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Intercropping teak (*Tectona grandis*) and maize (*Zea mays*): bioeconomic trade-off analysis of agroforestry management practices in Gunungkidul, West Java

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Abstract Producing high quality timber meeting export standards requires intensive tree management. Using a tree-crop interactions model (WaNuLCAS) we analyzed tree management practices in intercropped teak (*Tectona grandis*) and maize (*Zea mays*) compared to teak and maize monocultures. Tradeoff analysis in intercropped teak and maize was designed in a three-treatment factorial: initial teak density (1600 trees ha^{-1} (2.5 m × 2.5 m), 1111 trees ha^{-1} (3 m × 3 m) and 625 trees ha^{-1} (4 m × 4 m)), thinning intensity (light (25 %), moderate (50 %) and heavy (75 %) of tree density), and pruning intensity (40 % and 60 % of crown biomass). Cumulative maize yield in the first 5 years of teak growth increased 10–38 % when tree density was reduced. All simulated intercropping practices produced a higher wood volume than a monoculture, as trees benefit from crop fertilization. Maximum wood volume (m^3 ha^{-1}) was obtained at initial tree density of 625 trees ha^{-1}, 25 % of which was thinned in year 5 and another 25 % in year 15 with 40 % of the crown pruned in years 4, 10 and 15. However, greater stem diameter as can be obtained with further thinning is rewarded with higher market price per volume of wood. Profitability analysis taking into account the cost of labour (for maize production, thinning and pruning) and its effect on additional timber revenue showed that the highest net present value and return to labour was provided by the system with 50 % thinning in year 5. Economic optimization was not sensitive to variations around the default price assumptions.

Keywords Agroforestry · Ex-ante analysis · Management practices · Smallholder teak · Trade-off analysis

Introduction

Teak (*Tectona grandis*) provides high-value wood for furniture and other products. Asia holds more than

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95 % of the world's natural and planted teak resources, and more than 80 % of the world's planted teak resources, with India (38 %), Indonesia (29 %) and Myanmar (9 %) leading (Kollert and Cherubini 2012). Indonesia, with its greatest production on Java, is the biggest teak sawn timber exporter in the world (Pandey and Brown 2000). Global demand for teak wood has risen annually. FAO estimates demand for all types of wood has increased more than 50 % in 15 years (FAO 2009). Historically export-quality teak was primarily supplied by Perum Perhutani (Government Forest Plantation Company), but their plantations can no longer guarantee sufficient teak wood supply. Hence, smallholder teak growers have become an important source of wood for the teak industry (Roshetko et al. 2013).

A major challenge for smallholder teak growers is the production of high quality wood that meets export standards, as this generally requires intensive silvicultural management. The lack of silvicultural management, knowledge and skills linked to the prevailing market incentive system is a key problem for smallholder producers (Roshetko and Manurung 2009). Most teak growers continue to depend on natural regeneration of their teak plantations. Weeding and fertilizing are mainly carried out for the intercrops. Most farmers do not practice thinning and pruning for high productivity and quality of timber. Pruning is primarily conducted to collect fuel wood from branches, rather than for controlling timber quality. Branches are cut, leaving 15-20 cm-long- branch stubs. Thinning is considered as useless and even detrimental to teak stands and more likely to be carried out on high grade timber, as farmers often cut the biggest tree to sell when they need the cash. But, along with participation of teak growers in various project-run silviculture activities, a better understanding on the purpose of these treatments grew as part of a recently completed project (Roshetko et al. 2013).

An extensive literature exists on optimum teak spacing (Ola-Adams 1990), effect of thinning (Kanninen et al. 2004; Perez and Kanninen 2005; Roshetko et al. 2013), effects of pruning (Viquez and Perez 2005; Roshetko et al. 2013) and effects of intercropping practices both on growth and profitability (Djagbletey and Bredu 2007; Kumar et al. 1998; Affendy et al. 2013; Noda et al. 2012). However, results and recommendations depend on context. Height and diameter of teak growth in mixed plot with *Leucaena* were 45 % taller and 71 % larger than in monoculture plot (Kumar et al. 1998). Intercropped teak - *Salacca zalaca* (Affendy et al. 2013), teak—sugarcane/maize/cassava (Noda et al. 2012) can give a higher profit than monoculture teak. However, cumulative effect of the interactions between the various management practices affecting teak growth require fine-tuning for specified climate and soil conditions of a multiple combination of practices such as spacing, pruning and thinning. The way tree and possible intercrop growth is affected by such practices can be tested directly in the field by establishing long-term multifactorial experiments, but this process requires a lot of time, labour, and funds. Thus, bio-economic simulation models can help in pre-selecting candidate management regimes for locally relevant conditions of soil, climate, tree and crop properties, and prices for products, labour and inputs (Santos-Martin and van Noordwijk 2011). In weakly integrated bioeconomic models, economic analysis is conducted after biological results have been generated; in strongly integrated bioeconomic models, economic decisions by managers (farmers in our case) are represented by model parameters and included in the dynamic biological model. An example of a strongly integrated bioeconomic model is including the decision whether or not to continue intercropping, based on information of the performance of previous crops, input costs, and market prices.

The objective of this study was to explore growth and production of teak in smallholder systems with maize as intercrop under different tree management practices in Gunungkidul, Central Java using the water, nutrient and light capture in agroforestry systems (WaNuLCAS) model, with direct bioeconomic feedbacks on crop decisions, and to evaluate its economy using profitability analysis. We chose maize for intercropping as it is one of the main staple foods in the study area and it is also a recommended crop (besides groundnut and cassava) to be integrated in smallholder teak plantation. Specific objectives of the model study were: (1) to simulate growth interactions of teak—maize under different management options: initial spacing, thinning, and pruning, (2) to analyze the different management options from the biophysical and economic prospective to identify the best and the most profitable management practices for smallholder teak under local conditions, (3) to analyze sensitivity of the results under shifts in prices.

Materials and methods

Brief description of WaNuLCAS model

The WaNuLCAS, a tree-soil-crop interaction model for agroforestry systems, was developed by the World Agroforestry Centre to deal with a wide range of agroforestry systems (van Noordwijk and Lusiana 1999; van Noordwijk et al. 2011). The model was chosen for this study because it simulates dynamic processes of above and below ground plant growth, has the flexibility to represent tree– crop management options and direct economy-based farmer decisions regarding continuing or stopping intercropping.

The model has spatial resolution at the plot scale, represented by a four-layer soil profile and four spatial zones where trees and/or crops can be planted in any of the zones. The time resolution of the model is a daily time step. The model takes into account three main component resources: light availability (for aboveground resource), water and nutrient (N and P) availability (for belowground resources) that shared by tree and crops based on above- and belowground architecture and phenology. These components, their interaction are interpreted in different modules including cropping management options (van Noordwijk and Lusiana 1999; van Noordwijk et al. 2011).

The model has been previously used to model fallow rotational systems (Walker et al. 2008), sugarcane (*Saccharum officinarum*)—rubber (*Hevea brasiliensis*) systems (Pinto et al. 2005), monoculture of *Gliricidia sepium* (Wise and Cacho 2005), agroforestry systems in semi arid region (Muthuri et al. 2004) and trade-offs analysis for timber-based agroforestry (Santos-Martin and van Noordwijk 2009).

WaNuLCAS model calibration and validation

Prior to the use of WaNuLCAS model for exploring growth and production of smallholder teak under different tree management options, a series of model calibration and validation to test validity of the model was conducted. The calibration and validation includes: (1) model parameterization, (2) model performance evaluation by comparing measured and simulated data. Figure 1 presents the work flow of WaNuLCAS model simulation leading to profitability and sensitivity analysis applied in this study. We used the model output to estimate the profitability of different tree management options separately from the model as a standalone ‘economic’ module was found to be efficient for further analysis of sensitivity to other economic input variables. Profitability analysis module inside WaNuLCAS model is relatively simple as it translates current input and labour use and products harvested into (discounted) economic performance indicators, which are used to determine when to stop further intercropping. Further post hoc economic analysis can be done in spreadsheets using WaNuLCAS outputs.

The data used for model calibration and validation was from experimental plots of smallholder timber trees (mixed systems of teak, acacia (*Acacia mangium*) and other species) in Wonosari, Gunungkidul, Central Java (Roshetko et al. 2013). Teak has been successfully planted for the last 50 years to restore degraded smallholder land in Gunungkidul. The teak was chosen by farmer as it is easily managed and can be mixed with other trees and crop. However, silvicultural management in the area are still limited. Hence the purpose of the experiment is to identify the effects of various levels of pruning and thinning on productivity, growth and log quality of smallholder teak and the chosen experimental plot represented smallholder teak in the area.

In the experiment, pruning was applied to teak in three levels of pruning: (1) no pruning, (2) 50 % pruning, and (3) 60 % pruning. Thinning was applied to teak and acacia three years after planting in two levels: (1) no thinning, and (2) 40 % of total tree density. Hence we have six treatment combinations for model calibration and validation. In each treatment, growth of tree (diameter and height) was monitored for about 2.5 years (2007–2008) with 6 months interval. Hence, we had 5 points of measurement data to be compared with simulation results. Overall, result of simple statistical analysis (ANOVA), there were significant differences in thinning treatment ($p < 0.05$), but not in pruning treatment.

The 40 % of thinning was applied unevenly by select trees that have low growth performance. Irregular tree spacing of acacia and teak is common in Gunungkidul. Based on field inventories an average spacing of 5 m × 18 m for acacia and 1.5 m × 3 m for teak were used for this simulation. In WaNuLCAS model, the thinning was applied regularly that results 3 m × 3 m as final spacing for teak.

During the first three years, maize was planted for two cropping season per year. Nitrogen (N) and

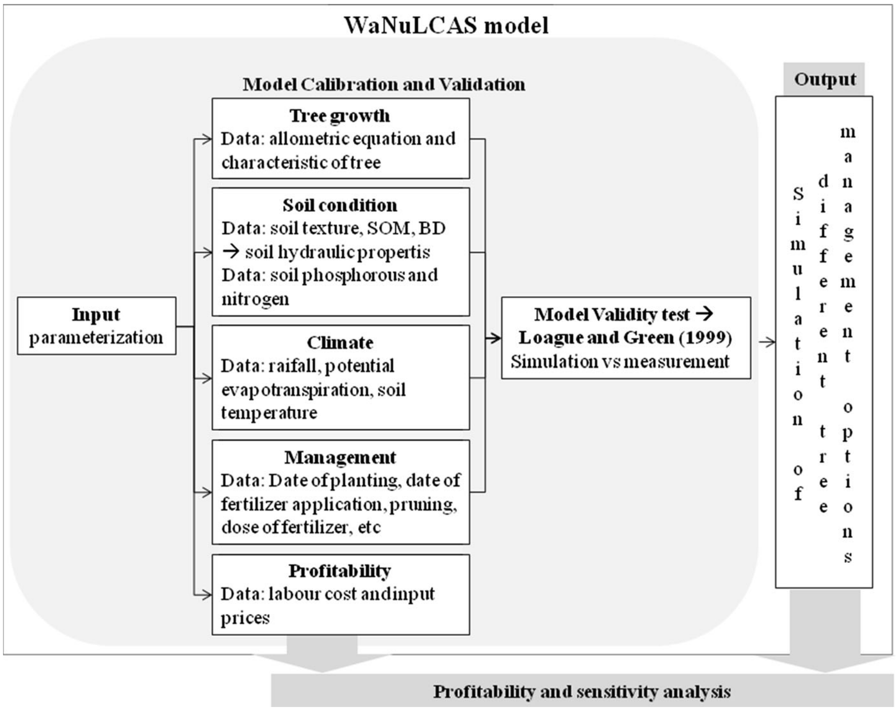

Fig. 1 WaNuLCAS model simulation and profitability analysis working flow applied in this study

phosphorous (P) were applied to maize 90 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}, respectively. The amount of N was applied twice, half at planting time and half at a month after planting. The amount of P was applied once at planting time.

Model parameterization

Climate and soil Based on secondary data of rainfall of Karangmojo station, the study area has mean annual rainfall of approximately 1750 mm. Rainfall is distributed with a peak in December–March and a dry season in May–September (Fig. 2). Relative air humidity ranges from 70 to 90 %, with annual mean maximum and minimum air temperatures of 27 and 24 °C, respectively. Daily rainfall data for model parameterization was generated within the model based on these monthly data.

Soil texture of the area is classified as silty clay and clay for top soil and sub soil, with pH around 6. Table 1 present more detail of soil physical and chemical properties of four different layers with depth interval 0–10, 10–25, 25–40 and 40–100 cm, respectively used for model parameterization. The data are result of laboratory analysis except for bulk density. Bulk density was estimated using a pedotranfer function (Wösten et al. 1995). Default values of N (ammonium and nitrate) concentrations were used within this simulation, as the N default values are derived from similar cropping systems in Indonesia and no site-specific data were available.

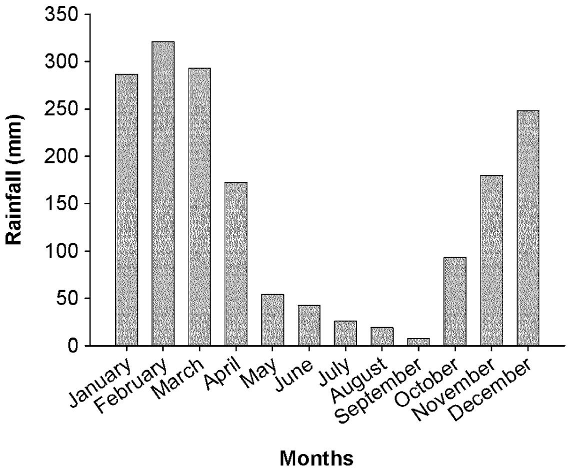

Fig. 2 Average monthly rainfall 1989–2008 (Karangmojo station)

Tree Above ground tree growth in WaNuLCAS model is simulated using empirical allometric biomass

Table 1 Soil physical and chemical properties used for model parameterization

Soil layer (cm)	Sand (%)	Silt	Clay	pH H_2O	pH KCl	BD (g cm^{-3})	C (%)	N	C/N	P_2O_5 (ppm)	CEC (cmol/kg)	Stone (%)
0–10	11.33	40.67	48.00	6.10	5.19	1.233	1.07	0.10	11.05	9.23	28.65	1.67
10–25	11.33	40.67	48.00	6.10	5.19	1.233	1.07	0.10	11.05	9.23	28.65	13.33
25–40	6.00	25.33	68.67	6.30	5.28	1.146	0.45	0.04	10.40	1.85	34.74	13.33
40–100	6.33	25.33	68.33	6.25	5.37	1.146	0.46	0.04	10.53	1.32	32.86	23.33

equation as a function of stem diameter ($Y = aD^b$) for each tree component (total biomass, leaf and twig biomass, wood biomass and litterfall) (van Noordwijk and Mulia 2002). The above ground tree growth is also simulated based on other tree growth parameters such as width and high of crown, leaf weight ratio, specific leaf area, light extinction coefficient, etc. (van Noordwijk and Lusiana 1999; van Noordwijk et al. 2011). The allometric equation (Table 2) used in this study was developed using Fractal Branching Analysis method (Van Noordwijk and Mulia 2002). Other growth parameters such as width and high of crown, specific leaf area, and growth rate used field measurement data and calibrated to capture simulation result close to the measurement result through sensitivity analysis. Table 8 in Appendix presents details of teak and acacia characteristics. Belowground tree growth in all zones and layers can be assumed constant, thus a maximum root length density per zone and layer is given as an input.

Evaluation of model performance

Evaluation of model performance was conducted by comparing measured and simulated data of tree height and tree diameter. Statistical indicators proposed by Loague and Green (1991) (Table 3) and coefficient regression were used to evaluate the performance of the model.

Table 2 Allometric equation ($Y = aD^b$) to simulate tree growth; Y = tree biomass (kg per tree), D = tree diameter (cm)

Species	Tree biomass	a	b
Acacia mangium	Total	0.356	2.240
	Stem	0.304	2.238
	Leaf + twig	0.035	2.406
	Litterfall	0.002	3.326
Tectona grandis	Total	0.153	2.382
	Stem	0.104	2.358
	Leaf + twig	0.049	2.427
	Litterfall	0.002	3.004

Simulation of different tree management options

The following management options were applied to identify the “best tree management options” for teak from the prospective of tree spacing (tree density ha^{-1}); level and time of pruning; and level and time of thinning.

1. Intercropped teak and maize (two cropping season per year):
    a. Initial teak density, trees ha^{-1} (tree spacing, m): 1600 (2.5 m × 2.5 m); 1111 (3 m × 3 m); 625 (4 m × 3 m),
    b. Year of thinning (% thinning): 10 (25 %); 5 (25 %) and 15 (25 %); 5 (25 %) and 20 (25 %); 5 (50 %) and 15 (25 %); 5 (50 %) and 20 (25 %),
    c. Year of pruning (% of crown pruned): 4 (40 %), 10 (40 %), 15 (40 %); 4 (60 %), 10 (60 %), 15 (60 %).
2. Teak monoculture: without pruning and thinning; allowing weeds to grow; with initial tree density 1200, 800, 400, 833, 556, 278, 469, 313, and 156 trees ha^{-1}.
3. Maize monoculture: two cropping season per year.

The maize production was stopped once the preceding maize yield was no longer profitable, here we use ‘the stopping rule’ option which is calculated based on current input and labour use and products harvested. N and P were applied only to maize 90 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}, respectively. The N was applied twice, half at planting time and half at a

Table 3 Statistical criteria for model evaluation result according to Loague and Green (1991)

Criteria	Symbol	Calculation formula	Range	Optimum
Maximum error	ME	$Max\lvert P_i - O_i\rvert_{i=1}^{n}$	≥ 0	0
Root mean square	RMSE	$\left(\sum_{i=1}^{n}\frac{(P_i - O_i)^2}{n}\right)^{\frac{1}{2}} x \frac{100}{O_{mean}}$	≥ 0	0
Coefficient of determination	CD	$\frac{\sum_{i=1}^{n}(O_i - O_{mean})^2}{\sum_{i=1}^{n}(P_i - O_{mean})^2}$	≥ 0	1
Modeling efficiency	EF	$\frac{\left(\sum_{i=1}^{n}(O_i - O_{mean})^2 - \sum_{i=1}^{n}(P_i - O_i)^2\right)}{\sum_{i=1}^{n}(O_i - O_{mean})^2}$	≤ 1	1
Coefficient of residual mass	CRM	$\frac{\left(\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i\right)}{\sum_{i=1}^{n}O_1}$	≤ 1	0

P_i predicted values, O_i observed values, n number of samples, O_{mean} the mean of the observed data

month after planting. All the P was applied at planting time. The teak was harvested at year 30. The more detail combination of tree management options or scenarios is presented in Table 4.

Trade-off analysis of different tree management options

Results of simulation of different tree management options was then analyzed and emphasized on trade-off analysis between maize yield and teak growth of intercropping practice, therefore the results were analyzed by plotting wood volume relative to monoculture versus crop yield relative to monoculture (Fig. 3). Net positive interaction within the system was achieved once the combination of tree and crop yield above 1:1 line or $X > 1$, and vice versa. The analysis of different tree management options was also done by comparing between options.

Profitability analysis of different tree management options

In order to analyze economic gain of each tree management option, labour use and input from the farming activities were analyzed using profitability analysis adapted from Gittinger (1982) and Monke and Pearson (1989). The analysis requires a set of key data on farming activities, market prices of each input and its related simulation output results to be included in the analysis. The general profitability indicator used in longer term estimation is net present value (NPV) and return to labour (RtL).

$$NPV = \sum_{t=0}^{t=n}\frac{R_t - C_t}{(1+i)^t}$$

where: R_t is revenue at year t, C_t is cost at year t, t is time denoting year and i is discount rate.

The indicator point out that it is profitable if $NPV > 0$. The annual cash flows are the net benefits (revenue minus costs) generated from the investment during its lifetime. These cash flows are discounted or adjusted by incorporating the uncertainty and time value of money (Gittinger 1982). Returns to labour were defined as the labour cost at which the NPV is zero. It's a relevant base of comparison for family farms where labour is the primary asset, and where alternative employment options outside agriculture exist.

A farm level assessment was developed for each tree management option. A compilation of farm level inputs labour, prices of fertilizers, chemicals, planting materials, and tools required for the options was formed based on actual data collected and observed in the field. The input data was collected from 275 household in 37 hamlets between August and September 2007. The available data were classified, quantified and valued based on farmers' actual practice. Assessment of labour was based on the observation at farm gate level and excluding the labour involved in the production and processing of input (which was supposedly included in its price). Prices of inputs were incorporated and estimated using local market prices, which included an interest rate of 8.2 % and Rupiah currency exchange rate (USD 1 = IDR 10,894), equal to the prices and rates during data collection in 2009. A labour wage rate for Gunungkidul was also included at USD 2.75 per day. Results from the crop and tree growth simulations were used as input data to set up detailed farm budgets.

To correspond with the simulation, tree diameters are used as standard to estimate teak log volume as

Table 4 Detail of simulation different tree management options or scenarios

No.	Systems	Initial tree density, tree ha^{-1}	Initial tree spacing, m	% thinning (year of thinning)		Pruning		Final tree density, tree ha^{-1}	Final tree spacing, m
				1st thinning	2nd thinning	Year of pruning	% crown pruned		
1	Crop monoculture	Two cropping season per year							
2	Tree monoculture[a]	1600	2.5 × 2.5	–	–	–	–	1600	2.5 × 2.5
3		1111	3 × 3	–	–	–	–	1111	3 × 3
4		625	4 × 4	–	–	–	–	625	4 × 4
5		1200	2.5 × 3.3	–	–	–	–	1200	2.5 × 3.3
6		800	5 × 2.5	–	–	–	–	800	5 × 2.5
7		400	5 × 5	–	–	–	–	400	5 × 5
8		833	3 × 4	–	–	–	–	833	3 × 4
9		556	6 × 3	–	–	–	–	556	6 × 3
10		278	6 × 6	–	–	–	–	278	6 × 6
11		469	4 × 5.3	–	–	–	–	469	4 × 5.3
12		313	8 × 4	–	–	–	–	313	8 × 4
13		156	8 × 8	–	–	–	–	156	8 × 8
14	Tree + Crop[b]	1600	2.5 × 2.5	25 (10)	–	4, 10, 15	40	1200	2.5 × 2.5/5 × 2.5
15							60		
16				25 (5)	25 (15)		40	800	5 × 2.5
17							60		
18				25 (5)	25 (20)		40		
19							60		
20				50 (5)	25 (15)		40	400	5 × 5
21							60		
22				50 (5)	25 (20)		40		
23							60		
24		1111	3 × 3	25 (10)	–	4, 10, 15	40	833	3 × 3/6 × 3
25							60		
26				25 (5)	25 (15)		40	556	6 × 3
27							60		
28				25 (5)	25 (20)		40		
29							60		
30				50 (5)	25 (15)		40	278	6 × 6
31							60		
32				50 (5)	25 (20)		40		
33							60		
34		625	4 × 4	25 (10)	–	4, 10, 15	40	469	4 × 4/8 × 4
35							60		
36				25 (5)	25 (15)		40	313	8 × 4
37							60		
38				25 (5)	25 (20)		40		
39							60		
40				50 (5)	25 (15)		40	156	8 × 8
41							60		
42				50 (5)	25 (20)		40		
43							60		

[a] Allow weeds to grow

[b] The cropping season will automatically stopped once the yield no longer profitable

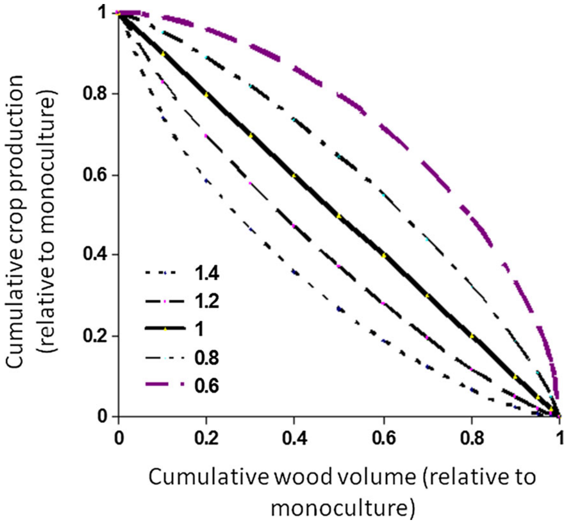

Fig. 3 Expected trade-off between tree and crop performance in simultaneous agroforestry systems, with net negative ($X < 1$) or net positive ($X > 1$) interactions

practiced by traders at the research site. The use of the diameter-based pricing represents the actual practice in the field. This approach is commonly used to measure forest stand potential, especially in tree gardens and plantation forests. Once the volume is estimated, the price of teak logs are determined, which follows the standardized sales price matrix of Perum Perhutani, a state-owned enterprise which manages teak plantations in Indonesia. It is assumed in the matrix that the teak logs have a length of >4 m. Using the same classes of diameter from the matrix, prices are then adjusted to meet the actual sale prices during data collection. The price adjustment used an assumption of 10 % increase based on the Perum Perhutani Directoral Decision 1148/Kpts/Dir/2011. Table 5 shows the adjusted prices, which is used to assess profitability of the different tree management options. Further, the price of maize (IDR 2200) was the yield price per kilogram during data collection (BPS Gunungkidul 2007).

Sensitivity analysis

Sensitivity analysis was applied to better understand the responses of the various NPVs to changes in discount rate, wage rate and price ratio of teak and maize for each scenario. Four discount rates were included in the test, where 7.2 % was equal to the inflation rate during data collection, and 3.6, 14.4, and 8.2 % representing various levels of risk factors for sensitivity analysis. The wage rate of USD 2.75 was used on the basis actual wage rate in Gunungkidul during data collection. The wage rate of USD 3.02 is an estimated increase of 10 %, which was a normal anticipated wage increase in the region. The ten different price ratios for teak-maize were included in the simulation, i.e. 0.53, 0.60, 0.67, 0.76, 0.87, 1.05, 1.09, 1.13, 1.17, and 1.20, to see the how it would affect NPV if prices of teak and maize changes 10, 20 % and so forth.

Table 5 Adjusted price based on classes of diameter for smallholder teak (in USD m^{-3})

Length (m)	Diameter (cm)					
	10–15	16–20	21–23	24–26	27–29	30–34
<1	86.6	130.6	167.8	201.9	230.4	329.2
1–1.9	98.1	148.0	200.5	241.2	275.3	364.0
2–2.9	115.5	174.1	218.0	262.3	299.2	406.6
3–3.9	132.8	200.2	250.6	301.6	344.0	489.9

Source Perum Perhutani Directoral Decision 1148/Kpts/Dir/2011

Results

Model calibration and validation

Comparisons of simulated and measured tree heights and tree diameters are presented in Fig. 4a. Evaluation of the model performance of those parameters is presented in Table 6. Evaluation of tree diameter comparisons indicated a moderately good fit between model estimates and field data with a coefficient determination and a coefficient regression of 1.19 (optimum value 1) and 0.91 (optimum value 1), respectively. Discrepancy results are shown for 40 % thinning with 50 or 60 % canopy pruned. These differences closely link with the measured data that those two treatments have higher initial tree diameter compare to the other treatments (Fig. 4b). Evaluation on the tree height indicated the same trend.

Table 7 present average of increment of tree diameter and tree height of both measurement and simulation, it demonstrates the effect of thinning and pruning. Thinning improves the growth of retained

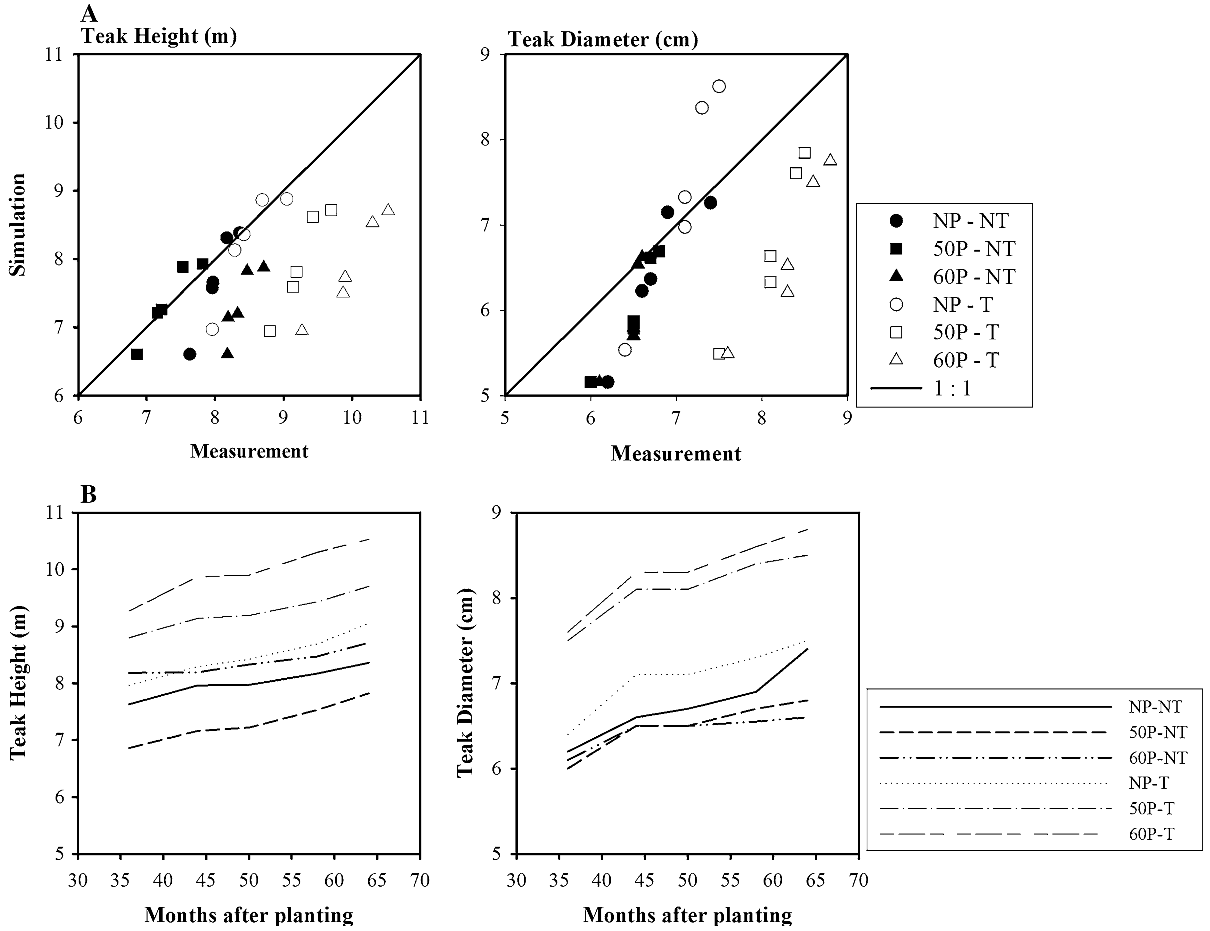

Fig. 4 **a** Comparison of simulated and measured tree height (m) and tree diameter (cm). **b** Result of measured tree height (m) and diameter (cm). *P* pruning, *T* thinning, *NP* no pruning and *NT* no thinning. Total number of measurement is 5 points of measurements per treatment

Table 6 Result of model evaluation using WaNuLCAS version 3.2

Criteria	Tree height (m)	Tree diameter (cm)
CD (1)	0.62	1.19
CRM (0)	0.10	0.09
EF (1)	−0.61	0.16
RMSE (0)	13.49	12.23
ME (0)	0.36	1.12
a (1)	0.90	0.91

The criteria are according to Loague and Green (1991). The given results are for all treatments

ME maximum error, *RMSE* root mean square error, *EF* model efficiency, *CRM* coefficient of residual mass, *CD* coefficient of determination, a coefficient regression

trees by 0.086 m in height and 0.067 cm in diameter. Model simulation predicted thinning effect on diameter growth three times greater than field measurements. This difference is explained by thinning practice. In the field, trees thinning is applied unevenly by removing trees with low growth performance, while in the WaNuLCAS simulation, thinning was applied evenly. Both simulation and measurement results show that the pruned trees tend to growth slower compare to un-pruned trees. Simulations predicted tree diameter response 0.02–0.19 cm slower than field measurement. This difference is explained by the pruning practice. In the field only the lower branches of trees are pruned, while in WaNuLCAS

Table 7 Comparison of simulated and measured tree height (m) and diameter (cm)

Treatments	Tree height (m)		Tree diameter (cm)	
	Measurement	Simulation	Measurement	Simulation
NP-NT	0.18	0.44	0.30	0.53
50P-NT	0.24	0.33	0.20	0.38
60P-NT	0.13	0.32	0.13	0.37
NP-T	0.27	0.48	0.28	0.77
50P-T	0.23	0.44	0.25	0.59
60P-T	0.32	0.44	0.30	0.56
Thinning effect	0.086	0.089	0.067	0.217
Pruning effect of no thinning	0.004	−0.120	−0.138	−0.151
Pruning effect of thinning	−0.003	−0.036	0.000	−0.195

The given results are average of increment of five points both measurement and simulation

P pruning, *T* thinning, *NP* no pruning, *NT* no thinning

simulation, pruning is applied by reducing the biomass of the tree stand canopy, not starting with the lower branches of the individual tree crowns.

Trade-off analysis of different tree management options

All tree management options are substantially above the straight trade-off curve, suggesting that there is indeed a benefit to be obtained by combining trees and crops compared to separate monocultures (Fig. 5). The lowest cumulative maize yield provided by the system with narrow spacing (2.5 × 2.5 m) and it is 10–37.5 % higher than if the tree spacing is widened at 3 × 3 m or 4 × 4 m. In this instance, where teak wood is the main target of the systems, maize intercropping at the early stage of tree growth is a clear advantage at either low or high tree population density.

Figure 6b shows the effect of intensity and timing of thinning and pruning on wood volume at year 30. Thinning from 25 to 50 % of tree population density gives positive response to wood volume (m^3 ha^{-1}), but from 50 to 75 % gives negative response to wood volume. Five years delay of thinning (waiting until trees are 10 years old) slightly decreasing the wood volume. The result also shows that 60 % of pruned crown cause trees to growth slower compare to 40 % of pruned crown. How these pruning managements affect the subsequent wood quality such as knots in the wood are not explicitly include in the model.

At year 30, the highest teak wood volume (m^3 ha^{-1}) is provided by the system with initial tree density 625 trees ha^{-1}, with a 25 % thinning at year 5 and another 25 % thinning at year 15 and 40 % of the crown pruned at year 4, 10 and 15 (Fig. 6a). However, greater stem diameter per tree (wood volume per stem) is provided by 50 % of thinning at year 5 results rather than 25 % of thinning at year 5 (Fig. 6a). In other words, The more intense the first thinning, the greater impact on tree diameter growth. Greater stem diameter is rewarded with higher market price. The lowest wood volume is provided by the system with initial tree density 1600 trees ha^{-1}, with a 25 % thinning at year 10 and 60 % of the crown pruned at year 4, 10 and 15.

Profitability analysis of different tree management options

Profitability assessment showed that the value of land and labour profitability are favourable for all tree management options (NPV > 0) and returns to labour were higher than the daily wage rate (RTL > USD 2.75) (Fig. 6c, d). Calculated profitability using diameter-based price showed consistency in NPV value, where the intercropped practices provides higher return to land compared to monoculture practice. The highest NPV and RtL were obtained from intercropped teak and maize with initial tree density of 625 trees ha^{-1} with a 50 % thinning at year 5 and another 25 % thinning at year 15 and 40 % of the crown pruned at year 4, 10 and 15. Further tests on the responses of various NPVs to changes in discount rate, labour rate, and ratio of teak and maize prices (results not shown) did not reveal shifts in the relative order of the tree management options. The optimization conclusions were robust under the parameter conditions tested.

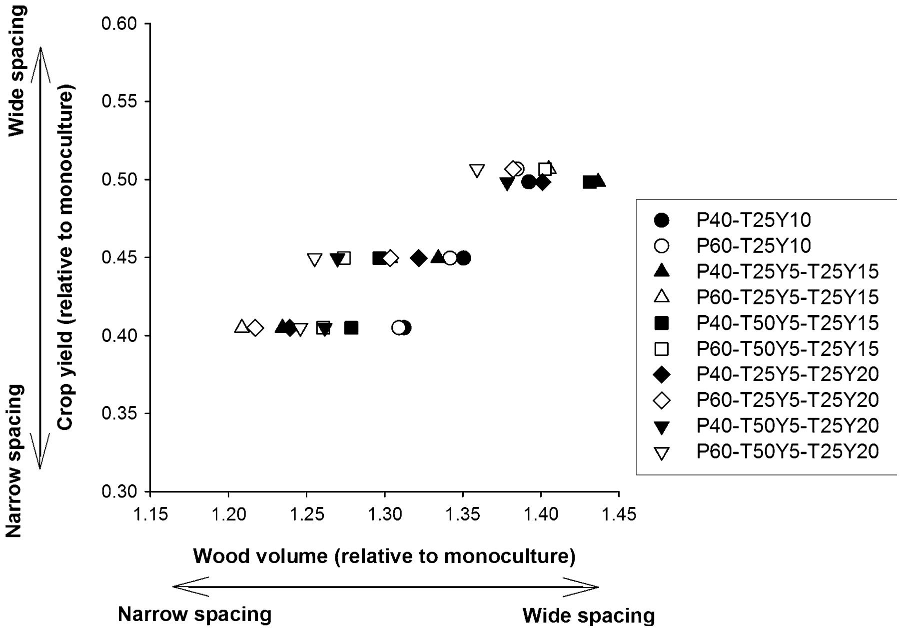

Fig. 5 Trade-off analyses between tree and crop performance at various tree management options. *P* pruning, *T* thinning, *Y* year; i.e. P40-T25Y5-T25Y15: 40 % crown pruned, thinning 25 % at year 5 and 25 % at year 15. Wood volume is the volume of remaining trees in field at year 30 (harvest time). Total number of simulation is 43 simulations

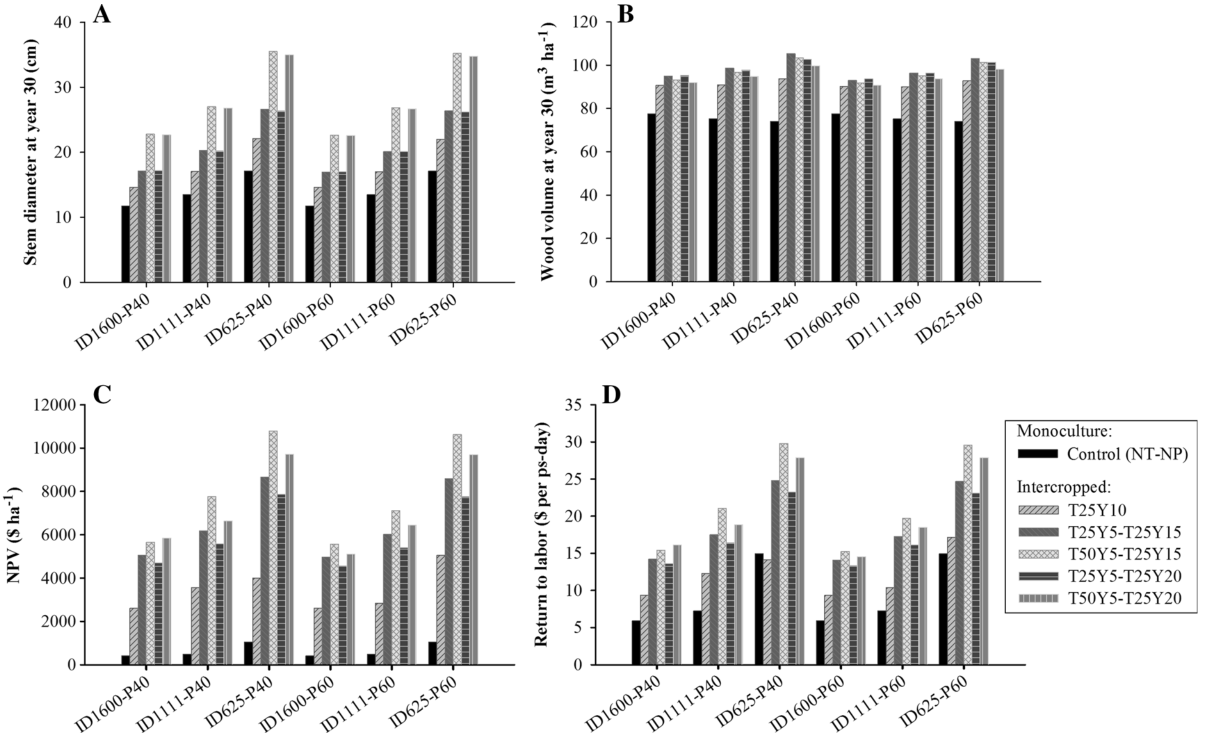

Fig. 6 Stem diameter, cm (**a**); wood volume, m^3 ha^{-1} (**b**); NPV, \$ ha^{-1}(**c**) and return to labour, \$ per ps-day (**d**) of intercropped and monoculture practices presented at various treatments. Control (NT-NP) is monoculture without thinning and pruning. *P* pruning, *T* thinning, *Y* year, *ID* initial tree density, i.e. T25Y5-T25Y15 is intercropped practices with 25 % thinning at year 5 and another 25 % at year 15; ID1600-P40: initial density 1600 and 40 % crown pruned. Wood volume is the volume of remaining trees in field at year 30 (harvest time). Total number of simulation is 30 simulations

Discussion

Planting maize in the early stages of teak growth provides a clear advantage compared to teak monoculture, according to the model results for both low and high teak population density. Similar studies and results have been reported by Santos-Martin and Van Noordwijk (2009) and Khasanah et al. (2010) and are at least in part due to the fertilizer use in cropping years.

Simulated teak diameter increase for wider tree spacing or lowering initial tree density was consistent with results of Ola-Adams (1990). However, the result of the current WaNuLCAS model for a typical tree with average properties did not represent the variation in growth that occurs in the landscape and the selection that occurs when thinning is practiced unevenly by removing trees, which grow slowly, suffer from pests or diseases, or have poor form. Although in the model thinning practice is applied evenly, the results were consistent with studies by Kanninen et al. (2004) and Perez and Kanninen (2005).

The result of pruning treatment shows that the greater the pruning intensity, the greater the negative impact on teak growth (diameter and height), this is found at either low or high teak population density. This result is consistent with Bertomeu et al. (2011). In contrast, Roshetko et al. (2013) reported that in combination with thinning, pruning to 60 % of total height yield result greater incremental diameter and height growth compared to pruning to 50 % of total height. However, the affect of pruning managements on subsequent wood quality such as knots in the wood are not explicitly include in the model. Viquez and Perez (2005) reported that the more intensive pruning results the less knots in the wood.

In practice, pruning and thinning practices are not implemented on a daily basis, which lowers the need of labour. Therefore, targeting lower tree density is an efficient management option. Additionally, lower tree density results in larger tree diameters and larger diameters are rewarded with price premiums (Perdana et al. 2012). From the three simulated initial tree density, the lowest density of 625 ha^{-1} is calculated as more profitable than the higher density. Returns to labour were found to exceed the labour wage rate in the study area (USD 2.75 day^{-1}), which means that households could afford to hire labour and still make a profit. However, most households manage their teak systems with family labour.

The profitability analysis showed no negative values across the tree management options, including maize monoculture. Santos-Martin and van Noordwijk (2011) found that intercropped maize with high-value timber in the Philippines was approximately break-even when private (farm gate) prices were used, but inclusion of trees became profitable at social prices (price at national border, net of taxes and subsidies), applicable at societal level.

Our results for teak in this part of Java suggest that even at private prices teak intercropped with maize is preferable over maize monoculture. With the phasing out of maize at plot level, farm-level management may require multiple plots in different phases of the production cycle and/or alternative sources of employment while the trees mature. The current analysis did not yet reflect farmers' perceived economic risks in the alternative systems. Sensitivity analysis on the ranking of the various systems under price fluctuations, however, suggested that optimum management practices appear to be robust around the parameter values used.

Conclusion

The present results show that, according to the process-based model, maize intercropping in the early stages of tree growth is clearly advantageous either at low or high tree population density, as it justifies for farmers the use of fertilizer. Maximum wood volume (m^3 ha^{-1}) is obtained at initial tree density of 625 trees ha^{-1}, 25 % of which was thinned in year 5 and another 25 % in year 15 with 40 % of the crown pruned in years 4, 10 and 15. Maximum stem diameter per tree (wood volume per tree) is provided with the same initial tree density and crown pruning, but more intensive thinning 50 % at year 5 and another 25 % at year 15. As greater stem diameter is rewarded with higher market price per volume of wood, thus the highest NPV and RtL was provided by the system with the highest stem diameter.

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Appendix

See Table 8 in Appendix.

Table 8 Detail tree growth characteristic applied in the model

Parameters		Units	Teak	Acacia
Growth stage	Length of vegetative cycle	Days	3285	1095
	Length of generative cycle	Days	120	199
	Earliest day to flower in a year	Julian day	300	180
	Latest day to flower in a year	Julian day	330	210
	Initial stage	–	0.25	0.25
	Stage after pruning	–	0.20	0.20
Growth	Max. growth rate	kg m^{-2}	0.02	0.02
	Fraction of growth reserve	–	0.05	0.05
	Leaf weight ratio	–	0.25	0.75
	Specific leaf area	m^2 kg^{-1}	12.66	4.95
	Water requirement for dry matter production	l kg^{-1}	300	300
	Tree growth follows Rubber tree rules?	–	0.00	0.00
Fruit	Fruit growth follows Oil Palm rules?	–	0.00	0.00
	Fraction biomass allocated to fruit	–	0.00	0.00
Crown	Max. crown height above bare stem	m	16.20	13.00
	Ratio between crown width and height	–	0.60	2.00
	Max. crown radius	m	7.80	10.00
	Maximum leaf area index	–	5.00	5.00
	Ratio leaf area index min. and max.	–	0.10	0.50
Light capture	Relative light intensity at which shading starts to affect tree growth	–	1.00	1.00
	Extinction light coefficient	–	0.35	0.50
Rain interception	Rainfall water stored at leaf surface	mm	1.00	0.80
Tree water	Coefficient related to tree root conductivity	cm day^{-1}	0.00	0.00
	Plant potential for max. transpiration	cm	−1000	−1000
	Plant potential for min. transpiration	cm	−15,000	−15,000
N fixation	Type of N2 fixation	–	0.00	1.00
	Proportion of N from atmosphere	–	0.00	0.25
	Fraction of reserve pool for N2 fix.	–	0.00	0.10
	Dry weight cost for N2 fixation	–	0.00	0.01
	Responsiveness of N2 fix. to N stress	–	0.00	0.50
N concentration	N concentration in carbohydrate reserves	g g^{-1}	0.01	0.01
	N concentration in leaf component	g g^{-1}	0.01	0.02
	N concentration in twig component	g g^{-1}	0.02	0.01
	N concentration in wood component	g g^{-1}	0.01	0.00
	N concentration in fruit component	g g^{-1}	0.02	0.01
	N concentration in root component	g g^{-1}	0.01	0.01

Table 8 continued

Parameters		Units	Teak	Acacia
P concentration	P concentration in carbohydrate reserves	g g^{-1}	0.02	0.00
	P concentration in leaf component	g g^{-1}	0.00	0.00
	P concentration in twig component	g g^{-1}	0.00	0.00
	P concentration in wood component	g g^{-1}	0.00	0.00
	P concentration in fruit component	g g^{-1}	0.00	0.00
	P concentration in root component	g g^{-1}	0.00	0.00
Litterfall	Litterfall caused by drought	day^{-1}	0.01	0.01
	Treeshold value for litterfall due to drought	–	0.90	0.99
	Reducing factor for N of litterfall	–	0.85	0.70
	Reducing factor for P of litterfall	–	0.85	0.70
Litter quality	Lignin fraction of litterfall	–	0.40	0.40
	Lignin fraction of pruned biomass	–	0.40	0.45
	Lignin fraction of root	–	0.20	0.20
	Polyphenol fraction of litterfall	–	0.15	0.15
	Polyphenol fraction of pruned biomass	–	0.25	0.25
	Polyphenol fraction of root	–	0.10	0.10
Allometric branching (above ground)	Apply allometric equation?	–	1	1
	Intercept for total biomass equation	kg	0.153	0.356
	Power for total biomass equation	cm^{-1}	2.382	2.240
	Intercept for branch biomass equation	kg	0.104	0.304
	Power for branch biomass equation	cm^{-1}	2.358	2.238
	Intercept for Leaf&twig biomass equation	kg	0.049	0.035
	Power for Leaf&twig biomass equation	cm^{-1}	2.427	2.406
	Intercept for litterfall equation	kg	0.002	0.002
	Power for litterfall equation	cm^{-1}	3.004	3.326
	Wood density	kg m^{-3}	700	530
Roots	Root tip diameter	cm	0.10	0.10
	Max. root length density in layer1-zone1	cm cm^{-3}	0.37	1.11
	Max. root length density in layer1-zone2	cm cm^{-3}	0.47	0.05
	Max. root length density in layer1-zone3	cm cm^{-3}	0.55	0.00
	Max. root length density in layer1-zone4	cm cm^{-3}	0.15	0.00
	Max. root length density in layer2-zone1	cm cm^{-3}	0.12	0.09
	Max. root length density in layer2-zone2	cm cm^{-3}	0.09	0.16
	Max. root length density in layer2-zone3	cm cm^{-3}	0.11	0.19
	Max. root length density in layer2-zone4	cm cm^{-3}	0.04	0.20
	Max. root length density in layer3-zone1	cm cm^{-3}	0.05	0.18
	Max. root length density in layer3-zone2	cm cm^{-3}	0.04	0.14
	Max. root length density in layer3-zone3	cm cm^{-3}	0.05	0.12
	Max. root length density in layer3-zone4	cm cm^{-3}	0.02	0.12
	Max. root length density in layer4-zone1	cm cm^{-3}	0.03	0.29
	Max. root length density in layer4-zone2	cm cm^{-3}	0.02	0.03
	Max. root length density in layer4-zone3	cm cm^{-3}	0.02	0.00
	Max. root length density in layer4-zone4	cm cm^{-3}	0.02	0.00

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