Transformation of Lowland Rainforest into Oil-palm Plantations and use of Fire alter Topsoil and Litter Silicon Pools and Fluxes

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Abstract

The effects of land use and fire on ecosystem silicon (Si) cycling has been largely disregarded so far. We investigated the impacts of land use and fire on Si release from topsoils and litter of lowland rainforest and oil-palm plantations in Jambi Province, Indonesia. Lower concentrations of Si in amorphous silica (ASi) were found in oil-palm plantation topsoils ($2.8 \pm 0.7 \text{ mg g}^{-1}$) compared to rainforest ($3.5 \pm 0.8 \text{ mg g}^{-1}$). Higher total Si concentrations were detected in litter from oil-palm frond piles ($22.8 \pm 4.6 \text{ mg g}^{-1}$) compared to rainforest litter ($12.7 \pm 2.2 \text{ mg g}^{-1}$). To test the impact of fire, materials were burned at 300 °C and 500 °C and were shaken with untreated samples in simulated rainwater for 28 h. Untreated oil-palm topsoils showed a significantly lower Si release ($p \leq 0.05$) compared to rainforest. The fire treatments resulted in an increased Si release into simulated rainwater. Si release from oil-palm topsoils and litter increased by a factor of 6 and 9 (500 °C), respectively, and Si release from rainforest topsoils and litter by a factor of 3 and 9 (500 °C). Differences between land use were related to initial ASi and litter Si concentrations, and to losses of soil organic matter during burning. We conclude that transformation of rainforest into oil palm plantations could be an important and immediate Si source after a fire event but may indirectly lead to a decrease in the long-term Si availability to plants.

Keywords Silicon cycle · Land use transformation · Fire · Solubility

1 Introduction

Since the mid-20th century, tropical rainforests in Asia have undergone progressive transformation into monoculture plantations of rubber (*Hevea brasiliensis*) and oil palm (*Elaeis guineensis*) [1, 2]. In Indonesia, Sumatra experienced a transformation towards oil-palm plantations with a loss of up to 7.5 million ha of lowland rainforest from 1990 to 2010, of which 1.1 million ha is located in Jambi Province [3, 4]. These changes led to an increase in the use of fire

[5, 6], as fire is commonly applied during the conversion of lowland rainforest into oil-palm plantations [7, 8]. Since 1984, the use of fire for land conversion has been prohibited in Indonesia [7].

Even though forest fires can be caused by natural factors (e.g. El Niño Southern Oscillation (ENSO) [6]), human activities are the main cause of fires in Indonesia [6, 8]. Once an oil-palm plantation has been established, fire is usually not anymore applied as a management practice (e.g. for pest management). However, natural and human-induced fires were detected within established oil palm plantations in the past [9–11]. For instance, Cattau et al. [10] found that 16.6% of detected fires on Sumatra and Kalimantan were located within legal agro-industrial oil-palm concessions between 2012 and 2015.

Fire affects above- and below-ground ecosystem nutrient cycles [12–14]. Nutrients can be volatilized and lost to the atmosphere or transformed into highly soluble forms. These soluble forms can be readily taken up by plants, but they are primarily lost through leaching, surface run off and erosion [12]. Thus, fire events provide short-term replenishment of

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soil fertility, [7, 15] but on a long-term perspective, they cause a considerable loss of nutrients from the system [6, 12, 13, 16].

While the effect of human-induced fire on various nutrients in soils has been extensively studied in the past [6, 12, 13, 16], silicon (Si) has been largely disregarded in this respect [17–19]. Si is a quantitatively major inorganic constituent of higher plants, and has been proven to be beneficial to the plants' health [18, 20, 21]. Furthermore, the global biogeochemical Si cycle has gained increasing attention, not only because of the closely linked processes of weathering of silicate minerals and CO₂ transfer to the lithosphere [22], but also because of an increasing awareness of its value for improving crop productivity [20, 23].

Little attention has been paid to the effect of fire on the solubility of Si compounds in soil and litter after conversion of forest to arable land or plantations. Nygugen et al. [24] found that 46% of the total Si in rice-straw ash was in soluble form, indicating that burned litter from Si-accumulating plants increases Si availability in agroecosystems. Xiao et al. [25] found that burning of rice straw at 250–350 °C led to the destruction of organic structures and exposure of enclosed amorphous silica. Thus, the observed loss of organic matter was accompanied by an increased Si release to solution [25]. Unzué-Belmonte et al. [19] showed that fire increased the solubility of biogenic silica (BSi) in O horizons of soils by a factor of 40 under spruce forest and of 20 under beech forest. BSi is one of the most reactive Si pools in soils and mostly composed of phytoliths, i.e., amorphous silica grains formed by plants [26]. The enhanced BSi solubility after fire treatment was supposed to be related to organic matter loss and degree of crystallization [19].

To the best of our knowledge, no study has yet focused on the impact of transformation from rainforest to oil-palm plantations, and the use of fire involved therein, on Si cycling. However, it is important to study Si cycling in this regard, because oil palms are considered Si-accumulating plants [27], and oil-palm plantations are susceptible to erosion of topsoils, which generally contain the highest amounts of plant-available Si [25, 28]. Thus, the aim of this study was to determine the effect of a) land use / land cover (LULC) and b) burning on the solubility of Si compounds in topsoils and litter from lowland rainforest and oil-palm plantations. Thereby, we hypothesized that fire leads to increased Si release from topsoils and litter. Since oil-palm plantations have undergone topsoil erosion and possibly several fire events with subsequent increased Si leaching, we expected oil-palm plantations to have less soluble Si in their topsoils than lowland rainforest.

2 Material and Methods

2.1 Study Sites and Experimental Design

The study area was located in Jambi Province, 60 km south of Jambi city (°1 55' 40" S, °103 15' 33" E, 70 ± 4 m above sea level), in south-west Sumatra, Indonesia [2]. The soils at the study sites are predominantly Acrisols, mostly with loamy texture, having 26–47% clay, a soil reaction around pH 4.5, and soil organic carbon stocks of 6 kg m⁻² at 0–10 cm depth [29]. The humid-tropical climate with a mean annual temperature of 26.7 ± 0.2 °C and mean annual precipitation of 2235 ± 381 mm is characterised by two rainy seasons in March and December, and a dry period in July and August (1991–2011; climate station of the Meteorological, Climatological and Geophysical Agency of Indonesia at Jambi Sultan Thaha airport). We studied three smallholder oil-palm plantation study sites (HO2–4, 50 x 50 m) that were established by the Collaborative Research Centre 990 [2]. These plantations are typically divided into oil-palm row and inter-row (Supplementary Figure “sampling_oilpalm”). In every second inter-row, old, chopped-off oil-palm fronds are piled up (Supplementary figure “sampling_oilpalm”). Plantation ages range from 7 to 16 years, and the plantations are subject to common smallholder-management practices [2]. According to interviews with smallholders conducted by Kurniawan et al. [30] the selected oil-palm plantations were established after clearing and burning the previous jungle rubber, which in turn had previously replaced lowland rainforest. The three studied rainforest sites (HF2–4, 50 x 50 m) were established by the Collaborative Research Centre 990 [2] within the protected Harapan Rainforest. The Harapan Rainforest is a former area of forestry that has been protected since 2007 to restore and recover the ecosystem structure and biodiversity.

2.2 Soil and Litter Sampling and Sample Preparation

Samples were collected from three oil-palm plantations (HO2–4) and three rainforest sites (HF2–4). Under oil-palm plantations, litter was collected from frond piles, directly above the soil surface (n = 3 for each plot), and soil was sampled at 0–1 cm depth in inter-rows, in the middle between 4 oil palms, with equal distance to each palm (n = 3 for each plot) (supplementary figure). Fire mainly affects soil properties in the uppermost cm of the soil [16, 31–33]. Under rainforest, litter was sampled in an area of 20 x 20 cm (n = 3 for each plot), and soil was sampled below this area at 0–1 cm depth (n = 3 for each plot) (supplementary figure). The litter was composed of dead and initially decomposed

and fragmented plant material. The samples were dried (24 h, 40 °C), the soil material was sieved (≤ 2 mm), and the litter was shredded by use of a plant mill. Soil organic matter (SOM) contents (assessed by loss of ignition; 430 °C, 4 h) of the soil samples were 26 - 74 g kg⁻¹ under oil-palm plantations and 85 - 207 g kg⁻¹ under rainforest. Organic matter contents of litter were 304 - 872 g kg⁻¹ for oil-palm litter and 566 - 915 g kg⁻¹ for rainforest litter (Supplementary Table).

2.3 Analysis of Amorphous Silica in Soil and Total Si in Litter

To determine sources of Si release from topsoils and litter samples, the concentrations of Si in the form of amorphous silica (ASi) in topsoils and total Si in litter were analysed. The ASi pool in soils contains BSi as well as non-biogenic amorphous silica, and is considered an important source of plant-available Si [34]. ASi in topsoil samples was assessed with an alkaline extraction [35, 36]. 40 mL of 1% Na₂CO₃ solution were added to 30 mg of soil sample in polypropylene tubes. The samples were digested for 5 h in a water-shaking bath (90 rpm) at 85 °C. Aliquots of 1 mL were subsampled after 3 h, 4 h and 5 h of digestion after cooling the tubes and centrifuging (3000 rpm, 5 min). Si concentrations of the aliquots were determined by the molybdenum-blue colorimetric method according to Grasshoff et al. [37].

Total Si contents of the litter samples were also quantified using an alkaline extraction [36]. Litter samples (50 mg) were digested for 16 h with 1% Na₂CO₃ solution (40 mL) in a shaking water bath (90 rpm) at 85 °C. The samples were centrifuged (3000 rpm, 5 min), and Si contents in the extracts were measured colorimetrically as described above.

2.4 Fire Treatment and Si Leaching

The fire treatment and Si leaching experiment followed the protocol of Unzué-Belmonte et al. [19] with minor modifications. Two different fire treatments were applied in order to simulate moderate fire (300 °C) and severe fire (500 °C), as induced by land clearing and slash-and-burn practices [14, 16, 38, 39]. Soil (6 g) and litter (0.5 g) samples were placed in crucibles and were burned for 15 min in a pre-heated furnace. Untreated soil (6 g) and litter (0.5 g) samples, and residues of burned samples were transferred to plastic tubes. Simulated rainwater (50 mL, [40]) was added in order to mimic natural conditions and natural solubility of Si compounds after burning. Chemical characteristics of simulated rainwater corresponded to rainwater of Palembang, Sumatra [41]: 0.1 mg L⁻¹ NH₄⁺, 0.0005 mg L⁻¹ Ca²⁺, 0.05 mg L⁻¹ K⁺, 0.13 mg L⁻¹ Na⁺, 0.45 mg L⁻¹ NO₃⁻, 0.49 mg L⁻¹ SO₄²⁻ and 0.19 mg

L⁻¹ Cl⁻ (Supplementary Table). In this study, we focused on monitoring Si release from samples, independently from environmental changes (e.g. pH increase) caused by a fire event. To avoid pH dependence of Si release, the pH in the solution of fire-treated samples was adjusted to the pH of the solution of untreated samples (topsoils to pH 4, litter to pH 4.5) by adding 0.1 M HCl. The Si leaching experiment was carried out on a horizontal shaker (100 rpm) for 28 h, whereby aliquots were collected at 9 time intervals (5 min, 30 min, 1 h, 2 h, 5 h, 10 h, 21 h, 24 h and 28 h). At each time interval, the tubes were centrifuged (3000 rpm, 5 min) and an aliquot of 1 mL was filtered (45 µm, PES). Si was analysed as described in Section 2.3. The experimental setup was tested on laboratory standard soil (n = 4) and showed consistent variability and Si concentrations among the replicates.

2.5 Statistical Analyses

Statistical analysis of ASi and total plant Si data was performed on log transformed grand means (n = 3 replicates within each sampled plot) of replicate plots (n = 3 plots under rainforest, and 3 under oil-palm plantations). After positive testing of normal distribution and variance homogeneity, statistical differences between LULC types was calculated with one-way analysis of variance (ANOVA) by using the SPSS 26.0.0.0 software.

For the leaching experiment, a linear mixed effect (LME) model [42] with temporal autocorrelation structure was used to assess significant differences between Si concentrations over 9 time intervals. LULC effects on Si release were tested including LULC types and time as fixed effect and plot-ID as random factor. Effects of fire on Si release were tested including treatments (untreated, 300 °C, 500 °C) and time as fixed effect and plot-ID as random factor. Statistical analysis was conducted on the grand mean (n = 3) of the replicate plots (n = 3). A Tukey HSD post-hoc comparison was used to identify significant differences between single treatments. Differences were considered significant at $p \leq 0.05$. Statistical analysis was conducted using R 3.0.2 software package. All results are expressed as grand mean $\pm$ standard error (SE), relating Si release in µg or mg per g of soil or litter.

3 Results

3.1 ASi in Soils and Total Si in Litter

ASi concentrations of rainforest topsoils were on average higher (3.5 ± 0.8 mg g⁻¹) than those of topsoils in inter-rows of oil-palm plantations (2.8 ± 0.7 mg g⁻¹), although no significant difference was detected ($p = 0.35$) between

Fig. 1 **a** Concentrations of Si in amorphous silica (ASi) in untreated topsoils and **b** total Si in untreated litter from oil-palm plantations and rainforest (for all topsoils & litter $n = 9$, for ASi from oil palm topsoils $n = 8$). Boxes indicate interquartile ranges and whiskers extend 1.5 times the interquartile range below or above the box. Letters of treatments indicate significant differences ($p \leq 0.05$) between land-use/land-cover types calculated with one-way analysis of variance (ANOVA)

both LULC types (Fig. 1a). Total Si concentrations in oil-palm litter ($22.8 \pm 4.6 \text{ mg g}^{-1}$) were generally higher than those in rainforest litter ($12.7 \pm 2.2 \text{ mg g}^{-1}$) but there was no significant difference between the two either ($p = 0.053$) (Fig. 1b).

3.2 Si Release from Untreated Topsoils and Litter

The Si leaching experiment with simulated rainwater showed clear differences in Si release between LULC types (Fig. 2). Si release from untreated oil-palm plantation topsoils ranged from $0.4 \pm 0.2 \text{ } \mu\text{g g}^{-1}$ (after 5 min) to $8.1 \pm 1.5 \text{ } \mu\text{g g}^{-1}$ (after 28 h). Si release at all time

intervals was significantly lower ($p \leq 0.05$) for oil-palm plantation topsoils than for rainforest topsoils, for which Si release ranged from $3.2 \pm 0.5 \text{ } \mu\text{g g}^{-1}$ (after 5 min) to $20.4 \pm 2.8 \text{ } \mu\text{g g}^{-1}$ (after 28 h, Fig. 2a). Compared to the underlying topsoils, Si release from litter was 6 - 25 times higher under oil-palm and 1.6 - 2.2 times higher under rainforest (Fig. 2b). Untreated litter showed greater variability between field replicates. Yet no significant differences ($p \leq 0.05$) between LULC types were observed, although the average Si released from untreated oil-palm litter was higher for each time interval (e.g., $44.3 \pm 11.9 \text{ } \mu\text{g g}^{-1}$, after 28 h) than that from untreated rainforest litter (e.g., $32.2 \pm 7.5 \text{ } \mu\text{g g}^{-1}$, after 28 h, Fig. 2b).

Fig. 2 Silicon (Si) released into simulated rainwater from **(a)** untreated topsoils and **(b)** litter samples (grand mean $\pm$ SE, $n = 9$) from oil-palm plantations and lowland rainforest. Letters indicate significant

differences ($p \leq 0.05$) between LULC types calculated from LME model with repeated measurement ANOVA and Tukey HSD post-hoc test

3.3 Si Release from Burnt Topsoils and Litter

Si release of burnt samples was enhanced compared to untreated samples (Fig. 3). The 300 °C and 500 °C treated topsoil samples of both LULC types showed significantly more Si release ($p \leq 0.05$) at all time intervals than the untreated samples. The topsoil samples of oil-palm plantations burnt at the two different temperatures did not differ significantly, although the 500 °C treated samples generally showed greater Si release ($44.6 \pm 5.9 \mu\text{g g}^{-1}$ after 28 h) than the 300 °C treated samples ($35.2 \pm 6 \mu\text{g g}^{-1}$ after 28 h, Fig. 3a). Si release from 300 °C treated rainforest-topsoil samples ($81.3 \pm 12.6 \mu\text{g g}^{-1}$) exceeded that from 500 °C treated rainforest-topsoil samples ($64.8 \pm 4.3 \mu\text{g g}^{-1}$, Fig. 3b), but without significant difference. The average Si release from burnt

rainforest-topsoil samples was 2.3 (300 °C) and 1.5 (500 °C) times that of burnt oil-palm topsoil samples, however, with high variability between field replicates (Fig. 3a and b).

The burnt litter samples of both LULC types showed a high variability of Si release between field replicates. 300 °C treated litter of oil palm and rainforest showed a clear increase of Si release compared to untreated litter, however, without significant difference to the untreated samples (Fig. 3c, d). Si release from 500 °C treated litter was significantly greater ($p \leq 0.05$) than that from untreated litter but did not differ significantly from that of 300 °C treated litter (Fig. 3c, d). Overall, the average Si release from burnt oil-palm litter was 1.5 - 2.1 (300 °C) and 1.4 - 1.9 (500 °C) times that of burnt rainforest litter.

Fig. 3 Silicon (Si) release into simulated rainwater from untreated and burnt (300 °C, 500 °C) topsoil and litter samples (grand mean $\pm$ SE, $n = 9$) from oil-palm plantations and lowland rainforest. Letters within the graph indicate significant differences ($p \leq 0.05$) between

LULC types calculated from LME model with repeated measurement ANOVA and Tukey HSD post-hoc test. a: oil-palm topsoils, b: rainforest topsoil, c: oil-palm litter, d: rainforest litter

4 Discussion

4.1 Si Release from Topsoils and Litter of Oil-palm Plantations and Rainforest

Untreated topsoil and litter samples subjected to the Si leaching experiment with simulated rainwater released only small amounts of Si. Comparatively higher concentrations of plant-available Si (as extracted by 0.5 M acetic acid) were measured in topsoils of oil-palm plantation inter-rows in Colombia at 6.8–84.2 $\mu\text{g g}^{-1}$ [27]. No other comparable study of Si concentrations in topsoils of oil-palm plantations does exist yet, thus results between Munevar and Romero [27] and our study may differ, because different extraction procedures were applied [27].

The observed decreased release of Si from untreated topsoil samples of oil-palm inter-rows, compared to rainforest topsoil samples (Fig. 2a), suggests that readily mobilizable Si fractions in the topsoils of oil-palm inter-rows were altered by LULC transformation. The decreased Si release in oil-palm inter-rows may be related to the decrease of Si pools that are rapidly mobilizable. The ASi pool of O and A horizons, mainly made up of BSi, is generally considered the major source of readily available Si, while the contribution of other pedogenic forms of Si is negligible, as previously observed [43]. This is in agreement with our results, as rainforest topsoils (having higher ASi concentrations) showed greater Si release than oil-palm topsoils (having lower ASi concentrations) (Figs. 1a, and 2a). However, no clear correlation between released Si and ASi was found (data not shown), suggesting that other Si pools could also contribute to Si release into rainwater. As phytoliths represent the main fraction of BSi in topsoils [34], we suppose that losses of ASi in the topsoils of oil-palm plantation inter-rows are caused by disruption of phytolith return through litter decomposition [44–46], because the oil-palm inter-rows do not receive litter from oil palms. In addition, topsoil erosion, a common phenomenon in oil-palm plantations, may involve export of phytoliths and may therefore be an important driver of phytolith and SOM losses from inter-rows of oil-palm plantations [28, 47–50]. The ASi concentrations and amounts of Si released from rainforest topsoil samples (Figs. 1a, and 3b) are assumed to reflect intact Si cycling comparable to other tropical ecosystems [44, 45, 51].

The litter samples released similar amounts of Si as O horizon samples that were studied by Unzué-Belmonte et al. [19]. They leached O horizon material (0.1 g) from Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*) with rainwater (10 mL) for 24 h. Si release from oil-palm litter observed in our study was in the range of Si release from O horizon material of spruce ($60 \pm 10 \mu\text{g g}^{-1}$), and Si release from rainforest litter in our

study was similar to Si release from O horizons under European beech ($40 \pm 3 \mu\text{g g}^{-1}$) [19]. In general, we found increased Si release from untreated oil-palm litter compared to untreated rainforest litter after 28 h of leaching (Fig. 2b). This finding corresponds well with the difference in total Si concentrations of oil-palm and rainforest litter (Fig. 1b). Munevar and Romero [27] analyzed the concentration of total Si of 418 oil-palm leaf (No. 17) samples in Colombia. Si concentrations ranged from 0.9 to 4.1 wt.-% (mean 2.3 ± 0.7 wt.-%). Although Munevar and Romero [27] used a different extraction procedure (20 mL of 4.5 M HF and 1 M HCl), we found similar total Si concentrations in the Indonesian oil-palm litter samples taken from the frond piles (1.4–4.2 wt.-%, mean 2.3 ± 0.5 wt.-%, Fig. 1). Total Si concentrations in the rainforest litter (0.6–2.1 wt.-%, mean 1.3 ± 0.2 wt.-%) were in agreement with total Si concentrations found in litterfall of tropical tree species in Borneo (up to 1.4 wt.-%) [52] and Congo (1.5 ± 0.2 wt.-%) [44].

Differences in Si release of litter samples from rainforest and oil-palm plantations were not statistically significant, due to the high variability between field replicates of both LULC types. The observed variability in the Si release from oil-palm litter may be caused by different ages of frond piles, and varying plantation ages [2]. The plantation ages varies between 7 to 16 years [2], thus frond pile ages might have the same age range. The age of the frond piles and the phytoliths enclosed in the litter may be a relevant factor on Si release, as a number of studies found a dependency of phytolith dissolution rate on phytolith age, with increasing phytolith stability over time [36, 44, 53, 54]. An effect of litter age caused by different decomposition stages is not expected, as Si release from bamboo and horsetail litter was shown to be independent of cellulose hydrolysis [55]. The observed variability in the litter samples from rainforest may be explained by the great diversity of tropical rainforests [56], which may involve differences in Si uptake between plant species [57, 58] as well as differences in phytolith solubility.

4.2 Impact of Fire on Si Release from Topsoils and Litter

Burnt topsoils and litter samples clearly showed an increase in Si release compared to untreated samples (Fig. 3). These results are in agreement with those of e.g., Xiao et al. [25], Guo and Chen [59] and Unzué-Belmonte et al. [19], who also found increased Si release from plant litter after burning (350–500 °C). Although we did not find a significant difference between the two temperatures applied, the amounts of Si released from topsoils and litter samples burned at 500 °C generally exceeded those released from samples burned at 300 °C (Fig. 3). This trend would

be in agreement with results of Unzué-Belmonte et al. [19], who found a dependency of Si release on fire temperature. This temperature-depending Si release might apply to the Si release from burnt litter and topsoils of rainforest and oil-palm plantations in Sumatra as well.

Si release in our experiment was not influenced by pH, as we kept this factor largely constant. Thus, the increase in Si release after burning must have been related to other factors. It can be explained by the combustion of the organic matrix surrounding the phytoliths during the burning of the topsoil and litter samples. We assume that in this way Si compounds that had previously been protected in the biomass were exposed, and that thus the burning led to an increase in reactive surface area of Si compounds and hence enhanced Si release from the samples [19, 23, 44, 60]. In addition, the combustion of organic matter may have reduced hydrophobicity [61–64], allowing for increased water contact, in turn leading to enhanced Si release.

The differences between LULC types with respect to Si release from burnt topsoil and litter samples were similar to those observed for untreated samples, with Si release from oil-palm litter exceeding that of rainforest litter, and Si release from rainforest topsoil samples exceeding that of oil-palm inter-row topsoil samples (Fig. 3a and b). Possible explanations include the difference in SOM contents between oil-palm plantations and rainforest, topsoil erosion in inter-rows of oil-palm plantations, and differences in ASi and total Si pools as discussed above (see Sections 4.1, and 4.2). In addition, decreased Si release from oil-palm inter-row topsoil samples compared to rainforest topsoil samples may be due to the use of fire in the course of establishing new oil-palm plantations. If a large fraction of Si in litter and topsoils becomes more readily mobilizable after burning, this mechanism may lead to a sudden and substantial increase in Si leaching and export from the soil-plant system, especially under the humid-tropical conditions of the study area. Thus, the observed decreased Si release from topsoils of oil-palm plantation inter-rows may be the result of previous use of fire in the course of land conversion, triggering initial Si losses (Section 2.1) [30].

Fires were relatively infrequent in Indonesia prior to anthropogenic impact, and the increase in the frequency of fire events over the past decades was related to land use and increasing population [65–67]. Episodes with increased frequency of fire events naturally occur during drought years induced by ENSO and the Indian Ocean Dipole (IOD). Short-lived local fires can also occur out of these periods [10] [11]. In Indonesia, fires were detected in rubber, wood fiber and oil-palm plantations, forested areas and shrubland [10, 11, 68, 69]. Cattau et al. (2016) [10] reported that 16.6% of the fires detected between 2012 and 2015 on Sumatra and Kalimantan were located within legal agro-industrial

oil-palm concessions. Adrianto et al. (2019) [69] showed that in Riau Province on Sumatra, Indonesia, most fires occur when forest or shrubland is converted to oil palm, wood fibre and logging plantations. They showed, that in regions that did not change land-cover a total area of $0.017 \text{ km}^2 \text{ y}^{-1}$ was affected by fire in plantations over the period 2002 - 2016 compared to shrubland ($0.067 \text{ km}^2 \text{ y}^{-1}$) and primary wet and dry forests ($0.001 \text{ km}^2 \text{ y}^{-1}$) [69]. Marlier et al. (2015) [68] reported that in 2006 most of the plantation-related fire emissions on Kalimantan came from oil-palm concessions (33% of the area and 67% of the emissions of fires). According to Kurniawan et al. (2018) [30], the oil-palm plantations from our study were established after clearing and burning the previously grown jungle rubber, which before had replaced lowland rainforest. Although the frequency of fires is much lower in oil-palm plantations than in forests, both land-cover types are affected by fires, which in turn may have an impact on Si cycling.

The results of fire-treatment experiments conducted in the laboratory are not directly transferable to field situations, because fire intensity and duration may vary widely [39, 67, 70], depending on fuel load, water content of the biomass [71], stacking pattern, climatic conditions and the size of the area that is burned [67, 70]. Thereby, the duration of a fire may range from minutes up to several hours [70]. Temperatures may vary from maximum surface temperatures of $400 \text{ }^{\circ}\text{C}$ in a ground fire (affecting litter and organic layer) [72] to $\geq 500 \text{ }^{\circ}\text{C}$ in shifting-cultivation fires [73]. In shifting-cultivation experiments conducted in Jambi Province, soil-surface temperatures during fire events varied widely, from 100 to $600 \text{ }^{\circ}\text{C}$ within the impacted area [67]. Temperatures of $600 \text{ }^{\circ}\text{C}$ were even exceeded where material with high fuel loads (e.g. tree trunk) burned [67]. Temperatures selected for our study were in the range of the temperatures that were measured in the field studies mentioned above, in order to assess the Si release from litter and topsoil induced by moderate ($300 \text{ }^{\circ}\text{C}$) and severe fire ($500 \text{ }^{\circ}\text{C}$). These temperatures likely occur during clearance for agricultural and plantation development. In most laboratory experiments combustion times of 5 - 25 min were applied [39, 74, 75]. It is yet still unknown, how the duration of a fire impacts the Si release from burned soil and plant material. Further studies on the duration of fires are necessary for a better understanding of the variation of Si leaching from burned litter and soil.

The heat transfer into the soil depends e.g. on the surface temperature, the duration of exposure, and the water content and pore-size distribution of the soil [76]. A temperature of $218 \text{ }^{\circ}\text{C}$ was measured in 1 cm soil depth under windrows that were burned after clearing a tropical rainforest [77], but those temperatures could be exceeded in the presence of heavy fuel loads [38]. In this study, the

uppermost 0 – 1 cm of topsoil was used for the laboratory experiment, because it has been demonstrated, that fire mainly affects soil properties in the uppermost cm of the soil [16, 31–33].

5 Conclusions

Based on our observations, we conclude that LULC transformation from rainforest to oil-palm plantations results in alteration of Si pools in topsoil and litter. The management of oil-palm plantations leads to a spatially uneven redistribution of soil Si, as Si return to soils mainly takes place under frond piles that are usually heaped up in every second inter-row. Topsoil erosion further enhances Si depletion of the soil under inter-rows. In addition, burning substantially enhances Si release from litter and topsoils. The high amounts of Si that are released to the soil after the fire are prone to leaching under the given climatic conditions. Thus, Si losses are to be expected after conversion of rainforest to oil-palm plantations involving burning as practice. However, the knowledge about the impact of transformation of lowland rainforest into oil-palm plantations on Si cycling is still very limited. Neither the extent of Si losses nor the effects of the spatially uneven Si distribution in oil-palm plantations are known. Such knowledge is needed, as oil palms are considered Si-accumulating plants, and their increased uptake of plant-available Si may considerably alter soil Si pools. Given the global relevance of oil-palm cultivation, the potential effects of these practices should be subject of future research, as they might lead to enhanced soil Si depletion, especially in naturally heavily Si-depleted soils of the tropics. An option to avoid potential Si depletion of soils under oil-palm plantations could be the return of the ash that is produced during oil production, as Si fertilizer on plantations.

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Compliance with Ethical Standards

Conflict of interests The authors declare that they have no conflict of interest.

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