AGRIVITA VOLUME 38 No. 1 FEBRUARY - 2016 ISSN : 0126 - 0537

EVALUATION OF LAND AND WATER MANAGEMENT OPTIONS TO ENHANCE PRODUCTIVITY OF RUBBER PLANTATION USING WaNuLCAS MODEL

Andi Nur Cahyo [1*)], Mukand Singh Babel [2)], Avishek Datta [2)], Krishna Chandra Prasad [3)] and Roberto S. Clemente [4)]

[1)] Sembawa Research Centre
Jl. Palembang-Jambi Km.29, Banyuasin, South Sumatera 30001, Indonesia
[2)] Asian Institute of Technology
[3)] UNESCO-IHE, Netherland
[4)] University of the Philippines Los Baños
[*)] Corresponding author E-mail: nurcahyo.andi@yahoo.co.uk

Received: August 5, 2015/ Accepted: January 6, 2016

ABSTRACT

This research aimed to determine the best land and water management by arrangement of plant spacing, irrigation, and drainage of rubber plantation in order to improve rubber plantation productivity. This research was done using The WaNuLCAS (Water, Nutrient and Light Capture in Agroforestry System) model to determine the best land and water management under several scenario combinations of two factors. The first factor was rubber plant spacing arrangement system, which consisted of three levels, i.e. single row (3 x 7 m), single row (3 x 6 m) and double row (2 x 6 x 14 m). The second factor was water management treatment, which consisted of four levels, i.e. without irrigation and drainage, irrigation in dry season, drainage in wet season, and irrigation and drainage in dry and wet season respectively. The results showed that drainage treatment could enhance rubber plantation productivity. Moreover, rubber plantations which were using single row (3 x 7 m), single row (3 x 6 m) and double row (2 x 6 x 14 m) had no significant difference on latex production per hectare.

Keywords: land and water management; rubber plantation; WaNuLCAS

INTRODUCTION

Natural rubberis a source of foreign exchange for Indonesia (US$ 2.96 billion in 2010) (FAO, 2013). Besides that, it provides income to over 11 million people in Indonesia, especially in Sumatra and Kalimantan (Rubber Research Centre, 2008). Indonesia's natural rubber production is about 3.08 million t year^{-1} (FAO, 2013). Therefore, Indonesia is the second biggest natural rubber producer in the world after Thailand.

Rubber tree has been traditionally cultivated in area with tropical climate especially humid zones and in area with tropical and monsoonal climates as the favorable area for the growth of this tree (Rao and Vijayakumar, 1992; Rao *et al.,* 1998).The favorable climatic conditions for rubber tree growth are a place with: (1) minimum rainfall rate of 2,000 mm year^{-1} and distributed evenly along the year with 125 to 150 rainy days year^{-1}; (2) maximum and minimum temperature is about 29 to 34^{o}C and 20^{o}C or more respectively with monthly average is about 25 to 28^{o}C; (3) humidity is about 80%, and (4) sun shine is about 2,000 hours year^{-1} and the daily duration is 6 hours (Webster and Baulkwill, 1989; Vijayakumar *et al*., 2000).

Generally, rubber tree achieves optimum yields when the agroclimate condition has no high fluctuation round the year. Previous study showed that variability of rainfall, relative humidity, temperature, and sunshine were the main reasons why rubber yield fluctuated (Jacob *et al*., 1989; Rao and Vijayakumar, 1992; Rao *et al.*, 1998). Rubber production can be higher if adequate rainfall is distributed evenly round the year (Rao*et al.*, 1993; Rao *et al*., 1998). For example, an unusual drought in South India decreased yield about 36-61% compared to the normal wet season yield (Rao *et al.,* 1998). This indicates that rubber trees need irrigation particularly in the dry season when the rainfall is not evenly distributed.

Cite this as: Cahyo, A.N., M.S. Babel, A. Datta, K.C. Prasad and R.S. Clemente. 2016. Evaluation of land and water management options to enhance productivity of rubber plantation using WaNuLCAS model. AGRIVITA. 38(1): 93-103. doi: 10.17503/agrivita.v38i1.583
Accredited: **SK No.81/DIKTI/Kep/2011**
Permalink/DOI: **http://dx.doi.org/10.17503/agrivita.v38i1.583**

In Indonesia, due to the occurrence of dry season, rainfall is not evenly distributed throughout the year. Therefore, rubber yield fluctuated during a year in Indonesia. It has been indicated that water should be available between permanent wilting point and field capacity, otherwise drought would resulted in plant stress (Larcher, 2001; Ayutthaya, 2010). Furthermore, intensity and duration of drought stress caused regional variation in annual rubber yields (Rao, 1993; Rao *et al*., 1993; Rao *et al*., 1998). In addition, drought stress happens when the soil water availability decreases under the thresholds that suppress transpiration and growth (Breda *et al*., 2006; Ayutthaya, 2010). Girth and biomass of irrigated rubber tree was significantly higher than the girth and biomass of rubber tree without irrigation (Vijayakumar *et al*., 1998). Moreover, irrigation in dry season of rubber tree plantations around equator could reduce immature period by 6 to 12 months (Jessy *et al*., 1994; Mak, 2006). Furthermore, irrigation at 50% of crop evapotranspiration (ETc) could reduce immature period of rubber planted in non-traditional area from 10 to 6 years (Vijayakumar *et al*., 1998).

Rubber tree achieves optimal growth if the rainfall is about 125 mm month^{-1} round the year (Rao and Vijayakumar, 1992; Vijayakumar *et al*., 1998). On the other hand, rainfall intensity in wet season in Indonesia reaches more than 200 mm month^{-1}. This amount is enough and even exceeds the requirement of rubber tree to achieve optimal growth and yield. In order to improve the growth and yield of rubber tree, the excess water from rainfall should be drained. Besides that, rubber plant spacing is also should be arranged in order to manage the optimum plant utilization of water, nutrient and light, so the optimum growth and yield of rubber tree can be achieved. To achieve the optimal result of this arrangement, evaluation of several scenarios should be conducted. This evaluation can ideally be performed by conducting the intercropping system trials in the experimental field, but these trials would be time consuming and cost-prohibitive. The alternative ways of performing this evaluation is by using a model. Simulation of water balance, nutrient and light capture can be conducted by using WaNuLCAS model.

WaNuLCAS is a simulation model that can explain the interaction between tree and/or crop in the agroforestry system and the usage of water, nitrogen and light environment (van Noordwijk and Lusiana, 1999). The WaNuLCAS model was developed to evaluate the interaction between soil, tree and crop in an agroforestry system where trees and crops overlap in space and/or time (World Agroforestry Centre, 2012).

The model is able to simulate a time analysis of plant/tree interactions and their usage of the resource (water, nutrients and light). Additional information about the utilization of resources by the trees and crops and yield data can be received if soil character is provided. The nutrient requirement is determined by the model from empirical relationships of nutrient uptake and dry matter production (van Noordwijk *et al*., 2004; Michalczyk, 2008).

Besides WaNulCAS, other models are also available to simulate intercropping system, for example HyPAR, STICS-CA and Always. HyPAR simulation is based on the interception of light and usage of water, availability of light and water under crop canopy, annual tree biomass increment, water and nutrients uptake competition between the roots of trees and crops and tree photosynthetic daily allocation (Dupraz, 2002). Whereas for STICS-CA, the simulation scene is divided simply in two areas: under and outside the vertical projection of the canopy of the dominant species. Simple allometry functions are used to formulate dominant canopy expands. Leaf water interception and stem flow are used for water budget calculation (Dupraz, 2002). In addition, in Always model, the main five components of a silvopastoral system (the tree, the animal, the soil, the sward and the microclimate) are linked to the biophysical simulations of the processes. In this model there is no integrated soil tillage, leaf area, root length and rotation variations from zero to a maximal value linked to the processes (Dupraz, 2002).

In this research, WaNuLCAS model was used due to the ability of the WaNuLCAS model to simulate interaction between trees and crops in an agroforestry system. Generally, this research aimed to determine the best land and water management by arrangement of plant spacing, irrigation, and drainage of rubber plantation in Banyuasin, South Sumatra, Indonesia.

MATERIALS AND METHODS

The study area was in Sembawa Village, Banyuasin District, South Sumatra Province, Indonesia. Geographically, it is located arround

03º55.684' S and 104º32.382' E at an elevation of 10 m above sea level.

This research was done using WaNuLCAS model to determine the effect of rubber tree spacing and water management on the growth and yield of rubber tree. Simulation of the model was started from the beginning until the end of rubber tree life span (27 years).

WaNuLCAS model requires some input like weather (rain, evaporation, soil temperature), soil (soil layer depth, nutrient content, bulk density, texture, organic matter, pH and cation exchange capacity), field management (plant age and nutrient management), tree and crop data. In this research, WaNuLCAS model set up had been done based on Sembawa Research Center Experimental Field weather, soil, management, tree and crop data (Figure 1).

The weather data was taken from Sembawa climate station consist of daily precipitation, soil temperature and class A pan evaporation from year 1985 to year 2011. In addition soil characteristic data (soil layer depth, nutrient content, bulk density, texture, organic matter, pH and cation exchange capacity) of each layer were collected from secondary data of a field site available in Sembawa Research Centre (Khasanah *et al*., 2008) (Table 1).

Management data consisted of planting date (age of the tree) and nutrient management (fertilizer rate applied to the rubber tree). These data were collected from the field management office of Sembawa Research Centre. Furthermore, rubber tree characteristic data were taken from 'crop and tree library' available in WaNuLCAS model.

In addition data on the growth and yield of rubber tree were needed for calibration and validation. Data on the growth (stem diameter) was obtained from literature that recorded stem diameter data from rubber tree at the age of 6 to 17 years old (Rosyid *et al.*, 1997). In addition, rubber tree stem diameter data at the age of 27 years was observed directly from the field.

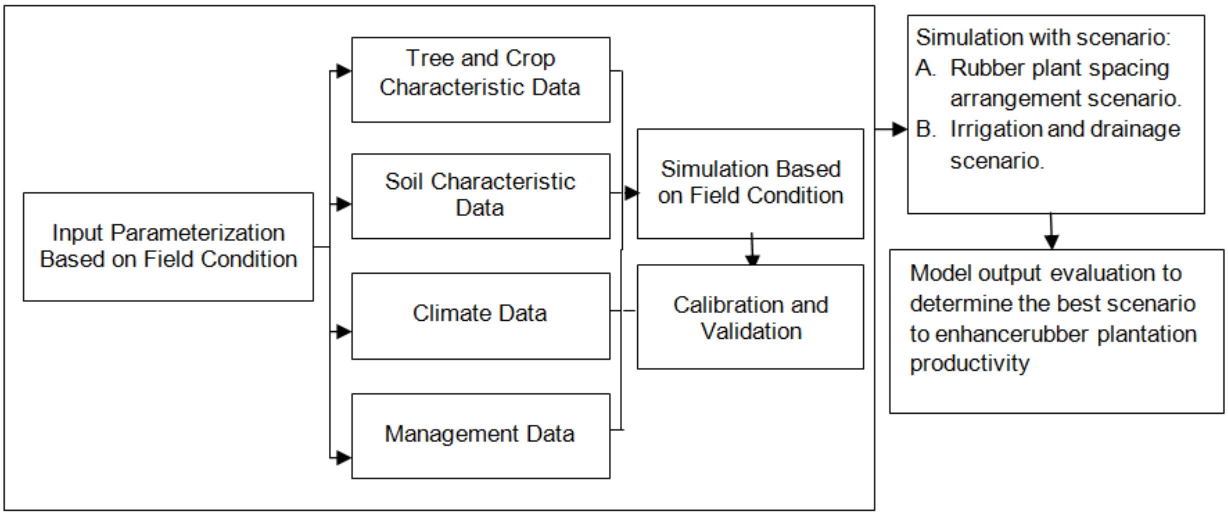

Figure 1. Research methodology framework

Table 1. Soil characteristic in Sembawa Research Centre experimental field (Khasanah *et al*., 2008)

Layer	Layer Depth (cm)	BD (g cm^{-3})	Clay (%)	Silt (%)	C-Org (%)	P (mg cm^{-3})	pH	CEC (me 100g^{-1})	Texture
1	0 – 5	1.34	27.5	24.33	1.43	7.13	4.46	9.28	Sandy Clay Loam
2	5 – 20	1.35	30.42	23.50	1.06	6.02	4.47	7.75	Sandy Clay Loam
3	20 – 50	1.35	34.64	21.44	0.59	5.77	4.58	9.21	Clay Loam
4	50 – 100	1.33	40.05	21.23	0.35	6.31	4.52	8.82	Clay

Yield of rubber tree was collected from Sembawa Research Centre data record (Rubber Research Centre, 2011). The rubber tree growth data consist of stem diameter data at the age of 6, 7, 8, 9, 10, 11, 15, 16, 17, 27 years. Whether the yield data consist of latex yield at the age of 7 until 24 years of rubber tree.

Calibration was conducted by some adjustments on parameters inside tree and crops library. This calibration was conducted to adjust the output value is near to the observed data. Validation also conducted to test whether that the output of the model is fair or not. In this research, some parameters such as stem diameter and latex yield were calibrated and validated. The methods used in the calibration and validation were Pearson correlation coefficient, the goodness of match (GOM) (Lippe *et al*., 2007; Michalczyk, 2008) and root mean square error (Loague and Green, 1991; Khasanah *et al*., 2008). The Pearson correlation coefficient and the goodness of match describe how well the compared values fit together and how strong they were correlated each other. Whereas the root mean square error describes how much is the deviation between compared data. The formula is given as follows:

$$GOM_{total} = \left(\frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}\right)$$

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})\,(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\,\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}$$

$$RMSE = \left[\sum_{i=1}^{n} {(P_i - \bar{O})^2}/{\text{n}}\right]^{0.5} \times \frac{100}{\bar{O}}$$

Where :

GOM total	= GOM for the whole growth cycle, here for all measurements
r	= Pearson correlation coefficient
RMSE	= root mean square error
Pi	= the predicted values
Oi	= the actual values
n	= the number of samples
$\bar{P}$	= average of predicted values
$\bar{O}$	= average of observed values

Simulation was conducted by using a combination of several scenarios of management practices to optimize the growth and yield of rubber tree. The scenarios were:

A. Rubber plant spacing arrangement scenario:
- A.1. Rubber plant spacing 3 × 7 m (density: 476 trees ha^{-1})
- A.2. Rubber plant spacing 3 × 6 m (density: 555 trees ha^{-1})
- A.3. Double row rubber plant spacing 2 × 6 × 14 m (density: 500 trees ha^{-1})

B. Irrigation scenario:
- B.1. Without irrigation
- B.2. Irrigation in dry periods
- B.3. Drainage in wet periods
- B.4. Irrigation in dry periods and drainage in wet periods

Statistical analysis was conducted using Completely Randomized Design method with 95% confidence interval to determine whether the values of the output between each scenario are significantly different or not.

RESULTS AND DISCUSSION

The results of calibration and validation of rubber tree stem diameter and latex yield parameters using Pearson correlation coefficient (r), goodness-of-match (GOM) methods (Lippe *et al*., 2007) and root mean square error (RMSE) (Loague and Green, 1991; Khasanah *et al*., 2008) (Table 2).

Table 2 shows that the r and GOM values rubber tree girth and latex yield parameters were more than 0.95. It mean that the predicted value was fit with observed value and both of them were strongly correlated. RMSE values in the rubber tree girth and latex yield calibration show how big is the deviation of the predicted value compared to observed value. It shows that the model error was very small.

Table 2. r, GOM and RMSE values resulted from calibration of rubber tree parameters

Parameter	r	GOM	RMSE
Stem girth (cm)	0.99	1.01	7.91
Yield (latex) (kg)	0.97	1.09	31.82

Table 3. r, GOM and RMSE values resulted from validation of rubber tree parameters

Parameter	r	GOM	RMSE
Stem girth (cm)	0.98	0.97	9.12
Yield (latex) (kg)	0.83	0.96	22.70

In this research, validation activities were also done to ensure that WaNuLCAS model setup is valid to run the simulations (Table3).

Table 3 shows that the Pearson correlation coefficient (r) and goodness of match (GOM) of stem girth is close to 1 (more than 0.95). It means that the observed and predicted values in this parameter was strongly correlated each other. Table 3 also shows that r value for latex yield is only 0.83. This condition was caused by the fluctuations of latex yields in some years that were unpredicted by the model. The fluctuations of latex yields were caused by the usage of latex stimulant and tapping panel movement from downward to upward tapping panel when the downward bark finish. Overall, these calibration and validation results show that the simulation result of different scenarios is reliable in the actual field.

From the simulation of combination of several scenarios, some output parameters were produced. First parameter that has been produced is rubber tree girth (Table 4).

Table 4 presents that drained rubber tree fields resulted higher girth than rubber tree in the field without drainage system. Furthermore, in the field without drainage system, double row plant spacing arrangement scenario also produced higher girths than base case and single row plant spacing arrangement. This condition could happen because water logging phenomenon usually happened in the peak of wet periods (December - February) in this area.

Under double row plant spacing arrangement system, there were some nearby plants in the rows, using only two meters plant spacing. The nearby plant spacing makes the density of the roots was very high.Most crop models assume that water absorption of a plant has a high correlation to the root length density (Rowse *et al*., 1978; Belmans *et al*., 1979; Lascano and van Bavel, 1984; Barataud *et al*., 1995); Radersma and Ong, 2004). This relationship is used in WaNuLCAS (van Noordwijk and Lusiana, 2000; Radersma and Ong, 2004). Therefore, the densely roots impact the root system ability to absorb enormous water from the root zone especially in the nearby plant spacing rows. Therefore, the amount of water under the soil was not too much (no water logging), so the soil air circulation will be maintained in an optimal condition. Consequently, optimum root respiration will be achieved and retardation of root growth will be avoided. Due to this condition, nutrient uptake was optimum, thus rubber tree growth rate will be optimum also. Finally, if the field is not drained, double row plant spacing arrangement system resulted bigger girth than other plant spacing arrangement.

In contrast, in the single row plant spacing arrangement system, the density of root system were not as high as in the double row plant spacing arrangement system. Thus, water absorption by root system was lower than in the double row plant spacing arrangement system. This arrangement will avoid a high competition for rubber tree to absorb nutrition and water from the soil, but the capacity of root system water suction per square meter in the rubber row was less than in the double row plant spacing arrangement system. Therefore, if the availability of water under the soil was too much and not drained, water logging could happen in the single row plant spacing arrangement system. In the water logging condition, oxygen diffusion was limited, therefore most plants were suffered from oxygen lack (Bartholomeus *et al*., 2008).

Table 4. Rubber tree girth parameter simulation result (cm) at the age of 27 years

Scenario	No Irrigation and Drainage	Irrigation in Dry Periods	Drainage in Wet Periods	Irrigation and Drainage
Base Case, Single Row, 3 x 7 m (476 trees ha^{-1})	94.31 d	94.21 d	114.65 a	114.65 a
Single Row, 3 x 6 m (555 trees ha^{-1})	89.16 e	89.06 e	109.01 b	109.01 b
Double Row, 2 x 6 x 14 m (500 trees ha^{-1})	102.83 c	102.96 c	111.79 ab	111.85 ab

Remarks: Values followed by the different letter are significantly different at 95% confidence interval of Completely Randomized Design

In addition, the rate of gaseous diffusion in the soil under water logging condition was about 100 times lower than gaseous diffusion in the air (Kennedy *et al*., 1992; Zaidi *et al*., 2004). Thus, the rubber tree girths under single row plant spacing arrangement systems were smaller than rubber tree girths under double row plant spacing arrangement system.

Water logging condition did not happen when drainage treatment was conducted. Rubber fields which were treated by drainage system, both single and double row plant spacing arrangement system reached girth 16 and 18% higher respectively than rubber field which were not treated by drainage system, as presented in Table 4. The superior growth of rubber trees which were treated by drainage scenario was achieved because drainage system avoids water logging condition in the root zone. Thus the optimum ability of root system on the extraction of water from the soil could be achieved.

Overall, the growth of rubber tree stem diameter from the age 0 until 27 years for three water management scenarios are presented in Figure 2, Figure 3, Figure 4 and Figure 5.

Figure 2, Figure 3, Figure 4 and Figure 5 show that under single row plant spacing arrangement system, the higher girth was achieved by rubber trees which were treated by drainage system in the wet periods. This condition indicated that the negative effect of dry periods were not as bad as wet periods. In the wet periods, the water infiltrated into soil layers was excessively and affect water logging effect in the soil. Thus drainage activity leads the excessive water in the soil layer was disposed and water logging was avoided. Therefore, by drainage treatment, optimum growth rate of rubber tree could be achieved. Moreover, Figure 2, Figure 3, Figure 4 and Figure 5 show that when rubber trees were young (0 - 4 years old), rubber field with single row plant spacing arrangement system had a better growth than double row plant spacing arrangement system. After four years, under double row plant spacing arrangement system, rubber tree girth was gradually higher than single row plant spacing arrangement system. It happened because in the young stage (immature rubber period), when the root system still on above water table, rubber trees which were planted under single row plant spacing arrangement system had lower root density. Therefore, they had lower nutrient uptake competition than rubber trees which were planted under double row plant spacing arrangement system.

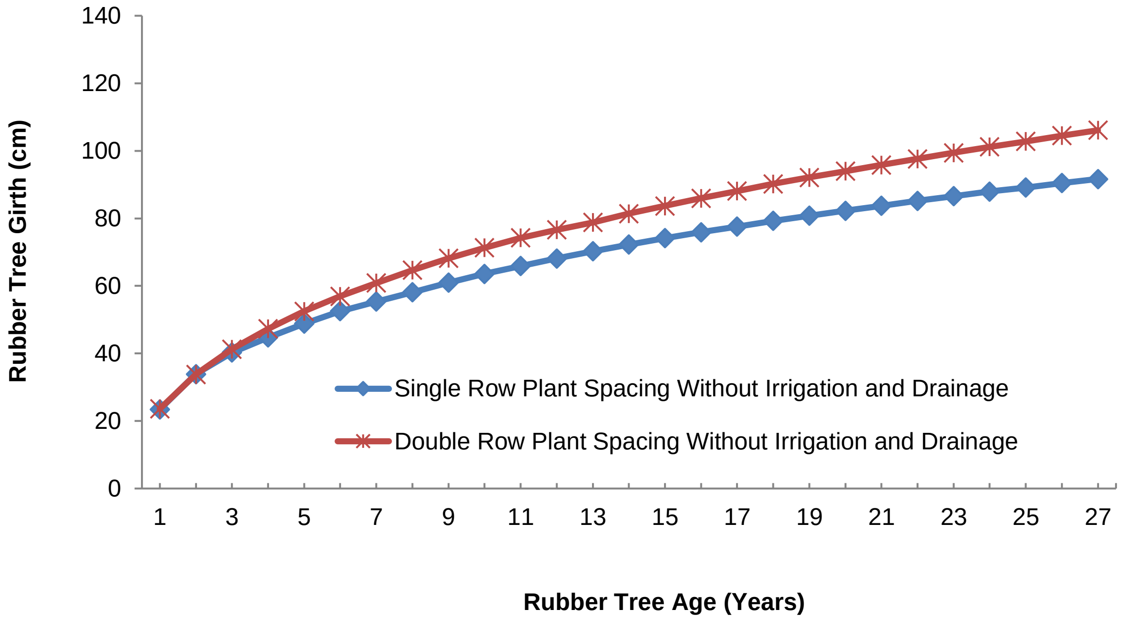

Figure 2. The growth of rubber girth under scenario without irrigation and drainage

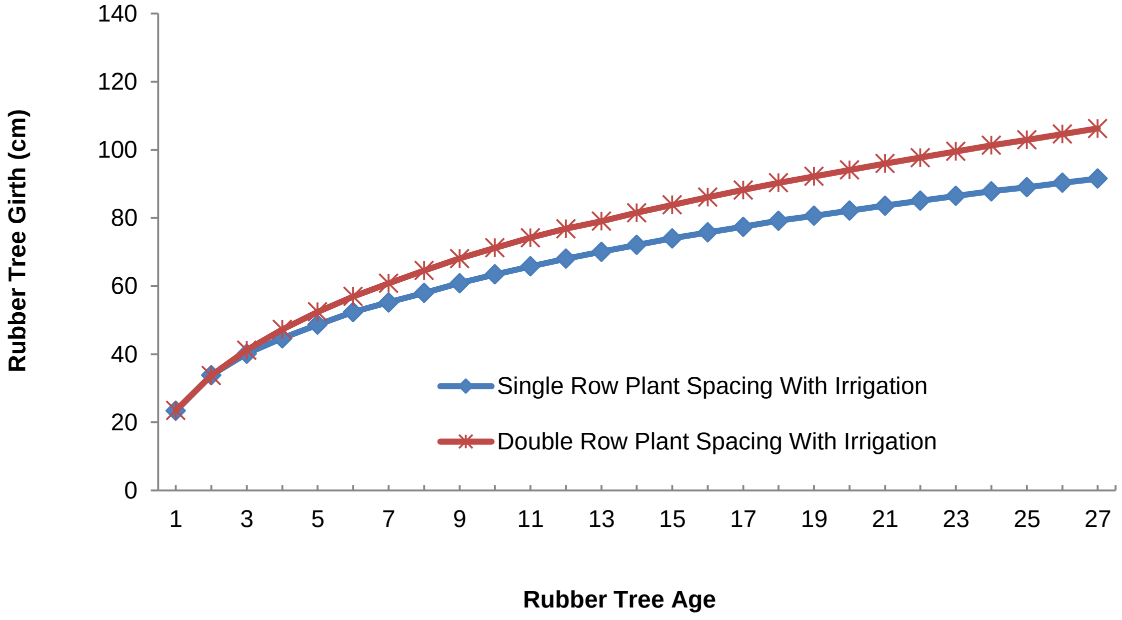

Figure 3. The growth of rubber girth under scenario with irrigation

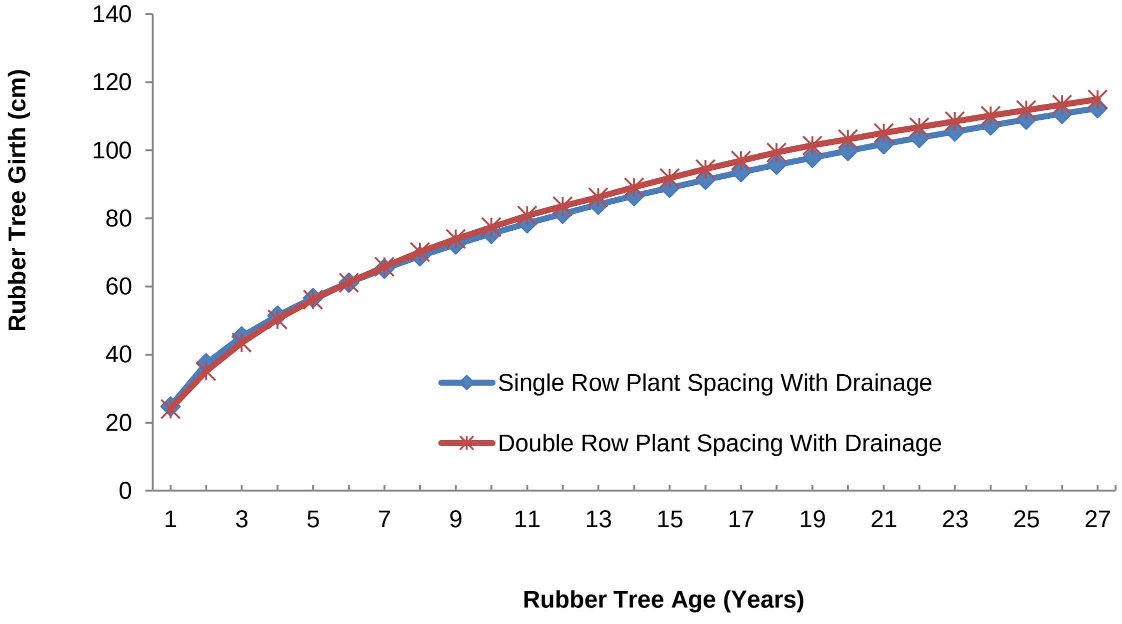

Figure 4. The growth of rubber girth under scenario with drainage

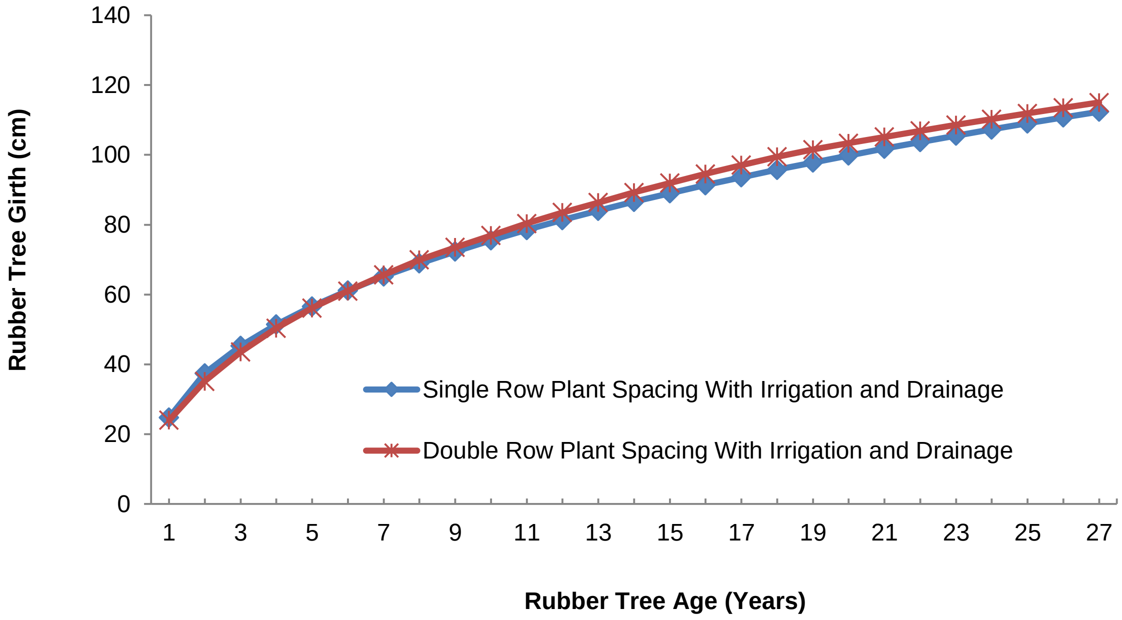

Figure 5. The growth of rubber girth under scenario with irrigation and drainage

Table 5. Simulation result of latex production (t ha^{-1} $year^{-1}$)

Scenario	No Irrigation and Drainage	Irrigation in Dry Periods	Drainage in Wet Periods	Irrigation and Drainage
Base Case, Single Row, 3 x 7 m (476 trees ha^{-1})	1.64 b	1.63 b	2.72 a	2.72 a
Single Row, 3 x 6 m (555 trees ha^{-1})	1.64 b	1.64 b	2.80 a	2.80 a
Double Row, 2 x 6 x 14 m (500 trees ha^{-1})	1.98 b	1.97 b	2.77 a	2.78 a

Remarks: Values followed by the different letter are significantly different at 95% confidence interval of Completely Randomized Design

Similar to rubber tree girth, the rubber yield parameter simulation output also shows that drainage treatment could produce higher latex production than scenario without drainage system as presented in Table 5.

Table 5 presents that for all field treated by drainage system, latex production per hectare of single row plant spacing arrangement system (3 x 6 m) was not significantly different from double row plant spacing arrangement system and single row (3 x 7 m) respectively. This condition happened due to single row plant spacing arrangement system (3 x 6 m) consist of 555 trees ha^{-1}, 55 and 79 trees denser than double row (2 x 6 x 14 m) and single row (3 x 7 m) plant spacing arrangement system.

Table 5 also presents that all plant spacing arrangement system which were drained produced higher latex production compared to all scenarios without drainage system. Latex production of drained rubber tree field rose 66, 70, and 69% respectively for single row (3 x 7 m), single row (3 x 6 m) and double row plant spacing arrangement system compared to single row (3 x 7 m) without drainage system. Moreover, for double row plant spacing arrangement without drainage system, latex production were not significantly different from single row (3 x 7 m) without drainage system. This fact indicates that double row plant spacing arrangement system was not significantly brought a better condition for root system than in single row plant spacing arrangement system under a water logging problem. Therefore, it can be concluded that drainage system is needed to avoid water logging problem in this area, so rubber tree growth and yield can be increased.

CONCLUSIONS AND SUGGESTIONS

From this research, it can be concluded that drainage system is the best water management option to enhance rubber plantation productivity. The productivity could increase 65, 70 and 39% for single row (3 x 7 m), single row (3 x 6 m) and double row (2 x 6 x 14 m) respectively if drainage was applied. Moreover, rubber plantations which were using single row (3 x 7 m), single row (3 x 6 m) and double row (2 x 6 x 14 m) rubber plant spacing arrangement system had no significant difference on latex production per hectare.

Based on the result of this research, it can be recommended that in the water logging area, drainage system for rubber plantation should be held to enhance the productivity of rubber plantation. Furthermore, if the cost of drainage system development is too high, it is better to plant the other kind of trees that more tolerant to water logging condition to prevent failure risk because of water stress.

REFERENCES

Ayutthaya, S.I.N. 2010. Change of whole-tree transpiration of mature *Hevea brasiliensis* under soil and atmospheric droughts: analyze in intermittent and seasonal droughts under the framework of the hydraulic limitation hypothesis (Doctoral dissertation). Retrieved from https://tel. archives-ouvertes.fr/tel-00719009 (NNT: 2010CLF22044). (tel-00719009).

Barataud, F., C. Moyne, N. Breda and A. Granier. 1995. Soil water dynamics in an oak stand: II. A model of the soil-root network compared with experimental data. Plant and Soil 172 (1): 29-43. doi: 10.1007/ BF00020857

Bartholomeus, R.P., J.P.M. Witte, P.M. van Bodegom, J.C. van Dam and R. Aerts. 2008. Critical soil conditions for oxygen stress to plant roots: Substituting the feddes-function by a process-based model. Journal of Hydrology 360 (1-4): 147-165. doi: 10.1016/j.jhydrol.2008.07.029

Belmans, C., J. Feyen and D. Hillel. 1979. An attempt at experimental validation of macroscopic-scale models of soil moisture extraction by roots. Soil Science 127 (3): 174-185.

Breda, N., R. Huc, A. Granier and E. Dreyer. 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63 (6): 625-644. doi: 10.1051/forest:2006042

Dupraz, C. 2002. Tree-crops interaction models: State of the art report. Retrieved from http://www1.montpellier.inra.fr/safe/english/results/annual_report/Deliverable1.1.pdf. Accessed on September 15, 2012.

FAO. 2013. Food and Agricultural commodities production. FAOSTAT. Retrieved from: http://faostat.fao.org/site/339/default.aspx. Accessed on April 24, 2013.

Jacob, J.L., J.C. Prevot, D. Roussel, R. Lacrotte, E. Serres, J. d'Auzac, J. M. Eschbach and H. Omont. 1989. Yield limiting factors, latex physiological parameters, latex diagnosis and clonal typology. In: J. d'Auzac, J.L. Jacob and H. Chrestin (Eds.), Physiology of rubber tree latex. Boca Raton: CRC Press. pp. 345-382

Jessy, M.D., M. Mathew, S. Jacob and K.I. Punnoose. 1994. Comparative evaluation of basin and drip systems of irrigation in rubber. Indian Journal of Natural Rubber Research 7 (1): 51-56.

Kennedy, R.A., M.E. Rumpho and T.C. Fox. 1992. Anaerobic metabolism in plants. Plant Physiology 100 (1): 1-6. doi: 10.1104 /pp.100.1.1

Khasanah, N., T. Wijaya, T. June, B. Lusiana and M. van Noordwijk. 2008. Growth of rubber (*Hevea brasiliensis*) in mono-culture and mixed systems with acacia (*Acacia mangium*) a case study in Sembawa, South Sumatra: II. Simulation using WaNuLCAS model (in Indonesian). Jurnal Penelitian Karet 26 (1): 49-64.

Larcher, W. 2001. Physiological plant ecology: Ecophysiology and stress physiology of functional groups (4th edition). Berlin: Springer-Verlag. pp. 517.

Lascano, R.J. and C.H.M. van Bavel. 1984. Root water uptake and soil water distribution: test of an availability concept. Soil Science Society of America Journal 48 (2): 233-237. doi: 10.2136/sssaj1984. 03615995004800020002x

Lippe, M., N.V. Dung, T.D. Vien, T.T. Kien, T. Hilger and G. Cadisch. 2007. WaNuLCAS modelling of improved swidden agriculture systems by indigenous fallow management with *Melia azedarach* in the uplands of Ban Tat, Northern Vietnam. Proceedings from International Agricultural Research for Development Conference (October, 9-11 2007). Germany: University of Kassel-Witzenhausen and University of Göttingen.

Loague, K. and R.E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology 7 (1-2): 51-73. doi: 10.1016/ 0169-7722(91)90038-3

Mak, S. 2006. Effects of fertilizer and irrigation on yield and quality of rubber (*Hevea brasiliensis*) grown at Chanthaburi province, Thailand (Unpublished Master Thesis). Kasetsart University. Thailand.

Michalczyk, A. 2008. Parameterisation and modelling of growth and yield development of mango (*Mangifera indica* L.) in North Thailand with application of the WaNuLCAS model (Unpublished Master Thesis). Humboldt-Universitat Zu Berlin. Berlin.

Radersma, S. and C.K. Ong. 2004. Spatial distribution of root length density and soil water of linear agroforestry systems in sub-humid Kenya: Implications for agroforestry models. Forest Ecology and Management 188 (1-3): 77-89. doi: 10.1016/j.foreco.2003.07.021

Rao, P.S. and K.R. Vijayakumar. 1992. Climatic requirements. *In* Sethuraj, M.R. and N.M. Mathew (Eds.), Natural rubber: biology, cultivation and technology. Amsterdam: Elsevier Science Publishers. p. 200-219

Rao, P.S. 1993. Water balance in the rubber growing regions. Plant Physiology and Biochemistry 20 (1): 56-61.

Rao, P.S., K. Jayarathnam and M.R. Sethuraj. 1993. An index to assess areas hydrothermally suitable for rubber cultivation. Indian Journal of Natural Rubber Research 6 (1-2): 80-91.

Rao, P.S., C.K. Saraswathyamma and M.R. Sethuraj. 1998. Studies on the relationship between yield and meteorological parameters of para rubber tree (*Hevea brasiliensis*). Agricultural and Forest Meteorology 90 (3): 235-245. doi: 10.1016/ S0168-1923(98)00051-3

Rosyid, M.J., G. Wibawa and A. Gunawan. 1997. Rubber based farming systems development for increasing small-holder' income in Indonesia. Proceedings from Farming System Aspects of the Cultivation of Natural Rubber (*Hevea brasiliensis*) Symposium. Srilanka: International Rubber Research and Development Board.

Rowse, H.R., D.A. Stone and A. Gerwitz. 1978. Simulation of the water distribution in soil: II. The model for cropped soil and its comparison with experiment. Plant and Soil 49 (3): 533-550. doi: 10.1007/ BF02183279

Rubber Research Centre. 2008. Road map: Processing and marketing of rubber (in Indonesian). Palembang: Rubber Research Center, Sembawa Research Institute.

Rubber Research Centre. 2011. Field management report (in Indonesian). Palembang: Rubber Research Center, Sembawa Research Institute.

van Noordwijk, M. and B. Lusiana. 1999. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Systems 43: 217-242.

van Noordwijk, M. and B. Lusiana. 2000. WaNuLCAS version 2.0, Background on a model of water, nutrient and light capture in agroforestry systems. Bogor: International Centre for Research in Agroforestry (ICRAF). pp. 186.

van Noordwijk, M., B. Lusiana and N. Khasanah. 2004. WaNuLCAS version 3.1, Background on a model of water nutrient and light capture in agroforestry systems. Bogor: International Centre for Research in Agroforestry (ICRAF). pp. 246.

Vijayakumar, K.R., S.K. Dey, T.R. Chandrasekhar, A.S. Devakumar, T. Mohankrishna, P.S. Rao and M.R. Sethuraj. 1998. Irrigation requirement of rubber trees (*Hevea brasiliensis*) in the subhumid tropics. Agricultural Water Management 35 (3): 245-259. Amsterdam: Elsevier.

Vijayakumar, K.R., T.R. Chandrashekar and V. Philip. 2000. Agroclimate. *In* George, P.J. and C.K. Jacob (Eds.), Natural rubber: Agromanagement and crop processing. Kerala: Rubber Research Institute of India. p. 97-116.

Webster, C.C. and E. J. Baulkwill. 1989. Rubber. New York: John Wiley and Son. pp. 614.

World Agroforestry Centre. 2012. WaNuLCAS, a model of Water, Nutrient and Light Capture in Agroforestry Systems. http://www.worldagroforestry.org/regions/southeast_asia/resources/wanulcas.Accessed on September 13, 2012

Zaidi, P.H., S. Rafique, P.K. Rai, N.N. Singh and G. Srinivasan. 2004. Tolerance to excess moisture in maize (*Zea mays* L.): Susceptible crop stages and identification of tolerant genotypes. Field Crops Research 90 (2-3): 189-202. doi: 10.1016/j.fcr.2004.03.002