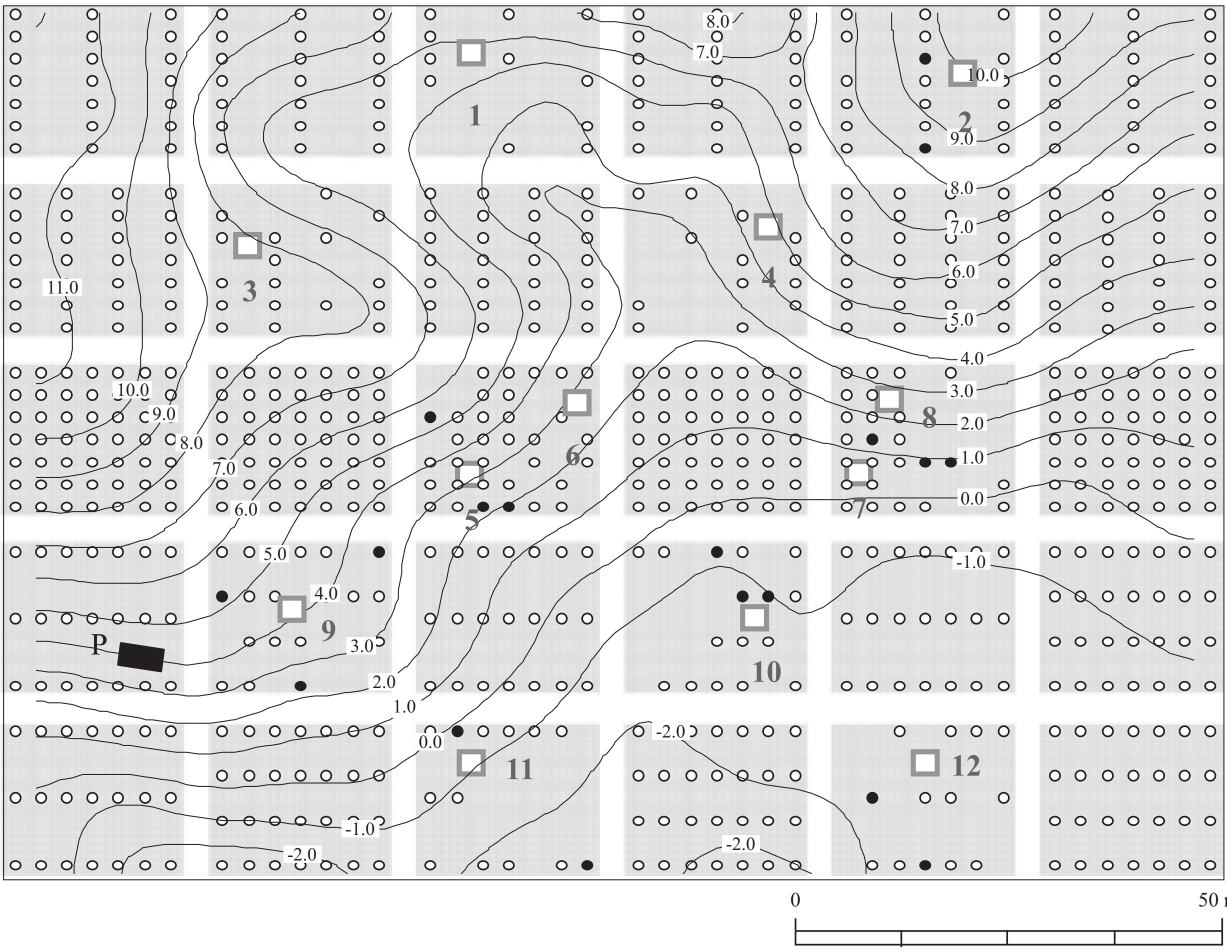

Fig. 2. Topographical map of the experimental stand

Open circles are living trees. Solid circles are dead trees. The number in the contour indicates the relative height in meters. Open squares with numbers show the location of sensors. The closed bar indicates the location of the soil pit. Screened squares show the initial quadrats before the line thinning.

3. Topographic index, drying rate calculation, and statistical analysis

The topographic index, described as ln(α/tanβ) (α = upslope contributing area per unit contour length; tanβ = local slope angle) is used for hydrological modeling and represents the hydrological characteristics at each landscape position conceptually[4,17]. The topographic index also called a wetness index, describes the tendency of contributing water flow from upper slope. The slopes and topographic indexes at each measurement site were estimated from our topographical survey data using Grass 6.0 (http://grass.itc.it/index.php).

Twelve events, which were comparably longer drying periods lasting 5 to 10 days after rainfall, were selected for study (Fig. 3). For each event at all measurement sites, a linear regression was deduced between days after rainfall and the VSW without the first 24 h data. The regression was described to the formula:

$$\theta = -ax + b$$

where θ is the volumetric soil water content and x is the number of the days of drying period. The slope of the formula, a parameter, was termed the drying rate (DR). Normalized DR, which corresponds to DR divided by tree density, was also estimated for removing the tree density effect at each site. We used the Kruskal–Wallis test to examine the differences for each event and site, and the Steel-Dwass test to perform multiple comparisons (JMP 5.0.1J; SAS institute and R 2.3.1[18]).

Results

1. Drying rate

During the study period, the soil water content at 30 cm fluctuated in response to the rainfall events (Fig. 3). No obvious long dry periods that continued for more than 1 month were observed. After excluding the first 24 h of the drying period, the VSW decreased linearly with accompanying wavy diel fluctuation at all sites and for all events (Fig. 3 lower, Fig. 4.). A close linear relationship was observed between days after rainfall and the VSW when the first 24 h after a rainfall were excluded. Based on the linear regressions, a strong correlation was observed

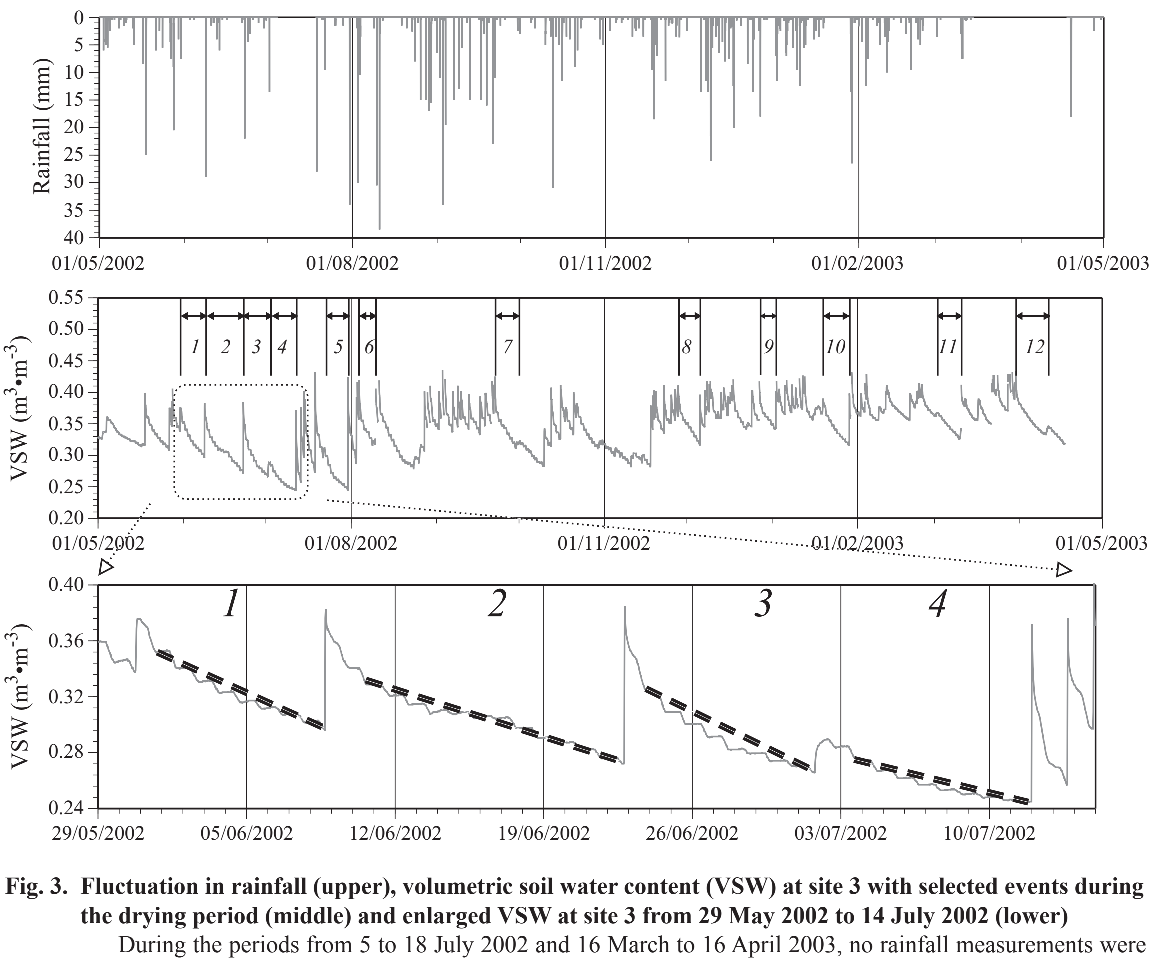

Fig. 3. Fluctuation in rainfall (upper), volumetric soil water content (VSW) at site 3 with selected events during the drying period (middle) and enlarged VSW at site 3 from 29 May 2002 to 14 July 2002 (lower)
During the periods from 5 to 18 July 2002 and 16 March to 16 April 2003, no rainfall measurements were taken. Numbers in the middle and lower figures indicate the selected drying periods.

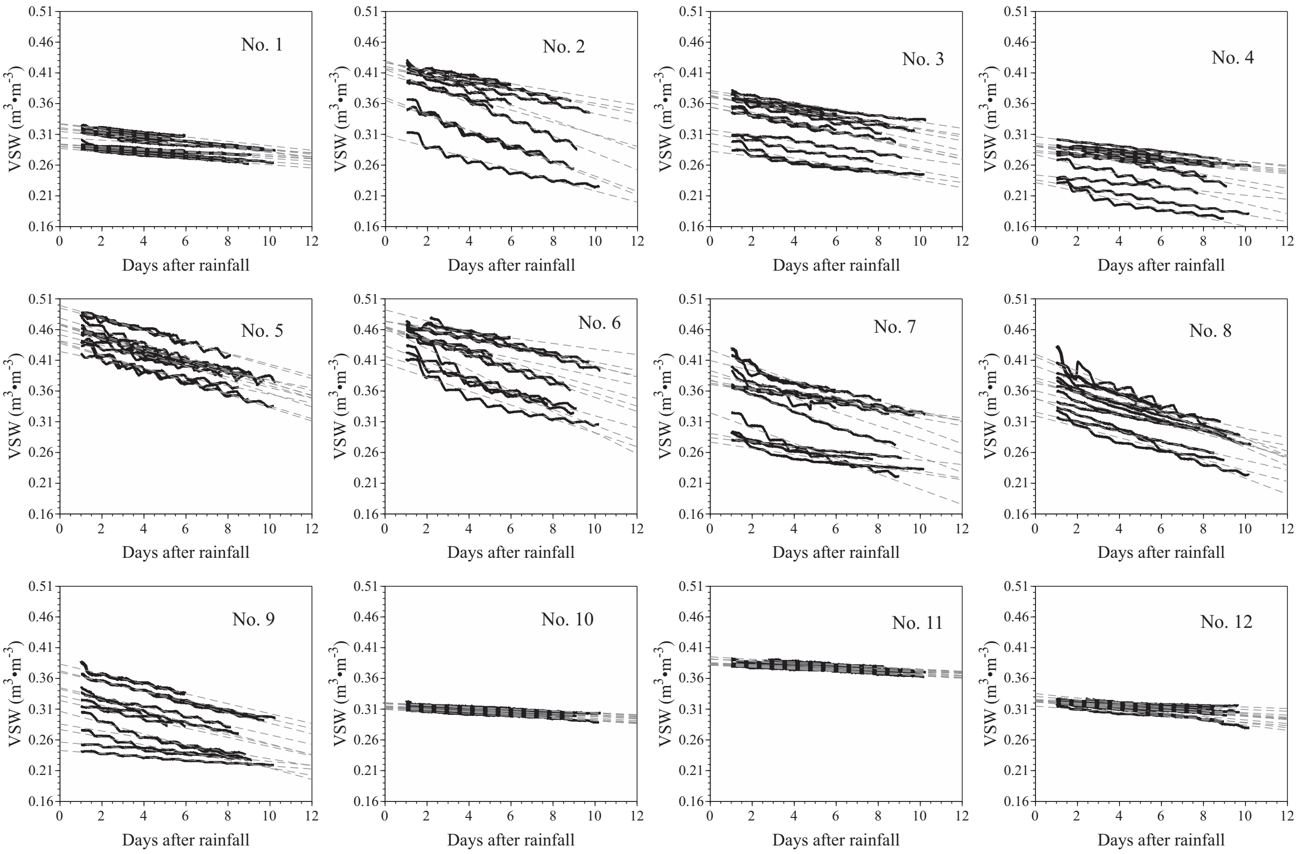

Fig. 4. The 12 drying processes at each site
The VSWs for the 24 h after rainfall were excluded.

between the 30-cm soil water content and time ($p < 0.01$, $0.813 \leq r^2 \leq 0.998$; Table 2).

2. Distribution of the VSW and DR and their relationship to tree density and topographic index

The median VSW of all the data at 12 o'clock was higher at sites 5 and 6 and lower at sites 1 and 4 (Fig. 5). The range in the VSW at sites 10–12, which corresponded to the bottomland, was obviously smaller than at the other sites. No significant relationships were observed between the VSW and tree density within a 10-m radius from the sensor, and between the VSW and the topographic index (Fig. 6).

The median DR was higher at sites 2, 5, 6, and 8 and lower at 1, 10, 11, and 12 (Fig. 5). A significant relationship ($p < 0.01$) occurred between the log-transformed tree density and the median DR (Fig. 6). This relationship fit to the following formula:

$$y = 8.00 \ln(x) - 11.0 \ (r^2 = 0.71)$$

where x = tree density and y = the median DR.

A significant relationship was also observed between

Table 2. Parameters of the linear regressions between the number of days after the last rainfall and the decrease in VSW

No. of site	a ($\times 10^{-3}$)* Average	S. E.	b ($\times 10^{-1}$) Maximum	r^2 Range
1	2.75	0.266	3.28	0.813–0.993
2	9.61	0.966	4.30	0.933–0.993
3	6.01	0.309	3.81	0.897–0.994
4	4.65	0.537	3.06	0.883–0.995
5	9.29	0.428	4.99	0.935–0.974
6	9.95	0.896	4.92	0.880–0.992
7	7.83	1.000	4.27	0.814–0.992
8	10.3	0.852	4.20	0.880–0.998
9	6.92	0.625	3.83	0.928–0.994
10	1.72	0.109	3.20	0.900–0.989
11	1.64	0.107	3.95	0.877–0.979
12	2.66	0.258	3.35	0.914–0.989

$\theta = -ax + b$; where θ is the volumetric soil water content and x is the number of days after the last rainfall; r^2 is the coefficient of determination.
*: The a value was termed the drying rate (DR).

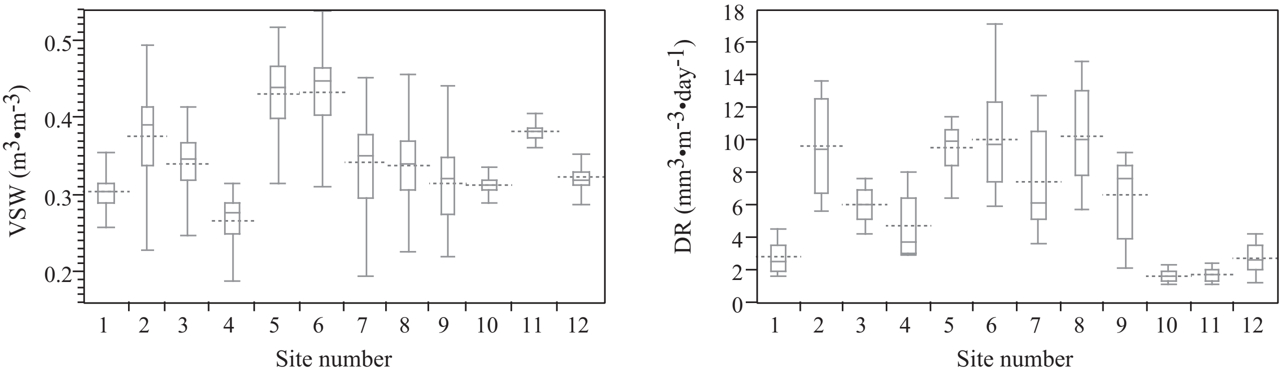

Fig. 5. VSW (upper) and DR (lower) distribution at each measurement site

The top, bottom and line through the middle of the box correspond to the 75th, 25th and 50th (median) percentiles. The vertical lines of each box extend from the 10th percentile to 90th percentile. The dotted line across the box corresponds to the average. Every VSW was at the 12 o'clock value (n = 285–365).

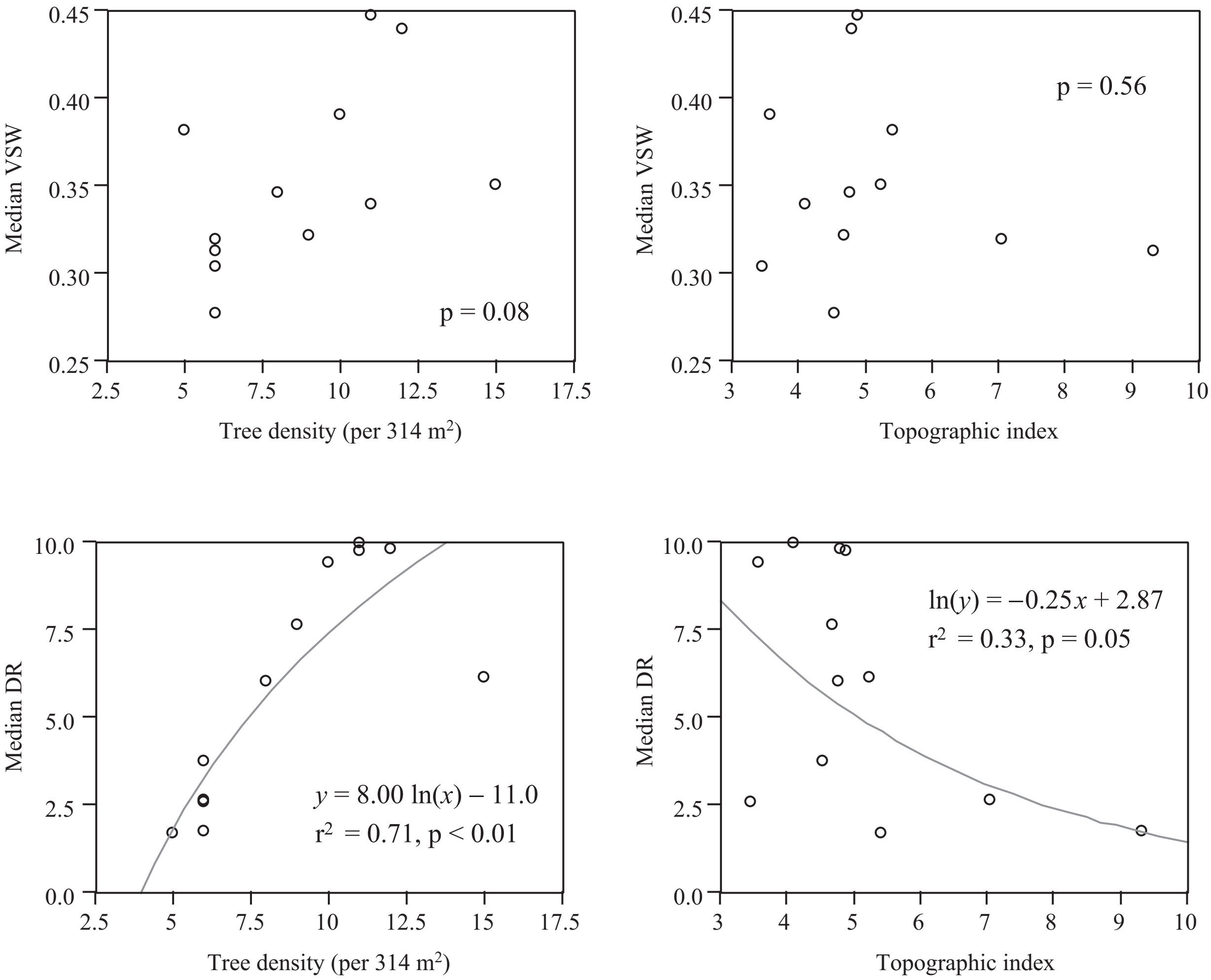

Fig. 6. Relationships between the median VSW and median DR and the tree density and topographic index

the topographic index and the median DR ($p = 0.05$), but no significant relationship was observed between the median VSW and tree density, or between the median VSW and the topographic index.

The normalized DR divided by tree density removed the effect of vegetation. The results of the normalized DR showed that sites 1 and 10–12 had statistically lower values than the other sites (Fig. 7). As sites 10–12 corresponded to the bottomland, the DR was lower for bottomland than the other locations. No difference in the DR was observed between crests and slopes. A significant linear relationship was also detected between the topographic index and the median normalized DR ($p = 0.038$).

Discussion

The DR was closely related to the tree density (Fig. 6), suggesting that the drying process was influenced by evapotranspiration at the study sites. Western et al. showed that soil water is controlled by topography under dry conditions, but by more complex factors under humid conditions[21]. In this stand, soil water condition was thought to be greatly influenced by thinning treatment. Because *A. mangium* uses a great amount of water based on studies of its water-use efficiency[7,10,12] and stem water content[22], the results for the DR are reasonable. Stand-density management in plantations might strongly affect the process of soil water drying in the humid tropics.

In the bottomland, the range in the VSW was smaller than at the other sites, reflecting the lower DR in the bottomland. The lower normalized DR for sites 10–12 reflects a simplex effect of landscape position in the bottomland (Fig. 7). Alisols and Acrisols are associated with Gleysols in depressions and on plains[8]. In the bottomland, the topographic indexes were high, and wet conditions are thought to be maintained for a long time. In fact, we observed a gleyic horizon at a depth of 110 cm in the bottomland. These results describe the properties of the bottomland well.

The difference of the DR between bottomland and other landscape positions was obvious, but no difference was observed between crest and slope (Fig. 7 left). This might be due to the small scale of this study area and limited twelve measurement sites. On the other hand, the relationship between the topographic index and the median normalized DR was significant (Fig. 7 right). The median normalized DR described the hydrological characteristic of each measurement site well. The topographical index calculated in this study is not from the whole catchment area, but only from the research area. More precise topographic information would enlarge the correlation coefficient between the topographic index and the median normalized DR.

In this study, the DR detected the effect of vegetation and landscape positions better than the median VSW, suggesting the difficulty in solely interpreting the soil water value. This difficulty is attributable to many complex fac-

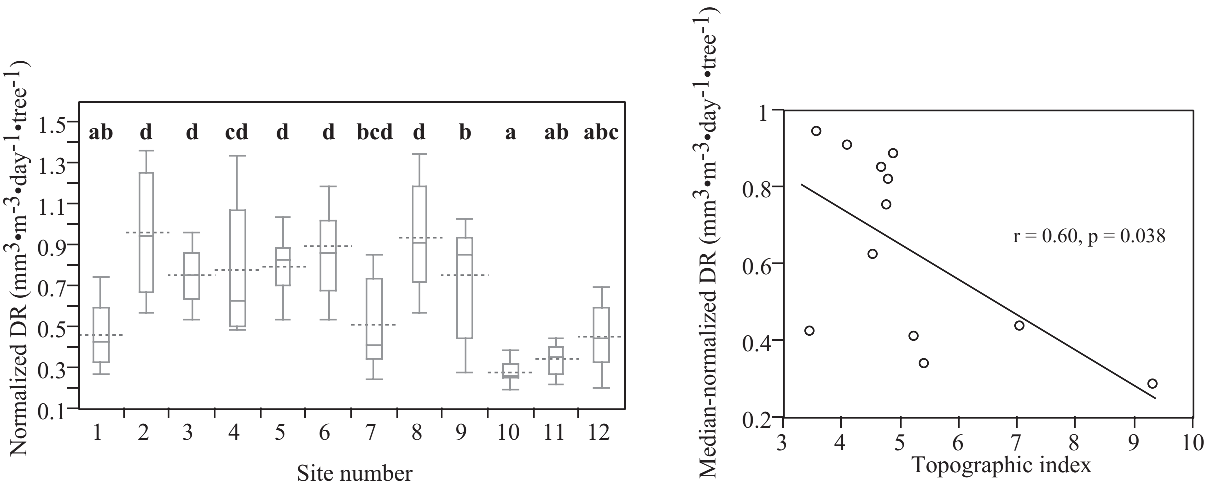

Fig. 7. Normalized DR distribution for each measurement site (left) and relationship between the topographic index and median-normalized DR (right)

The normalized DR corresponds to DR divided by tree density.

Left: The top, bottom, and line through the middle of the box correspond to the 75th, 25th, and 50th (median) percentiles. The vertical lines of each box extend from the 10th percentile to 90th percentile. The dotted line across the box corresponds to the average. Different letters indicate statistically significant differences among the sites determined using Steel–Dwass test ($P < 0.05$).

tors, such as the infiltration rate, porosity, texture, landscape position, and aboveground vegetation. Overall, the DR proved to be a better indicator of the soil water value under humid tropical conditions.

Soil water content of the first 24 h after rainfall might be in the period of gravity drainage (Fig. 3 lower). The diel fluctuation (Fig. 3 lower, Fig. 4) was thought to be due to the temperature dependency of the sensor and the effect of transpiration by the trees around the sensors. However, the regressions had high coefficients of determination and the diel fluctuation was negligible (Table 2).

Conclusions

The DR was strongly correlated with the tree density, suggesting that evapotranspiration was a major factor controlling the soil water regimes in this stand. The results for the lower DR and smaller range in the VSW well described the wet gleyic characteristic of the bottomland. The DR appears to be a better indicator for detecting vegetation and topographic effects on the soil water conditions than the representative value of the VSW in the humid tropics.

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