

Transpiration, growth and latex production of a Hevea brasiliensis stand facing drought in Northeast Thailand: the use of the WaNuLCAS model as an exploratory tool

Laurie Boithias, Frederic Do, Supat Isarangkool Na Ayutthaya, Junyia Junjittakarn, S. Siltecho, Claude Hammecker

► **To cite this version:**

Laurie Boithias, Frederic Do, Supat Isarangkool Na Ayutthaya, Junyia Junjittakarn, S. Siltecho, et al.. Transpiration, growth and latex production of a Hevea brasiliensis stand facing drought in Northeast Thailand: the use of the WaNuLCAS model as an exploratory tool. *Experimental Agriculture*, Cambridge University Press (CUP), 2012, 48 (1), pp.49-63. <10.1017/S001447971100086X>. <ird-00653618>

HAL Id: ird-00653618

<http://hal.ird.fr/ird-00653618>

Submitted on 9 Jan 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

MODELING DROUGHT IMPACT ON *H. BRASILIENSIS*

2

TRANSPIRATION, GROWTH AND LATEX PRODUCTION OF A

4

HEVEA BRASILIENSIS STAND FACING DROUGHT IN

NORTHEAST THAILAND: THE USE OF THE WANULCAS MODEL

6

AS AN EXPLORATORY TOOL

8 By L. Boithias ^{a,1}, F.C. Do ^b, S. Isarangkool Na Ayutthaya ^c, J. Junjittakarn ^c,

S. Siltecho ^d and C. Hammecker ^e

10 ^a IRD, UMR Eco&Sols, Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand , and

^b IRD, UMR Eco&Sols, Campus SupAgro-INRA, Montpellier, France, and

12 ^c Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand, and

^d Land Development Department, region five, Khon Kaen, Thailand, and

14 ^e IRD, UMR Eco&Sols, Land Development Department, Bangkok, Thailand.

¹corresponding author: CNRS, UMR EcoLab, ENSAT, Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France, l.boithias@gmail.com

SUMMARY

16 To benefit from the growing world demand for natural rubber, *Hevea brasiliensis* is
increasingly planted in drought prone areas, such as in the southern part of northeast
18 Thailand. Modelling can be a useful approach in identifying key points of improvement
for rubber tree cultivation in such water-limited areas. The first objective of this study
20 was to test the possibility of using the WaNuLCAS model as an exploratory tool to
simulate water-use, growth and latex production in a pure stand on a daily basis. The
22 second was to evaluate the relative accuracy of predictions with the current model
version. Finally, the third aim of this study was to identify particular parameterizations
24 which may be adapted to improve overall prediction quality.

Model outputs were compared to measurements recorded in a mature rubber tree
26 stand of RRIM 600 clones growing in the water-limited area of northeast Thailand. The
period of analysis concerned seven months of full foliation, from May to November,
28 including a severe drought spell. Whole-tree transpiration was estimated by xylem sap
flow measurement from eleven trees. The results show that the model was able to
30 simulate daily and seasonal change of soil water content, tree transpiration, girth
increment and latex production within plausible ranges. However, under detailed
32 scrutiny, the predictions show large inaccuracies compared to the observations: soil water
content ($R^2 = 0.461$, $RMSE_{rel} = 35\%$), tree transpiration ($R^2 = 0.104$, $RMSE_{rel} = 94\%$),
34 tree girth increment ($R^2 = 0.916$, $RMSE_{rel} = 208\%$) and latex production ($R^2 = 0.423$,
 $RMSE_{rel} = 169\%$). As soil water content was overestimated during the driest periods, no
36 water stress was predicted and transpiration, growth and latex production were logically

overestimated during such periods. However, tree transpiration was also largely
38 overestimated in conditions of non-limiting soil water availability with high evaporative
demand. Hence, two key points of parameterization and improvement are identified for
40 better simulation in our conditions: the soil water balance and particularly the ratio
between water infiltration and run-off; and the regulation of transpiration under high
42 evaporative demand. In conclusion, WaNuLCAS model is usable as an exploratory model
to simulate water use, growth and production for a pure rubber tree stand. However, in
44 our conditions of much degraded soil and high evaporative demand, the modules of soil
water balance and tree transpiration require particular parameterizations and
46 improvement.

INTRODUCTION

48 As a consequence of increasing demand for natural rubber and competition with oil palm
in the traditional areas, the extension of *Hevea brasiliensis* cultivation is accelerating in
50 drought-prone areas, such as in the southern part of northeast Thailand. Although growth
and latex production are two distinct physiological phenomena in rubber trees (Rao et al.,
52 1998), they are both strongly related to evaporative demand and water availability. The
importance of the water relations for latex production is known (Pakianathan et al.,
54 1989), and some authors have studied the impact of water constraints on tree water status,
girth increment and latex production (Rao et al., 1990; Chandrashekar et al., 1998). Water
56 stress generally results from an imbalance between transpiration, driven by evaporative
demand, and root-water-uptake allowed by soil water availability. Drought stress occurs
58 whenever soil water availability drops below a certain threshold, thus inducing

restrictions to transpiration and growth. Frequently, but not invariably, soil dryness is
60 coupled with strong evaporation caused by air dryness. Conversely, an atmospheric
drought may occur despite water being available in the soil. A model that predicts tree
62 water use, tree growth and latex production model can be a useful tool to analyze key
points of improvement in rubber tree cultivation in water-limited areas. Growth models
64 have become a tool for making rational land use decisions and for monitoring sustainable
agricultural systems if their capacity to predict crop response and identify management
66 options is well established (e.g. Verdoodt et al., 2004). They can help to identify
environmental factors limiting growth and resource use and to assess productivity and
68 profitability at various time scales (e.g. Shamudzarira and Robertson, 2002). For
perennial crops much less work on production models has been carried out, probably due
70 to data limitation, relatively high research costs and the difficulties of accumulated errors
in long term simulations (Zuidema et al., 2005).

72 The WaNuLCAS model (Water Nutrients and Light Capture in Agroforestry
Systems) was developed by the International Centre for Research on Agroforestry
74 (ICRAF, Indonesia) as a research tool with the major objective to synthesize existing
knowledge and hypotheses on above- and below-ground resource-use by trees and crops
76 at the patch-scale (Van Noordwijk and Lusiana, 1999). Although it can undertake
economic evaluations, WaNuLCAS is primarily a biophysical model that also provides a
78 great range of outputs, including soil water, transpiration, growth of trees and crops for a
given environment. This model was chosen for this study since it has already been
80 parameterised for pure rubber tree stands and it included a specific module of latex
production. However, it has mainly been used for long term (multi-annual) predictions of

82 rubber tree growth in pure stand (Yahya, 2007) or in agro-forestry systems (Pinto et al.,
2005). Moreover, to our knowledge, this model has not been tested for rubber tree
84 growing in drought prone area. Hence, this study had three aims: firstly, to test the
possibility of using the WaNuLCAS model as an exploratory tool to analyze relationships
86 between water use, growth and latex production on an intra-annual, daily basis and in a
pure stand. The second was to evaluate the relative accuracy of the simulations of soil
88 water content, tree transpiration, cambial growth and latex production. Finally, the third
objective was to identify key features in the various parameterizations which may be
90 adapted to improve overall prediction quality in drought prone areas. To address these
issues, simulations were compared to field measurements in a mature rubber tree stand
92 growing in the water-limited area of northeast Thailand. The period of analysis concerned
seven months of full foliage and latex tapping from May to November. Four sub-
94 periods were distinguished, combining contrasted magnitudes of evaporative demand and
soil water availability.

96 MATERIALS AND METHODS

The WaNuLCAS model

98 Version 3.2 of the WaNuLCAS model is used in this study. WaNuLCAS was developed
as a collection of modules in which processes are computed at a daily time step. A short
100 description of the modules used for the simulation is given below. For more theoretical
background on the modules we refer to the original model documentation of Van
102 Noordwijk and Lusiana (1999).

The soil is divided into four layers in the vertical and four spatial zones in the horizontal, and each layer is characterised by different soil properties (Figure 1). The soil hydraulic module includes pedotransfer functions (Wösten et al.1998) that are used to derive the constants of the Van Genuchten (1980) equation depending on soil texture, bulk density and soil organic matter content. These constants determine the relationship between soil water content, soil water potential, hydraulic conductivity and potential tree water uptake in each cell. To calculate water infiltration, the model estimates a layer-specific field capacity. Two definitions of field capacity are used: (i) field capacity is the soil water content at which downward drainage would become less than a critical value of conductivity (K_{crit}) and would effectively stop, or (ii) field capacity is the soil water content that is in hydrostatic equilibrium with a water table at a distance defined from the bottom of layer 4. The highest of these two values in any cell is used. A saturated hydraulic conductivity (K_{sat}) is generated from the pedotransfer functions. The water balance includes vertical and horizontal transport. It incorporates the water balance inflows and outflows described in Table 1 at daily time steps.

Surface run-off occurs if (i) daily rainfall exceeds daily maximum infiltration or (ii) daily rainfall exceeds the soil potential water storage. Allocation to surface runoff or infiltration in the first soil layer depends on a ratio, called SSI in this study, that is the ratio between a reference K_{sat} (for degraded soil) and the K_{sat} generated by the pedotransfer function. Infiltration then follows the tipping bucket principle for wetting subsequent layers of soil, filling a cascade of soil layers up to their field capacity.

Tree water uptake, i.e. transpiration, is driven by evaporative demand, with the possibilities determined by tree root length density and soil water availability in the

126 various cells to which a plant has access. A “potential transpirational demand” is
estimated from LAI and ET_0 . Hence, the transpiration depends on a water demand
128 reduction factor or stress factor:

$$\tau = f(\theta)\tau_0$$

130 where τ is the tree water demand, $f(\theta)$ is the water demand reduction factor (where
 θ is the soil water content) and τ_0 is the potential transpirational demand. The reduction
132 factor depends on the “plant water potential” which is estimated from the “soil water
potential”.

134 Canopy light capture is determined by the LAI, the canopy height and the Beer’s
law extinction coefficient specific to rubber trees. The growth reserve pool varies with
136 the tree potential growth and the minimum stress factor regarding light, water and
nitrogen. Part of the growth reserves are allocated to growth. Allometric equations are
138 used to relate tree girth to tree biomass. They allocate predicted biomass to the different
tree components: below-ground and total, above-ground biomass, which in turn is
140 partitioned into roots, leaves and twigs, as well as branches. As for tree growth, part of
the “tree growth reserves pool” is allocated to “daily latex production”. Tapped latex
142 depends on the “fraction of latex stock” that can be tapped every day (“tapping fraction”)
and on existing “Brown Bast”, a physiological disease that induces a reduction of latex
144 production (Paardekooper, 1989). The version of WaNuLCAS used only predicts latex
production using a d/2 tapping pattern (one day of tapping – one day of rest).

146 *Data measurements*

Experiment site and forestry system: The experiment site was located in Baan Sila (N15°
148 16' 23.6" E103° 04' 51.3", altitude = 150 m) between Satuk and Khu Muang in the
Buriram province of northeast Thailand. The field was a monoculture stand of RRIM600
150 rubber clones planted in 1995 (i.e. 12 years old in 2007) at a 7mx2.5m tree spacing over
5.5ha, in a deep sandy soil. Average annual rainfall in this area is 1176 mm (Khu Muang
152 station). The wet season lasts from May to October but intermittent dry spells often occur
in June and July. Rubber trees have been tapped since June 2003. The stand was
154 modelled as a half alley system as shown in Figure 1. The 2-D unit represents a flat area
3.5m wide and 1.8m deep. The width was arbitrarily split into four zones of 1, 1, 1 and
156 0.5 m. Layer bottoms were set according to the main variations of soil properties in the
profile, at depths of 0.25, 0.5, 1 and 1.8m. Trees were grown in zone 1 at a density of 571
158 trees.ha⁻¹ (Table 2 (a)).

Water balance

160 Soil physical properties: the main soil properties (Hartmann et al., 2006) of each
modelled layer are provided in Table 2 (b). Textures were assumed homogeneous in the
162 four zones. The soil was degraded and poorly structured. Bulk density was high in layer
2: this compaction resulted from previous cassava cultivation. Saturated hydraulic
164 conductivities (*K_{sat}*) were measured with four replications. The magnitude of the
measured standard deviation suggested significant spatial variability of this parameter.

166 Soil water storage, infiltration and evaporation: WaNuLCAS requires the daily
inputs of two climatic variables: rainfall and reference evapotranspiration. In Baan Sila,

168 climatic data (air temperature, relative humidity, global radiation, wind speed and
rainfall) were automatically recorded every 30 minutes with a Minimet station (Skye
170 Instruments Ltd, U.K.) in an open field located to the east of the rubber stand, 50m away
from any tree. Recorded climate data were then aggregated as maximal/minimal
172 (temperature, humidity), average (wind speed) or cumulated (radiation, rainfall) daily
values. Daily values of reference potential evapotranspiration were calculated using the
174 Penman-Monteith equation. Figure 2 shows the input values of climatic data. 2007
rainfall was approximately 965mm (879mm from May to November), 18% less than the
176 long-term annual average. The wet season is often interspersed with a short dry and hot
period (scarce rainfall and high evaporative demand) in June and July, a feature which
178 occurred in 2007. Dry and cool conditions prevailed again from November. Climate data
inputs were set equal in the four spatial zones. In the rubber stand, volumetric soil water
180 content was measured once or twice each month with a neutron probe (Troxler 3300,
USA) calibrated for the experimental soil. Calibration was carried out separately for the
182 upper (0-0.2m depth) and lower (0.2-1.8m depth) layers. Measurements were made every
0.2m from the ground down to a depth of 1.8m. Twelve access tubes of 2.0m in length
184 were set up in pairs: one tube in the planting line between two trees, and the other one in
the middle of the inter-row. Average measured moisture from the 12 tubes were used as
186 observational data. Initial soil water contents (i.e. in May) are given in Table 2 (b). The
K_{crit} value was calculated in order to get the field capacity of layer 1 equal to the soil
188 water content at a soil water potential of -100 cm. No water table was observed below the
stand in Baan Sila. A value of 10m depth was set as input for the distance from the
190 bottom of layer 4 to the supposed water table. Thus, the value of field capacity computed

from definition (ii) was insignificant. The *SSI* parameter (influencing the ratio between
192 run-off and infiltration) was calibrated in order to obtain soil water stock values during
periods of high rainfall (August-September-October) similar to observed values.

194 Daily tree water use, i.e. transpiration, was estimated by the daily total sap flow in
trunk xylem, ignoring changes in tree water storage (Isarangkool Na Ayutthaya et al.,
196 2010). The measurements of xylem Sap Flow Density (SFD) on 11 trees in Baan Sila
were made using the Transient Thermal Dissipation (TTD) system (Do and Rocheteau,
198 2002; Isarangkool Na Ayutthaya et al., 2010). A cycle of 10min heating and 20min
cooling was used to measure sap flow density every 30min. The zero flux signal was
200 determined every night assuming that sap flow was negligible at the end of the night (see
details in Isarangkool Na Ayutthaya et al., 2010). Probes were inserted into the trunks at a
202 height of 1.8m above the soil. At this height, average sapwood area was estimated to be
2.04 dm² (SD = 0.47). Three probes were inserted into each trunk to take circumferential
204 variability into account. An average radial profile of sap flux density was also taken into
account (Isarangkool Na Ayutthaya et al., 2010). All probes were connected to a data
206 logger (CR10X, Campbell Scientific, Leicester, U.K.). Hourly SFD was cumulated over a
24h period to calculate daily SFD and multiplied by sapwood area. Average daily total
208 flow of the representative trees was divided by the soil surface theoretically available for
a tree (17.5m²) in order to estimate the observed tree water uptake in mm. Isarangkool Na
210 Ayutthaya et al. (2011) provide a detailed analysis of a data subset of these field
measurements of water use.

212 Tree growth and light capture: the potential growth (0.01kg.m⁻²) was taken from
WaNuLCAS default values. As inputs, the model required initial stem and canopy above-

214 ground biomasses (Table 2 (a)). Total above-ground biomass was calculated using
allometric relation between girth and weight. Constants for RRIM600 rubber trees were
216 set according to Chantuma et al. (2004):

$$W = 0.0082 * G^{2.5623}$$

218 where W is the above ground tree weight in kg and G the tree girth in cm,
measured at 170cm above the ground. The simulated girth increments were compared to
220 observations. The girths of 232 trees were measured using a metre rule once or twice per
month in 2007 in Baan Sila. The maximum LAI (Table 2 (a)) for the year 2007 was
222 measured by collecting fallen leaves in one square meter open boxes from November
2007 till the complete defoliation at the end of January 2008. Root biomass and root
224 length density were assumed constant for the simulation period. The average profile of
root length density was taken from measurements in the site (Table 2 (b), Pierret et al.,
226 unpublished report). Default model values were used for other physiological parameters.

Latex production: Observed latex production was estimated from the amount of
228 rubber sheets produced each tapping day on the whole plot, knowing the number of
tapped trees and an average weight per rubber sheet of 1200g. The “tapping fraction” was
230 calibrated to fit the range of expected latex production at the start of tapping period in
May, taking into account the fact that 30% of the trees of the plot were suffering from
232 Brown Bast and that the tapping system in the model could only be $d/2$ instead of the
observed $2d/3$. The used parameters in the latex module are given in Table 2 (c). Other
234 parameters have been set following WaNuLCAS default values.

Evaluation of model predictions

236 The simulation covers the period from May the 1st to November the 30th in 2007. The
simulation assumed no limitations due to nutrients (nitrogen or phosphorus), weeds and
238 pests. Predicted data regarding soil water content, transpiration, girth increment and latex
production were compared to field measurements. The analysis used determination
240 coefficients (R^2) and relative root mean square errors $RMSE_{rel}$:

$$RMSE_{rel} = \frac{100}{\bar{O}} \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}$$

242 where O and P represent observed and predicted values, respectively, and \bar{O}
represents the observed value average. The number of observations is n . R^2 and $RMSE_{rel}$
244 for transpiration estimates were compared over the seven months of study and for the
four climatic sub-periods (Figure 2): one combining high evaporative demand and low
246 soil water constraint (May); two periods combining high evaporative demand and high
soil water constraint (June-July and November); and one combining low evaporative
248 demand and low soil water constraint (August-September-October).

RESULTS

250 *Water balance*

Soil water content: Observations ranged from 5 to 25% (Figure 3). Soil moisture
252 decreased in each layer during the short dry period of June and July. Model results
followed the same pattern but they were often overestimated, particularly in layer 3. R^2 of
254 layers 1, 2, 3 and 4 were 0.218, 0.307, 0.277 and 0.496, respectively, and $RMSE_{rel}$ values
were 34.7, 39.8, 68.7 and 22.3%, respectively. For the total profile, R^2 and $RMSE_{rel}$ values

256 were 0.461 and 34.9%, respectively.

Tree transpiration: Measured values ranged from 0.3 to 2.3mm.d⁻¹ (Figure 4).
258 Transpiration dramatically decreased during the intermittent droughts in June and July. It
also progressively decreased in November at the beginning of the long dry period.
260 Predicted and observed values were in the same range during periods without soil water
constraint and with low or moderate evaporative demand ($ET_0 < 2\text{mm.d}^{-1}$, September-
262 October). In contrast, model-predicted values were significantly overestimated in periods
of high evaporative demand ($ET_0 > 2\text{mm.d}^{-1}$: start of May, June and July, November).
264 Moreover, the dramatic reduction of transpiration in June and July due to soil drought
was not simulated. Finally, R^2 and $RMSE_{rel}$ values equalled 0.104 and 94 %, respectively.

266 *Tree growth*

Observed tree girth increased at the beginning of the rainy season (May-June) and then
268 stopped and decreased in July in accordance with the decline in transpiration (Figure 5).
Girth increased again from August to October. The total increment reached 1.3cm over
270 the seven-month period. The model significantly overestimated girth increment. Final R^2
and $RMSE_{rel}$ values were 0.916 and 208 %, respectively.

272 *Latex prediction*

Observed values ranged from 1.3 and 19kg.ha⁻¹.d⁻¹ and the pattern was not correlated to
274 variation in transpiration (Figure 6). As for growth, the model did not predict any
reduction due to water stress and the latex production is largely overestimated. Total
276 predicted production (2888 kg.ha⁻¹) was twice the measured production (1416kg.ha⁻¹)

over the simulated period. Finally, R^2 and $RMSE_{rel}$ values were 0.423 and 169 %,
278 respectively.

DISCUSSION

280 *WaNuLCAS model as an exploratory tool*

The test of the possibility of using WaNuLCAS model as an exploratory tool for a pure
282 rubber tree stands appeared to be successful. It simulated daily changes in transpiration,
girth increment and latex production within plausible ranges (Silpi et al., 2006;
284 Pakianathan et al., 1989; Watson, 1989). In addition, the model runs were easily
implemented and several shortcuts were available to test the schematic inputs of rainfall,
286 ET_0 , etc.

Relative accuracy of simulations

288 With the current model version and parameters, results showed large inaccuracies for
certain model predictions: soil water content ($R^2 = 0.461$, $RMSE_{rel} = 34.9\%$), tree
290 transpiration ($R^2 = 0.104$, $RMSE_{rel} = 94\%$), tree girth increment ($R^2 = 0.916$, $RMSE_{rel} =$
208.4%) and latex production ($R^2 = 0.423$, $RMSE_{rel} = 169.5\%$). However, as the water
292 shortage in June and July was not predicted by the model, the significant overestimations
in girth increment and latex production appear logical and can not be discussed in further
294 depth. Hence, the focus of this investigation is foremost on the soil water balance and tree
water use. Model estimations of tree transpiration were correct in conditions without soil
296 and atmospheric droughts. Major inaccuracies resulted from (i) the non-prediction of soil
water shortage and (ii) the overestimation of tree transpiration under high evaporative

298 demand and non-limiting conditions of soil water.

The soil water shortage was not predicted because the soil water content was
300 overestimated in all layers except in the lowest one. In WaNuLCAS, as in all reservoir
models, infiltration water fills each layer of soil until their field capacity is reached and
302 the excess moisture wets the subsequent soil layer. The speed of the process depends on
the infiltration rate. When the deepest layer reaches its field capacity, excess water is then
304 lost by deep drainage. A small error in predicting soil water content in upper layers may
thus be amplified in deeper layers. Bias in predicting soil water content can come from
306 errors in predicting (i) the layers field capacity and (ii) the infiltration rate of each layer,
particularly in the upper-most layer which determines the infiltration/runoff ratio. Aware
308 of these points, measured *Ksat* and a calibrated ratio between infiltration and runoff (*SSI*)
were used. The default values of *Ksat* and *SSI* provided by the pedotransfer functions of
310 WaNuLCAS were even higher than our estimated values and induced even greater
overestimates of soil water content. Other authors reported inadequacies of the
312 pedotransfer functions and predicted infiltration by WaNuLCAS for tropical soils
(Hodnett and Tomasella, 2002; Walker et al., 2007; Pansak et al., 2010). To explain the
314 overestimate of soil water content, despite the use of measured *Ksat* and calibrated *SSI*
values, several hypotheses are proposed. Firstly, measured *Ksat* is still overestimated,
316 particularly in the upper layer. This is possible because the variability between field
measurements of *Ksat* was very large (Table 2 (b)). Moreover, significant surface
318 flooding and run-off were observed for each important rainfall event. Secondly, the
infiltration of water is not homogeneous between the tree row and in the inter-row space.
320 Surface flooding and run-off was of greater importance in the inter-row spaces which are

at a lower level than the tree rows. In addition, preferential vertical flow may occur in the
322 inter-row spaces, which may induce deep, localised drainage.

In addition, the model overestimated maximum transpiration because it simulated
324 tree transpiration that follows the evaporative demand without any stomatal regulation
due to atmospheric conditions. The only water-regulation included in the model
326 originates from soil water shortage, similar to the majority of models. However, observed
data showed that effective regulation of transpiration occurred above ET_0 equal to 2.0mm
328 (Fig. 4). This is, however, a very recent result for rubber trees (Isarangkool Na
Ayyuthaya et al., 2011), which may differ according to the clone (here RRIM 600). The
330 regulation of transpiration at high evaporative demand, whatever the soil water
availability, has been quoted for several species and environments (David et al., 2004;
332 Bovard et al., 2005; Oguntunde et al., 2007; Bush et al., 2008). Moreover, the
overestimate of transpiration in the simulation should further decrease the soil water
334 reserve, which emphasizes the current overestimation of soil water content by the model.
The current version of the WaNuLCAS model has, however, already predicted correct
336 values of rubber tree growth and production over long periods in other regions (Pinto et
al., 2005; Yahya, 2007). We assume that these results likely correspond to environmental
338 conditions without high evaporative demand.

Key points of parameterization and improvement

340 Under the conditions of degraded soil and high evaporative demand investigated, the key
point of parameterization and improvement are the soil water balance and the regulation
342 of tree transpiration under high evaporative demand. It is likely that the ability to separate

soil properties between horizontal zones in the model will facilitate the improvement of
344 the simulated soil water balance. This is particularly the case in rubber tree plantations,
where several years of different soil-, weed- and litter-management practices between
346 tree row and inter-row spaces may influence the topography and soil properties related to
soil water infiltration and balance. Secondly, the regulation of transpiration as a function
348 of evaporative demand requires the introduction of a new equation or reduction factor.
The transpiration model in Granier et al. (2000) provides an example of a multiple
350 regulation of canopy conductance where atmospheric drought is taken into account
whatever the soil water conditions.

352

CONCLUSIONS

In conclusion, the WaNuLCAS model appears to be a useful exploratory tool for the
354 simulation of water use, growth and latex production in a pure stand of rubber tree on a
daily basis. Results do, however, show that under the conditions of degraded soil and
356 high evaporative demand investigated, the modules of soil water balance and tree
transpiration require particular parameterizations and improvement in order to more
358 accurately represent these processes.

360

Acknowledgments. The authors thank all French and Thai counterparts from the
362 Institute of Research for Development (IRD), the Khon Kaen University and the Land
Development Department. We particularly thank the Land Development Department of

364 Bangkok and Dr. Darunee Chairod for the assistance in neutron probe measurements. We
are grateful to Dr Henri Robain for his support as coordinator of the agreement program
366 between IRD and the Rubber French Institute. We are also very grateful to Mr. Chaipat
Sirichaiboonwat who welcomed us so kindly in his rubber tree plantation. Finally, we
368 sincerely thank Ms Ni'matul Khasanah (ICRAF, Indonesia), Dr Fiona Tummon (CNRS,
France) and Dr Erwan Motte (STARLAB, Spain) for their kind assistance in achieving
370 this work.

Funding. This Thai-French research was funded by the French Institute of
372 Research for Development (IRD), the Rubber French Institute (IFC) and by
Michelin/Socfinco/SIPH Plantations companies.

374

REFERENCES

- 376 Bovard, B.D., Curtis, P.S., Vogel, C.S., Su, H.-B. & Schmid, H.P. (2005). Environmental
controls on sap flow in a northern hardwood forest. *Tree Physiology* 25:31-38.
- 378 Bush, S.E., Pataki, D.E., Hultine, K.R., West, A.G., Sperry, J.S. & Ehleringer, J.R.
(2008). Wood anatomy constrains stomatal response to atmospheric vapor
380 pressure deficit in irrigated, urban trees. *Oecologia* 156:13-20.
- Chandrashekar, T.R., Nazeer, M.A., Marattukulam, J.G., Prakash, J.P., Annamalainathan,
382 K. & Thomas, J. (1998). An analysis of growth and drought tolerance in rubber
during the immature phase in dry subhumid climate. *Experimental Agriculture*
384 34:287-300.

- Chantuma, A., Chantuma, P., Rhutherman, S., Tsongpanich, P., Bunnuaam, W., Kongsilp,
386 J. & Kesawapitak, P. (2004). Carbon sequestration: direct rubber biomass
measurement and visual wood weight, IRRDB Meeting, Kunming, China.
- 388 David, T.S., Ferreira, M.I., Cohen, S., Pereira, J.S. & David, J.S. (2004). Constrains on
transpiration from an evergreen oak tree in southern Portugal. *Agricultural and*
390 *Forest Meteorology* 122:193-205.
- Do, F. & Rocheteau, A. (2002). Influence of natural temperature gradients on
392 measurements of xylem sap flow with thermal dissipation probes. 2. Advantages
and calibration of a non-continuous heating system. *Tree Physiology* 22:649-654.
- 394 Granier, A., Loustau, D. & Breda, N. (2000). A generic model of forest canopy
conductance dependent on climate, soil water availability and leaf area index.
396 *Annals of Forest Science* 57:755-765.
- Hartmann, C., Lesturgez, G., Do, F., Maeght, JL., Isarangkool Na Ayutthaya, S. &
398 Nandris, D. (2006). Rubber tree Trunk Phloem Necrosis in North-East Thailand:
1-Investigations on soil heterogeneities and disease distribution, IRRDB Meeting,
400 Ho Chi Minh City, Vietnam, 13-16 November 2006.
- Hodnett, M.G. & Tomasella, J. (2002). Marked differences between van Genuchten soil
402 water-retentions parameters for temperate and tropical soils: a new water-
retention pedotransfer function developed for tropical soils. *Geoderma* 108:155-
404 180.
- Isarangkool Na Ayutthaya, S., Do, F.C., Pannengpetch, K., Junjittakarn, J., Maeght, J.L.,
406 Rocheteau, A. & Cochard, H. (2010). Transient thermal dissipation method of

- xylem sap flow measurement: multi-species calibration and field evaluation. *Tree Physiology* 30:139-148.
- 408
- Isarangkool Na Ayutthaya, S., Do, F.C., Pannengetch, K., Junjittakarn, J., Maeght, J.L.,
410 Rocheteau, A. & Cochard, H. (2011). Water loss regulation in mature *Hevea*
brasiliensis: effects of intermittent drought in the rainy season and hydraulic
412 regulation. *Tree Physiology* (doi:10.1093/treephys/tpr058, advance access
published July 11).
- 414 Oguntunde, P.G., Van de Giesen, N. & Savenije, H.H.G. (2007). Measurement and
modeling of transpiration of a rain-fed citrus orchard under subhumid tropical
416 conditions. *Agricultural Water Management* 87:200-208.
- Paardekooper, E.C. (1989). Exploitation of the rubber tree. In *Rubber*, 349-414. (Eds
418 C.C. Webster and W.J. Baulkwill). Tropical Agriculture Series, Longman
Scientific and Technical. Singapore.
- 420 Pakianathan, S.W., Haridas, G. & d'Auzac J. (1989). Water relations and latex flow. In
Physiology of rubber tree latex, 233-256 (Eds J. d'Auzac, J.L. Jacob and H.
422 Chrestin). CRC Press, Inc, Florida.
- Pansak, W., Hilger, T., Lusiana, B., Kongkaew, T., Marohn, C. & Cadish, G. (2010).
424 Assessing soil conservation strategies for upland cropping in Northeast Thailand
with the WaNuLCAS model. *Agroforestry Systems* 79:123-144.
- 426 Pinto, L.F.G., Bernardes, M.S., Van Noordwijk, M., Pereira, A.R., Luisiana, B. & Mulia,
R. (2005). Simulation of agroforestry systems with sugarcane in Piracicaba,

- 428 Brazil. *Agricultural Systems* 86:275-292.
- Rao, G.G., Rao, P.S., Rajagopal, R., Devakumar, A.S., Vijayakumar, A.S. & Sethuraj,
430 M.R. (1990). Influence of soil, plant and meteorological factors on water relations
 and yield in *Hevea brasiliensis*. *International Journal of Biometeorology* 34:175-
432 180.
- Rao, P.S., Saraswathyamma, C.K. & Sethuraj, M.R. (1998). Studies on the relationship
434 between yield and meteorological parameters of para rubber tree (*Hevea*
 brasiliensis). *Agricultural and Forest Meteorology* 90:235-245.
- 436 Shamudzarira, Z. & Robertson, M.J. (2002). Simulating response of maize to nitrogen
 fertilizer in semi-arid Zimbabwe. *Experimental Agriculture* 38:79-96.
- 438 Silpi, U., Thaler, P., Kasemsap, P., Lacoïnte, A., Chantima, A., Adam, B., Gohet, E.,
 Thanisawanyangkura S., & Ameglio, T. (2006). Effects of tapping activity on the
440 dynamics of radial growth of *Hevea brasiliensis* trees. *Tree Physiology* 26:1579-
 1587.
- 442 Van Genuchten, M.T. (1980). A closed-form equation predicting the hydraulic
 conductivity of unsaturated soils. *Soil Science Society of America Journal* 44:892-
444 898.
- Van Noordwijk, M. & Lusiana, B. (1999). WaNuLCAS, a model of water, nutrient and
446 light capture in agroforestry systems. *Agroforestry Systems* 43: 217-242.
- Verdoodt, A., Van Ranst, E. & Ye, L. (2004). Daily simulation of potential dry matter
448 production of annual field crops in tropical environments. *Agronomy Journal*

96:1739-1753.

- 450 Walcker, A.P., Mutuo, P.K., Van Noordwijk, M., Albrecht, A. & Cadish, G. (2007).
Modelling of planted legume fallows in Western Kenya using WaNuLCAS. (I)
452 Model calibration and validation. *Agroforestry Systems* 70:197-209.
- Watson, G.A. (1989). Climate and soil. In *Rubber*, 125-163 (Eds C.C. Webster and W.J.
454 Baulkwill). Tropical Agriculture Series, Longman Scientific and Technical.
Singapore.
- 456 Wösten, J.H.M., Lilly, A., Nemes, A. & Le Bas, C. (1998). Using existing soil data to
derive hydraulic parameters for simulation models in environmental studies and in
458 land use planning. Report 156, SC-DLO, Wageningen (the Netherlands), 106 pp.
- Yahya, A.K. (2007). Estimating growth (girth), yield and aboveground biomass of *Hevea*
460 *brasiliensis*: Validation of the WaNuLCAS model. *Journal of Rubber Research*
3:183-192.
- 462 Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L. & Anten, N.P.R. (2005). A
physiological production model for cocoa (*Theobroma cacao*): model
464 presentation, validation and application. *Agricultural Systems* 84:195-225.

466

Table 1. In- and outflows elements of WaNuLCAS water balance

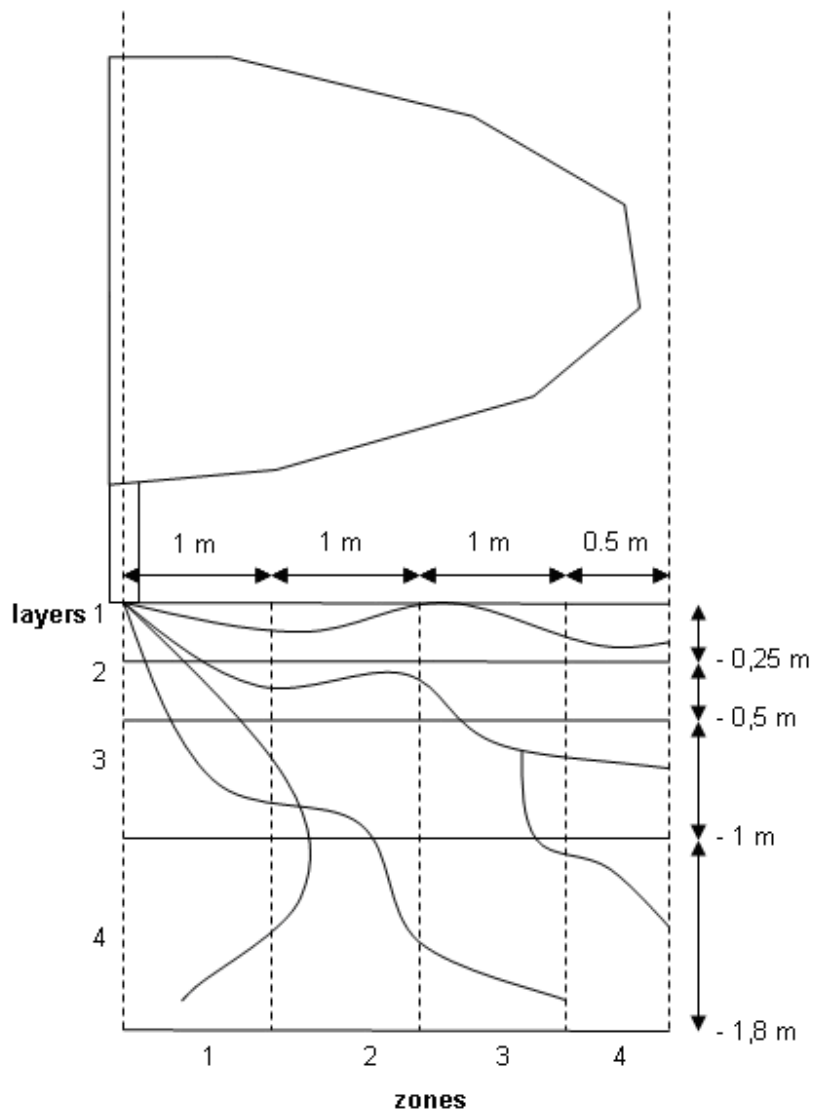
In	Out
Initial soil water content for each cell	Final soil water content for all zones and layers
Allocated rainfall to infiltration	Allocated rainfall to surface run-off
	Drainage from bottom of soil profile
	Soil evaporation
	Evaporation of canopy intercepted water
	Transpiration by tree

468

470

Table 2. Inputs set in WaNuLCAS for simulation initialisation.

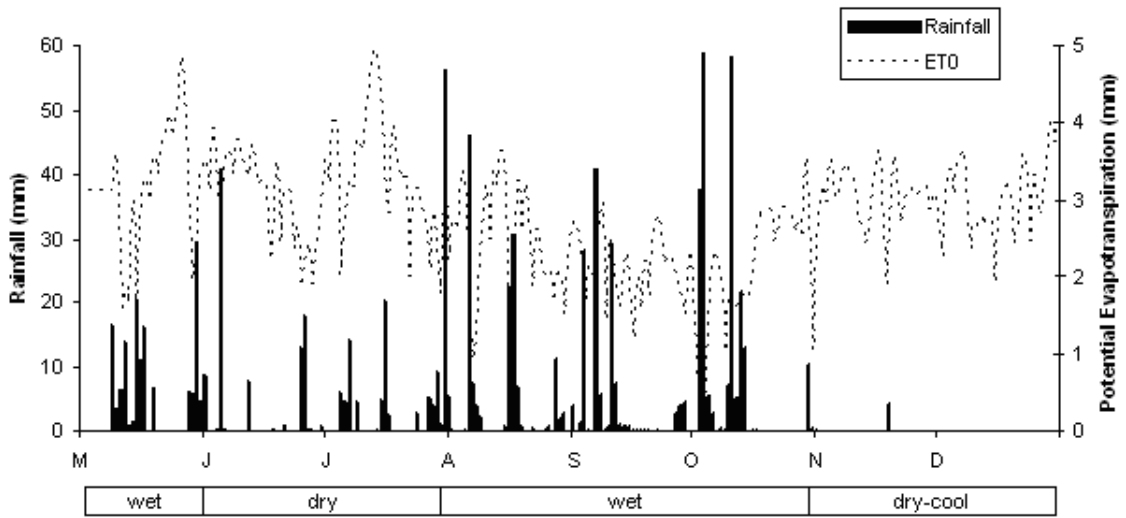
(a) Agroforestry system and tree dimensions								
Tree density (tree.ha ⁻¹)				571			Initial canopy biomass (kg.tree ⁻¹)	51.1
Initial stem biomass (kg.tree ⁻¹)				97.7			Canopy height (m)	12
Stem height (m)				3			Canopy max. width (m)	3.5
Max. Leaf Area Index				3.89				
(b) Soil physical inputs and initial root distribution in the four zones								
	Clay (%)	Silt (%)	Organic matter (%)	Bulk density (g.cm ⁻³)	Ksat (cm.d ⁻¹)		Initial soil water content (cm ³ .100cm ⁻³)	Initial tree roots distribution (cm.cm ⁻³)
Layer 1	9.9	24.2	0.78	1.5	12	(SD=20.0)	20.76	2.5
Layer 2	13.3	24.3	0.32	1.65	16.1	(SD=40.4)	17.63	2
Layer 3	20.2	22.7	0.34	1.5	30.4	(SD=23.3)	14.90	1.5
Layer 4	20.2	23.6	0.34	1.5	0.8	(SD=1.0)	11.03	1
(c) Latex production								
Influence by Brown Bast				Yes			Tapped girth fraction	0.3
Tappable height (cm)				150			Tapping slice (cm)	0.29
Min. stem girth for tapping (cm)				30			Tapping fract. in tapping period	0.06



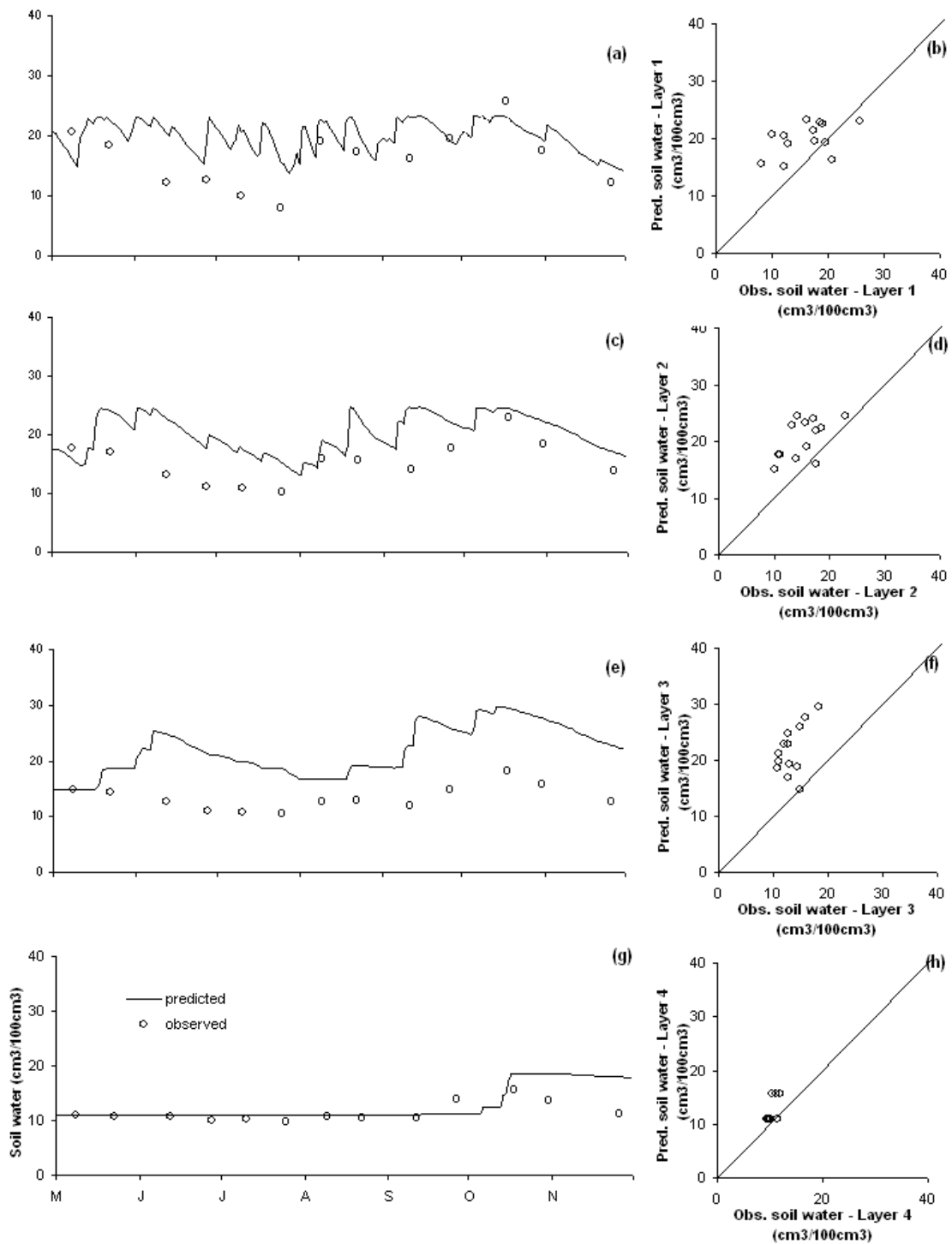
472

474

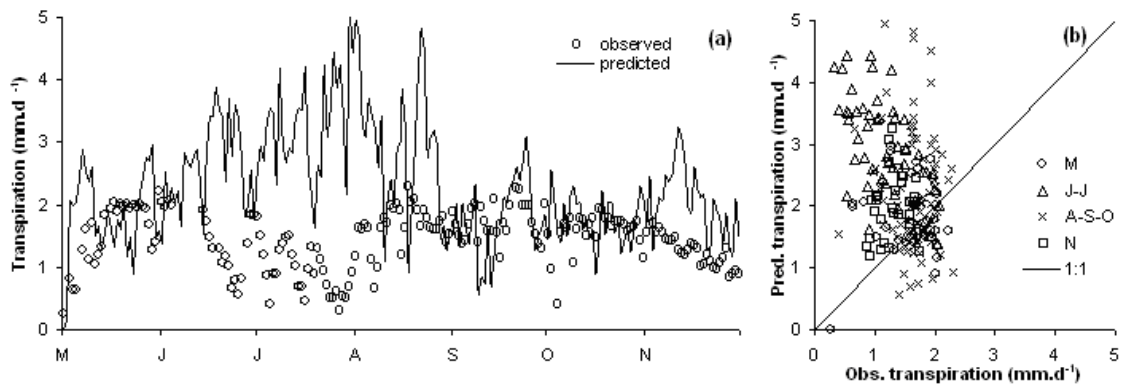
Figure 1. General layout of soil layers and spatial zones in the WaNuLCAS model. Modelled trees were planted in Zone 1. Adapted from Van Noordwijk and Lusiana (1999).



476 Figure 2. Daily climate data from May to December 2007: rainfall and reference evapotranspiration.



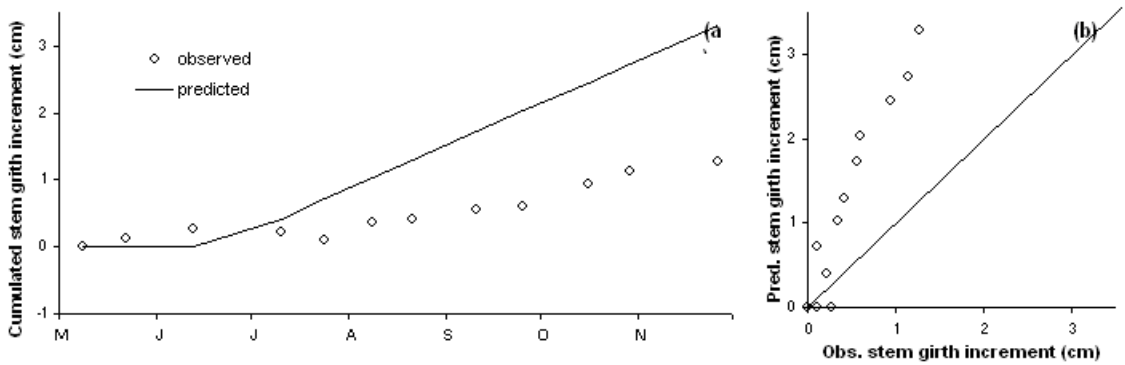
478 Figure 3. Observed and predicted soil water content: (a) and (b) Layer 1; (c) and (d) Layer 2; (e) and (f) Layer 3; (g) and (h) Layer 4. Diagonal lines indicate the 1-1 lines.



480

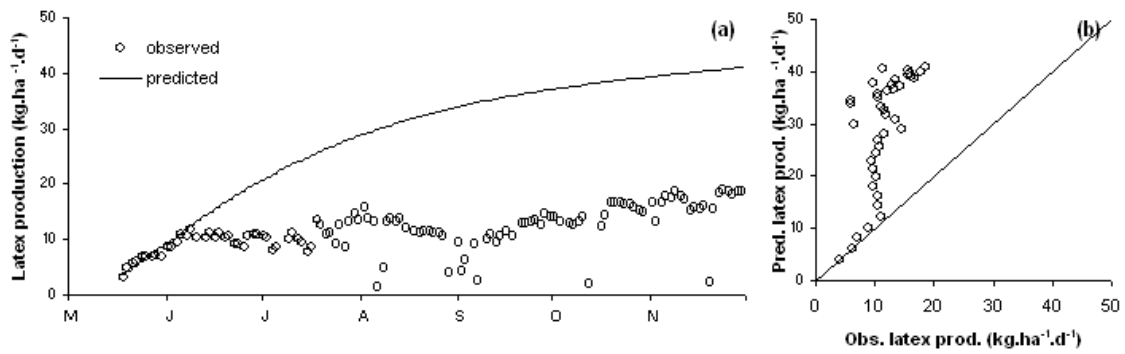
Figure 4. (a) Observed and predicted tree transpiration; (b) Predicted vs. observed. Diagonal line indicates the 1-1 line.

482



484

Figure 5. (a) Observed and predicted cumulated stem girth increment; (b) Predicted vs. observed. Diagonal line indicates the 1-1 line.



486

Figure 6. (a) Observed and predicted latex production; (b) Predicted vs. observed. Diagonal line indicates the 1-1 line.

488