THE EFFECTS OF LAND USE CHANGE ON ATMOSPHERIC NUTRIENT DEPOSITION IN CENTRAL SULAWESI

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With 7 figures, 4 tables and 1 photo
Received 01. June 2012 · Accepted 21. January 2013

Summary: Deposition rates in remote areas due to anthropogenic emissions are increasing in Asian countries and elsewhere. The burning of biomass in slash-and-burn activities, in addition to burning fossil fuel result in higher rates of atmospheric deposition at forest and agricultural sites. An investigation of bulk depositions in Central Sulawesi was conducted at 13 field sites along a land use cover gradient that included natural and unused sites, slash-and-burn sites, and consolidated agricultural systems around and in the Lore Lindu National Park, an area of more than 2310 km². Bulk depositions rates were measured with passive ion exchange collectors. Our results show that Central Sulawesi generally experiences low deposition rates. Depositions that originate mainly from anthropogenic sources, such as nitrate, are very low, i.e. between 0.1 and 0.8 kg ha^{-1} a^{-1}, but increase to 2.4 nitrate kg ha^{-1} a^{-1} near slash-and-burn areas. Similar patterns were found for elements such as potassium and calcium. Indeterminate depositions were found for geogenic elements such as iron, manganese and aluminium and in some cases phosphorus. A principal component analysis allowed differentiation between the contributions of different sources and different element to the total deposition impact in most cases. Specific deposition rates were recorded for different land use systems. The main factor that generated different deposition patterns was biomass burning resulting from slash-and-burn activities. The latter determined the composition of atmospheric depositions of nearby sites, but the more distant sites inside the national park do not appear to be influenced by these anthropogenic activities yet.

Zusammenfassung: Stoffeinträge steigen permanent durch anthropogen verursachte Emissionen auch in entfernt gelegenen Landschaften Asiens. Ursache hierfür ist neben der Verbrennung fossiler Energieträger auch die Verbrennung frischer Biomasse durch Brandrodung. Zur Messung von Depositionseinträgen für ein 2310 km² großes Gebiet in Zentral Sulawesi wurden 13 Messstellen zur Depositionserfassung mit Passivsammlern eingerichtet. Es konnte gezeigt werden, dass die Depositionseinträge in Sulawesi meist gering sind, und für Nitrat-Stickstoff (NO_3-N) zwischen 0,1 und 0,8 kg ha^{-1} a^{-1} liegen. Auf Flächen in der Nähe von Brandrodungsgebieten steigt der Depositionseintrag jedoch auf 2,4 kg NO_3-N ha^{-1} a^{-1}. Für Kalzium und Kalium finden sich ähnliche Depositionsmuster, während für Aluminium, Mangan und Eisen andere Emissionsfaktoren eine Rolle spielen. Es konnte gezeigt werden, dass für Zentral-Sulawesi für unterschiedliche Landnutzungssysteme unterschiedliche Elementzusammensetzungen eingetragen werden. Depositionsmaterial kann aus lokalen Feuern (Brandrodung), dem Meer oder Staub aus geogenen Quellen stammen. Für die Landnutzungstypen konnten spezifische Depositonseinträge bestimmt werden. Emissionen aus Brandrodungsaktivitäten beeinflussen die Nährstoffeinträge in einem lokalen Umkreis an der Nationalparkgrenze. Waldflächen im Nationalpark sind von diesen Emissionen bisher noch unbeeinflusst.

Keywords: Bulk deposition, Indonesia, rural landscape, air transport, land use system, slash-and-burn

1 Introduction

Tropical ecosystems are unique in their species richness, and are commonly adapted to low nutrient availability. Global change, already affecting the tropics, is associated with high emissions from industries and traffic, which generate increasing atmospheric nutrient depositions, in particular nitrogen (N). In all probability, higher nutrient availability will lead to an additional shift in species composition and loss in species richness (Rockström et al. 2009; Phoenix et al. 2006) in the remaining rain forest fragments. Anthropogenic sources for atmospheric depositions primarily originating from fossil fuel combustion are rising globally; this holds particularly true for industrial areas in Asian countries (Aas et al. 2007). Therefore, higher nutrient availability in tropical Asian ecosystems is to be expected. Agricultural sources add to these anthropogenic depositions. For less developed regions in the tropics, biomass burning in the course of slash-and-burn activities is an important anthropogenic source of many nutrients, especially nitrogen, and sulphur (Rocha et al. 2005; Andreae and Merlet 2001; Chang et al. 1987).

DOI: 10.3112/erdkunde.2013.02.01 ISSN 0014-0015 http://www.erdkunde.uni-bonn.de

Under near natural conditions, coastal tropical rain forests generally experience higher deposition rates than more continental sites (Schroth et al. 2001; Filoso et al. 1999; Hofhansel et al. 2011; Chuyong et al. 2004)). In particular, elements such as alkali metals and alkali earth metals are deposited at higher rates at maritime sites than at continental sites (Calil et al. 2010; Oziegbe et al. 2011).

Sulawesi is an island with low industrial production and urbanization. Mainly small holders practice land use with traditional cultivation and nearly without any synthetic fertilizers. Therefore, only very low depositions originating from anthropogenic sources were expected, as Sulawesi is also far away from any larger industrial and great urbanization areas. Dechert et al. (2005) measured moderate depositions for nitrate (2.6 kg ha^{-1} a^{-1}) at a single site in Central Sulawesi. Other investigations showed that deposition rates of 0.6 kg NO_3-N ha^{-1} (Ayers 2002) are low for tropical forests.

Basically, there are two relevant anthropogenic sources for atmospheric nitrogen deposition. They are either industrial sources or land use changes. We assumed that any deposition originating from supraregional sources, such as storms, large scale fires or industrial pollution, could be considered to be negligible during the time of our investigation unless events were registered by all stations that had been installed across Central Sulawesi. Large forest fires frequently occur during ENSO years – e.g., similar to those that occurred on Kalimantan in 2006 (Sundarambal et al. 2010) – and may therefore induce elevated atmospheric depositions.

This study started in 2007 after a weak El Nino ended in Indonesia in November–December 2006 and positive rainfall anomalies, caused by a La Niña event during June until August 2007 (Yulihastin et al. 2009; Behera et al. 2008). Industrial sources can also be neglected for Central Sulawesi, this leaves land use change as the dominant source for anthropogenic atmospheric depositions. Land use on Sulawesi commonly starts with rain forest conversion to corn and cocoa cultivation by slash-and-burn activities. Such sites can be considered as hotspots of biomass burning, and represent potential highly relevant sources for elevated atmospheric depositions of anthropogenic origin. Nitrate may therefore be regarded as an anthropogenic deposition indicator for land use in our investigation. Since hardly any fertilization is used, the annual or perennial crops planted subsequent to slash-and-burn activities are very probably not sources of elevated atmospheric depositions. The nutrients released by land use outside the Lore Lindu National Park do not stop at the boundary of the national park. Therefore, it is a key interest of this study to determine the quantity of indirect anthropogenic impact by elevated atmospheric depositions on the Lore Lindu National Park. This is generally difficult to determine because miscellaneous anthropogenic sources impede further differentiation. Therefore, the impact of slash-and-burn activities on atmospheric depositions is more clearly detectable in Central Sulawesi than at other less remote sites. Large slash-and-burn areas were observed along the border of the Lore Lindu National Park, and these are still increasing as has been demonstrated by Erasmi et al. (2010).

Consequently, some moderate hotspots of atmospheric depositions originating from forest conversion and land use were expected. To account for the spatial and temporal variability, 13 meteorological sites around and in the National Park were additionally equipped with passive ion exchange collectors (IER-collectors). Sampling was conducted at monthly intervals for aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), nitrate (NO_3), sodium (Na) and phosphorus (P).

Our hypothesis was that local increasing slash-and-burn activities influence the adjacent ecosystems in small pattern with anthropogenic depositions of nitrate and phosphorus. Furthermore, we expected to find marine influence.

2 Materials and methods

2.1 Study sites

The Lore Lindu National Park is located in the centre of Sulawesi, which is an Indonesian island. This National Park (1° 18´S, 120° 5´ O) covers an area of more than 231000 ha, and is mostly covered by lowland and submontane rainforests with altitudes starting at 200 m a.s.l. and extending up to 2610 m a.s.l. The area is affected by the inner tropical convergence zone (ITC) and ENSO effects, which can cause lower precipitation during the months from June to September. The analysis of ENSO events since 1987 by Leemhuis (2005) revealed a reduction of rain by 70–100% from July to September for the extreme ENSO event of 1997. For "regular" ENSO events (1987, 1991, 1994) reductions of 25 to 40% were registered for these month. The total rainfall in the research area (Fig. 1) is approximately 2500 mm $year^{-1}$ (Gutzler et al. 2010)

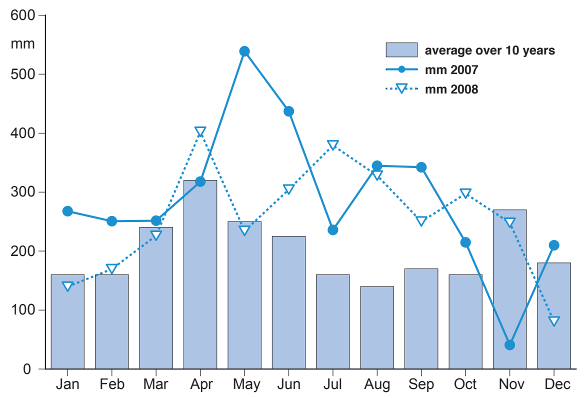

Fig. 1: Monthly precipitation during the time of investigation at the study site Nopu slope 2 (data: GUTZLER (2011) and monthly average from station Lindu and Kaipirore over 10 years (1931 - 1941) according to the report of BERLAGE (1949), modified

and exhibits seasonality in a long-term observation of thirty years (BERLAGE 1949). According to ALDRIAN and SUSANTU (2003), the Lore Lindu National Park is located in an intermediate zone of the main Indonesian climate regions with a yearly rainfall regime that is strongly influenced by the Asian–Monsoon–System. Between March and June variable, humid south-easterly winds reach eastern Sulawesi, which causes the first rainy season of the year. Then the south-easterly winds from the dryer Australian landmass prevail, initiating the dry season from August to October. The second shorter, but even wetter rainy season from November to December is generated by humid north-westerly winds from Kalimantan (WHITTEN et al. 2002). As a result of the proximity to the equator (ITC), the area is influenced by convective rainfall throughout the entire year. The total quantity of annual rainfall is spatially variable and depends largely on the topography and elevation. Valleys such as the Palu valley, which are situated in a north–south direction, or intramontane basins such as the Gumbasa valley and Wanga/Watumaeta are in the rain shadow of the steep surrounding mountains.

At Nopu slope 2 (Fig. 2) 2007 (3452 mm) and 2008 (3059 mm) the annual rainfall was above the annual average of 2500 mm (Fig. 1) but with a dry November 2007 (41mm). On average each month has rainfall quantities of more than 100 mm. According to KLEINHANS (2003) and GUTZLER (2011) 50–60% of rainfall events lie between 7–62 mm.

Land use systems at the boundaries of Lore Lindu National Park are mainly cacao agroforestry systems and annual crops managed by smallholders partly as slash-and-burn agriculture with maize in the first year (CLOUGH et al. 2010; JUHRBAND et al. 2010). The deforestation rate at the border and inside the national park has been increasing since 2001. The annual rate of deforestation was 0.32% a^{-1} (Fig. 2) from 2001–2007 according to ERASMI et al. (2007). Commonly, cacao planting followed 2–3 years of annual crop planting. Burning activity is concentrated in the drier periods, i.e. primarily in January and February, before the main rainy season starts.

The research area with the main fire sites in 2007 and 2008 is shown in figure 2. Data on fire hotspots are taken from the "LANCE FIRMS MODIS Fire/Hotspot" archive at http://earthdata.nasa.gov/firms (last access 08 May 2012). Details on the MODIS (Moderate Resolution Imaging Spectroradiometer) fire product are available from GIGLIO et al. (2003). The Modis hotspots show only the larger fires, because smaller slash-and-burn activities are normally either too small to be detected by the satellites or the weather conditions are not favourable for such detection. The main fire activities are concentrated in the area of the Napu valley near Wanga and Talabosa. The smaller slash-and-burn fires at Nopu between November 2007 and March 2008 were not visible by Modis, but were observed by the STORMA (Stability of Rainforest Margins) team during permanent research for the experimental catchment. During this period, only the fire on the 11/01/2008 in Nopu Valley was detected by Modis (Fig. 2). Forest area and land use were mapped from a Landsat/ETM+ satellite image for the year 2007 in a 1000 m radius around each field site (Tab.1). It can be seen that the sites cover a land use intensity gradient from consolidated cropland areas (for example Talabosa, Toro, Watumaeta) to natural rainforest sites with minor land use (Bariri). Certainly, both natural sites as well as slash-and-burn reveal high forest coverage as forest that can be burnt is required for this. Therefore, satellite detection is only useful in combination with ground observations.

2.2 Field sampling

Atmospheric depositions were monitored at 11 sites around the Lore Lindu National Park area and two sites inside the park (Fig. 2). Altitudes range from 364 m a.s.l. at Salua to 1374 m a.s.l. in Bariri. Passive IER-collectors (KÖHLER et al. 2012) in three replications were used to monitor depositions at the individual sites. Sampling began on the 2nd of

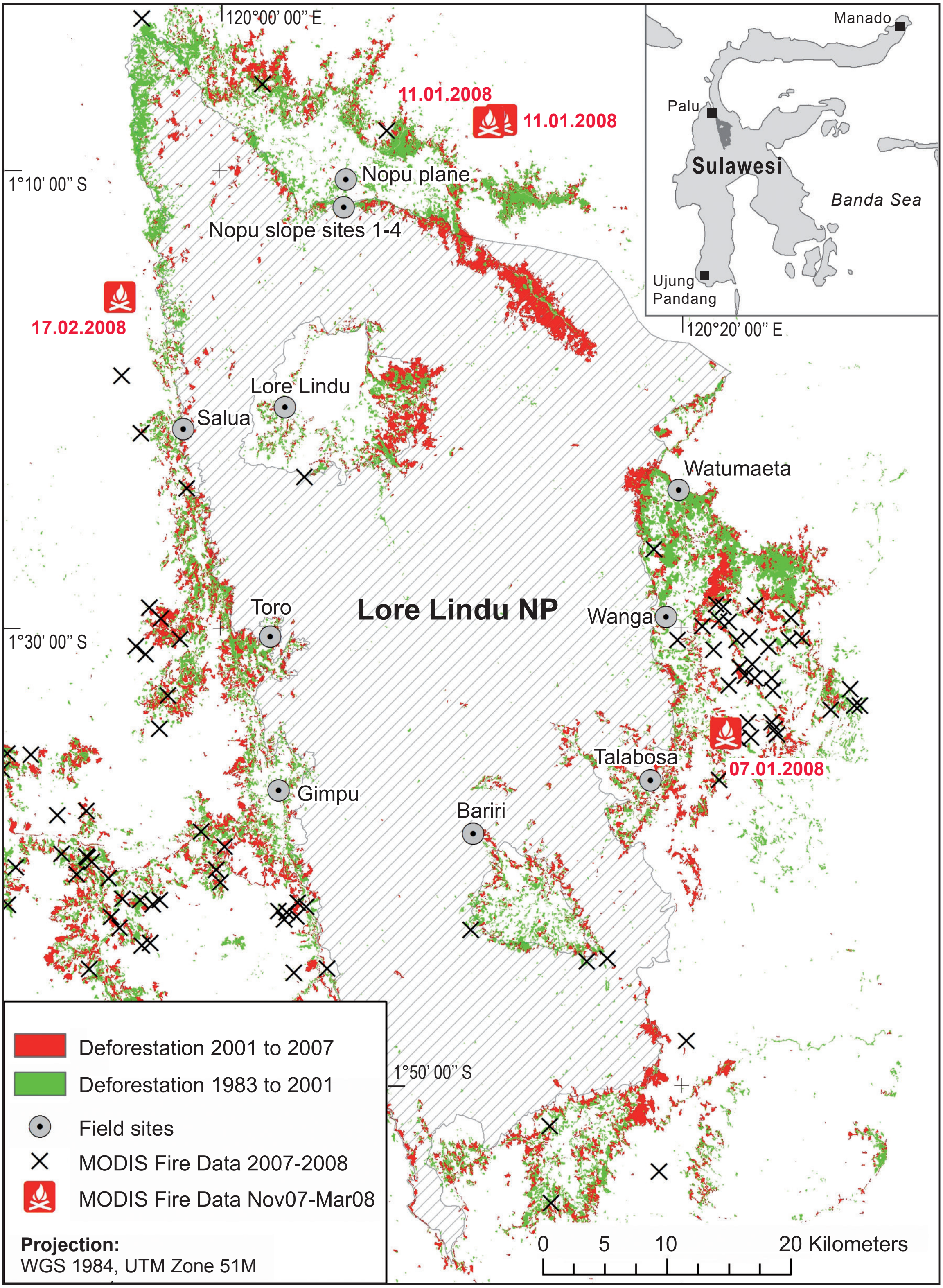

Fig. 2: Overview of the Lore Lindu National Park study area with the field sites and spatial patterns of deforestation activities. In addition, fire hotspots in Central Sulawesi, Indonesia for the time period 2007–2008 are shown

Tab. 1: Land cover statistics (in % of total land cover) for a 1000 m radius around field sites in 2007

Land Cover 2007 in %	Forest	Cropland: Plantations (Coconut)	Cropland: Plantations (Cocoa)	Mosaic Cropland / Tree Cover	Wetlands	Grassland	Cropland: Paddy	Water
Bariri	75.0	0.0	3.1	0.0	0.0	18.7	3.2	0.0
Gimpu	8.5	3.4	28.5	4.5	0.0	0.0	53.6	1.4
Gimpu	8.5	3.4	28.5	4.5	0.0	0.0	53.6	1.4
Lore Lindu	18.2	0.0	52.4	0.8	0.7	2.7	22.4	2.7
Nopu plane	0.1	0.0	82.6	0.3	0.0	0.5	15.9	0.5
Nopu slope 1	8.0	0.0	72.4	4.6	0.0	5.8	9.1	0.0
Nopu slope 2	75.3	0.0	14.1	3.2	0.0	4.0	3.4	0.0
Nopu slope 3	60.9	0.0	21.4	5.0	0.0	6.0	6.7	0.0
Nopu slope 4	90.1	0.0	4.8	1.9	0.0	1.3	1.5	0.3
Salua	80.8	0.9	5.5	1.0	0.0	6.2	5.3	0.3
Talabosa	16.7	0.0	25.3	1.9	0.0	26.6	28.9	0.6
Toro	32.6	1.9	14.9	7.7	0.0	5.8	36.9	0.2
Wanga	17.4	0.0	14.0	0.1	0.0	47.9	20.5	0.0
Watumaeta	27.0	3.1	24.2	1.6	0.0	22.6	21.4	0.1

January 2007 and ended on the 2nd of January 2009. From the onset until the 31st of May 2007, the sampling interval was twice a month and thereafter at monthly intervals for all locations except for the Nopu sites (Nopu plane, Nopu slope 2 and Nopu slope 3), which were sampled twice a month until August 2007. On the hillside area at the border of Lore Lindu National Park near the village Nopu, where slash-and-burn activities have been recorded since 2004/2005, the sites Nopu slope 2 and later the sites Nopu slope 1 and Nopu slope 4 were set up during the 26th of January 2007 and 15th of August 2007, respectively. The numbering of the Nopu slope sites represents the elevation level and land use change which started at the lowest site which is Nopu slope 1.

2.3 Sampling design

At each site, three Ion Exchange Resin Collectors (IER-collectors), described in Köhler et al. (2012), were installed within an area of 2 m in diameter (Photo 1). The bulk deposition sampler consists of a funnel of 283.53 cm² at the top connected to a PVC-tube with a diameter of 8 mm and filled with ion exchange resins. The whole IER samples, i.e. the tube with ion exchange resin, were brought to and analysed in the STORMA laboratory in Palu.

2.4 Sample preparation and routine analyses

The ion exchange resin samples were weighed and homogenized. A subsample of approximately 10 g was taken and extracted twice with 50 ml sulphuric acid (2 M) to determine cations and P. To measure NO_3-N, the extraction of another 10 g of ion exchange resin was performed with a solution of sodium chloride (1 M). The extracted samples were measured using an ICP-OES 2000 DV (Perkin Elmer). NO_3-N was analyzed using a CFA-System AA3 Autoanalyser (Bran&Luebbe). Analysed Elements were aluminium (Al), calcium (Ca), potassium (K), iron (Fe), magnesium (Mg), manganese (Mn) and sodium (Na). Analysed anions were nitrate-N (NO_3-N) and phosphorous (P). To obtain the deposition for an investigated area, the extracted element concentration was first calculated for the entire ion resin mass and then related to the area of the funnel. The average of the three replications on each site was calculated as deposition rate.

The IER-Collector functions independently from the amount of rainfall by collecting all deposited ions on the surfaces of the resin (Köhler et al. 2012). Consequently, no data on precipitation is needed to calculate the quantity of atmospheric deposition for a given area. This is an advantage compared to the "classical" bulk samplers, since such calculations (concentrations measured in sub-

Photo 1: IER-collector at the field station

sample multiplied by the quantity of precipitation) are associated with relevant uncertainties as was discussed by Köhler et al. (2012.) The collected nutrients are retrieved from the surfaces of the resin and are valid for the surface area of the collecting funnel (in this case 283.53 cm^2) and exposure time (here two weeks or one month).For the extrapolation to a larger area (in this case hectares), simple multiplication was used as it was assumed that depositions are equally distributed within this area. The results are presented in kg ha^{-1}a^{-1} to allow better comparison to other investigations.

The programs SPSS 14 and PAST 2.01 (Hammer et al. 2001) were used for statistical data analysis. Three land use systems were selected based on the satellite land use cover classification (2007), and data obtained from field observations. These were: (1) a natural site representing unused areas of low human influence; (2) agriculture sites representing agricultural production systems such as corn, cocoa or vegetables and (3) forest conversion sites representing active slash and burn sites. To classify the sites according to their deposition rates a cluster analysis (Ward's method) was applied and correlations between element depositions data were tested (Pearson). Monthly data of bulk atmospheric deposition, excluding Na, at each site was used for the cluster analysis. To obtain information on the potential sources of deposition, a principle component analysis (PCA-analyze) was performed.

3 Results

The bulk deposition at the different study sites around the Lore Lindu National Park for total deposited mass for the elements Al, Ca, Fe, K, Mg, Mn, Na, NO_3-N and P were unevenly distributed in time and space. In 2007, total deposition varied between 23.2 kg ha^{-1}a^{-1} and 45.7 kg ha^{-1} a^{-1} and between 28.4 kg ha^{-1} a^{-1} and 53.2 kg ha^{-1} a^{-1} in 2008 (Tab. 2). Most site-specific total deposition rates were higher in 2008. This surplus was mainly due to Na and ranged from 16% to 69%. At the Wanga and Watumaeta sites the annual total depositions were nearly identical between the two years. For the Bariri and Nopu plane sites the total depositions were approximately 10% lower in 2008 than in 2007. Without Na deposition, bulk deposition were higher in 2008 only at three sites namely Nopu slope 3 (22%), Nopu slope 2 (10%) and Gimpu (10%).

For both years Salua, Nopu plane and Nopu slope 2 formed the group with the highest annual deposition rates. The group of Toro, Wanga, Watumaeta and Talabosa exhibited the lowest annual deposition rates. Bariri showed high depositions in 2007 and low deposition rates in 2008. The absolute maximum of more than 53 kg ha^{-1} a^{-1} of total bulk deposition was measured at Nopu slope 1 and Nopu slope 4, which were only investigated in 2008. These two sites had also the highest deposition rates for NO_3-N and are situated in the area of high slash-and-burn activities. Rates for elements such as Ca, K and Na were also relatively high. In 2007 the element exhibiting the highest deposition was Ca (Tab. 2), an element with potential geogenic, pedogenic and anthropogenic (slash-and-burn) sources. Ca exhibited nearly the same ranking from highest to lowest annual values as the total bulk deposition rates. This relationship was basically maintained in 2008, despite the fact that Na was the element with highest deposition rates. K, as a biogenic and marine aerosol, was the third most deposited element in both years. The annual K deposition was between 1.6 and 5.7 kg ha^{-1} in 2007 and increased in 2008 from 2.4 to 10.6 kg ha^{-1}.

Tab. 2: The annual element deposition in kg ha^{-1}a^{-1} at the sites in Lore Lindu National Park for the years 2007 and 2008; for 2007 NO_3-N-deposition were measured for 10 months, numbers in bold and italics show the lowest level; bold numbers show the highest level

Fe	K	Mg	Mn	Na	NO_3	P	total 2007	Al	Ca	Fe	K	Mg	Mn	Na	NO_3	P	total 2008
2007	2007	2007	2007	2007	2007	2007		2008	2008	2008	2008	2008	2008	2008	2008	2008	
2.5	5.6	1.3	0.2	6.8	***0.4***	0.9	35.4	***0.8***	***4.6***	***0.5***	***2.4***	***0.9***	***0.1***	21.1	0.2	***0.7***	31.2
1.2	3.2	1.3	***0.1***	***6.3***	0.6	0.9	***23.2***	1.1	8.7	0.6	4.3	1.8	**0.2**	20.8	0.3	1.4	39.3
2.4	2.8	2.4	**0.3**	6.8	0.7	1.1	31.6	1.4	8.1	1.3	3.9	1.9	**0.2**	17.9	0.5	1.4	36.7
2.4	**5.7**	2.0	0.2	**11.6**	**1.4**	1.0	**45.7**	1.0	11.1	1.3	8.4	2.0	**0.2**	14.8	0.7	1.4	40.9
								1.5	**15.5**	0.7	5.7	1.8	***0.1***	**23.9**	**2.7**	1.3	**53.2**
0.8	5.6	1.8	***0.1***	9.4	0.9	0.8	33.1	1.1	10.4	1.0	7.5	**3.2**	***0.1***	19.6	1.4	1.2	45.6
1.4	3.9	1.6	***0.1***	10.2	1.3	**1.4**	29.6	***0.8***	8.8	***0.5***	8.6	2.0	***0.1***	14.3	1.6	1.4	38.1
								1.0	14.9	***0.5***	**10.6**	2.6	**0.2**	20.0	2.0	1.2	53.0
1.7	5.4	**2.7**	***0.1***	8.0	0.7	1.2	36.7	1.7	12.0	0.7	8.5	2.6	**0.2**	20.1	0.4	**2.0**	48.0
1.8	3.0	1.2	***0.1***	7.2	0.6	0.8	25.3	**2.3**	5.8	**1.9**	3.2	2.1	**0.2**	14.3	***0.1***	1.1	31.0
1.0	***1.6***	***1.1***	***0.1***	10.1	0.6	0.7	24.4	1.1	5.5	0.8	3.7	1.1	***0.1***	14.7	0.8	***0.7***	***28.4***
1.7	1.8	1.2	***0.1***	8.6	0.6	***0.6***	29.1	***0.8***	6.0	0.7	3.1	1.4	***0.1***	15.1	0.4	0.8	28.5
2.0	2.1	2.1	0.2	8.6	0.7	***0.6***	30.3	1.5	6.8	1.5	4.2	2.1	**0.2**	***12.6***	0.2	1.4	30.5

A cluster analysis of all element depositions in 2008 with normalized values excluding Na-depositions (Ward's method) (Fig. 3) resulted in the formation of three main groups. Na was excluded from this analysis because it dominated all depositions and represented nearly 50% of the total.

One main group with great differences in total element deposition consists of the Nopu sites (Nopu slope 1-4), which exhibit the highest deposition rates. The second group contains all of the other sites except Bariri and Talabosa, which formed the group exhibiting low atmospheric deposition. The cluster analyses mainly confirmed the observations. Talabosa lies between natural and agricultural sites (Fig. 3) because agriculture is practiced there and the cluster for nitrate alone shows a closer connection to the Nopu sites, it is discussed separately from Bariri in the following. The strong influence of NO_3-N originating from slash-and-burn activities was also revealed by the cluster analyses done for the NO_3-N values for 2008 (Fig. 4). All Nopu sites formed one separate group, except for Nopu plane, which is located approximately 500–900 m from Nopu slope 1 and approximately 3000 m from Nopu slope 4; it was assigned to another group. This elucidates the local effects of slash-and-burn together with the predominant wind direction from slope bottom (Nopu plane) to upper slopes (Kleinhans 2003). Bariri, with a low deposition of 0.2 kg ha^{-1} a^{-1} NO_3-N, is considered to be a separate group in this calculation. Talabosa with a lower total annual deposition of 0.1 kg ha^{-1} a^{-1} is also separated from but close to the other agricultural sites because its monthly deposition rates are as homogeneous as at Bariri. In general, most sites, except for the Nopu sites, show low NO_3-N deposition rates below 0.8 kg ha^{-1} a^{-1}.

High deposition rates of NO_3-N and K indicate high slash-and-burn activities at the sites Nopu slope 1, Nopu slope 4 and Nopu slope 2 and are grouped

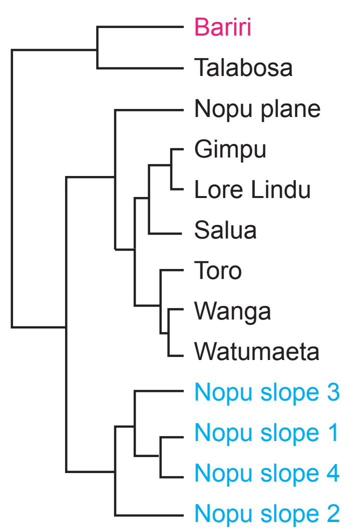

Fig. 3: Cluster (Ward's method) over all elements except for Na (values zero-one normalized) and all sites for 2008, different colours (red = natural; black = agriculture sites and blue = slash-and-burn sites) stand for the different land use sites. Because all input data were normalised, a legend for distance is not used

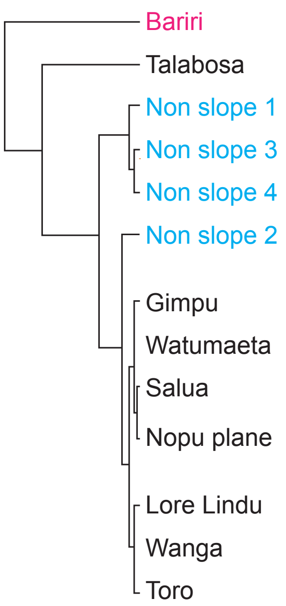

Fig. 4: Cluster (Ward's method) based on the NO_3-N values for 2008, different colours (red = natural; black = agriculture sites and blue = slash-and-burn sites) stand for the different land use sites. Because all input data were normalised, a legend for distance is not used

as **slash-and-burn** sites as supported by the cluster analysis. The second group contains sites of **consolidated agriculture** usage (smallholder annual crops and agroforestry (cacao)), like Talabosa, Watumaeta, Wanga, Toro, Nopu slope 3, Salua, Gimpu, Lore Lindu and Nopu plane. Bariri occupies a special position as a remote area near the closed rainforest and with low deposition (lowest for NO_3-N, P and K) and can be interpreted as a group of its own, i.e. as a **natural site.** Field observations during these years confirm both (1) the stable agricultural conditions without new slash-and-burn activities at Watumaeta and Talabosa and (2) the still natural rainforest conditions at Bariri (see Fig. 2).

The influence of slash-and-burn activities for the annual deposition of NO_3-N is shown in figure 5. Only the sites Nopu slope 1, Nopu slope 4 and Nopu slope 3 exhibited above average (Av) NO_3-N-deposition.

The slash-and-burn land use type shows the highest average deposition rates for total and most macro nutrients (Tab. 3). The natural site (Bariri) exhibits nearly 50% less element deposition than the other land use systems for all elements; except for Na.

The results of a principal component analyse (PCA) show that several sources are very probably responsible for the element depositions (Fig. 6). All element concentrations were normalised for the calculations. The second component in the PCA analysis shows high loading for K and high negative loading for Al and Fe (geogenic sources). The third component has high positive loads for the anthropogenic element NO_3-N and in some cases for Ca. P and Mn exhibit high negative loads.

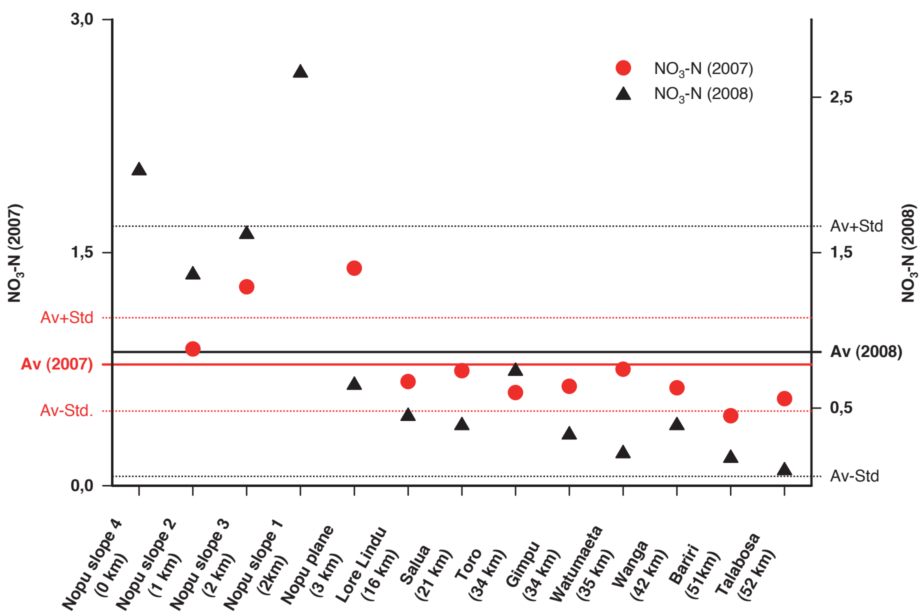

Fig. 5: NO_3-N deposition for 2007 and 2008 at increasing distance to the sites Nopu slope with a high slash-and-burn activity (distance in kilometer (km)) from slash-and-burn area near Nopu slope 4

Tab. 3: Element deposition average for the different land use types (2008) in kg $ha^{-1}a^{-1}$

	Al	Ca	Fe	K	Mg	Mn	Na	NO_3-N	P	Total
Year 2008	2008	2008	2008	2008	2008	2008	2008	2008	2008	2008
Natural site	0.79	4.59	0.48	2.38	0.88	0.10	21.30	0.19	0.68	31.21
Acgriculture sites	1.38	8.00	1.10	4.90	1.87	0.18	16.29	0.42	1.29	35.44
Slash-and-burn sites	1.09	12.42	0.68	8.10	2.39	0.12	19.45	1.93	1.28	47.47

Al and Fe exhibit similar deposition rates and are indicator elements for geogenic dust (Fig. 6). A second group is formed by Na, as typical sea salt element (marine), and Mg. In part, K also results from marine input. NO_3-N is known as an anthropogenic indicator and exhibits a deposition rate similar to Ca. In the Plot, K is between the elements Na from sea salt source and NO_3-N (slash-and-burn source element) and can be interpreted as originating from both sources. For P highest significant correlation exist with the other elements Mn, Mg (2007) and Mn (2008).

The element indicators for slash-and-burn activities (NO_3-N, K and P) had significant correlations ($r^2 > 0.4$) with Ca, Mg and Mn. This may indicate a low bulk deposition level with a mixed signal of marine (Mg) and geogenic/pedogenic (Ca, Mn) sources.

For Na, the indicator of marine source deposition, the input increased with the beginning of the main rainy season in November 2007 and reached its maximum in April 2008 (Fig. 7). The Na-deposition at Bariri and Nopu slope 1 were similar, and the deposition at Toro was slightly lower because of the relief position in a small intramontane basin on the lee side.

With the start of the dryer season in January 2008 to March 2008 slash-and-burn activity increased; this was detectable as peaks in NO_3-N analysis. One peak (0.45 kg ha^{-1}) was registered in Toro

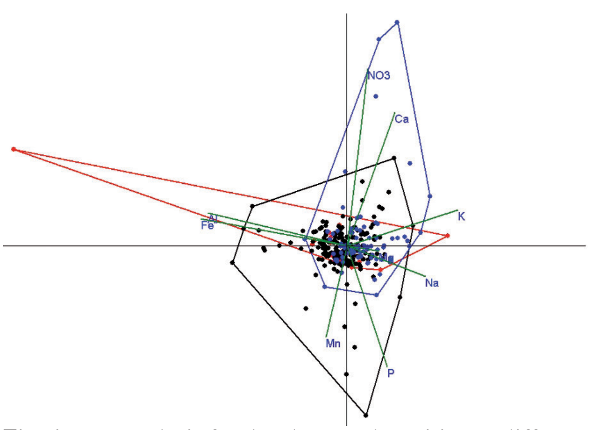

Fig. 6: PCA analysis for the element deposition at different sites, with red colour for natural site (Bariri), blue for slash-and-burn (Nopu slope sites) and black for agricultural sites

(March) and two peaks (1.57 kg ha^{-1} and 0.64 kg ha^{-1}) were detected at Nopu slope 1 in January and March, respectively. NO_3-N clearly reflected the anthropogenic event-driven deposition from the local slash-and-burn activities.

The deposition of K and P at Nopu slope 1 showed a dynamic similar to NO_3-N and was /higher than the other two sites. From May to September 2008, P deposition showed contradictory developments between Bariri and Nopu; this may have been due to slash-and-burn activities at Nopu. Elevated nutrient depositions of Ca, P and K have existed at Nopu since October 2007.

4 Discussion

The annual quantities of the main bulk cation deposition (Ca, Mg, K, and Na) were within the range of 11–37 kg $ha^{-1}a^{-1}$ published for submontane rainforests without anthropogenic local or regional impact by Hafkenscheid (2000). However, compared to other data published on atmospheric depositions for tropical rainforests (Tab. 4), these quantities are low. Solely for Na were relatively higher deposition rates recorded, as had been shown for other marine rainforest sites (Tab. 4).

The most intriguing results are probably the local deposition peaks, which were detectable due to the low natural background depositions. These peaks are best related to anthropogenic biomass burning mainly during land use change in the course of slash-and-burn activities. Threefold higher K-input, mainly at the Nopu sites, indicated the anthropogenic impact at slash-and-burn sites. Anthropogenic deposition signals were given by higher differences between natural site and slash-and-burn sites for NO_3-N (tenfold higher, Tab. 3). Without slash-and-burn, NO_3-N deposition around the Lore Lindu National park was low for most sites (0.2 and 0.8 kg ha^{-1} a^{-1}). Natural remote rainforest sites at Bukit Koto Tabang in Sumatra (Indonesia, 0.6 kg ha^{-1} a^{-1}, Ayers 2002) and in Ecuadorian rainforest (0.3 - 1.2 kg $ha^{-1}a^{-1}$, Rollenbeck 2010) showed comparable low NO_3-N depositions. Higher depositions of 1.4 up to 2.7 kg

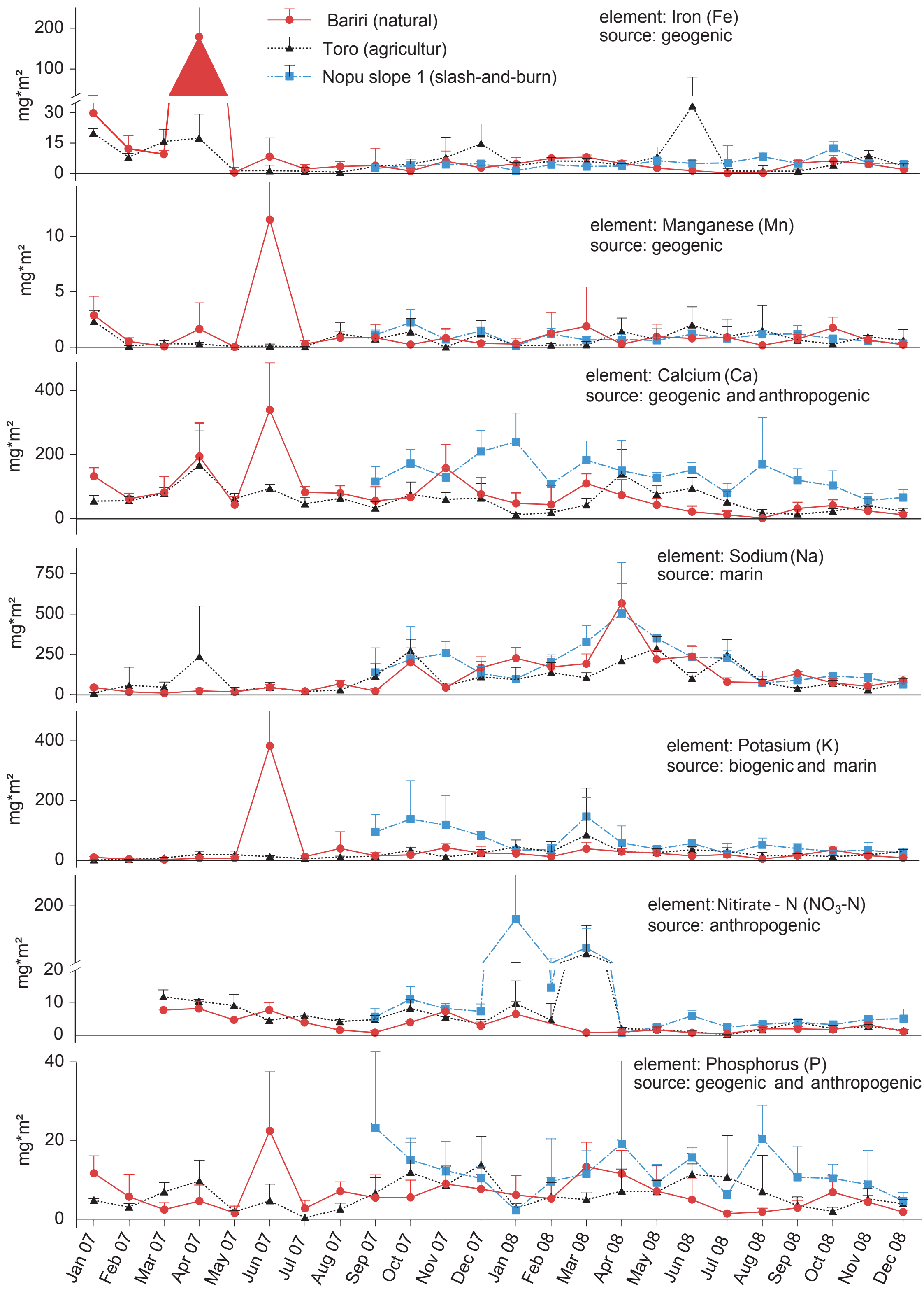

Fig. 7: The absolute monthly deposition for different elements at different land use types at Lore Lindu National Park

Tab. 4: Nutrient fluxes in incident rainfall in tropical lowland rainforests (kg ha^{-1} a^{-1})

Site	Altitude [m a.s.l.]	Rainfall [mm/year]	Ca	Mg	K	Na	NO_3-N	PO_4-P
1-4: continental								
Brazil-Manaus (1)	50	2622	0.80	0.30	2.60	–	1.40	0.07
Brazil-Rio Negro (2)	90	2900	2.50	0.40	0.70	2.50	0.80	–
Brazil-Rondonia (3)	143	2300	17.50	1.60	8.70	3.40	0.80	–
Venezuela Gran Sabana (4)	1300	2548	0.80	1.30	2.20	–	1.30	0.00
5-10: marine								
Brazil-Rio Grande do Sul (5)	175	1588	11.20	3.70	18.60	42.50	3.20	8,9 (P_2O_5)
Brazil-Mata Atlantica (6)	10	2235	5.60	1.60	6.40	75.20	–	–
Costa Rica SW (7)	70	5810	20.00	5.40	6.20	6.90	2.00	0.40
Costa Rica Monteverde (8)	1500	3191	5.80	2.40	3.00	20.50	1.70	0.05
Panama Cord.Central (9)	1200	3510	27.90	4.10	13.50	63.50	–	0.70
Puerto Rico (9)	425	3750	21.80	4.90	18.20	57.20	–	–
Kamerun Korup NP(10)	150	5370	9.30	5.30	7.80	–	1.50	1.10
Nigeria Ife-Ife (11)	215	1413	5.80	2.50	5.40	15.70	10.40	1.70
Malaysia (9)	870	2700	4.00	1.20	4.00	–	5.00	0.10
Sulawesi Lore Lindu National park (this investigation)	629-1375	~2500	4,6-19,4	0,9-3,2	1,6-10,6	6,8-21,1	0,1-2,7	0,6-2,0

(1) Schroth et al. 2001; (2) Filoso et al. (1999); (3) Germer et al. (2007); (4) Dezzo and Chacon (2006); (5) Calil et al. (2010); (6) Scheer (2011); (7) Hofhansel et al. (2011); (8) Hafkenscheid (2000); (9) Ashagrie and Zech (2010); (10) Chuyong et al. (2004); (11) Oziegbe et al. (2011); (G. Gerold personal information)

ha^{-1} a^{-1} were found in the area with high slash-and-burn activities in 2008 at Nopu (Nopu slope 1–4) and were consequently grouped together in the cluster analysis in figure 3. The highest deposition rates corresponded with the dry season (January–March 2008, Fig. 1) and the main slash-and-burn activities. These peaks very probably show not only spatial patterns during the dry season but temporal patterns between years as well. Slash-and-burn activities level off in landscapes that eventually are dominated by consolidated agriculture. An example is given for the area of Wanga and Watumaeta for which Dechert et al. (2005) reported elevated deposition rates of 2.6 kg ha^{-1} a^{-1} NO_3-N during times of high slash-and-burn activity in 2002. Just 5 to 6 years later only 0.2 to 0.7 kg ha^{-1} a^{-1} were measurable (Tab. 2), and biomass burning was low. Apparently, slash-and-burn activities do not affect large areas, as is shown by the very low absolute deposition in Talabosa and Bariri.

Rollenbeck (2010) described P mainly in association with natural sources, but Mahowald et al. (2005) refer to high P-levels in precipitation showing signals from biomass burning. Levels of P-deposition between 0.2 and 0.7 kg ha^{-1} a^{-1} (Williams et al. 1997; Veneklaas 1990; Muoghalu 2003) were low. In our investigation only three sites were in the medium ranges (0.7–0.8 kg P ha^{-1} a^{-1}) in 2008. The high P deposition at Salua in 2008 could be detected by Modis in course of the fire (Fig. 2), whereas other slash-and-burn sites showed no significant differences at low deposition rates. Hence, it can be assumed that there is a "near natural" background deposition originating from more distant sources or very homogeneous closer sources in Central Sulawesi. Part of the P deposition could be due to local burning of post harvest material, such as rice straw. Another fraction may originate from regional geogenic sources as is indicated by the same axe in the PCA-analysis for P and Mn (Fig. 7).

5 Conclusion

Loss of tropical rainforests with increasing land use activity and urbanization worldwide have contributed to increasing atmospheric depositions of essential cations and anions in the last 20 to 30 years, also in natural tropical ecosystems. For Central

Sulawesi most sites still showed low atmospheric nutrient inputs throughout the year, which corresponds well with the low influence of urbanisation and industrial areas on this agriculturally dominated island. Atmospheric depositions were dominated by marine depositions, and diffuse terrestrial sources appear to be responsible for Al, Fe, Mn and P deposition.

In our investigation local anthropogenic deposition by slash-and-burn and salt from the sea were the main factors for regional differences in mineral compositions. Local slash-and-burn activities significantly increased the main nutrient input of Ca, Mg, K and NO_3-N. Therefore, the consequences of continued biomass burning in the course of and following slash-and-burn land claims are higher nutrient depositions in undisturbed rain forest areas. These higher deposition rates have the potential to alter nutrient cycling, e.g., changes in the N/P ratios, which will have additional impact on the ecological stability of the remaining rain forest fragments. Therefore, this will have to be considered in more detail in studies on ecological functions and services of tropical rainforests, including questions of species composition and biodiversity shift. Further studies with longer measurement periods in recently dynamic forest conversion regions as Central Sulawesi are necessary and can contribute to answering open questions on nutrient cycle changes in tropical landscape ecosystems.

Acknowledgments

The authors are indebted to the German Research Foundation (DFG) for funding the study in the framework of the SFB 552. Support of the staff at the Storma Laboratory, Palu, Indonesia is gratefully acknowledged.

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