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Temperature dependence of natural rubber productivity in the southeastern Vietnam

Binh Thanh Nguyen[a,b,*], Mui Kim Dang[c]

[a] Environmental Engineering and Management Research Group, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[b] Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[c] Dong Phu Rubber Company, Binh Phuoc, Vietnam

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ABSTRACT

How natural rubber (NR, *Hevea brasiliensis MuÏl. Arg*) productivity responds to warmer temperature has been a major concern, especially since the global temperature is reported to be increasing. The current study was conducted in southeastern Vietnam, aiming to (1) evaluate the trend of NR productivity with increasing ambient temperature and (2) investigate interactive effects among soil type, NR clone, and temperature on NR productivity. The study was conducted in harvested NR plantations of 59,631 ha, using GT1 and PB235 clones planted on Ferralsols and Acrisols. Data of NR productivity and three temperature variables, mean temperature (Tmean), mean maximum temperature (Tmax) and mean minimum temperature (Tmin), were determined in 2007, 2008, and 2009 for the current study. The NR productivities of the two NR clones planted on two soil types were significantly and negatively correlated with Tmean and Tmin, but were not correlated with Tmax. While the interaction between soil type and Tmean on NR productivity was not significant, the interaction between soil type and Tmin was significant. NR plantations located on Ferralsols with low Tmin showed the highest productivity (7.9 kg $tree^{-1}$ $year^{-1}$). An interaction between Tmean and Tmin on NR productivity was also found; plantations located within the areas low in both Tmean and Tmin had the highest productivity (8 kg $tree^{-1}$ $year^{-1}$). Although two mechanisms (Tmin influencing latex flow and Tmean affecting latex regeneration) were proposed to explain how Tmin and Tmean influenced NR productivity, they were not proven and thus more study is needed. The findings also suggested that for the coming years of the present century, in which temperatures are likely to rise, global NR latex production could be significantly affected due to reduced productivity, indicating the need for more studies to verify trends and/or to find solutions.

1. Introduction

Warmer temperature has been frequently reported globally, and temperatures are even projected to continue to increase through the end of the current century (IPCC, 2007). Of cause, there is great variation locally and some areas were reported to rise more quickly than the others (IPCC, 2001). As temperature is a central climatic factor, governing life cycles of living organisms, a warmer temperature can have considerable impact on crop growth and productivity, depending on individual crops and regions (Lobell and Field, 2007). In tropical and sub-tropical areas, crop growth and productivity may suffer more seriously from global warming than in temperate zones (Rosenzweig and Parry, 1994). With warmer temperature, Lobell and Field (2007) reported a decrease in crop yield, while Myneni et al. (1997) found evidence suggesting an increase in plant growth in northern regions.

It is also well known that crops have different temperature response patterns associated with a particular habitat (Prentice et al., 1992). Natural rubber (NR, *Hevea brasiliensis Müll. Arg.*), originating in the Amazon basin, is best suited for regions having mean monthly temperature from 25 to 28 °C (Rao and Vijayakumar, 1992) and has been commercially planted in tropical and sub-tropical areas. The crop has recently been considered for cultivation for the dual purposes of timber and latex production (Gouvêa et al., 2013). So far, there have been few publications reporting the influence of warmer temperature on NR plantations (Raj et al., 2005). In particular, Rao et al. (1998) found a negative correlation between NR yield and maximum temperature in Kottayam, India. When ambient temperature reached 33 °C, Rao et al. (1990) found stomatal closure in clone RRII 105 and RRII 118. In contrast, Yu et al.

* Corresponding author at: Faculty of Environment and Labour Safety, Ton Duc Thang University, 19, Nguyen Huu Tho street, District 7, Ho Chi Minh City, Vietnam.
E-mail address: nguyenthanhbinh@tdt.edu.vn (B.T. Nguyen).

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(2014) reported a positive relationship between NR yield and Tmax in southwest China, indicating inconsistent results from different studies.

In the context of global warming, there is still a need for more studies to clarify the relationship between the temperature and NR productivity. For NR plantations, it is extremely hard to conduct such studies using the standard traditional experimental setup with treatments of varying temperature levels. Greenhouse experiments may be impractical, because the NR is a forest-tree crop having 20–30 m height and a long economic life cycle of a few decades. Spatial investigation based on a large-scale area with a considerable temperature difference may be an option, although it may potentially induce some experimental errors. For example, soil conditions, rainfall regime, and solar radiation may vary from site to site when studies cover large areas. Despite the disadvantages, spatial correlation has been used frequently in agriculture and meteorological fields. Li et al. (2010) used spatial correlation to investigate the relationship between wheat yield and important climatic factors across China. Bannayan et al. (2010) examined the correlation between climatic indexes and wheat and barley yield in northeast of Iran.

Natural rubber trees have been planted in Vietnam for almost 115 years, mostly concentrated within the southeastern region with mean temperature varying from 25.3 to 27.5 °C. With increasing global temperature, a consequent concern is the responsive trend of the NR plantations. To address the knowledge gap, the current study was conducted on 59,631 ha of NR plantations during the harvest period in southeastern Vietnam. Knowing that there was a clonal difference in climatic response (Raj et al., 2005; Priyadarshan, 2003), significant interactions between experimental sites (environmental factors) and NR clones reported from a study in Brazil (Rivano et al., 2013), we separately targeted the two most commonly grown clones, GT1 and PB235, on two soil types, Ferralsols and Acrisols. The study aimed to (1) examine the response of NR productivity to temperature variables (mean, maximum and minimum temperature) and (2) investigate interactive effects of soil type, clone and temperature on NR productivity.

2. Methods and materials

2.1. Studied areas

The current study was conducted on 59,631 ha of harvested NR plantations in the southeastern Vietnam (Fig. 1). The region is located from $12^0\ 2'$ to $10^0\ 29'$N and $105^0\ 55'$ to $107^0\ 43'$E. Although elevation of the region varies from 15 to 200 m, the studied plantations were located in relatively flat areas with slopes less than 8% and productivity not significantly affected by elevation variation (Nguyen, 2013). The region has a tropical climatic regime with high rainfall and temperature and distinct rainy and sunny seasons.

2.2. Natural rubber plantations

The studied plantations were fully managed by the Vietnam Rubber Group (VRG), with all plantations treated with relatively uniform maintenance and management (technical protocols, policy). The NR plantations normally go through two growth stages, immature and mature. The former is with young and unharvested trees, up to 7 years old, while the latter is the harvesting period. The harvesting period is divided into three stages: the initial stage was characterized by original bark tapping for the first 10 years; the second stage with renewing-bark tapping for the next 10 years; and the last stage had maximal harvesting. At the time the present study was conducted, a largest portion of the NR trees (82 plantations) fell into the second stage, and thus NR productivities measured from those plantations being at the 11th to 20th year of harvesting were processed.

There were 45 NR clones planted in the southeast region (spacing 6 m × 3 m and density 555 trees per hectare), but two clones, GT1 and PB235, comprised a majority of the planted trees (72% of the total harvested NR areas in the region) and thus were selected for the current study. Because the current study focused on the second harvesting stage (age 11–20th), 59,434 ha of NR plantations, occupying 39% of the total harvested area, were used. While there were several soil types reported within the region, the studied NR plantations were mostly located on two soil types, Acrisols and Ferralsols (FAO/UNESCO). The Acrisols were characterized by a light to moderate texture and high sandy portion, while the Ferralsols had a moderate to heavy texture and high clay content. In short, the current study was conducted on GT1 and PB235 plantations located on Ferralsols and Acrisols.

2.3. Data collection

Natural rubber productivity: data of natural rubber productivities used for current study were extracted from the database reported by Nguyen (2013). From 140,000 ha of NR plantations used in the previous study, 59,434 ha of GT1 (12,966 ha on Ferralsols, 13,745 ha on Acrisols) and PB235 (9,400 ha on Ferralsols, 23,322 ha on Acrisols) were selected at harvesting age (11–20th year) in the southeastern region for the current study. Latex productivities for individual year 2007–2009 were processed as replicates (repeated measurements).

Temperature variables: raw temperature variables including monthly mean temperature (Tmean, °C), monthly mean maximum temperature (Tmax, °C), and monthly mean minimum temperature (Tmin, °C) for 2007–2009 were collected from 32 weather stations across Vietnam, but only data from eight stations located within the study areas were shown in Fig. 1. The twelve-month temperatures of every weather station for individual years (2007–2009) were used for GIS-based spatial processing to extrapolate the temperatures associated with individual NR plantations. Monthly data of the three temperature variables, plus humidity (%) and rainfall are shown in Fig. 2.

2.4. Spatial processing

The GIS-based map of the currently studied plantations was extracted from the database from Nguyen (2013), and was used as a reference map, called plantation layer, for spatial analyses and joining temperature variables using ArcGis 9.3. The yearly means of the three temperature variables were digitalized and GIS-based data imported, forming 9 point layers (3 years × 3 temperature variables), which were further processed, following procedure presented in Nguyen et al. (2010). In brief, four basic steps were conducted to complete the procedure, including (1) Geo-statistical analysis (*Kriging*), (2) conversion to grid (*GA layer to grid*), (3) spatial analysis (*Raster calculator*), and (4) conversion to point layer (*Raster to point*). The layers created by step 4 were joined to the plantation layer and then exported to an Excel file for statistical analyses.

2.5. Statistical processing

Sigmaplot 12 (Systat Software Inc, California, USA) was used to examine the relationships between NR productivity and temperature variables. Means of individual temperature variables were calculated and used as a threshold for temperature based plantation grouping. Plantations having temperature values lower than the mean value were grouped into the low level and vice versa for the high level of the associated temperature. As a result, the current study was statistically considered a 3-factor

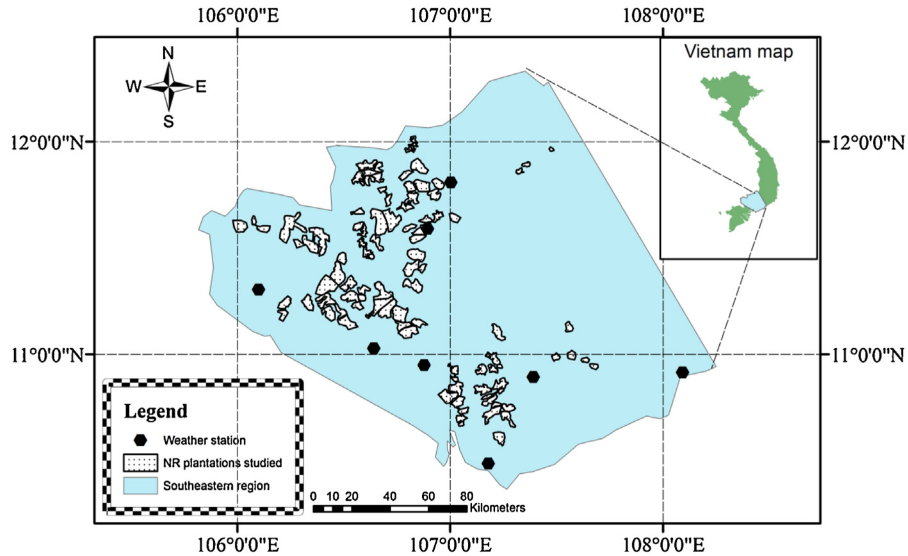

Fig. 1. Map of the southeast region of Vietnam, the studied plantations and weather stations.

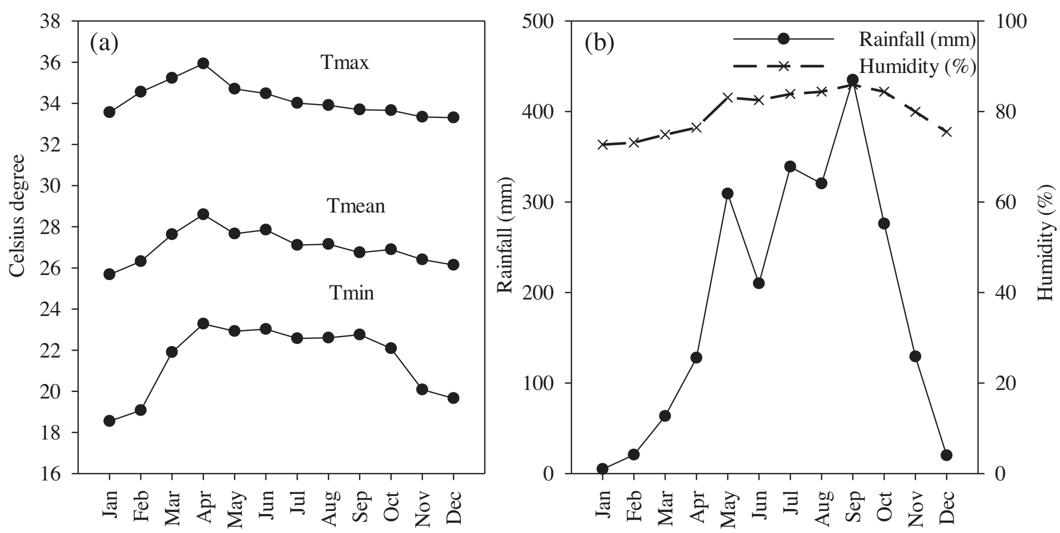

Fig. 2. Monthly variation in some basic climatic factors (Tmean, Tmax, Tmin, humidity and rainfall) of the studied area. Data were averaged over three years (2007–2009).

experiment with a completely randomized design and varying replicates (two levels of soil type × two levels of clone × two levels of temperature). The purpose of this consideration was to examine interactions of (1) soil type × clone × individual temperature variables, and of (2) clone × Tmean × Tmin on NR productivity. Analysis of Variance (ANOVA) was conducted following statistical model of factorial experiment with completely randomized design and varying replicates (Ott and Longnecker, 2011, p.891). The model for ANOVA is $Y_{ijmk} = \mu + \propto_i + \beta_j + \gamma_m + \alpha\beta_{ij} + \alpha\gamma_{im} + \beta\gamma_{jm} + \alpha\beta\gamma_{ijm} + \varepsilon_{ijmk}$; where γ_{ijmk} is the observed productivity of plantation k affected by *i* th level of factor 1 (soil type), jth level of factor 2 (clone) and mth level of factor 3 (temperature); μ is overall mean; $\propto_i$, β_j, γ_m are main effects of factor 1–3, respectively; $\alpha\beta_{ij}$, $\alpha\gamma_{im}$, $\beta\gamma_{jm}$, $\alpha\beta\gamma_{ijm}$are interactive effects of the three factors and ε_{ijmk} is random error. When ANOVA showed significant effect at $P \le 0.05$, the Tukey test was used to test the mean difference at $P \le 0.05$. All the ANOVA and Tukey tests were conducted using JPM 10 (SAS Institute Inc, North Carolina, USA). All figures except the first one reported from the current study were made by the Sigmaplot 12.

3. Results

3.1. Mean temperature (Tmean)

On Ferralsols, the mean productivities (kg tree^{-1} year^{-1}) of GT1 were 7.6, 7.4 and 6.5, and those of PB235 were 7.6, 7.1 and 6.3 for 2007–2009, respectively. On Acrisols, the mean yields of GT1 were 6.8, 6.6 and 6.5 and those of PB235 were 6.1, 6.3 and 6.0, respectively. With an increase in Tmean from 25.3 to 27.5 °C, NR productivities (kg tree^{-1} year^{-1}) decreased from 11.5 to 3.7 (GT1) and 11.5 to 3.0 (PB235) on Ferralsols and from 13.0 to 3.8 (GT1) and from 14.1 to 3.5 (PB235) on Acrisols (Fig. 3). The descending trends were significant, regardless of soil type and rubber clone, with R^2 from 0.19 to 0.44 and $P < 0.001$. The decreasing rates (kg latex per °C) were 3.6 (GT1) and 3.9 (PB235) on Ferralsols and 4.2 (GT1) and

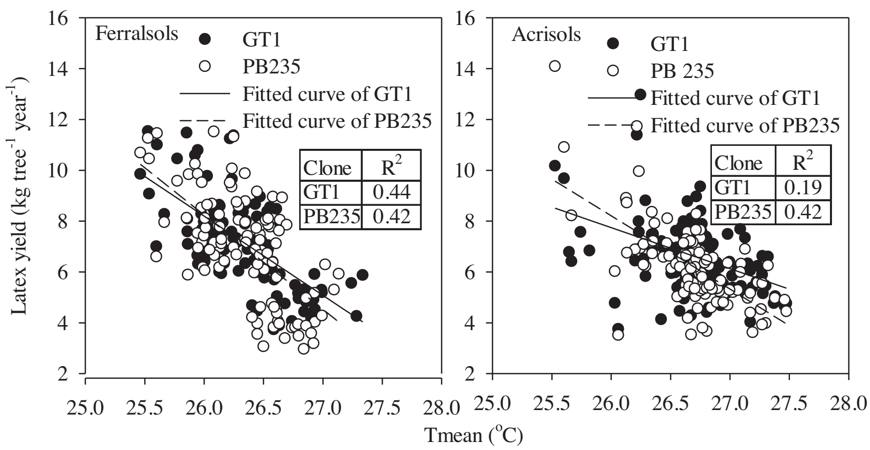

Fig. 3. Dependence of NR productivity (latex yield, kg tree^{-1} year^{-1}) on Tmean (°C). The adjusted correlation coefficients, R^2, are included within figure. The probability of the correlations is below 0.001.

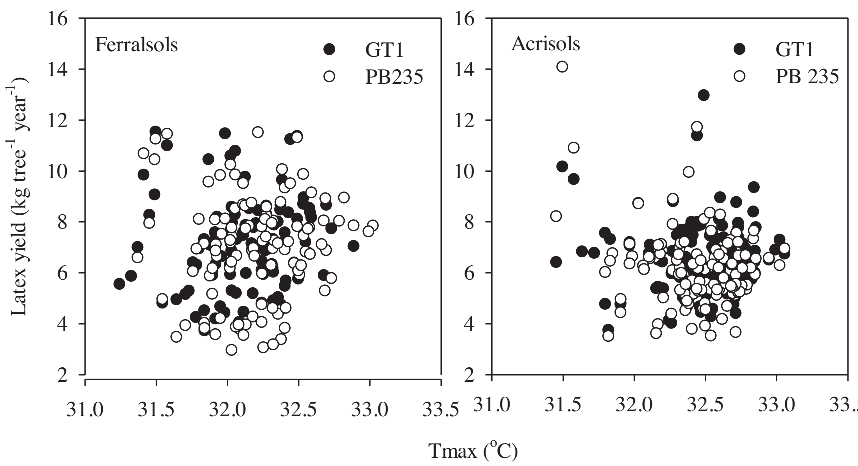

Fig. 4. Dependence of NR productivity (latex yield, kg tree^{-1} year^{-1}) on Tmax (°C).

4.8 (PB235) on Acrisols. On average, the declining rate was 4.1 kg latex per degree C for two clones and two soil types.

3.2. Mean maximum temperature (Tmax)

Fig. 4 showed that the correlations between Tmax and NR productivity of the two clones planted on two soil types were not significant. Tmax varied from 31.1 to 33.1 °C, while NR productivity varied randomly. As a result, the effects of Tmax were not subjected to further interaction analyses but are discussed in Section 4.1.

3.3. Mean minimum temperature (Tmin)

The dependence of NR productivity of the two clones on Tmin was similar to that on Tmean, which was a significantly decreasing trend with R^2 from 0.18 to 0.56 and $P < 0.001$ (Fig. 5). Tmin varied from 21.7 to 24.7 °C among the plantations. For every 1 °C rise in Tmin, the NR productivities (kg tree^{-1} year^{-1}) decreased by 2.6 (GT1) and 2.9 (PB235) on Ferralsols and 3.1 (GT1) and 3.6 (PB235) on Acrisols and on average it was 3.1 for the two clones and two soil types.

3.4. Interaction effects

Although Figs. 3 and 5 showed a significant dependence of NR productivity on Tmean and Tmin, the same Figs. did not show whether there was any significant interaction among the three factors (soil type, clone and temperature) on NR productivity. We used the means of Tmean and of Tmin to classify individual temperature values of the two temperature variables, respectively, into high (beyond the mean value) and low (below the mean value) levels for three-factor interaction tests. For the test (soil type × clone × Tmean), there was not any significant interactive effect on NR productivity found, and only one single effect of Tmean on NR productivity was significant (Fig. 6). Plantations located in low-Tmean areas produced significantly more latex (7.7 kg tree^{-1} year^{-1}) than those in high-Tmean areas (5.8 kg tree^{-1} year^{-1}). The two clones had similar productivities, regardless of soil type and Tmean level. Likewise, plantations located on Ferralsols had productivity similar to those located in Acrisols.

Meanwhile, Fig. 7 showed significant interacts between soil type and Tmin. The low Tmin coupled with Ferralsols resulted in the highest NR productivity (7.9 kg tree^{-1} year^{-1}), and coupled with Acrisols gave the second highest NR productivity (7.0 kg tree^{-1} year^{-1}). Tmin at high level coupled with Acrisols and Ferralsols produced the third and the lowest productivities, 6.0 and 5.2 kg tree^{-1} year^{-1}, respectively.

The examination of interactive effects among clones and the two temperature variables Tmean and Tmin on NR productivities was also interesting. A full interaction model, including three factors (clone, Tmean and Tmin) was fit, and the results were shown in

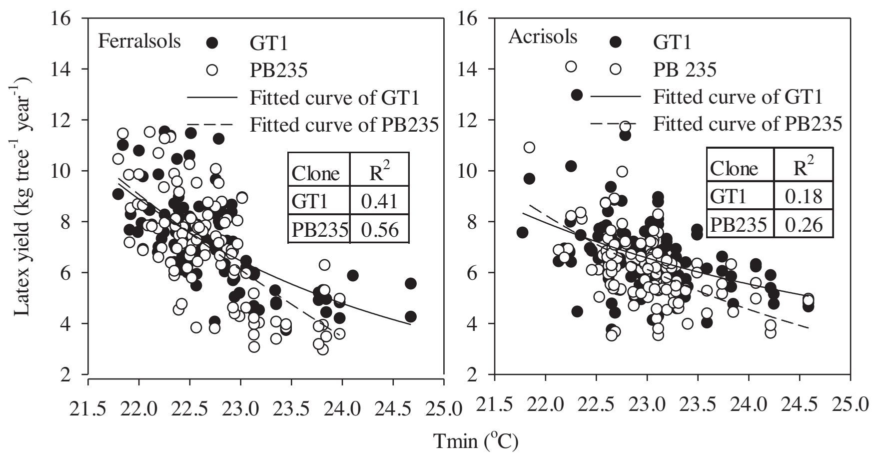

Fig. 5. Dependence of NR productivity (latex yield, kg tree^{-1} year^{-1}) on Tmin (°C). The adjusted correlation coefficients, R^2, are included within Fig. The probability of the correlations is below 0.001.

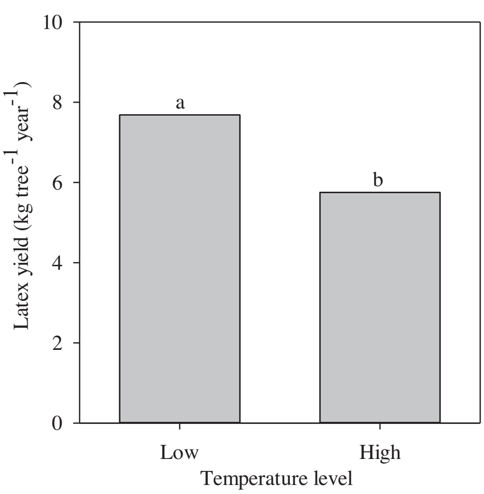

Fig. 6. Single effect of Tmean on NR productivity. The statistical fitted model was a full-interaction function of three factors (soil type × clone × Tmean). Within a panel, bars attached with the same letter were not significantly different with $P \leq 0.05$.

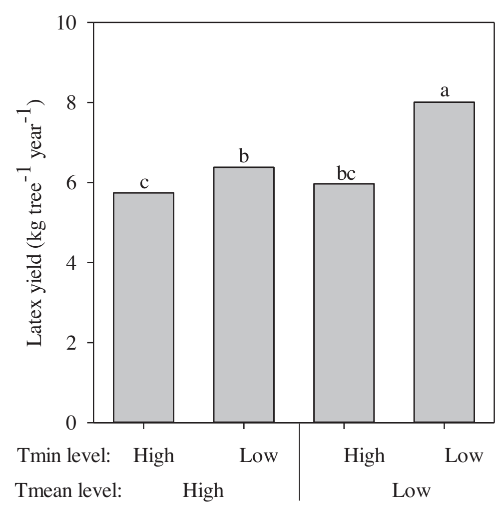

Fig. 8. Interaction effect of Tmean and Tmin on NR productivity. The fitted model was a full-interaction function of three factors (clone × Tmean × Tmean min). Bars attached with the same letter were not significantly different with $P \leq 0.05$.

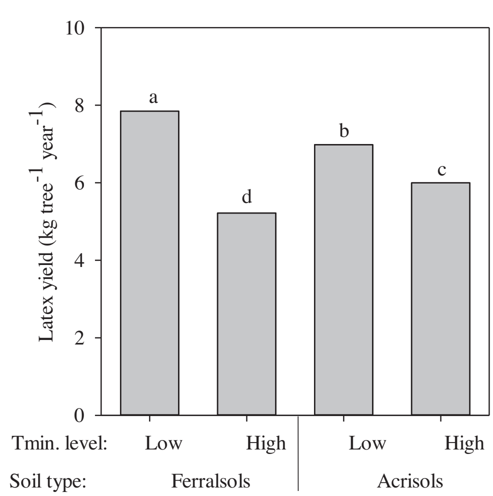

Fig. 7. Interaction effect of soil type and Tmin on NR productivity. The fitted model was a full-interaction function of three factors (soil type × clone × Tmean min). Bars attached with the same letter were not significantly different with $P \leq 0.05$.

Fig. 8 . There was only a significant interaction of Tmean × Tmin found. Plantations located within the areas having low levels of both Tmean and Tmin had significantly higher latex production (8 kg tree^{-1} year^{-1}) than other plantations, which produced from 5.7 to 6.4 kg latex per tree per year. This indicated that NR productivity depended on low levels of both Tmean and Tmin.

4. Discussion

4.1. Relationships between the NR productivity and temperature

The inverse relationship between NR productivity and Tmean and Tmin shown in the present study provided additional examples to confirm a negative trend in crop yield in response to a temperature rise (Peng et al., 2004; Conroy et al., 1994). For natural rubber trees, latex productivity was reported to have an inverse relationship with minimum temperature and mean temperature (Yu et al., 2014; Priyadarshan, 2003), similar to the present study. Temperature may directly influence latex productivity through latex flow and regeneration. The former was affected by the early-morning temperature, which was assumed to be around 15–18 °C for a optimal flow, while the latter was influenced by the after-10-am temperature, optimal at 27–28 °C (Priyadarshan and Clement-

Demange, 2004). In the current study, the absolute values of Tmean and Tmin, averaged over hourly temperatures of each day, were normally equal to the temperature values recorded after 10 am and in the early-morning time, respectively. It was also reported that a general responsive pattern of crop productivity to temperature change was a peaked curve (Adams et al., 2004). The studied range of Tmin values (21.7–24.7 °C) in the current study was far from and on the right side of the favorable temperature range, which reasonably explained the observed negative trend in NR productivity with increasing Tmin.

In the meantime, Tmean values examined in the current study varying from 25.3 to 27.5 °C were on the left side of the favorable range, suggesting that Tmean response pattern for NR productivity should be a positive curve. However, the current study showed a negative trend, which was not in agreement. Yu et al. (2014) reported similar result and they attributed it to the big difference in daily Tmin and Tmax from their studied areas. In addition, some possibilities could be the differences in (1) local ambient conditions, (2) investigated clones in the current study and compared to those reported by Priyadarshan and Clement-Demange (2004) and (3) clone and environmental condition interactions. Moreover, the Tmean values were more likely not equal to the temperatures recorded after 10 am, depending on locations and seasons, which could explain the difference. In either case, more studies are needed to identify the Tmean values at which NR productivity would reach the maximum level.

The correlations between Tmax and NR productivity reported in three studies was not consistent (current study—no relationship, a study by Rao et al. (1998)-negative relationship, and that by Yu et al. (2014)-positive relationship). Rao et al. (1998) attributed the impact of Tmax on NR productivity to induced soil moisture stress and reduced photosynthetic rate to explain their observations. Meanwhile, Yu et al. (2014) assumed that higher maximum temperature increased latex synthesis. The effect of soil moisture stress may be weak in the current study due to relatively even distribution of high rainfall and humidity during the warm months (from May to October) in the area studied (Fig. 2). In addition, while we conducted the current study based on a large-scale area, 59,631 ha of harvested plantations with yearly averaged temperature, the study by Rao et al. (1998) was at a tree-based scale with daily/monthly temperature data. Clonal difference may also partly explain the discrepancy. More importantly, the temperature values reported by Rao et al. (1998) were from 23.5 to 37.8 °C, while those from the current study ranged from 31.1 to 33.1 °C. The narrow range in Tmax in the present study may not have enabled us to show significant trend of NR productivity due to great variation in observed data.

4.2. Interactions

Ambient temperature may affect both the above and below ground portions of the plants. While the aboveground part of NR tree could be affected by the Tmean and Tmin directly, the below ground part was more likely influenced by soil temperature, which was reported to have a significant and positive correlation with air temperature (Jin and Mullens, 2014). Soil temperature can influence plant growth significantly as the root system resides within the top soil layers. For example, Powers (1990) reported nutrient (N and P) uptake of plants was significantly affected by soil temperature. Nevertheless, how strong the chain relationship (air temperature–soil temperature–plant growth) is could be modified by soil itself. Tmin at the low level, on one hand, may facilitate the latex flow, resulting in better NR productivity. On the other hand, lower soil temperature could adversely impact NR growth and productivity. The Ferralsols have a greater buffering capacity resulting from higher clay content and may better ameliorate the negative impact of the Tmin (at the low level) compared to Acrisols, producing a significant interaction between Tmin and soil type as shown in Fig. 7. Whereas Tmean may not induce adverse effects on NR productivity because Tmean (assuming it is equivalent to the after-10-am temperatures that affects latex regeneration) may not bring soil temperature to a lower level that would negatively influence rubber growth. This could explain the lack of an interaction between Tmean and soil type observed in the current study.

As discussed in Section 4.1, Tmean and Tmin should have different roles in influencing NR productivity, although they were well correlated ($R^2 = 73\%$, Fig. 2). The current study also showed a significant interaction between the two temperature variables on NR productivity (Fig. 8), strongly suggesting that Tmean and Tmin were both important to NR productivity. To achieve the highest productivity, the NR trees should be planted in areas with both low Tmin and Tmean values. Approximately 17,016 ha of plantation, occupying 29% of total area studied, meet these conditions.

In fact, the NR plantations grow in a particular environment climatically characterized by a number of factors such as temperature, rainfall, humidity, wind velocity and evapotranspiration etc. Therefore, their productivity is affected by the combination of the climatic factors, rather than any individual factor. Consequently, there were a few studies conducted to investigate NR productivity as affected by multiple climatic factors (Yu et al., 2014; Rao et al., 1998, 1990). Unfortunately, the interactive effects of the investigated factors on NR productivity were not statistically analyzed and reported. Rao and Vijayakumar (1992) documented that low soil water content coupled with high temperature resulted in leaf damage. The soil water status can also be affected by both rainfall and temperature through evapotranspiration. This indicates that effect of high temperature on soil water storage is greatly influenced by rainfall regime, resulting in interaction between temperature and rainfall distribution. The inconsistent result of relationship between Tmax and NR productivity reported from this study (neutral), by Rao et al. (1998, negative), and by Yu et al. (2014, positive) indicates site interaction. Actually, individual climatic factors can influence other factors, resulting in multiple-factor interactive effects on NR productivity, which are not investigated in the current study and thus necessitating more studies.

4.3. Temperature dependence model

The NR productivity showed a significant and linear relationship with Tmean, and an exponential decay relationship with Tmin. The latter indicated there were some Tmin points at which the NR productivity leveled off regardless of the change in Tmin, some even decreased further. In fact, the linear regression and exponential decay function may not be the best-suited models because temperature response patterns of crop yield should be a peaked function (Adams et al., 2004). This meant that there should be some temperature points resulting in maximum productivity. In order to see a peaked responsive curve, it is essential to investigate a larger temperature range (big difference from the high and low ends), rather than a narrow range as investigated. Nevertheless, the current study did not aim to examine the responsive model, but was designed to determine how NR productivity changed along with temperature variables, varying over the narrow range observed in the studied area. Therefore, the models that were fit met the objectives of the current study.

5. Implications and conclusions

The decreasing trend of NR productivity along with an increase in Tmean and Tmin, found in the current study, suggested that the overall NR production in Vietnam, and even the world, may face similar variation in the coming years of the current century, as temperature is projected to rise. Soil type, especially the one having high clay content, interacted with Tmin, supposedly by ameliorating the adverse influence of the Tmin on NR productivity. This mechanism was not tested, and thus more studies are needed. The significant interactions of Tmean and Tmin on NR productivity indicated the two temperature variables had different influencing mechanisms. It was more likely that the Tmean affected latex regeneration, while Tmin more strongly influenced latex flow and soil temperature. Again, this is an assumption, and therefore, more investigations should be conducted in order to mitigate the impact of the rising temperature.

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