Unexpected absence of control of rubber tree growth by soil water shortage in dry subhumid climate

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RESEARCH ARTICLE

Unexpected absence of control of rubber tree growth by soil water shortage in dry subhumid climate

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Abstract Rubber tree cultivation is presently expanding rapidly into dry subhumid areas. As a consequence, trees face a long dry season. Low growth rates are delaying the start of tapping. The relationship between the growth rate and the soil water availability is not clear. Therefore, we studied the origin of low growth rates. For that we analyzed the relationships between growth, plant water stress, and soil water availability along a toposequence with a soil depth gradient. The plantation of 3-year-old *Hevea brasiliensis* trees was located in northeast Thailand. Tree circumference, predawn leaf water potential (*p*), soil water potential (*s*), and micrometeorological parameters were monitored from 2007 to 2010. Results show spatial and temporal variability of growth with a threshold value of leaf water potential of −0.4 MPa for growth. This leaf water potential threshold was not associated with very dry soils as soil water potentials were higher than −0.05 Mpa. But the leaf water potential threshold was associated with a high air vapor pressure deficit higher than 3–4 kPa. Leaf water potential decreased when the soil at the bottom of the slope was saturated in the rainy season. These results provide, for the first time, evidence that soil water shortage is unexpectedly not the main cause of low growth rates. Dry air in the dry season and waterlogging in rainy season are major constraints.

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1 Introduction

Rubber cultivation was extended to many suboptimal areas during the late 1970s (Priyadarshan et al. 2005). In some of these areas, long dry periods, high temperatures, and high air vapor deficits are reported as being the main constraints (Rao et al. 1993; Priyadarshan et al. 2005). Growth rates are often low, resulting in tapping being delayed up to 9 years after planting instead of the 6–7 years that is normal in the main growing areas (Chandrashekar et al. 1998).

However, only few studies have focused on the variability in the growth rates of young trees in these suboptimal conditions. Chandrashekar et al. (1998) showed experimentally that the growth of various clones in the Konkan region of Western India was mainly in the wet season. In the same area, an irrigation experiment carried out by Vijayakumar et al. (1998) showed that irrigation could improve growth and reduce the age at which tapping could start. However, while the trees' hydraulic traits were compared in detail, little information was given on the relationships between growth, tree water status, and soil water status. It was, therefore, impossible to provide a clear analysis of the response of the trees' growth rates to water availability (Carr 2012). From a practical point of view, analyzing the relationships between growth, tree water status, and soil water status may help to identify and rank growth-limiting factors other than water. This could be seen as a preliminary step for the selection of suitable fields and/or management strategies within a region (Doré et al. 2008).

In addition to soil water shortage, high evaporative demands could be one of the causes of low rubber growth rates in these dry subhumid areas. Mohankrishna et al. (1991) reported that the maximum growth rate of irrigated rubber during the dry season was less than half the growth rate in the rainy season in an area with high air vapor pressure deficit (VPD) during dry season. Also, in a plantation of mature trees in northeast Thailand, Isarangkool Na Ayutthaya et al. (2011) showed that very dry air strongly limited transpiration regardless of the soil water availability. Another cause of slow growth in these areas might be the intermittent waterlogging resulting from the concentration of rainfall over a short period combined with poor drainage. The sensitivity of rubber trees to waterlogging has been reported by Watson (1989). Waterlogging is well known to farmers in northeast Thailand, and so, the presence of an impermeable, or poorly permeable, layer close to the surface was expected. No studies of *Hevea* have reported the effect of waterlogging in dry subhumid areas.

The aim of this study was to identify the causes of low growth rates of young trees in a plantation along a topographic gradient representative of the areas where rubber has been recently introduced in northeast Thailand. Three hypotheses were tested: (1) tree growth rates vary seasonally and along the toposequence, (2) Ψp is a good indicator of water stress and its temporal and spatial variability is well correlated with growth rates, (3) the relationship between leaf water potential (Ψp) and soil water potential (Ψs) is affected by waterlogging in the rainy season and high air vapor pressure deficit in the dry season.

2 Materials and methods

2.1 Study site

This study was conducted in a 3-year-old rubber plantation located in Ban Non Tun, Nong Waeng sub-district, Phra Yuen district, Khon Kaen province, Thailand (16°28'N, 102°45'E). At an elevation of 200 m, it is “the upland area” of northeast Thailand. The soils are classified as Paleustults/Paleaquults (Kheoruenromne 1987). The climate is classified as tropical savanna according to Koppen’s classification (Pidwirny 2006). The mean annual rainfall of about 1,200 mm falls mainly between May and October. The mean annual temperature varies from 26 °C to 27 °C.

The rubber plantation stretches along a NW–SE-oriented slope of about 5 %. The soil profile was composed of a medium–fine loamy sand layer at the surface, overlaying a clayey horizon covering fractured and highly weathered sandstone. The depth of the soil and the thickness of the various layers varied down the slope determined by the slope of the bedrock and the downward soil movement. Some soil physical and chemical characteristics along the toposequence are summarized in Table 1. Siltecho et al. (2010) reported the values of 0.05 and 0.30 for residual and saturated volumetric water content in the loamy sand layer at the site. The volumetric water contents at wilting point (−1.5 MPa) and field capacity (−0.01 MPa) of this layer were 0.09 and 0.19, respectively. These authors also showed that the clayey layer had a hydraulic conductivity of 0.1 cm h^{-1} and behaved as impervious horizon.

2.2 Clone and plantation management

The rubber trees were planted in July 2004 on a Ruzi grass (*Brachiaria ruziziensis*) meadow. Young budded plants of RRIM 600, the most common drought-tolerant clone in this region, were planted 3 m apart in rows. The soil surface was ridged in an attempt to facilitate water runoff and to minimize flooding under the trees. With a distance of 7 m between the rows, the tree density was about 476 trees ha^{-1} as recommended by the local advisory services (Rubber Research Center 2010). The inter-rows were not cultivated and were weeded with glyphosate herbicide applied every 3 months. The total fertilizer dose recommended for rubber by the local advisory services (80/20/40 g NPK per tree) was split into two applications in July and September. The fertilizer was applied within a 1-m-diameter circle around each tree and worked in to 5–7 cm deep. The overall management of this plantation was representative of the northeast Thailand and was similar to the standard practice in the traditional plantation area in south Thailand which has an ideal climate for *Hevea*.

2.3 Growth, tree mortality, and water potential measurements

Trunk circumference and tree mortality were measured for a row of 23 trees selected at the top, middle, and bottom parts of the slope, respectively. Trunk circumferences were measured twice a month at 1.50 m above the soil surface. The monitoring period ran from May 2007 until March 2011. The growth rate (millimeters per day) of each tree was calculated as the difference between two successive measurements divided by the number of intervening days. Monthly values (centimeters per month) were calculated from the average growth rates (millimeters per day) within the month. Trees with at least 75 % of necrotic aerial biomass were classified as dead, and the number of dead trees in each row monitored was recorded every year at the end of dry season.

The soil water potential (Ψs) was measured with three standard SMS 2000 tensiometers installed within each of the rows selected for monitoring the tree growth rate. They were placed in a group at about 0.30 m from a tree trunk selected as representative of the average growth in the row. They

Table 1 Soil characteristics down the slope of the study site in Khon Kaen province, Thailand (16°28'N, 102°45'E)

Topographic position	Depth (cm)	Soil texture	Clay content (%)	Bulk density	pH	SOM (%)	Total N (ppm)	Avail P (ppm)	Avail K (ppm)
Top of slope	0–15	Loamy sand	3.0	1.49	4.0	0.27	1.11	3.53	44.98
	15–70	Loamy sand	9.2	1.55	5.2	0.26	0.82	1.21	24.13
	70–80	Clay	13.0	1.65	5.5	0.14	0.64	0.88	57.67
	Bedrock	Sandstone							
Middle	0–18	Loamy sand	2.5	1.46	4.8	0.54	1.11	1.31	15.52
	18–95	Loamy sand	3.7	1.47	5.3	0.11	0.58	0.59	15.88
	95–160	Clay	27.4	1.65	5.7	0.16	1.23	0.59	135.09
	Bedrock	Sandstone							
Bottom	0–30	Loamy sand	2.0	1.38	5.7	0.07	1.11	1.02	34.96
	30–130	Loamy sand	6.0	2.00	5.3	0.28	0.71	0.85	38.86
	130–200	Clay	24.8	1.71	5.1	0.34	1.83	0.59	114.58
	Bedrock	Sandstone							

pH was determined in distilled water using 1/1 paste. Exchangeable K+ was titrated with a flame spectrometer after exchange with 1 M ammonium acetate (NH4OAc). Available phosphorus was determined using the Bray 2 method. Total C and total N were determined by Walkey and Black and Kjeldahl methods, respectively. Soil analyses were performed by LDD Bangkok Laboratory services

were inserted into the soil at depths of 0.10, 0.25, and 0.65 m (D). The hydraulic head (H) of the soil ($H<0$) was read directly once or twice a week. Ψs was monitored over the same period as the growth rate. The soil water potential (Ψs) was calculated using the equation—Ψs (millibar)=H (millibar)+D (centimeters). The limit of $H=-800$ mbar (−0.080 MPa), corresponding to the air entry pressure for these tensiometers, was never reached during the monitoring period. For each position in the toposequence, the average Ψs calculated using the values measured at the three depths was assumed to represent the average Ψs in the root zone for the trees studied. Neutron probe measurements showed that the water content in the clayey layer below the loamy sand layer remained unchanged over the whole of the dry season (not shown). Using three tensiometers per row was certainly not enough to represent all the variability within each row. Preliminary examination using auger prospections, however, showed that the variation in soil water content was much lower within each row than it was between rows along the toposequence. Moreover, the experimental design focused primarily on the relationships between soil and tree water statuses at different positions along the toposequence.

The leaf water potential (Ψp) was measured with a pressure chamber (PMS 1000, PMS Instrument Company, Corvallis, Oregon, USA). Measurements were taken every 2 weeks before sunrise on two fully expanded leaves sampled at the top of the crown of three representative trees in the top, middle, and bottom rows studied. Measurements were performed in situ, cutting the leaves immediately. It took about 45 min to complete all the measurements. Unlike the growth rate and Ψs, Ψp was only monitored up to October 2010 because of a technical problem.

2.4 Weather measurements and statistical analysis

A weather station (Campbell Scientific Inc., Logan, Utah) installed on the study site in 2006 recorded rainfall, air temperature, and relative humidity. The air VPD was calculated using the formula:

$$\mathrm{VPD} = (100 - \mathrm{RH}/100) * \mathrm{SVP}$$

where RH is relative humidity and SVP is saturated vapor pressure estimated from air temperature (Murray 1967).

Repeated-measures ANOVA using SAS Proc GLM (SAS Institute Inc 1999), was used to test the effect of the position in the toposequence and temporal factors (months and years) on the variables measured. The annual circumference increment was calculated over the period of 12 months from April of one calendar year until March of the next year. All means were separated using the Tukey's test at the $P<0.05$ level. Mean values of circumference increments in Figs. 1 and 2 were calculated from 46 measurements at each position down the slope each month. Mean values of Ψp in Figs. 2 and 3 were calculated from 12 measurements at each position down the slope each month. Mean values of Ψs in Figs. 4 and 5 were calculated from 10 or 12 measurements at each position down the slope each month.

3 Results and discussion

To analyze the effect of soil water status on the growth rates of the young rubber trees along the toposequence, two main

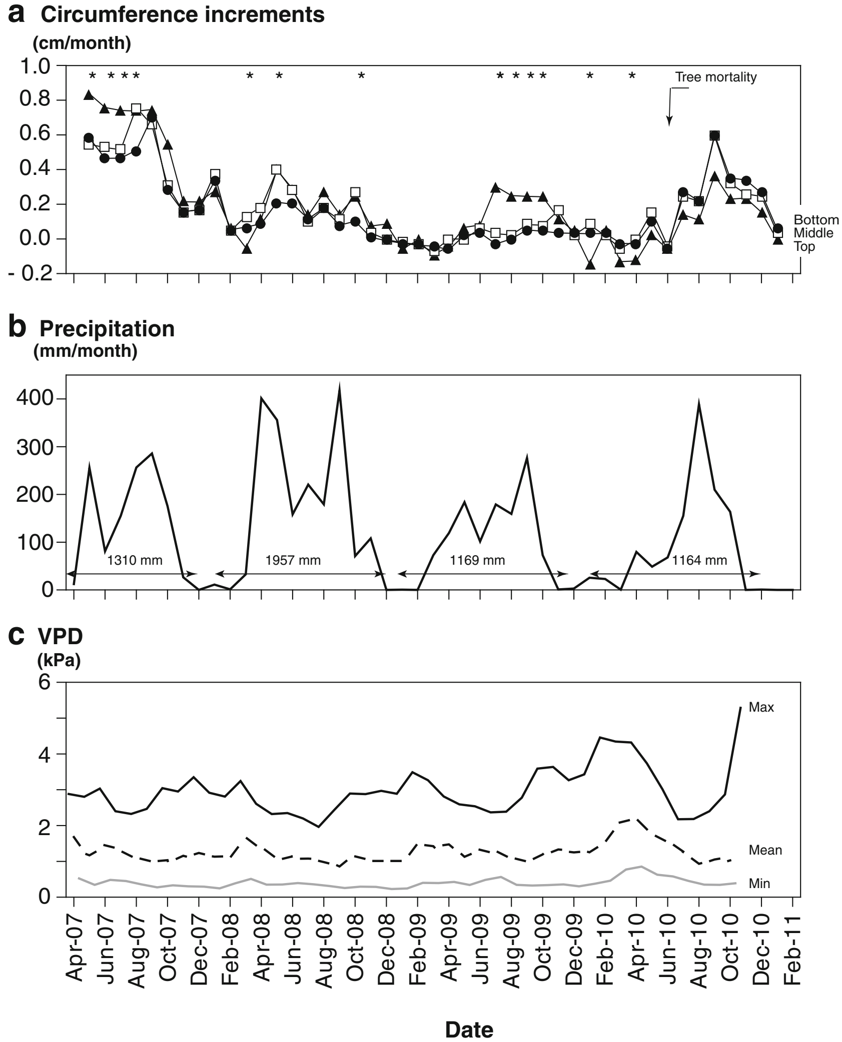

Fig. 1 Trunk circumference increment (n=46) (**a**), precipitation (**b**), vapor pressure deficit (**c**), in Ban Non Tun, Khon Kaen province, Thailand (16°28'N, 102°45'E) over 2007–2010. *Stars* in the *top* of **a** represent the date when significant differences between topographic positions were found. Values inserted in **b** are annual rainfall from 2007 to 2010 successively

parameters were chosen as indicators of soil and plant water status: the soil water potential within the soil volume colonized by roots (Ψs) and the predawn leaf water potential (Ψp). These parameters, the circumference of the trees and climatic variables, were monitored over the study period.

3.1 Trunk circumference, circumference increment, tree mortality, and weather

At the start of the monitoring in May 2007, 3 years after planting, the trunk circumference at 50 cm from the soil surface averaged 11.4 cm. In March 2011, 7 years after planting, the average trunk circumference had reached 20 cm. The average annual circumference increment over the monitoring period was 2 cm year^{-1} (Fig. 1a). The annual circumference increment was highest in 2007, with value of 3.9 cm year^{-1} and lowest in 2008 and 2009 with values of 1.3 and 0.5 cm yea^{-1}, respectively. Within each year, two distinct periods were identified: a period where the monthly circumference increments were usually positive (from April to October in 2007, 2008, and 2009 and from July to October in 2010) and the rest of the year where the circumference increments were zero or even negative. Except in 2010, circumference increments were lowest at the bottom and highest at the top of the slope. Most cases of negative circumference increments were found at the top of the slope. There was only one mortality episode up to the end of June 2010. Tree mortality was 22 % at the top of the slope, 9 % at the middle, and 0 % at the bottom.

Average annual rainfall was 1,400 mm. The year 2007 was relatively wet, with total rainfall (1,310 mm) close to the upper quartile of the historical records. The year 2008 was very wet, with a total rainfall (1,957 mm) 45 % above the upper quartile of the historical records, and there was exceptionally high rainfall until November. Years 2010 and 2009 had average rainfall (1,164 and 1,169 mm), but in 2010 rainfall was very low until the month of June. Each year, at least 92 % of the annual rainfall fell within the 7 months from April to October (Fig. 1b). Mean monthly temperatures ranged from 2 °C 3 to 25 °C in December to

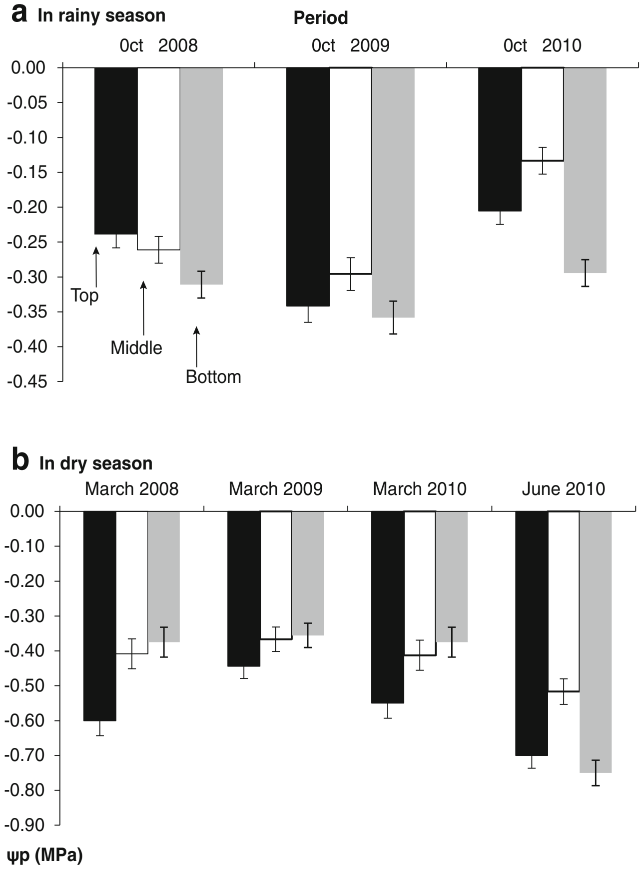

Fig. 2 Predawn leaf water potential (Ψ*p*) of *Hevea* down the slope in the rainy season (**a**) and the dry season (**b**). *Bars* are standard errors (n=12)

30 °C to 33 °C in March. Mean monthly humidity ranged from 53 % to 60 % in January to 73 % in August. The daily maximum value of air VPD was above 2 kPa during the entire monitoring period (Fig. 1c). The peaks of 3–4 kPa were usually in March. The highest peaks were in 2010. Even at night, the vapor pressure deficit never fell to zero but ranged from 0.2 to 0.8 kPa.

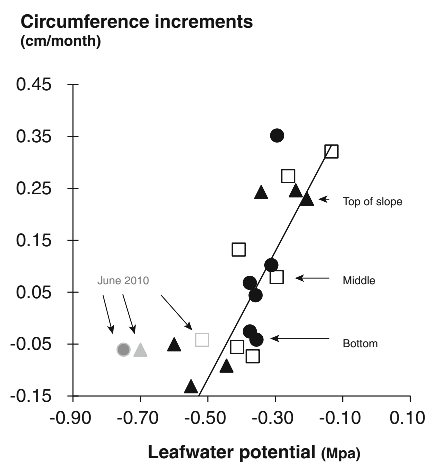

Fig. 3 Relationship between predawn leaf water potential (Ψ*p*) and circumference increments of *Hevea* trunks in the months of October and March 2008 to 2010 and June 2010. The linear regression model is based on the data of October and March, Growth=1.06 x+0.46; r^2= 0.60; P<0.01; n=18

Seven years after planting, the trunk circumference is 60 % lower than the value of 50 cm generally reached at this age in areas with ideal climate for *Hevea*. Latex tapping could, therefore, not be started at the end of the study even though the plantation had reached its seventh year. The pattern of growth within a year was consistent with Chandrashekar et al. (1998, 2002) who showed that, under similar climatic conditions, there was no growth outside the rainy season. Moreover, the tree shrinkage (negative circumference increments) observed during the dry season has also been reported by Chandrashekar et al. (1998, 2002) for young rubber trees and Bucci et al. (2008) for trees in the Amazonian forest. During the rainy season, the growth was below the range of 1.0 cm to 1.5 cm month^{-1} found by Devakumar et al. (1999) in an irrigation experiment carried out in a drought-prone area on the west coast of India. This suggests that limiting factors other than water deficit affected the growth in the study area. Even in the rainy season, the daily maximum vapor pressure deficit values were largely above the critical values of 1.8 kPa reported by Isarangkool Na Ayutthaya et al. (2011) as closing the stomata regardless of the soil water status. Considering the long dry season and the high daily vapor pressure deficit even in rainy season, both the annual and daily periods favorable to growth appeared to be short. The mortality episode observed in June 2010 was preceded by a 4-month period combining low rainfall with the highest air vapor pressure deficit over the monitoring period. This suggests that tree mortality was due to water stress. This is supported by Sangsing et al. (2004), who showed that xylem conduits in rubber trees are relatively vulnerable to cavitation, and (McDowell et al. 2008), who considered that mortality may be due to the avoidance of drought-induced hydraulic failure via stomatal closure, resulting in carbon starvation and a cascade of downstream effects such as reduced resistance to biotic agents.

3.2 Circumference increment versus Ψ*p*

The highest values of predawn leaf water potential were observed during the rainy season where they ranged from −0.13 to −0.35 MPa. Differences between months over the rainy season were not significant. The lowest values were usually observed at the end of the dry season in March and ranged from −0.40 to −0.70 MPa, except in 2010, when Ψ*p* continued to decrease until June. At the end of the rainy season, Ψ*p* tended to be lower at the bottom of the slope than at the top (Fig. 2a), indicating water stress at the bottom of the slope. At end of the dry season (except in June 2010), Ψ*p* was significantly lower at the top of the slope than at the

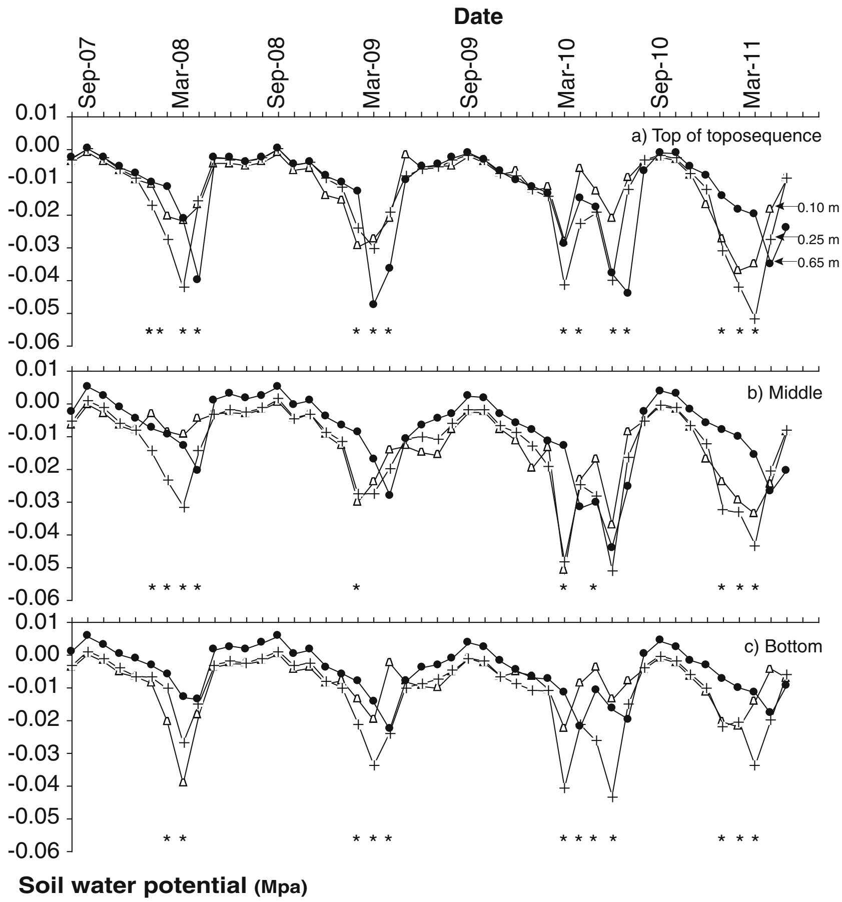

Fig. 4 Soil water potential (Ψs) at three soil depths (0.10, 0.25, and 0.65 m) from September 2007 to March 2011. *Stars* in the *bottom* represent the date when significant differences between soil depths were found (n=10)

bottom, indicating that the water stress was higher at the top than at the bottom of the slope (Fig. 2b). The range of Ψp values was similar to that reported by Isarangkool Na Ayutthaya et al. (2011) for mature trees of the same clone in northeast Thailand.

The correlation between circumference increment and Ψp over 3 years (2007–2010) at the three positions down the slope was significant (Fig. 3, $y=1.06\ x+0.46$; $r^2=0.60$; $P<0.01$; $n=18$). This showed that water stress had a major effect on trunk growth and the presence of a threshold of about −0.4 MPa, below which growth was zero or negative. This threshold was in agreement with Isarangkool Na Ayutthaya et al. (2011) who found that the whole-tree hydraulic conductance decreased dramatically when Ψp was below −0.4 MPa.

3.3 Soil water potential (Ψs) versus Ψp

During the rainy seasons, the soil water potential Ψs was usually close to zero and sometimes positive (Fig. 4a, b, and c). The highest Ψs was at 0.65 m depth and increased down the slope. Ψs was lowest in March, at the end of the dry season, ranging from −0.04 to−0.05 MPa and being sometimes significantly lower at the top of the slope. In 2010, there was a dry season with two very dry periods in March and June. The measurements of Ψs at 0.10, 0.25, and 0.65 m depth indicated that the soil dried unevenly, particularly at the top and the bottom of the slope (Fig. 4a, b, and c). The values of Ψp were five to ten times lower than Ψs (Fig. 5). Using the measurements at the middle of the slope as the upper boundary of $\Psi p/\Psi s$ (regression line $\Psi p=5.92$, $\Psi s-0.23$, $r^2=0.77$, $P<0.01$, $n=7$), data below this boundary were:(1) severe waterlogging ($\Psi p>-0.01$) mostly at the

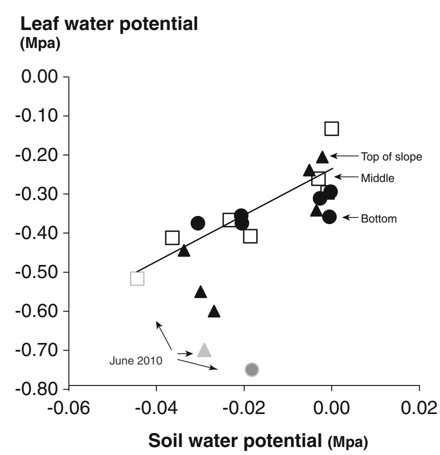

Fig. 5 Relationships between soil water potential (Ψs) and leaf water potential (Ψp) in the months of October and March 2008 to 2010 and June 2010. The linear regression is based on the data collected at the middle of the slope, $\Psi p=5.92\ \Psi s-0.23$; $r^2=0.77$; $P<0.01$; $n=7$

bottom of the slope, (2) high air vapor deficits combined with uneven soil drying in March 2008 and 2010 at the top of the slope and in June 2010 at the top and bottom of the slope.

The measurements of Ψs did not show that the soil was subject to serious drying in the dry season. Ψs during the dry season was never below −0.05 MPa, which means that it was far from the soil water potential at wilting point (−1.5 MPa). This moderate water shortage cannot be the primary cause of zero or negative growth in the dry season. Given the high predawn water potential disequilibrium, in particular, in June 2010, when the air vapor deficits reached its highest values of 4 kPa, we assumed that the dryness of the air was a major cause of the growth inhibition in the dry season. This has also been suggested by Donovan et al. (2001) based on an experiment in glasshouse comparing tree species with canopies bagged and un-bagged to eliminate overnight transpiration that followed sunny days. The results also suggest that the uneven drying of the expected root-colonized soil might have also been responsible for predawn disequilibrium during dry season. In fact, as reported by Ameglio et al. (1999) from experimental studies, a few roots in a wet soil layer may not have time to supply enough water for ensuring overnight the equilibrium between soil water potential and predawn leaf water potential. The particularly high air vapor pressure deficit at the study site is probably related to its particular geographical features. It is located at the east of the Petchaboon Mountains and is, therefore, sheltered from the moisture laden air from the southwest monsoon (Limpinuntana 2001).

During the rainy season, it is likely that waterlogging combined with high dry air at some periods of the day were, via their negative effect on predawn leaf water potential, the major causes of the low growth. Predawn disequilibrium during rainy season was particularly high at the bottom when the soil was very waterlogged. The effect of waterlogging on predawn leaf water potential disequilibrium has not been reported to date. This study provided insights on some limitations of using leaf water potential as an indicator of soil water shortage. Based on field observations, it showed that waterlogging and high air vapor pressure deficit could be responsible for low leaf water potential and reduced growth.

3.4 Origin of waterlogging and consequences for the nutrient status of the trees

Waterlogging in the rainy season was particularly acute at the bottom of the slope owing to the accumulation of the lateral flow over an impermeable layer at 1.35 m below the surface. The soil characteristics were representative of one of the most recent new areas for rubber plantation in northeast Thailand. In earlier new areas, such as Nong Khai province in upper Khorat, near the Mekong River (approx. 18°N, 103°E) and in the Buriram province in the lower part of the Khorat plain (approximately 14°N, 103°E), Rantala (2006) reported that often the soils were not well drained, and plantations of the RRIM 600 clones did not reach tapping size until 8–10 years. In a recent study carried out in a mature plantation closer to the study site (in Satuk district, approx. 15°N, 103°E), the soil was deeper than that for this study, with a bedrock starting more than 4 m below the surface. The 1.50-m deep loamy sand upper layer was on a clayey layer of bulk density of 1.55–1.70 Mg m^{-3} (Gonkhamdee et al. 2010) which suggests that there is also a local risk of waterlogging in other areas of northeast Thailand. Based on model simulations, Masaki et al. (2011) found that seasonal differences in precipitation will intensify in northeast Thailand in the future: Precipitation will increase in the rainy season and decrease in the dry season. Moreover, air temperature will increase. In such a scenario, waterlogging in rainy season and drought in the shallow soils at the top of the slopes in the dry season will become even more serious than shown in our results.

It is likely that waterlogging, in conjunction with high lateral drainage and erosion during rainy season, caused high nitrogen losses and low soil nutrient availability. The leaf nitrogen content measured in 2010 was 22 g kg^{-1}. This was far below the critical value of 30 g kg^{-1} reported by Pushparajah and Tan (1972) for the RRIM 600 clone. A legume cover crop (*Pueraria phaseolides*) introduced in 2007 in the interrows of a separate plot at the study site increased leaf nitrogen content by 30 % and doubled the circumference increments in 2010 (data not shown). However, they were still lower than the “standard” value, suggesting that other factors, waterlogging and very dry atmospheric conditions in this case, were the major causes of low growth rates.

4 Conclusion

This study set out to identify the causes of low growth rates along a toposequence which was representative of the conditions where young rubber trees suffer from low growth rates in northeast Thailand. It examined the relationships between growth rate, leaf water potential, soil water potential, and air vapor pressure deficit at various times over four consecutive years at three positions along the toposequence.

The original contribution provided by this study was evidence that low soil water potential was not the only cause of low leaf water potential and the resultant low growth rates. The relationship between soil and leaf water potential was significantly affected by waterlogging, high dry air, and heterogeneity in water availability through the expected root-colonized soil. Low growth rates seemed to be caused by a combination of waterlogging, soil drying, and dry air rather than a simple lack of water. Moreover, it was likely that waterlogging and lateral drainage reduced the soil nitrogen availability. The selection of locations and management strategies for rubber plantations in this area should take all these factors into account. In a climatically suboptimal region, the choice of soil characteristics is critical for tree survival through the dry season. Moreover, the soil drainage should provide optimal conditions during the short rainy season which is favorable to growth. More research on the effect of high vapor pressure deficits and transient waterlogging, with its effect on the nutrient cycle, is needed to provide a sustainable extension of rubber plantations into drier areas.

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