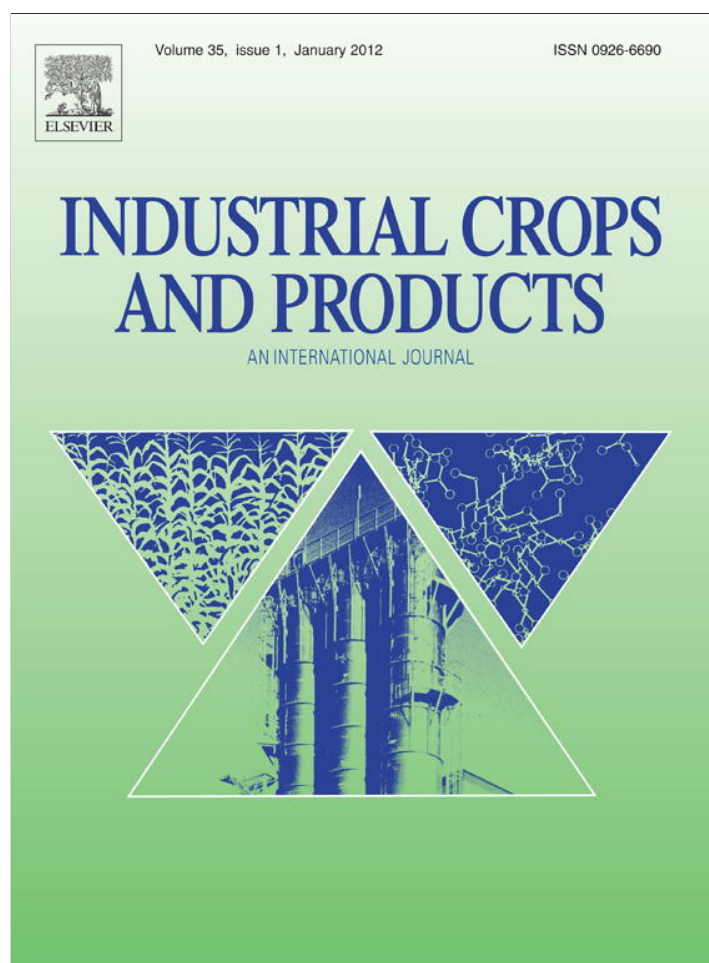


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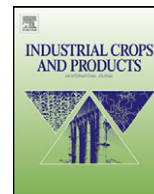
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Large-scale altitudinal gradient of natural rubber production in Vietnam

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ABSTRACT

Investigation of elevation dependence of latex productivity of natural rubber (NR, *Hevea brasiliensis* Mull. Arg.) plantations and determination of elevation thresholds for landuse management are an urgent need of study. The current study was, therefore, conducted, aiming to investigate altitudinal gradient of NR production in Vietnam. The study was based on 146,000 ha of harvested NR plantations located from the southeast region to highland. There were 45 NR clones planted in the areas studied and GT1, the clone planted with a largest portion, was examined separately from the other 44 clones, combined in processing (the Rest). Three main variables, latex productivity, individual yield and tapping density were calculated for two tapping periods, from year 1 to 10 (1–10) and from year 11 to 20 (11–20). Over the investigated elevation range, 15–738 m, the latex productivity declined at different rates, 109 for GT1 (1–10), 127 for GT1 (11–20), 110 for the Rest (1–10) and 117 kg ha⁻¹ year⁻¹ for the Rest (11–20) for every 100-m increase in elevation. An S-like curve, obtained by fitting latex productivity along the altitudinal gradient using 3-order polynomial could be separated into three stages, of which the first and the last stages were characterized with a rapid drop of, and the middle was with a stability of, latex productivity. With a rise in elevation, tapping density (tapped tree ha⁻¹) and individual yield (kg tree⁻¹ year⁻¹) significantly declined. As tapping density increased, individual yield declined whereas latex productivity rose. The results indicated that not all lands are suitable for a good NR production and that only areas with elevation under a certain magnitude depending on individual NR clones should be considered for NR cultivation. The altitudinal gradient of NR production could involve a number of soil and climatic variables, which need to be further investigated.

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1. Introduction

Natural rubber (NR, *Hevea brasiliensis* Mull. Arg.) tree is an important industrial crop being largely planted in many tropical and semi-tropical countries, such as India, Indonesia, Malaysia, Thailand and Vietnam. Natural rubber latex is the raw product greatly needed as an input material in many industrial production disciplines such as tyre industry, mattress and glove production. Highly evaluating its economy contribution and environmental role, many NR planting countries are planning to expand NR plantations to remote non-traditional marginal areas (Priyadarshan and Goncalves, 2003). A large portion of the expansion has been allocated at high-altitude areas. Planting NR plantations on high lands disregarding geographic elevation limit may face difficulty in improving effectiveness of NR production caused by unfavorable conditions on the high-level areas.

Altitudinal gradient is a concept describing the change in geographic elevation, a physical state of a particular site on the earth,

relative to sea level. Change in altitude may be accompanied by variation in microclimatic factors, such as temperature, moisture, atmospheric pressure, rainfall, sunshine, season length and even human landuse. For example, Jensen (1984) and Green and Harding (1980) reported a decline in soil and air temperature with an increase in elevation. Partial pressure of CO₂, a gas necessarily needed for photosynthetic process of plants, also moves down along an altitude rise. Actually, altitudinal gradient could be considered as a representative variable for multiple climatic and soil factors.

In general, elevation dependence of terrestrial plant production has been reported to be inversely proportional, indicating negative relationship. For example, Sharma et al. (2009) reported a significantly negative relationship between species richness and tree density with elevation from the temperate forest at Himalaya. Plant photosynthesis was proven to be adversely affected by low air and soil temperature at elevated altitudes (Cabrera et al., 1998). Fujimura et al. (2010) reported a positive trend between CO₂ concentration and photosynthesis rate of spring wheat, suggesting that low partial pressure of CO₂ at high sites may limit photosynthesis capacity and consequent yield of the crop.

Nevertheless, the dependent pattern may vary from studies to studies (Rahbek, 1995; Takahashi and Miyajima, 2008). For

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example, Thomson et al. (2002) reported a highest dry wheat yield at immediate elevation (400–500 m) whereas the yield declined with a further increase and/or decrease in elevation. Reasons they proposed to explain the observation were high precipitation and mild temperature at the middle elevation. Furthermore, Friend et al. (1989) even observed a positive relationship between altitude variation and photosynthesis rate of a number of species in central region Scotland. These suggested that elevation–plant production relationship could be modified by local environmental factors, meaning that elevation dependence of plant production may be case specific.

However, such dependent pattern of the NR tree has not been published at all. Compared to the low-altitude land, the high land potentially bears some constraints adversely affecting NR development, such as low temperature and poor soil conditions. Although a few studies reported temperature effects on NR production and growth (Rao et al., 1990, 1998; Mai et al., 2009), no study showed the relationship between NR production and geographical elevation. Therefore, there is a need of studies addressing the gap.

In principle, latex productivity could be estimated through two variables, tapping density (tapped tree ha⁻¹) and individual latex yield (kg tree⁻¹ year⁻¹). These two variables, likely elevation dependent, may be inversely related with another, indicating negative relationship. More tapped trees per area, on one hand, may increase population (whole plantation) productivity, but on the other hand, may reduce individual yield due to competition for soil nutrient, water and other climatic factors. Therefore, it is also necessary to investigate the relationships in order to examine whether there is any optimal level of the tapping-density variable at which NR plantation would yield a highest latex productivity.

To address the knowledge gaps and the needs, the current study was conducted, based on a large commercial area of NR plantations in southeast region and highland of Vietnam. Change in elevation may have significant impacts on many aspects of NR plantations, ultimately resulting in changes in tapping density, individual yield and latex productivity. Three main questions were addressed (1) what was the dependent pattern of latex productivity on the altitudinal gradient; (2) was there any dependence of tapping density and individual yield on elevation variation; and (3) was there any connection between tapping density with individual yield and with latex productivity.

2. Materials and methods

2.1. Study areas

The current study was based on a large area of harvested NR plantations, located from southeast region to highland, 10°25' to 15°4' N and 105°50' E to 109°29' E in Vietnam (Fig. 1). Total areas of the plantations investigated were 146,000 ha, and three NR databases for 2007, 2008 and 2009 were processed (Table 1). The total plantation area investigated slightly varied between the three years due to uprooting and replanting of ineffective aged-NR areas and new opening for harvesting of young ones. There were two main soil groups, Ferralsols and Acrisols (FAO), under the investigated plantations. Some basic climatic environmental features, such as temperature, rainfall, sunshine, wind velocity, evaporation and topography of the study areas were described in more details by Priyadarshan et al. (2005).

The NR plantations investigated are owned by a commercial corporation, the Vietnam Rubber Group (VRG), which controlled and managed the plantations through its belonging companies and plantations. Eighteen companies located within the study areas had NR plantations used for the current study. Individual NR companies established a few plantations, each of which managed a few

hundred to a few 10,000 ha of NR on average. There were 129 NR plantations involved in the current study in total. The NR tree was planted on block unit, which was typically 25 ha in size, but may vary, based on actual, local area and topography.

2.2. Data collection

The VRG established a Technical Management System from the headquarter (Technical Management Unit) to the belonging companies and plantations (Technical Department/Technical Unit). The system took responsibility of making and promulgating a General Technical Document (VRG, 2004), a collection of different specific technical protocols, applied broadly over the NR plantations under the VRG's ownership. Consequently, it would be reasonable to assume that all plantations investigated were applied with the same technical protocols, such as fertilizer utilization, herbicide and insecticide treatments, and harvesting technology, as recommended from the General Technical Document.

Each year, the Technical Management System conducted an inventory, which helped managing the NR plantations. As a consequence of the inventory activities, a big NR database containing necessary information of the NR plantations was formed each year and part of which for three years, 2007, 2008 and 2009 were filtered and processed for the current study.

2.3. Elevation and map of the NR plantations studied

The map of the NR plantations studied was made using a GPS (Global Positioning System) device to record coordinate position of individual NR plantations. The coordinate data were imported into ArcGis 9.3 for mapping the area studied. Elevation of the plantations studied was obtained using the Global Mapper to assess Worldwide Elevation Data at 30-m resolution. An USGS (United States Geological Survey) DEM (Digital Elevation Model) file obtained for the whole territory of Vietnam was additionally incorporated into ArcGis 9.3, converted to a point layer, which was then spatially joined to the NR plantation map in order to get averaged altitudes of individual NR plantations.

2.4. Statistical analysis

The NR database was processed and calculated for tapping density (tapped tree ha⁻¹), individual yield (kg tree⁻¹ year⁻¹) and latex productivity, which was defined as a ton of dry rubber latex per ha per year (ton ha⁻¹ year⁻¹). Because NR trees have been planted on separate basic blocks, data collected from singular blocks of the same plantations were averaged, and the averaged data of a plantation was processed as a basic observation/plot for the current study. The averaging was done based on tapping-age groups (years 1–10 and years 11–20) and clones (GT1 and the Rest). Linear and non-linear regression fittings were performed to examine dependent patterns of the variables on altitudinal gradient and of within the three variables. To determine an acceptable right fit model, which should meet three conditions (1) it should be simple, (2) it should result in sufficiently high correlation coefficient and (3) it should be explainable, TableCurve 2D (Systat Software Inc.) was used. When a fit model was selected, Sigmaplot 11 (Systat Software Inc.) was used to fit desired relationships based on the selected model.

3. Results

Because the current study focused on the altitudinal gradient over a large area, effects of the other factors rather than elevation should be kept well equally over the observed units, the plantations. It would be assumed that the technical-management factors, which were stated clearly in the General Technical Document by

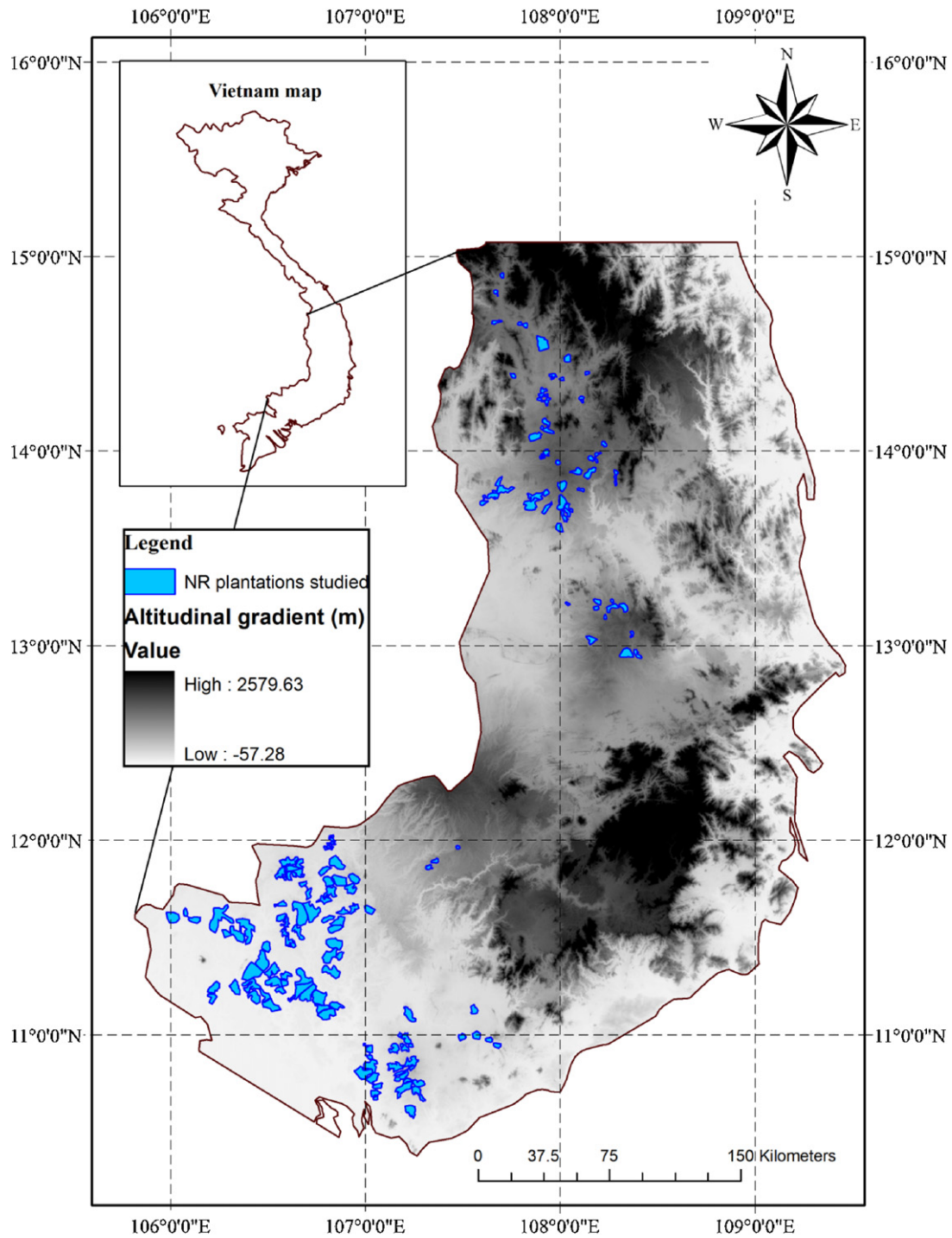


Fig. 1. Map of the NR plantations studied.

Table 1

Distribution of NR plantations (ha) studied over two soil types, 3 investigated years and the altitudinal gradient.

Altitudinal gradient (m)	2007		2008		2009	
	Ferralsols	Acrisols	Ferralsols	Acrisols	Ferralsols	Acrisols
<200	40,643	71,443	38,977	69,564	35,785	65,376
200–400	9985	0	9737	0	9621	53
400–600	11,161	1249	11,219	1288	11,390	1283
>600	11,598	4218	11,775	5027	11,438	5024
Sum	73,387	76,910	71,707	75,878	68,235	71,736

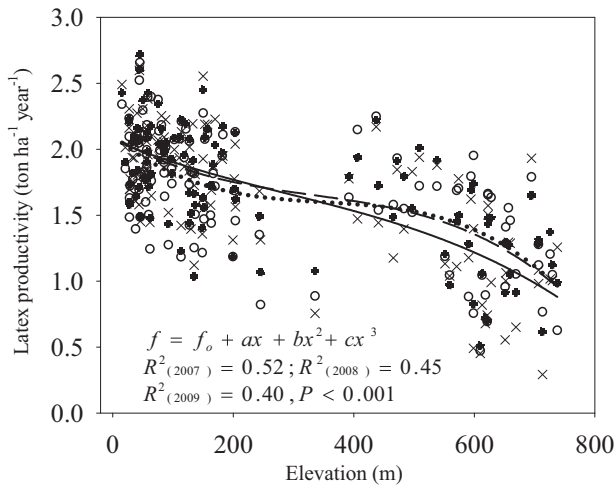


Fig. 2. Responsive pattern of overall latex productivity ($\text{ton ha}^{-1} \text{year}^{-1}$) of individual years investigated over the altitudinal gradient. The thin X and solid line were observed data and fit curve of 2007 database. The crosses and long dashed line were those of 2008 and the opened circles and dotted line were those of 2009.

the VRG (2004), were applied relatively equally over the NR plantations studied. Other factors such as productivity variation between investigated years, NR clones, soil types and tapping ages were noticed to potentially influence the results of the current study and thus Figs. 2 and 3 were analyzed. Overall latex productivity of the three investigated years, 1.68, 1.68 and 1.66 $\text{ton ha}^{-1} \text{year}^{-1}$ for 2007, 2008, and 2009 respectively, showed no significant difference from each other using Ttest procedure. Analysis of overall responsive patterns of latex productivity over the elevation range showed similarity between the three databases (Fig. 2). As a result, latex productivity over the 3 years of the same plantation was averaged for further investigation.

There were 45 NR clones planted within the study plantations. Of the entire 146,000 ha of NR plantations investigated, about 44,000 ha was under GT1 clone, occupying 30% of the total area. Because a large portion of the study area was planted with the GT1, the plantations under this clone were investigated separately from the other clones, which were combined in processing and labeled as “the Rest” throughout the current study. Therefore, response of

one clone, GT1, and the Rest, 44 combined clones, to the altitudinal gradient, was investigated and reported.

Soil types may play an important influence on NR production. However, Fig. 3 showed similarity in responsible pattern of latex productivity as a function of tapping age on the two soils. Ttests were conducted and showed no significant difference between the two soils in latex productivity, separately averaged for GT1 and the Rest. Correlation coefficients (r^2) were calculated and showed strong connection in latex productivity between the two soil groups (Fig. 3). Consequently, the observed data from the two soil groups were merged into one composite source for the remaining processes, thereby minimizing the effects of the soil types.

Fig. 3 also showed significant variation in latex productivity at different tapping ages. The productivity increased for the first ten tapping years, then maintained relatively stable for the next ten years, and finally dropped down for the last years. Latex harvesting for the initial 10-year period (young tapping ages) was performed on virgin bark, and the middle 10-year period was done on renewed bark. The last period was observed with a rapid drop in productivity and tapping systems were complicated and highly differed among the belonging companies as this period was allowed to maximally harvest latex potential of the aged trees. Latex stimulation was conducted more frequently during the last period, and may vary greatly from company to company. It is, therefore, that, data from the two young periods were averaged separately and used for the current study, and those from the last period were eliminated.

Latex productivity ($\text{ton ha}^{-1} \text{year}^{-1}$) varied from 1.02 to 2.29 for GT1 (1–10), from 1.07 to 2.78 for GT1 (11–20), 1.01 to 2.26 for the Rest (1–10) and 1.11 to 2.59 for the Rest (11–20) (Fig. 4). Along the altitude increase, latex productivity decreased, following a cubic function. The 3-order polynomial fitted well to the observed data of latex productivity, with $P < 0.001$ and correlation coefficients, r^2 , from 0.35 at GT1 (11–20) to 0.59 at the Rest (1–10).

From the fit curve and fit equation, inflexion points and 95% confident intervals were calculated (Table 2). The inflexion point was determined by setting the second derivative of the fit equation equal Zero. The elevation solved out from the Zero equal second derivative equation was the inflexion point reflecting the point at which the 3-order polynomial fit curve changed sign. This elevation point was plugged into the fit equation to get the associated NR productivity. The inflexion point was lowest in the Rest (11–20), 315 m, and highest in the Rest (1–10), 404 m. The upper and lower thresholds of elevations and corresponding latex productivities

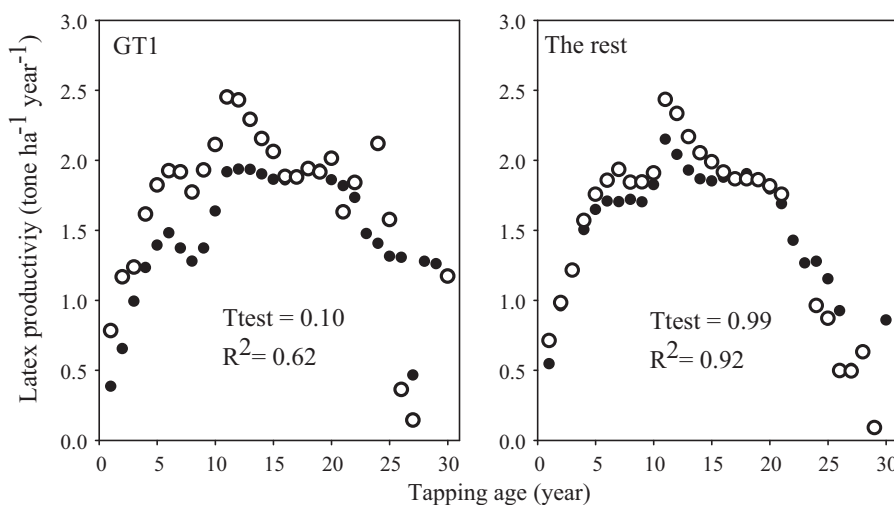


Fig. 3. Latex productivity ($\text{ton ha}^{-1} \text{year}^{-1}$) of NR plantations located on two major soil groups studied. The opened circles were observed data from Acrisols and the solid circles were those from Ferralsols. r^2 was correlation coefficient of latex productivity between the two soil groups. Ttest was to compare the productivity between the two soil groups.

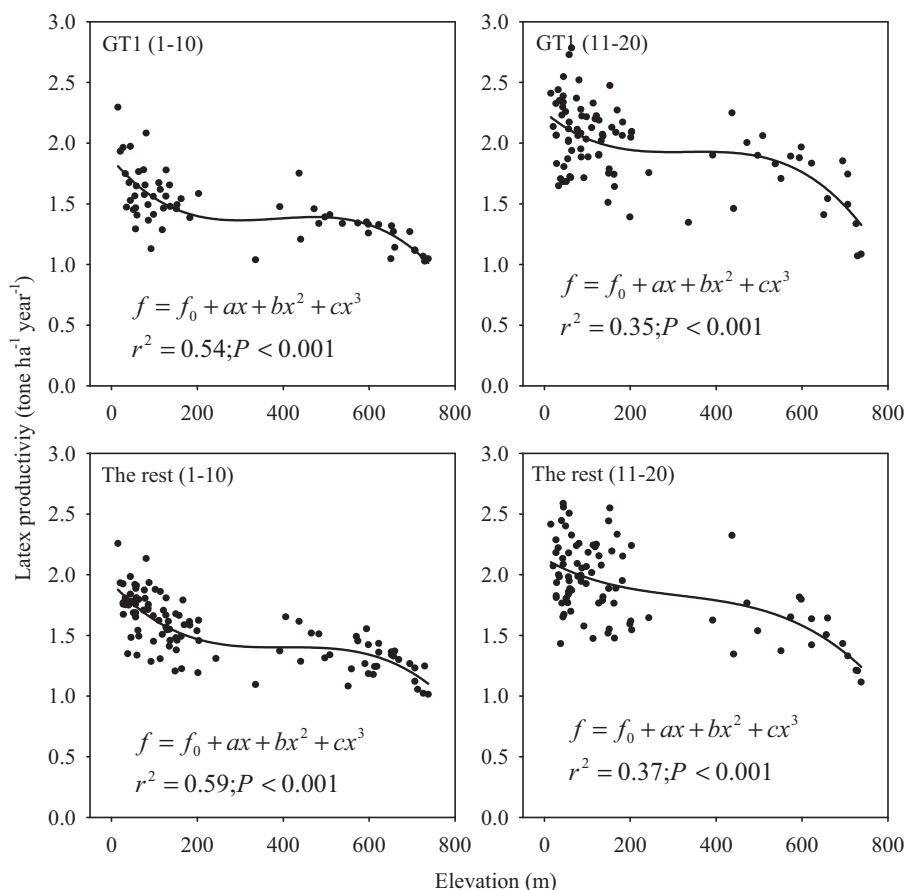


Fig. 4. Elevation dependence of latex productivity (ton ha⁻¹ year⁻¹). The productivity was averaged for 2 periods, 1–10 tapping years (1–10) and 10–20 tapping years (11–20) with respect to GT1 and The Rest.

were calculated by setting the fit equation equal the inflection-point associated productivity minus or plus the confident intervals, respectively. The upper elevation thresholds (m) were 630 for GT1 (1–10), 560 for GT1 (11–20), 600 for the Rest (1–10) and 490 for the Rest (11–20). Because there was a difference in upper thresholds between the two tapping periods of the same clone or clone groups, the thresholds of the same clone were averaged, resulting in 595 ± 35 m of the upper limit for GT1 and 545 ± 45 m for the rest clones investigated.

Tapping density and latex yield of individual NR tree were also elevation dependent variables, which moved down when the elevation increased from 15 to 738 m (Figs. 5 and 6). Tapping density rapidly dropped down as elevation rose from 15 to about 200 m, and then maintained relatively stable beyond the

200-m point. Non-linear exponential equation well fitted into the observed density data. Individual yield relatively slowly declined along the elevation increasing. Deficient second-degree polynomial gave a best fit with data points, with correlation coefficients from 0.13 in the Rest (11–20) to 0.37 in GT1 (1–10). The individual yield was high and relatively stable at the low-elevation plantations, below 400 m, whereas declined quite rapidly beyond that point.

An increase in tapping density resulted in a reduction in individual yield, whereas an increase in latex productivity (Fig. 7). Tapping density (tapped tree ha⁻¹) varied from 173 to 480 at GT1 (1–10) plantations, 207–437 at GT1 (11–20) plantations, 237–479 at the Rest (1–10) plantations, and 210–437 at the Rest (11–20) plantations. Individual yield dropped down quite rapidly when tapping

Table 2
Inflection points, 95% confident intervals and upper and lower thresholds of the elevation (m).

Estimated indexes	Elevation/productivity	GT1		The Rest	
		1–10 ^b	11–20 ^b	1–10 ^b	11–20 ^b
Inflection point	Elevation	386	333	404	315
	Productivity ^a	1.38	1.91	1.39	1.84
95% confident interval	Productivity ^a	0.092	0.107	0.063	0.106
Upper threshold	Elevation	630	560	600	490
	Productivity ^a	1.29	1.80	1.32	1.74
Lower threshold	Elevation	140	110	210	135
	Productivity ^a	1.47	2.01	1.45	1.94

^a Latex productivity (ton ha⁻¹ year⁻¹) was estimated using the fit curves and fit polynomial showed in Fig. 4 and Table 3.

^b 1–10 and 11–20 were denoted for tapping ages from year 1 to 10 and from year 11 to 20.

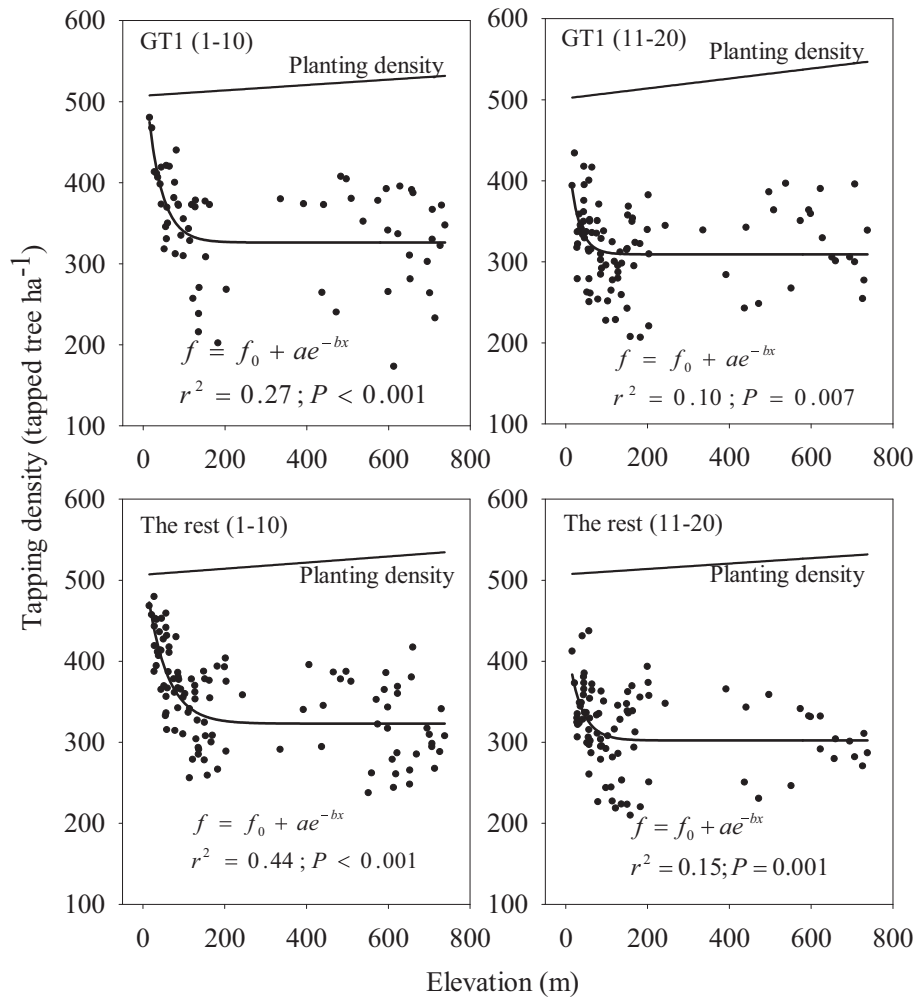


Fig. 5. Variation in tapping density (tapped tree ha⁻¹) along the altitudinal gradient. The top straight lines were the fit lines of planting density at establishment as a function of the altitudinal gradient.

Table 3
Coefficients of the fit models from Figs. 4–7.

Figure	Clone/tapping age	f_0	a	b	c	r^2	P
Fit model: $f = f_0 + ax + bx^2 + cx^3$ (latex productivity vs. elevation)							
Fig 4	GT1 (1–10)	1.87	-0.0043	1.18×10^{-5}	-1.02×10^{-8}	0.54	<0.001
	GT1 (11–20)	2.25	-0.0031	9.31×10^{-6}	-9.32×10^{-9}	0.35	<0.001
	The Rest (1–10)	1.93	-0.0040	9.85×10^{-6}	-8.13×10^{-9}	0.59	<0.001
	The Rest (11–20)	2.13	-0.0020	5.07×10^{-6}	-5.37×10^{-9}	0.37	<0.001
Fit model: $f = f_0 + ae^{-bx}$ (tapping density vs. elevation)							
Fig. 5	GT1 (1–10)	326.24	229.61	0.029		0.27	<0.001
	GT1 (11–20)	309.30	153.22	0.042		0.10	0.007
	The Rest (1–10)	323.07	204.68	0.021		0.44	<0.001
	The Rest (11–20)	302.35	130.69	0.031		0.15	0.001
Fit model: $f = f_0 + ax^2$ (individual yield vs. elevation)							
Fig. 6	GT1 (1–10)	5.00	-4.04×10^{-6}			0.37	<0.001
	GT1 (11–20)	6.81	-4.18×10^{-6}			0.20	<0.001
	The Rest (1–10)	4.63	-2.44×10^{-6}			0.24	<0.001
	The Rest (11–20)	6.49	-3.47×10^{-6}			0.13	<0.001
Fit model: $f = f_0 + ae^{-bx}$ (individual yield vs. tapping density)							
Fig. 7	GT1 (1–10)	3.98	78.89	0.016		0.16	0.009
	GT1 (11–20)	5.38	139.01	0.016		0.42	<0.001
	The Rest (1–10)	3.84	3.79	0.006		0.03	0.13
	The Rest (11–20)	4.70	60.17	0.012		0.45	<0.001
Fit model: $f = f_0 + ae^{bx}$ (latex productivity vs. tapping density)							
	GT1 (1–10)	1.37	8.63×10^{-6}	0.024		0.33	<0.001
	GT1 (11–20)	1.91	1.31×10^{-5}	0.026		0.07	0.04
	The Rest (1–10)	0.82	0.24	0.003		0.24	<0.001
	The Rest (11–20)	1.86	1.58×10^{-5}	0.023		0.02	0.35

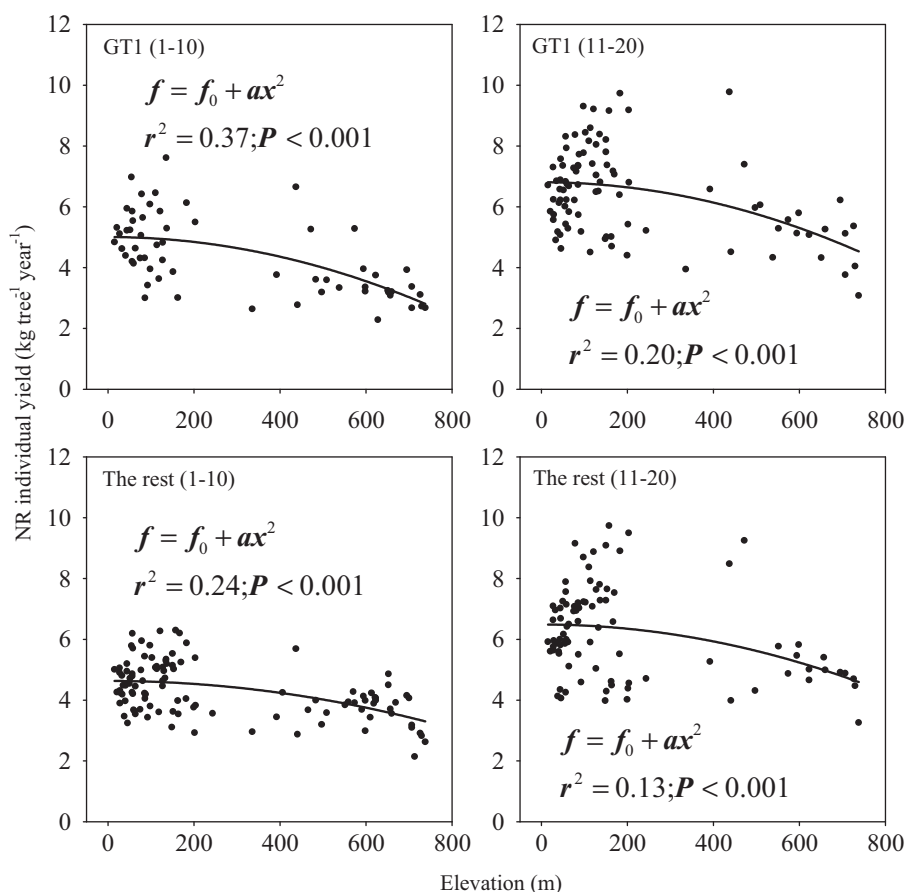


Fig. 6. Variation of individual yield (kg tree⁻¹ year⁻¹) along the altitudinal gradient.

density increased to about 350–400 trees ha⁻¹. In contrast, the latex productivity began with a fast rise at the same tapping density level.

Table 3 showed strong relationship between elevation and latex productivity, tapping density and individual yield with correlation coefficients, r^2 , varying from 10 to 59%. The coefficients of NR plantations at young tapping ages (1–10) were greater than those at old tapping ages (11–20). Relationship between tapping density and latex productivity and individual yield was also significant, except for individual yield of the Rest (1–10) and latex productivity of GT1 (11–20) and of the Rest (11–20) (Table 3).

4. Discussion

4.1. Elevation dependence

Overall, latex productivity declined at different rates, depending on clones and tapping ages, ex. 109 for GT1 (1–10), 127 for GT1 (11–20), 110 for the Rest (1–10) and 117 kg ha⁻¹ year⁻¹ for the Rest (11–20) for every 100-m increase in altitude. There were a few studies directly or indirectly addressing the elevation dependence of NR production, but no study showed the altitudinal gradient of latex productivity. Nevertheless, findings from the other studies were consistent with each other, and with the current study that increases in elevation suppressed NR production. For example, Song and Zhang (2010) reported greater aboveground biomass of NR plantations at lower-altitude areas (lesser than 500–600 m) than at higher areas (950–1020 m). Likewise, Jia et al. (2006) observed a negative relationship between aboveground biomass of NR plantations with elevated altitude, above 550 m. Tong (2006) and Phan et al. (2006), although conducting studies separately, showed better latex productivity and individual yield at

lower-elevation plantations than at higher plantations (see below for more discussion).

In more details, a third-order polynomial gave a good fit to the observed latex productivity along the altitudinal gradient (Fig. 4 and Table 3). An S-like curve of the fitting could be separated into three segments, of which the first one at lowest altitude range was characterized with a highest latex productivity, average 1.86 ton ha⁻¹ year⁻¹ for GT1 and 1.82 for the Rest. Studying on the same elevation range, Phan et al. (2006) showed 1.5 and 1.6 ton ha⁻¹ year⁻¹ of GT1 harvested at year 6 at elevation 40 m, Dau Tieng company and at elevation 86 m, Dong Phu company, respectively. These values could be comparable to those predicted from the current fit model (Fig. 4 and Table 3), 1.7 and 1.6 ton ha⁻¹ year⁻¹ at elevations 40 and 86 m, respectively, of the same clone. The second segment was observed with a median productivity, and the last one was with a lowest productivity. The current finding on GT1 productivity, 1.25 ton ha⁻¹ year⁻¹ at high elevation, 650 m, was close to the range reported by Tong (2006). The author showed latex productivity from 1.28 to 1.60 ton ha⁻¹ year⁻¹ from four fertilizer experiments located at similar elevations (the values were calculated based on information provided from his study and assumption of 9 tapping months per annum and 10 taps per month).

Consequently, S-like fit curves (Fig. 4) suggested that lands could be considered to be (a) suitable for NR cultivation when its elevation was under the lower threshold, (b) medium when the elevation was between the lower and upper limit points and (c) adverse when the elevation was beyond the upper point (Table 2). It should be noticed that the three-degree equation fitted well within the investigated elevation range, 15–738 m above sea level in the current study. Because NR tree was planted at elevation up to 1000 m (Jia et al.,

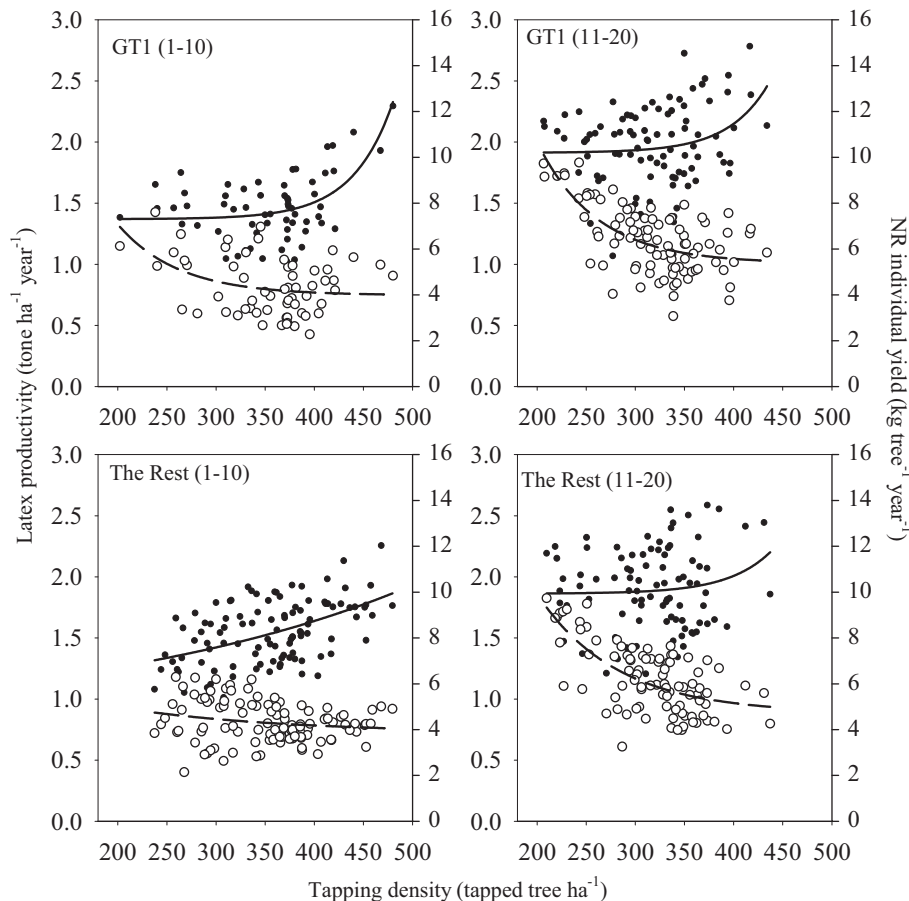


Fig. 7. Relationships between tapping density with latex productivity and with individual yield. Solid circles and solid line were denoted for observed data and fit curve on latex productivity. Opened circles and dashed line were those on individual yield.

2006; Song and Zhang, 2010), the cubic function may inappropriately fit well with the elevation extending out of the investigated range.

In the meantime, there were a number of studies addressing elevation dependence of production of other plants, ex. growth of an oilseed crop, *Lesquerella fendleri* (Dierig et al., 2006), Sitka spruce forest production (Worrell and Malcolm, 1990a), temperate forest species and diversity (Sharma et al., 2009), tropical forest production (Moser et al., 2011), tea growth and production (Squire et al., 1993) and wheat production (Thomson et al., 2002; Ferrara et al., 2010). A common finding from these studies was a decline in plant production or aboveground biomass when altitude increased. There were a number of variables analyzed and/or proposed to explain the decline trend, ex. temperature and wind velocity (Worrell and Malcolm, 1990b), temperature and rainfall (Kharkwal et al., 2005), temperature and soil fertility (Moser et al., 2011) and air partial pressure of CO₂ (Terashima et al., 1995). Actually, altitudinal gradient could be considered as a representative of, or an independent variable for, a number of dependent factors, including climatic variables, plant disease and soil properties. The elevation dependence of these factors could mainly account for the changes of the three variables investigated in the current study (Figs. 4–6).

Low temperature at high-altitude sites was normally noticed and recorded in order to investigate the altitudinal gradient of plant growth and production. Temperature induced significant impacts on photosynthetic capacity and activation energy for the photosynthesis of NR tree (Kositsup et al., 2009). Low temperature may cause a chilling stress to plants, which led to a reduced photosynthetic rate in cool locations, relative to in warm locations (Alam

et al., 2005). The low-temperature stress involved systematic complicated photochemical processes occurring under the leaf surface which resulted in low effectiveness of photosynthesis (Fryer et al., 1998). As a result, Priyadarshan et al. (2005) reported a negative relationship between NR yield and minimum temperature in India. Low temperature was also attributed to be a major reason causing a stop of NR harvesting for a few months in India (Mai et al., 2010).

Because plant pathogens could be greatly controlled by climatic conditions, NR disease is also an elevation dependent variable, which may considerably influence NR growth and productivity. Normally, one type of plant disease may develop favorably in a certain weather condition defined with a particular range of some main parameters, such as temperature and moisture. Practically, NR plantations located on the high areas in the current study was observed to be severely infected with disease, especially powdery mildew, a fungal disease caused by *Oidium heveae* Steinh. The incidence of the disease was determined by climatic variables, such as temperature, moisture, light and wind (Schnatho, 1965). Mild temperature and moist humidity in early summer time in the high areas may account for severe infection of the *Oidium* foliar disease, which could depress productivity and individual yield of NR plantations in the areas.

Although the current study was not focused on soil property variation along the elevation gradient, soil fertility could descend because of severe impact of soil erosion and nutrient leaching at high-elevation plantations investigated in the current study. In fact, Satisha et al. (2000) found a reduction in N, P and extractable Zn, whereas an increase in Fe and Cu with an altitudinal gradient from 100 to 700 m of NR planted soil in India. Zehetner and Miller (2006) observed negative relationships between elevation

and soil exchangeable bases, pH in water and erosion in Ecuador and concluded that temperature and leaching differences were the major reasons causing soil property variation along the altitudinal gradient. A decrease in temperature together with a rise in soil N deficiency as a consequence of elevation increasing was concluded to play an important role in determining aboveground biomass production of tropical forest in high areas (Moser et al., 2011).

Tapping density was also an elevation dependent variable, which was fitted well with a non-linear, exponential model (Fig. 5, Table 3). The variable was expressed by a number of trees harvested per ha per annum at individual NR plantations. It was noticed that only NR trees growing to 50 cm in circumference at 1.2-m height from rootstock were initiated for harvesting. As a result, this variable could be highly influenced by the altitudinal gradient during the immature period when the trees were young. The unfavorable conditions at high elevation may induce a significant adverse impact on the growth of the immature trees and the consequently reduced harvested density at mature stage. In addition, the tapping density could be affected by planting density, the variable measuring number of trees at establishment. However, this variable, planting density, was not much different between plantations at different elevations (Fig. 5).

In response to harsh environmental conditions, plants could develop protective mechanisms to adapt themselves to the new unfavorable environment (Smith, 1975; Fetcher et al., 2000; Bresson et al., 2009). This may explain the differences in elevation thresholds of the GT1 and the Rest (Table 2). GT1 was shown to be resistant or well adapted to harsh environmental conditions better than the combination of other clones, indicated through the upper elevation threshold (630 m for the young tapping period and 560 m for the old period) greater than the other clone combination (600 and 490 m for the young and the old periods, respectively). This is consistent with other studies. For example, GT1 was concluded to be low-temperature tolerant (Mai et al., 2010) and resistant to wind damage (Cilas et al., 2004), the two environmental constraints, which could be likely important in determining latex productivity at high-elevation plantations in the current study. GT1 was also proven to be better resistant to leaf diseases, especially *Corynespora conidium* (Cilas et al., 2004).

The correlation coefficients between elevation gradient and the three investigated variables higher at the young tapping period (1–10) than the old period (11–20) (Table 3) may indicate that the young trees could be more vulnerable to harsh environmental conditions than the aged ones. In other words, the aged trees could adapt to the environmental variation better than the young ones. The lower coefficients at the old tapping period could also be due to relatively greater variation of the three investigated variables with aged trees, when latex stimulant was controllably allowed to apply. In contrast, the young period was experienced with virgin-bark tapping and limited latex stimulant application, resulting in relatively consistent latex production over the young plantations.

Because the current study area stretched from southeastern to highland regions, along latitude magnitude (Fig. 1), one may claim that the latitudinal gradient may also have a certain impact to the current findings. In fact, I additionally performed statistical analyses to examine the relationship, and results showed weak correlation between latitudinal gradient and latex productivity.

4.2. Tapping-density dependence

Basically, the effects of tapping density on individual yield could be through competitions for nutrients in soil and other climatic factors, such as sunshine, water and CO₂. Negative relationship between the two variables as showed in Fig. 7 indicated the competitions could happen. However, the tapping density was more likely

important than the individual yield in determining the total latex productivity, as Fig. 7 showed a positive relationship between the tapping density and the latex productivity, irrespective of a decline in individual yield. This is comparable to the findings by Roy et al. (2005) who found highest individual yield and growth at a treatment of lowest planting density, whereas a greatest productivity at the treatment of highest planting density.

The latex productivity could be determined by the two variables, tapping density and individual yield, which was found to be inversely proportional. In theory, the productivity could reach a maximum value when the two variables are maintained at a certain level. Within the investigated tapping-density range, 173–480 tapped trees ha⁻¹, the peak point in latex productivity, however, was not found in the current study. Instead, the latex productivity was continuously positively correlated with the number of tapped trees ha⁻¹ (Fig. 7). This indicated that NR plantation should be maintained at a highest density of tapped trees, at least up to 480 tapped trees ha⁻¹ as shown in the current study, for a better productivity.

5. Implications and conclusions

The current great demand of nature rubber latex all over the world potentially pushes the NR planting countries to expand NR plantations rapidly to high-attitude regions, where are facing with many climatic and soil constraints. To maximize benefits from NR plantations, it is necessary to have a good landuse management, based on optimal landuse decision for NR cultivation. The current findings, negative relationship between elevation and latex productivity and the correlation pattern characterized with two rapid drops of productivity at elevation <200 m and from 500 to 550 (Fig. 4), suggested that not all lands were suitable for a good NR production and that only areas with elevation under a certain magnitude dependent on NR clones should be considered for NR cultivation. Tapping density is also an important variable, which should be maximized in order to gain a high productivity. To increase the density, possibly there are two ways to be considered, increasing planting density and improving growing conditions through technical managements to enhance NR growth at immature stage.

With a global climate change, especially warming temperature, well reported recently, a large portion of NR areas in many rubber planting countries may be influenced by the change. The low lands, which currently most suited for NR development may turn out to be unsuitable, whereas the high lands would become better suitable areas, when the global temperature would increase in a certain extent. The warming, although making the high lands suitable for NR development in terms of temperature, does not ensure a better productivity in the high areas. This may be because of the differences in (1) soil fertility resulted from great erosion, (2) low partial pressure of CO₂, (3) wind damage and (4) sunshine between the high lands and the low lands. Those variables in relation with NR development were not well investigated, and thus need more studies.

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