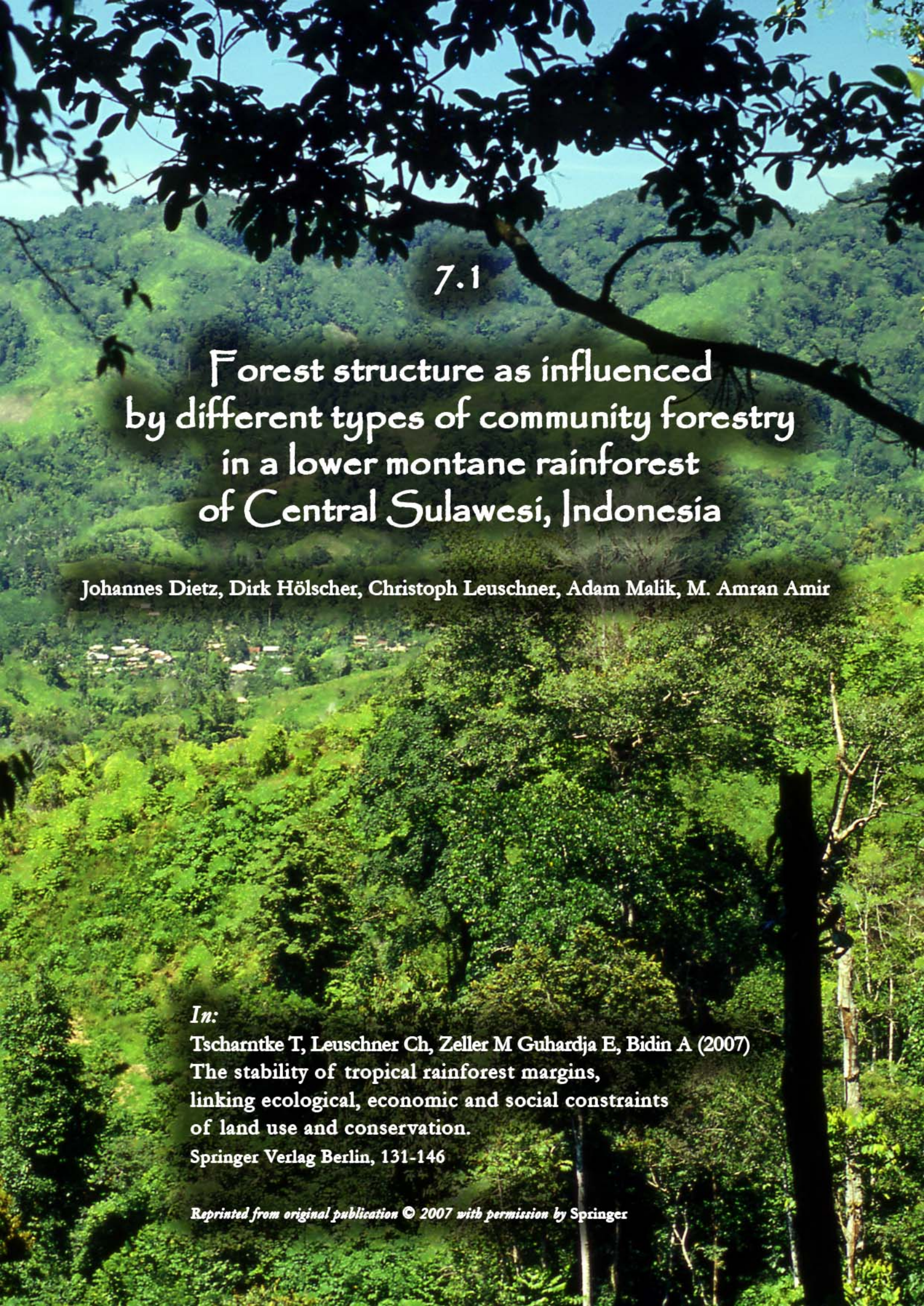


7.1

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Johannes Dietz, Dirk Hölscher, Christoph Leuschner, Adam Malik, M. Amran Amir

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Forest structure as influenced by different types of community forestry in a lower montane rainforest of Central Sulawesi, Indonesia

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Summary

Due to high deforestation rates, it is likely that in many regions tropical rainforests will survive in protected areas only. These refuges have to be surrounded by buffer zones where low impact forest management is permitted. In fact, increasing parts of the remaining rainforest areas are encroached by different types of low-intensity forest use. However, until now only few data exist on how different practices affect forest structure. The objectives of this study were to analyze differences in aboveground forest stand structure as caused by different types of forest utilization in the margin zone of a protected rainforest. The study was conducted in a lower montane rainforest region (800 - 1140 m) in the vicinity of the village of Toro in Central Sulawesi, Indonesia. We assessed the structure of twelve forest plots (0.15 ha each) which represented four types of forest use which are widespread in the study region. These types were natural forest without major disturbance, forest extraction of small-diameter timber, forest with selective extraction of large timbers and cacao agroforest plantations under trees remaining from the natural forest. The tree basal area ranged from relatively high values in the natural forests (52.5 m^2 per ha) to 19.4 m^2 per ha in the agroforest, and was paralleled by a decrease in tree height. Stem density peaked in stands where large timbers had been extracted

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and abundant tree regeneration had resumed, and it was lowest in the agroforest stands. Canopy openness, as estimated from 30 hemispheric photographs per plot, was lowest in the natural forest after small timber extraction (7 %) and highest in cacao agroforest (15 %). Leaf area index (LAI), as estimated from the same photos, averaged to 6.2 m^2 m^{-2} in the natural forest, 5.3 in the forests with small timber extraction, 5.0 in the forests with large timber extraction, and 5.3 on the agroforest plots. The latter result confirms earlier reports of relatively high leaf areas in the cacao agroforestry system. The relatively high LAI in forest stands after major timber extraction indicates a rapid recovery of leaf area after disturbance. We also analyzed the influence of stand structural parameters on rainfall partitioning into throughfall, stemflow and interception. In all forest stands we observed a close negative correlation between mean throughfall and tree height ($r^2 = 0.63$) indicating a higher interception loss in taller stands. We conclude that local forest management at low to moderate intensities, as it is common in the margin zones of protected forests, has a significant and quantifiable impact on several forest structural parameters which in turn may influence ecosystem functions such as rainfall partitioning in the canopy.

Key words: forest use, leaf area index, rainfall partitioning, rainforest, stand structure, stem density

1 Introduction

Over the past decades, tropical rainforests have been suffering increasing losses by conversion to other land cover types. South East Asia and especially some regions on the Indonesian archipelago including Central Sulawesi were identified as areas with high deforestation rates (Achard et al. 1998, Drigo 2004, FAO 2001). However, more subtle forms of forest disturbance as by selective logging on conservation lands are difficult to identify via satellite and are assumed to be underestimated so far (Asner et al. 2005). Based on recent analyses for five states of the Brazilian Amazon, selective logging doubled previous estimates of the total amount of forest degraded by human activities (Asner et al. 2005).

The high rates of forest conversion together with the rapidly proceeding forest degradation have long since called upon conservation efforts. It has been emphasized that protection requires the interaction with the people that traditionally live in and around the forests (Schweithelm 2004). Contemporary policies advocate buffer zone management by a low impact forest management which, according to Schweithelm (2004), can be developed from the experience of traditional communities that regulate the access to land and forest resources. For the Lore Lindu National Park in Central Sulawesi, such traditional structures and regulations are found in the village of Ngata Toro (Helmi 2005). There, customary law has created a zonation of the forest into different

use types which are distinguished by the local population. According to Helmi (2005), the "Wana" type of community forestry is predominantly a natural forest where only occasional rattan extraction takes place. In the "Pangale" small-diameter timbers can be extracted in the understorey, or alternatively, a restricted number of large stems can be selectively logged. Strong human intervention is characteristic for the "Pahawa Pongko" zone, which comprises cacao agroforests under a sparse canopy of large trees that remain from the natural forest (Helmi, 2005).

However, such definitions of land use are subjective and there is a need to quantify such categories by objective means (cf. Drigo 2004). Drigo (2004) suggests the translation from land use practice to land cover types where structural characteristics can be measured and monitored. Following this suggestion, the objective of our study was to identify and quantify the impact of different forest use practices on the stand structure of a lower montane rainforest in the region of the Toro village, Central Sulawesi. In a further study we analyzed the influence of stand structural parameters on rainfall partitioning into throughfall, stemflow and interception in order to relate stand structural characteristics to forest functions with respect to the hydrological cycle.

2 Materials and Methods

2.1 Study Site

This study was carried out in tropical rainforests of the sub-montane to lower montane elevation zone (800 - 1140 m a.s.l.) in the Toro Valley on the western boundary of the Lore Lindu National Park, Central Sulawesi, Indonesia. Twelve sites of 1500 m^2 each were chosen for the study, evenly representing all four investigated forest use types ($n = 3$): natural forest, forest with extraction of small-diameter timbers (hereafter termed 'small timber extraction'), forest with selective extraction of large timbers (hereafter termed 'large timber extraction'), and cacao plantations under trees remaining from the natural forest (agroforest). The four forest use types (natural forest to agroforest) generally occurred in the vicinity of the Village of Toro along a gradient of accessibility with natural forest being most distant and agroforest closest to the settlements. During the investigation period no management was observed on the forested sites while the cacao agroforests received conventional treatment of weeding and pruning. All sites were situated on moderately to severely steep slopes from 17° to 39°. The tree species composition in these forest types was studied by Gradstein et al. (this volume). They found Meliaceae, Lauraceae, and Sapotaceae to be dominant in natural forests, which shifted to Rubiaceae, Fagaceae, and Myristicaceae after both, small and large timber extraction. Moraceae, Myristicaceae, and Melastomataceae dominated in the investigated agroforests. The tree species richness varied little between natural forest stands and after small timber extraction, but was lower in stands

after large timber extraction and lowest in the agroforests (Gradstein et al. this volume).

2.2 Stand Inventory

On the forested sites, all trees with a diameter at breast height (dbh) of 10 cm or more were censused for dbh and height on the entire plot according to Kramer and Akça (1995). To account for smaller statured trees all individuals with dbh $<$ 10 cm, but higher than 2 m, were assessed on three randomly located subplots of 5 x 5 m within the plot. In the agroforests, all stems taller than 2 m were censused. Measurement of dbh was done using a metric measuring tape, height measurements were taken with a Vertex III ultrasonic hypsometer (Haglöf, Långsele, Sweden). Stand basal area was corrected for edge and slope effects.

2.3 Hemispherical Photography

Data on canopy structure was derived from hemispherical photographs which were obtained with a Nikon Coolpix 900 digital camera / Nikon FC-E8 fisheye-converter of 2048 x 1536 pixel resolution mounted on a HemiView leveling device (Delta-T, Cambridge, UK). For reduction of horizon effects on the sloped sites, the device was consistently placed at 1.3 m above the ground. Thirty pictures per site and campaign were taken at randomly located points on several occasions during the study period from January 2004 until April 2005. All images were analyzed with the software WinScanopy 2004a (Régent Instruments Inc., Sainte-Foy, Canada) for canopy openness under an opening angle of 30°, and with CanEye V 3.6 (INRA, Avignon, France) for estimates of leaf area index (LAI).

2.4 Statistical Analysis

Data were statistically analyzed using the SAS 8.2 software package (SAS Institute Inc., Cary, NC, US). Multiple comparisons among group means were conducted by analyses of variance (Duncan's test); a significance level of $p < 0.05$ was maintained throughout the analysis.

3 Results and Discussion

3.1 Stem Density

Koop et al. (1995) recognized the density of large trees as a good estimator for human influence on Sumatran rainforests. In our study region, the density of large stems with a diameter at breast height (dbh) larger than 50 cm also

Table 1. Aboveground forest structure in stands influenced by different types of community forestry in the region of Toro, Central Sulawesi. The different forest use types are: natural forest (NF), forest after small timber extraction (STE), forest after large timber extraction (LTE) and agroforest (AF). Significantly different means between forest types ($n = 3$) are indicated by different small letters (analysis of variance, Duncan's test, $p < 0.05$).

Forest use type	Elevation [m asl]	Stem density [n ha^{-1}]			Basal area [m^2 ha^{-1}]		DBH mean [cm]	Top height [m]	Mid height [m]	Leaf area index [m^2 m^{-2}]		Canopy openness [%]	
	plot center	height ≥2m	dbh ≥10cm	dbh ≥50cm	height ≥2m	dbh ≥10cm	dbh ≥10cm	top 10%	mean dbh	mean (n=30)	cv (n=30)	mean (n=30)	cv (n=30)
NF1	948	2272	472	103	68.6	62.8	30.3	42.9	25.1	5.7^{ab}	20.7	9.7	53.9
NF4	1042	1806	406	58	50.0	48.1	31.5	47.6	26.7	6.4^{a}	23.9	9.3	52.5
NF5	1130	3455	655	71	51.1	46.6	26.7	35.8	21.5	6.5^{a}	14.9	10.9	58.7
NF mean	1040	2511^{a}	511^{a}	78^{a}	56.6^{a}	52.5^{a}	29.5^{ab}	42.1^{a}	24.4^{a}	6.2^{a}	19.9	10.0^{ab}	55.0
Std Dev		850	129	23	10.4	9.0	2.5	5.9	2.7	0.4	4.6	0.8	3.2
STE2	873	2020	620	61	55.7	43.5	26.8	35.1	20.7	4.3^{de}	19.5	7.7	49.2
STE3	1078	3855	655	91	67.0	62.7	29.5	37.5	22.5	6.3^{a}	18.9	7.0	50.9
STE4	982	2420	620	72	41.4	48.7	23.2	35.3	18.4	5.2^{bc}	20.6	6.4	51.7
STE mean	978	2765^{a}	632^{ab}	75^{a}	54.7^{a}	51.6^{a}	26.5^{ab}	36.0^{ab}	20.5^{ab}	5.3^{a}	19.7	7.0^{a}	50.6
Std Dev		965	20	15	12.8	9.9	3.2	1.3	2.1	1.0	0.9	0.7	1.3
LTE1	974	5495	695	25	41.1	34.9	20.4	33.2	16.8	4.9^{bcd}	30.2	12.9	56.6
LTE3	827	3740	740	64	53.6	50.1	25.9	37.0	21.3	4.9^{cd}	24.4	8.2	48.5
LTE4	959	4052	652	55	34.6	30.2	22.1	27.1	18.7	5.2^{bc}	31.4	9.3	66.7
LTE mean	920	4429^{b}	695^{b}	48^{ab}	43.1^{ab}	38.4^{ab}	22.8^{b}	32.4^{b}	18.9^{b}	5.0^{a}	28.7	10.1^{ab}	57.2
Std Dev		936	44	21	9.6	10.4	2.8	5.0	2.3	0.2	3.7	2.4	9.1
AF2	952	1706	125	6	8.6	8.5	25.6	28.4	15.9	5.7^{ab}	31.6	19.7	85.7
AF3	832	2705	237	25	23.7	23.4	32.7	35.7	20.6	6.3^{a}	26.3	15.9	64.7
AF4	806	2612	247	51	26.5	26.3	38.1	35.0	19.9	4.1^{e}	26.1	9.8	86.7
AF mean	863	2341^{a}	203^{c}	28^{b}	19.6^{b}	19.4^{b}	32.2^{a}	33.0^{b}	18.8^{b}	5.3^{a}	28.0	15.1^{b}	79.0
Std Dev		552	68	23	9.6	9.6	6.3	4.0	2.5	1.1	3.1	5.0	12.4

appeared as good indicator of the intensity of forest use (Figure 1, solid bars). Highest values averaging at 78 and 75 stems per hectare were found in the natural forest and in forest after small timber extraction. Large timber extraction reduces the density to 48 stems per hectare. Agroforests contained an average of only 28 large trees per hectare (ranging between 6 and 51 stems per hectare, Table 1). The very large variability in the density of large-diameter stems in the agroforestry systems may be related to the personal experience and preference of the plot owners. A similar structural diversity in agroforestry systems was previously documented for other tropical regions by Ruf and Schroth (2004). Small stems (< 10 cm in dbh) averaged slightly above 2000 stems per hectare in the natural forest, but reached higher values after large timber extraction (Figure 1, hatched bars). In the gaps created by logging of big trees, abundant regrowth occurred with 3700 stems per hectare on the average. In the agroforest, the class of small stems included most of the planted cacao (*Theobroma cacao*) trees.

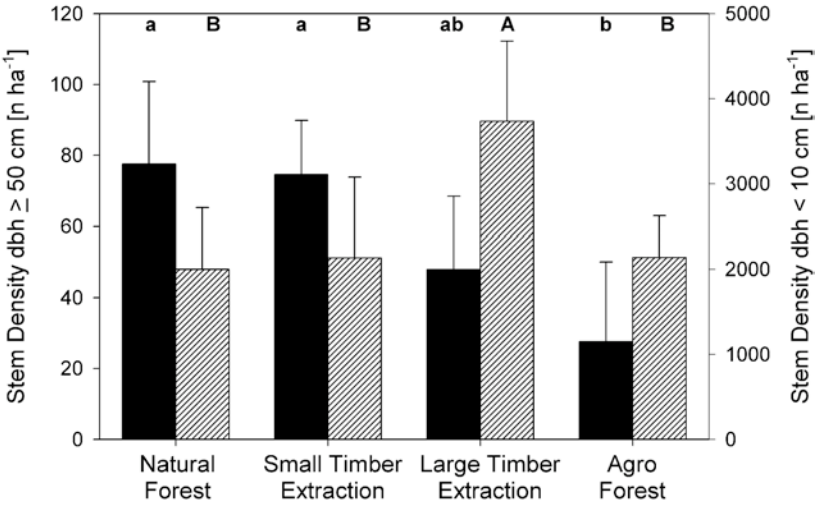


Fig. 1. Stem densities in four different forest use types. Number of all stems with diameter at breast height (dbh) $\geq$ 50 cm (solid bars, left) and dbh $<$ 10 cm per hectare (hatched bars, right)

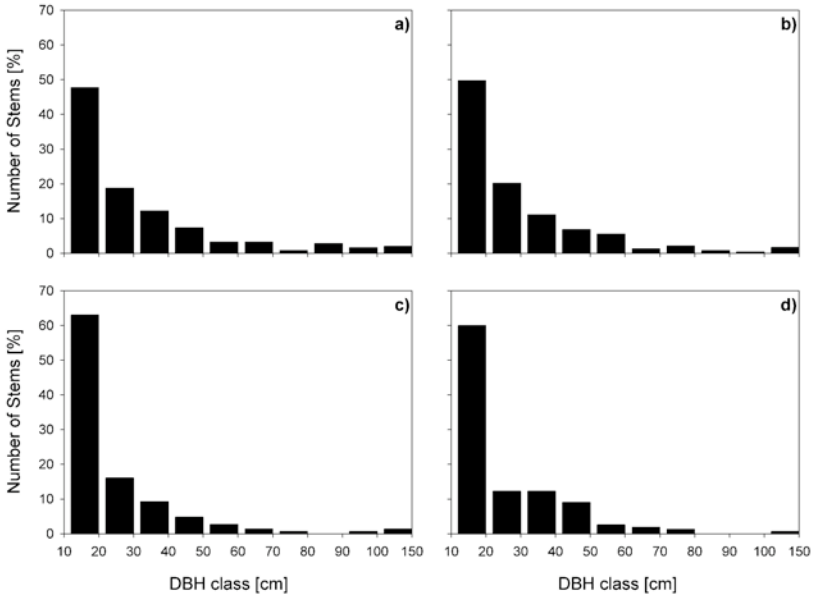


Fig. 2. Diameter distribution of all stems with dbh $\geq$ 10 cm in natural forest (**a**), after small timber extraction (**b**), after large timber extraction (**c**), and in agroforest (**d**)

Few remaining large trees and a high proportion of small stems were characteristic for both forest stands after large timber extraction and agroforest stands. This contrasted with natural forest stands and stands after small timber extraction. In the latter, the dbh class $<$ 20 cm contained less than 50 % of all stems, (Figures 2a and b), whereas after large timber extraction the proportion of trees in this diameter class reached values above 60 %. In the agroforest, the high proportion of thin stems mostly owed to planted crop trees (Figures 2c and d). Big trees were scarce in these two forest use types.

3.2 Basal Area and Stand Height

The abundance of large-diameter stems is known to be a good estimator of a stand's basal area of stems $\geq$ 10 cm dbh (McElhinny et al. 2005). Average basal areas of 52.5 and 51.6 m^2 per hectare in the natural forest and in stands after small timber extraction, respectively, seem to be relatively high, especially when the peak value of 62.8 m^2 ha^{-1} is considered. However, a comparison with other studies in natural forests above 600 m asl in the South East Asian region reveals that the values for the natural forests in Toro are indeed

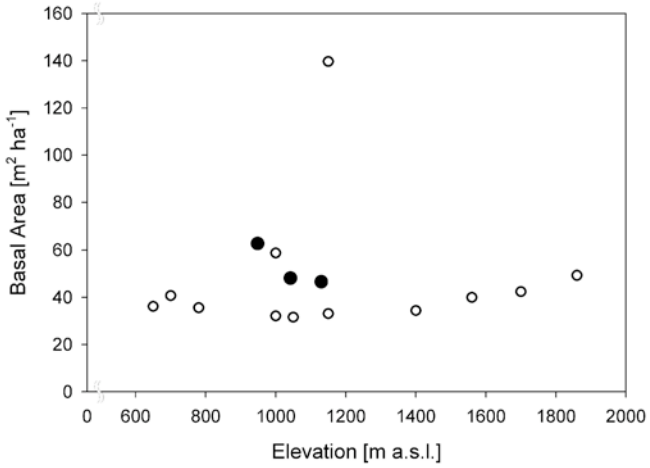


Fig. 3. Basal area of natural forests in the region of Toro, Central Sulawesi (this study, ●), compared to results from other studies in natural forests of South East Asia (○) above 600 m asl. Sources: Aiba and Kitayama 2002, Brodbeck 2004, Dietz et al. unpublished data, Hamann et al. 1999, Kessler et al. 2005, Kitamura et al. 2005, Sri-Gernyuang 2003

slightly above the average, yet they are still within the reported range (Figure 3). In our study region, the average basal area decreased to 38.4 m^2 ha^{-1} in stands after large timber extraction and dropped to 19.4 m^2 ha^{-1} in the agroforest. The decrease in tree basal area along the gradient of use intensity was paralleled by a decrease in tree height. The stand mid height, which is the height of a tree with the arithmetic mean of dbh (Kramer and Akça 1995), decreased from 24.4 m in the natural forest and from 20.5 m in stands after small timber extraction to 18.9 m in stands after large timber extraction and 18.8 m in the agroforest. The apparent drop in tree mean height between natural forest and forest after small timber extraction is statistically not significant. If existent, it may be caused by slight changes in environmental conditions between sites (cf. Takyu et al. 2002).

3.3 Leaf Area Index and Canopy Openness

Leaf area index (LAI) is a basic variable for modeling the energy and matter fluxes in forests; this parameter is also of great importance for vegetation models in the context of global change research (e.g. Asner et al. 2003). A variety of different assessment methods are used in the field (Breda 2003, Jonckheere et al. 2004). A consistent underestimation of LAI by indirect methods such as

hemispheric photography was reported by Breda (2003) but their growing potential was acknowledged. On the global scale, Asner et al. (2003) confirmed that indirect optical measurements of LAI were closer to the results from destructive assessments than interpolations derived from litter sampling or estimates obtained from allometric functions. The destructive sampling approach would have been very labor-intensive and would have conflicted with conservation policies in our forest plots, which are located in a national park. Since hemispheric photography is a rapid, sufficiently reliable and non-destructive approach for the assessment of canopy structure (Jonckheere et al. 2004), it was thus chosen in our study.

The LAI of evergreen forests may change seasonally with rainfall volumes and other climatic parameters (Asner et al. 2003, Breda 2003). Therefore, we analyzed most stands for their leaf area at three different times. However, in none of the stands, a distinct seasonality in LAI was observed (see Figure 4a for the LAI of a natural forest). This may be due to the largely non-seasonal rainfall distribution in the study region. The following results are based on photos taken during a measurement campaign in April 2005.

The LAI as derived from 30 photos within a plot varied only moderately in space within a plot. In the natural forest, the coefficient of variation (CV) ranged between 15 and 24 % which is similar to results found in natural forests of the Brazilian Amazon using a different, yet quite comparable method (Licor LAI 2000; Aragão et al. 2005). In our study region, the CV values in forest stands after large timber extraction and the agroforest stands ranged from 24 to 32 %. This corresponds with CVs measured in Amazonian secondary forests (Aragão et al. 2005). The average LAI of the natural forest stands in Sulawesi ranged from 5.7 to 6.5 m^2 m^{-2}. In their global review Asner et al. (2003) reported a mean ($\pm$ SD) LAI of 4.9 (2.0) for tropical evergreen broadleaf forests. Aragão et al. (2005) found values between 3.6 and 6.6 for natural forest in Amazonia, Trichon et al. (1998) reported values between 3.9 and 6.1 from rainforests in Sumatra, and similarly Kumagai et al. (2004) found values between 4.8 and 6.8 in Borneo. Roberts et al. (2004) obtained LAI values ranging from 4.1 to 8.0 for tropical lowland rainforests, with a tendency for higher values in Asia. Thus, the values obtained in Sulawesi are well within the range of other studies and they may also support slightly higher values in Asian tropical forests (Roberts et al. 2004). The average LAI of a given forest use type was 6.2 m^2 m^{-2} in the natural forest, 5.3 in forests with small timber extraction, 5.0 in forests with large timber extraction, and 5.3 in the agroforest. The variation between plots of the same use type was largest in the agroforestry systems, where values between 4.1 and 6.3 were observed (Figure 4b). The large variability between the agroforest sites may be explained with the already mentioned densities of large and small stems that differ greatly under permanent human influence (Ruf and Schroth 2004). Our relatively high average LAI values for agroforest confirm studies claiming that plantations in general (Asner et al. 2003), and cacao in Central Sulawesi in particular (Falk 2004), can maintain a comparably large leaf area. The relatively high LAI val-

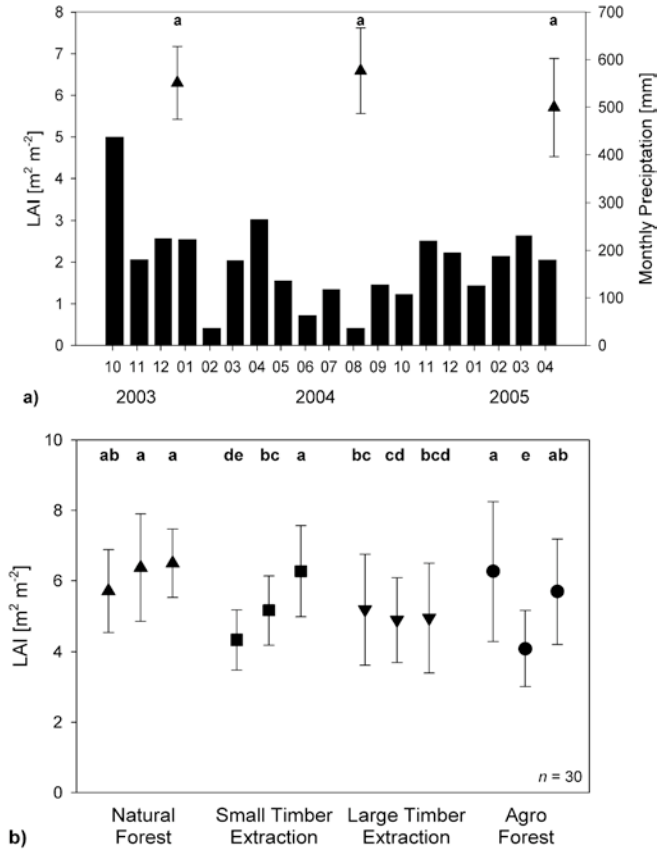


Fig. 4. Leaf area index (LAI) estimates from a natural forest on three different dates compared to the monthly rainfall volumes (**a**), and LAI values with standard deviation for all twelve plots grouped by forest use types (**b**); ($n = 30$ photos per stand, analysis of variance, Duncan's test $p < 0.05$)

ues in managed stands of Sulawesi are comparable to results from Amazonia, where only little differences in LAI between natural forests and selectively logged sites were observed (Aragão et al. 2005). The high proportion of regrowth after large timber extraction may contribute substantially to such high LAI values in Sulawesi.

The average canopy openness, as determined from photographs taken at 1.3 m above the ground, was between 10 and 11 % per site in the natural forest; it was considerably higher in cacao agroforest (between 16 and 20 %;

Table 1). The values obtained in the forest stands after small and large timber extraction did not differ significantly from those in the natural forest. Trichton et al. (1998) found canopy openness values below 10 % in mature Sumatran rainforests but they report much larger values for gap phases. Tobón Marin et al. (2000) found canopy openness values from 9 to 17 % in natural rainforests of western Amazonia. In the agroforest systems of Sulawesi, many large trees have been removed arbitrarily and to different extents by the plantation owners who subsequently plant crop trees in different densities. Thus, in the agroforest, we found the highest average canopy openness which was associated with a relatively high spatial variation in this parameter in a given stand and between different stands (Table 1).

4 Outlook – the relationship between stand structure and ecosystem functions

The aboveground structure of tropical forests has been shown to influence many ecosystem properties that control energy and matter fluxes, including radiation transmission, the temperature regime, the atmospheric saturation deficit (Leigh 1975, Montgomery 2004, Parton et al. 1996, Trichon et al. 1998), soil temperature, fine root biomass and turnover (Hertel et al. this volume), as well as the diversity of the soil fauna (Migge-Kleian et al. this volume) and of butterflies (Fermon et al. 2005). Forest structure is also considered to be an important parameter in the hydrological cycle of forests (e.g. Bigelow 2001, Bruijnzeel et al. 1993, Chappell et al. 2001, Hall 2003, Hölscher et al. 2004).

In our study plots in Central Sulawesi, we monitored throughfall with 30 funnel collectors each on all 12 plots, stemflow with 10 collectors per plot, and gross rainfall with rain gauges adjacent to each plot. The throughfall median was 70 % of incident precipitation in natural forest, 79 % in forest with small timber extraction, and 80 % in forest with large timber extraction and 81 %in the agroforest. Stemflow was estimated to be less than 1 % in all studied forest use types. Among the stand structural parameters that correlate with rainfall partitioning we found the best correlation between throughfall and mean tree height (the arithmetic mean height of all stems > 10 cm dbh). Considering all 12 plots from all four forest use types, the coefficient of determination (r^2) was 0.63 (Figure 5). We conclude that tree height is an easy-to-measure parameter that allows for an estimation of the throughfall volume along the disturbance gradient from natural forest to agroforest. In other studies, LAI has often been used for modeling the partitioning of rainfall into throughfall, stemflow and interception (Gash 1979, Gash et al. 1995), and has been described as a good parameter to estimate throughfall volumes (Hall 2003, Holwerda et al. in press). In contrast, LAI alone was not significantly correlated to throughfall (or rainfall interception) in our study. A possible explanation is that the total LAI and the associated canopy water storage differed only slightly between the studied stands while the vertical distribution of the foliage varied

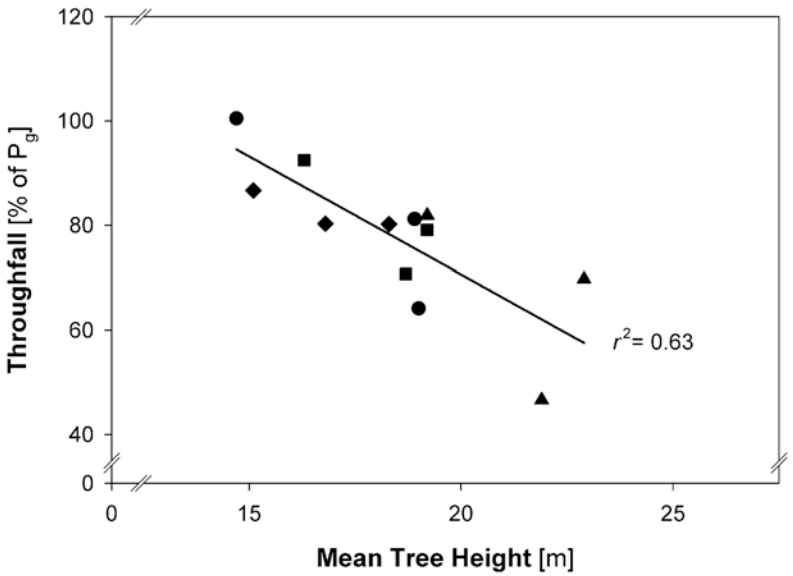


Fig. 5. Relationship between mean canopy height (arithmetic mean of all trees $\geq$ 10 cm dbh) and throughfall expressed in percent of gross rainfall (P_g) for 15 days of rainfall per plot ($r^2 = 0.63$, $p < 0.01$). Considered in the regression are three natural forest plots (▲), three forests after small timber extraction (■), three forests after large timber extraction (◆), and three agroforest sites (●).

greatly. Taller trees presumably increase the aerodynamic roughness length of the stand, resulting in a more effective turbulent energy exchange with the atmosphere. As a consequence, the canopy dries up more often between rainfall events in tall stands, while it remains wet for longer periods in stands with lower-statured trees and with a more clumped distribution of the leaf area.

5 Conclusions

We conclude that the different types of community forestry in Central Sulawesi changed stand structural characteristics considerably. We found strong effects on stem density, basal area and stand height, whereas the leaf area index seemed to be less affected. The changes in forest structure were associated with differences in the forest hydrological cycle as the volume of net precipitation increased with decreasing stand height.

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