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Late Holocene Human Impact on Tropical Soil Erosion in the Maritime Continent

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Key Points:

- Elevated fire occurrence and soil erosion around 3,500 years ago was most likely due to early swidden agriculture and Austronesian dispersal
- The impact of human land use on soil erosion was further amplified by increased rainfall intensity and seasonality
- The transition from swidden to permanent agriculture likely further accelerated soil erosion

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Human activities have profoundly modified the fluxes in the global sediment cycle. However, the anthropogenic forcing on soil erosion beyond instrumental records or historical documentation is largely unknown. Here we analyze markers for low-intensity fires and soil erosion in East Java over the past 5,000 years. We find evidence of a substantial human impact on fire occurrence due to the onset/intensification of swidden cultivation around 3,500 years ago, in the absence of changes in regional hydroclimate or vegetation. Highest soil erosion occurred during the past 500 years, coinciding with a transition toward permanent agriculture. Human-impacted soil erosion was further amplified by intense monsoonal rainfall and strong rainfall seasonality around 2,000 and 300 years ago. With such rainfall anomalies projected to occur with higher frequency and severity in the tropics under the ongoing greenhouse warming, our results suggest an accelerating erosion rate in the future, posing risks for natural resources.

Plain Language Summary Present-day human activities, such as agriculture and deforestation, are causing soil erosion and the associated removal of fertile soils. Land use throughout tropical Southeast Asia is especially intense with increased establishment of oil palm plantations. However, the manner and degree to which humans influenced soil erosion in this region in prehistoric times when instrumental records or historical documentations were not available is largely unknown. In an attempt to gain a picture of human land use and its effect on the soils and landscapes of East Java, Indonesia, we analyze chemical fossils preserved in the sediments of the seafloor. We find evidence of an increase in human activities around 3,500 years ago related to early farming practices. This timing corresponds to archeological evidence indicating the arrival of the Austronesian-speaking people in Java. Human-impacted soil erosion was further amplified by high summer rainfall and strong rainfall seasonality around 2,000 and 300 years ago. Such rainfall patterns are projected to occur more often and more severely not only in Southeast Asia but also in the global tropics under the ongoing global warming. Our results indicate that under these conditions, greater soil erosion will occur in the tropics in the future. This may pose risks for agriculture and human use of natural resources.

1. Introduction

Modern human activities dominate the fluxes of sediment supply and transport into the oceans: from 1950 to 2010 humans increased global soil erosion by around 200%, while at the same time reduced approximately 50% of global fluvial suspended load by damming (Syvitski et al., 2022). Human land use such as modern-day agriculture is the primary cause of accelerated soil erosion (Borrelli et al., 2017; Labrière et al., 2015). The soil erosion rate of cropland, for example, is 77 times higher than that of forests and 7 times higher than the average of other natural vegetation types (Borrelli et al., 2017). The Maritime Continent—the vast region between the Indian Ocean and the Pacific Ocean including the archipelagos of the Lesser and Greater Sunda Islands, Borneo, New Guinea, the Philippine Islands, the Malay Peninsula etc.—has some of the highest sediment yields (sediment load divided by

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drainage area) in the world (Syvitski et al., 2005), contributing to about 20% of the global sediment discharge in 2010 (Syvitski et al., 2022). It is also a region characterized by the most significant increases in soil erosion globally in the 21st century (Borrelli et al., 2017). With the highest yields from planted oil palms, intensive human land use there plays an important role in the modern-day sediment budgets (Meijaard et al., 2020). However, the extent to which prehistoric human activities caused soil erosion during the mid- to late Holocene in the Maritime Continent, that is the "deep root of the Anthropocene" (Roberts et al., 2021), remains largely unexplored, owing to poor preservation of evidence for human activities in hot and humid environments (Roberts et al., 2021; Stephens et al., 2019). This deep root can serve as a reference point and by comparing to modern-day, it is possible to quantify the changing magnitude of human influence on landscapes, such as the impact of industrial agriculture on soil erosion (Dotterweich, 2013).

Fire is considered to be of anthropogenic origin in tropical rainforests because natural fires are extremely rare in such environments (Bowman et al., 2011; Hoffmann et al., 2012). Therefore, nearly all modern fires throughout the Maritime Continent can be considered as human-induced (Reid et al., 2013). Consequently, evidence of past fires in the Maritime Continent can be used as an indicator of past human activities. Swidden cultivation (also called shifting cultivation or slash-and-burn) has been a fundamental agricultural practice in the tropics for centuries to millennia, in which areas of vegetation are cleared by slashing and burning, and then used for cultivation before being left fallow (Mertz et al., 2009). The fallow phase (5–20 years) is longer than the cultivation period (1–3 years) to allow for the regrowth of woody vegetation, before the area is cleared again (Mertz et al., 2009). Swidden induced soil erosion happens predominantly during the cultivation phase, and is one order of magnitude higher than that during the fallow period (Valentin et al., 2008). Over the past decades, political and economic pressures have caused a general transition from swidden agriculture into permanent land use types such as monoculture tree/crop plantations, annual cash crops and paddy rice fields (van Vliet et al., 2012). Such changes further accelerate soil erosion (van Vliet et al., 2012). Aside from human land use, hydroclimate affects soil erosion by the erosive power of rainfall, that is rainfall erosivity (Borrelli et al., 2017). The erosivity of rainfall can be quantified by rainfall intensity in general, with more intense rainfall causing more soil erosion (Borrelli et al., 2017).

Here, we reconstruct 5,000 years of soil erosion and fire occurrence based on molecular markers analyzed in marine sediments collected off East Java, Indonesia (Figure 1). We compare these results with a reconstruction of hydroclimate using the stable hydrogen isotope compositions (δD) of leaf wax lipids, which are not directly influenced by human activities, to differentiate the impact of prehistoric human activities on soil erosion from the role of changing hydroclimate. We use the stable carbon isotope composition ($\delta^{13}C$) of leaf wax lipids in parallel to assess the regional vegetation in the East Javanese catchment (Text S6 in Supporting Information S1).

2. Materials and Methods

2.1. Sediment Core Sampling

Samples were collected from the upper 250 cm of the sediment core GeoB10053-7 south off Java (8° 40.59′S; 112° 52.35′E; 1,375 m water depth). Analyses of leaf wax lipids and levoglucosan are based on the same set of samples. These samples were taken from depth intervals of two previous publications (Ruan et al., 2019, 2020) to increase the temporal resolution of the records specifically over the past 5,000 years. The depth intervals vary from 2 to 13 cm with an average of 5 cm. A clear distinction between new data and published data is stated in the data set files on Pangaea (https://doi.pangaea.de/10.1594/PANGAEA.962683) and shown in Figure 2. Branched glycerol dialkyl glycerol tetraethers (brGDGTs), on the other hand, were measured using a separate set of samples taken at 5 cm intervals with depths identical to the published lithogenic data set (Mohtadi et al., 2011). The lithogenic fraction of marine sediment represents the terrigenous fraction (Mohtadi et al., 2011). The age model of the core was established (Mohtadi et al., 2011), and updated using rbacon 3.1.1 and the Marine20 calibration (Blaauw & Christen, 2011) (details in Text S2 in Supporting Information S1). The average sample resolution is around 120 years. The marine sediments from our core integrate material from the catchment area of multiple rivers to the south of the volcanic arc mountain ranges of East Java (shown in Figure 1b), with fluvial discharge as the major transport process (Mohtadi et al., 2011).

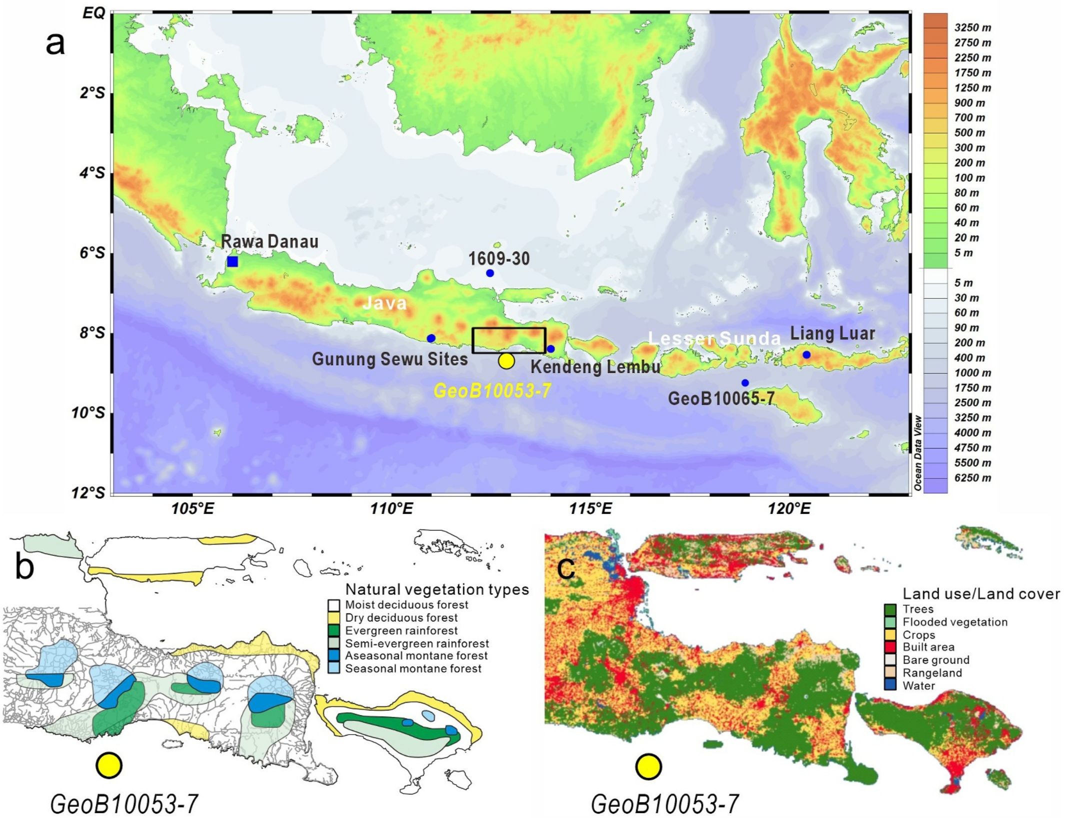

Figure 1. Site locations. (a) The locations of sediment core GeoB10053-7 (yellow dot) and other sites discussed in the text (blue dots). The black rectangle indicates the approximate catchment regions for GeoB10053-7. Figure constructed in Ocean Data View (http://odv.awi.de). (b) The regional distribution of natural vegetation types in East Java depends on the rainfall distribution as well as elevation (Whitten et al., 1996). Moist forest vegetation types dominate the area despite dry forests located in coastal regions. The modern rivers are shown by gray lines, modified from Houser et al. (2022). (c) Sentinel-2 land use/land cover of East Java (Karra et al., 2021). Since Java is one of the most densely populated areas in the world, most of the natural vegetation has been cleared due to intensive land use.

2.2. Lipid Extraction

The lipid extraction was performed on the freeze-dried samples. After adding an internal standard (squalane) to each sample, lipid extractions were carried out using a DIONEX Accelerated Solvent Extractor (ASE 200) first with a mixture of dichloromethane to methanol (9:1) and then with methanol, both at 1000 psi and 100°C (three cycles, 5 min each). For the extracts with dichloromethane to methanol (9:1), desulphurization was carried out with activated copper overnight at room temperature, before water was removed using 2-cm Na_2SO_4 columns. Saponification was carried out with 0.1 M KOH-solution, after which neutral fractions were recovered by *n*-hexane. Silica gel columns (5-cm) were used to separate the neutral fractions: elution with *n*-hexane, dichloromethane, and dichloromethane to methanol (1:1) yielded the apolar, ketone and polar fractions, respectively. The apolar fractions were additionally eluted with *n*-hexane over 5-cm $AgNO_3$-coated silica gel columns to remove unsaturated compounds. The hydrogen and carbon isotopes of leaf wax *n*-alkanes were measured using the apolar fractions.

2.3. Levoglucosan Analysis

Levoglucosan analysis was based on the methanol extracts as described by Ruan et al. (2020), using an Agilent 1290 Infinity Ultra-High Performance Liquid Chromatography coupled to an Agilent 6230 Time-Of-Flight (TOF) mass spectrometer. To account for biases due to sediment properties and sediment rates, the accumulation rate (AR) of levoglucosan (ng cm^{-2} kyr^{-1}) was calculated by multiplying its content (ng g^{-1}) with the dry bulk density

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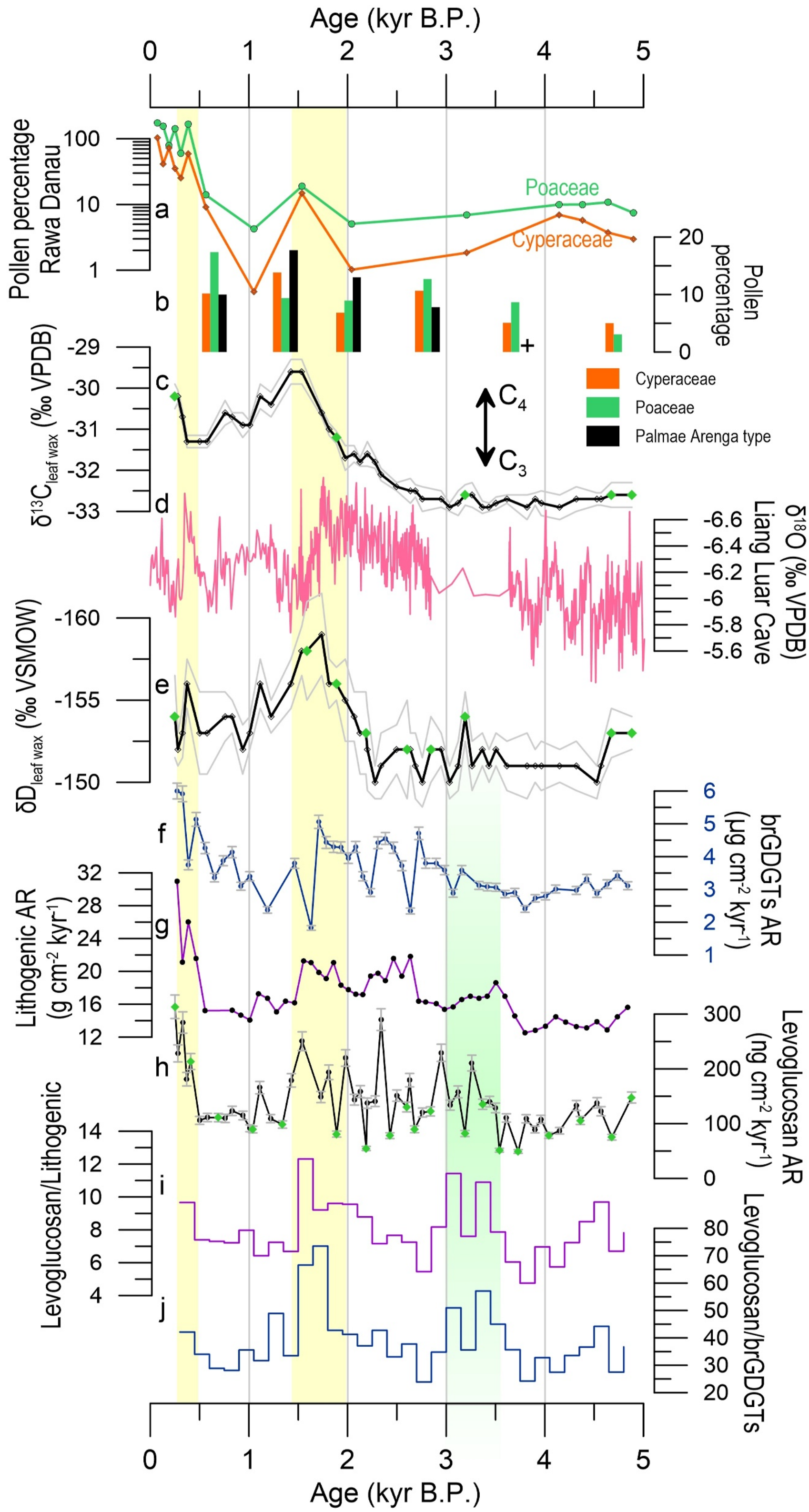

Figure 2.

of the sediment (g cm^{-3}), and the sedimentation rate (cm kyr^{-1}) based on the updated age model. The increase in levoglucosan AR is thus independent of the rise in fluvial sediment discharge.

2.4. Leaf Wax Lipid Analysis

The analyses of leaf wax lipids and their isotopes were performed as described previously (Ruan et al., 2019). Analytical details are provided in Text S6 in Supporting Information S1. The δD values were calibrated against the external H_2 reference gas, and are reported in ‰ against Vienna Standard Mean Ocean Water. The long-term mean absolute deviation of δD measurement based on the external standard was 3‰. Samples were analyzed in duplicate, except for five samples that were analyzed only once because of low compound abundances. The difference between the duplicates ranges from <1 to 4‰ with a mean value of 1‰ for each homolog (n-C_{29}, n-C_{31} and n-C_{33}).

The $\delta^{13}C$ values were calibrated against the external CO_2 reference gas, and are reported in ‰ against Vienna PeeDee Belemnite (VPDB). The long-term mean absolute deviation based on the external standard was 0.3‰. Samples were analyzed in duplicate, except for 13 samples that were measured only once due to low compound abundances after δD analyses. The difference between the duplicates ranges from <0.1 to 0.4‰ with a mean value of 0.1‰ for each homolog (n-C_{29}, n-C_{31} and n-C_{33}).

The δD ($\delta^{13}C$) values of the three homologs (n-C_{29}, n-C_{31} and n-C_{33}) show similar trends through the past 5,000 years, so a weighted average δD ($\delta^{13}C$) record is calculated based on three homologs (further details in Text S6 in Supporting Information S1).

2.5. GDGT Analysis

The method used for extracting GDGTs was as previously described (Chen et al., 2014) Briefly, lipids were extracted using ultrasonication, following the addition of internal standards including C46 GTGT. After saponification, the neutral fractions were separated with silica gel column chromatography, and GDGTs were eluted in F3 with MeOH. F3 were filtered through PTFE filters and analyzed using an Agilent 1260 Infinity II ultra-high-performance liquid chromatography-mass spectrometry (UHPLC-MS) system using the method as described by Tung et al. (2024). The contents of all the brGDGTs were added for the calculation of AR. Instrument performance was monitored by repetitive measurements ($n = 9$) of one standard sample before, between and after samples, yielding a precision of 4%.

3. Results

We use the AR of brGDGTs, markers for soil-derived organic matter (Hopmans et al., 2004), to indicate levels of soil erosion in the catchment of the sediment core GeoB10053-7 (Figure 2f). It is noteworthy that in marine environments, brGDGTs can also be produced in-situ (Sinninghe Damsté, 2016). In-situ produced brGDGTs are characterized by high $\#rings_{tetra}$ index values >0.7 (Sinninghe Damsté, 2016). The $\#rings_{tetra}$ index of GeoB10053-7 varies between 0.36 and 0.51, indicating a soil terrestrial origin of the brGDGTs (further details in Text S7 and Figure S2g in Supporting Information S1). The brGDGT AR increased from a mean value of 3 μg cm^{-2} kyr^{-1} between 5,000 and 3,500 years B.P. (before 1950 CE) to ∼3.5 μg cm^{-2} kyr^{-1} around 3,000 years B.P., and then from a mean value of 4.3 μg cm^{-2} kyr^{-1} between 2,000 and 1,500 years B.P. to a mean

Figure 2. Comparison of various proxy records from sediment core GeoB10053-7 and other sites. (a) Percentages of two C_4 plants, grass pollen (Poaceae, green) and sedge pollen (Cyperaceae, orange) in Rawa Danau, West Java. (b) Percentages of grass pollen (Poaceae), sedge pollen (Cyperaceae) and *Arenga* (an economically important plant) type pollen. "+" means that the *Arenga* type pollen is present at that depth but statistically not significant to calculate its percentage. The percentages in panels (a and b) are calculated on the pollen sum of the dryland trees and shrubs. (c) The weighted-average $\delta^{13}C$ values of n-alkanes of core GeoB10053-7. (d) $\delta^{18}O$ of Liang Luar Cave speleothems in Flores (Griffiths et al., 2009). (e) The weighted-average δD values of n-alkanes of core GeoB10053-7. (f) Accumulation rates of branched glycerol dialkyl glycerol tetraethers (brGDGTs) indicating levels of soil erosion. (g) Accumulation rates of the lithogenic fraction (Mohtadi et al., 2011). (h) Accumulation rates of levoglucosan indicating fire occurrence. (i) The ratio of levoglucosan accumulation rate to the lithogenic accumulation rate (ng/g). (j) The ratio of levoglucosan accumulation rate to the brGDGT accumulation rate (ng/μg). Green diamonds in panels (e and h) represent published data from refs (Ruan et al., 2019, 2020). Information about the errors is given in Text S3 and S6 in Supporting Information S1. The key time intervals in the discussion are highlighted by the green and yellow vertical bars.

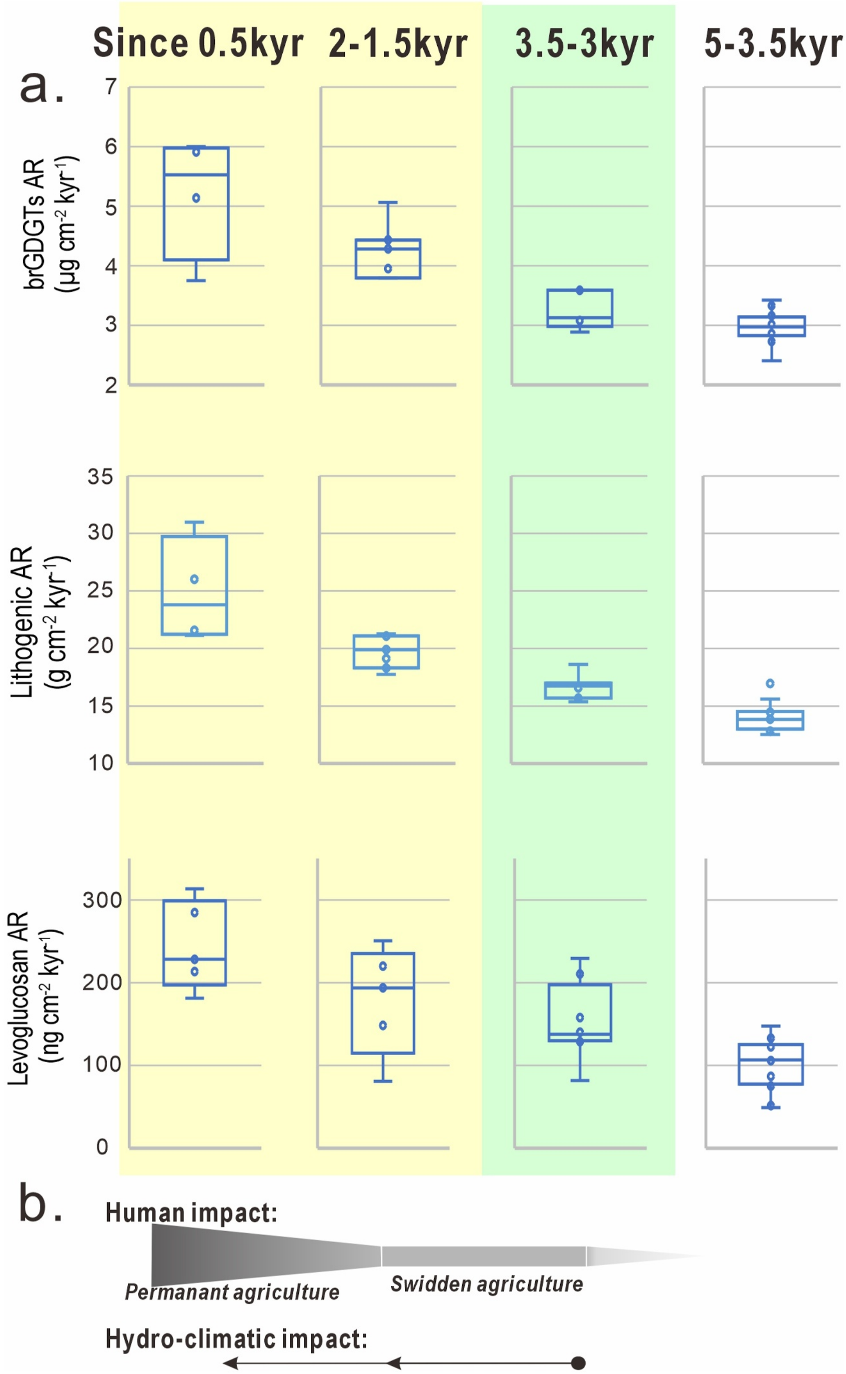

Figure 3. Comparison of proxy records during four key time intervals in Figure 2. (a) Box plots of accumulation rate distribution during each time interval. (b) Schematic representation of processes mostly likely causing the differences between time intervals.

value of 5.5 µg cm^{-2} kyr^{-1} over the past 500 years (Figures 2f and 3a). The maximum values occur in the most recent samples. The brGDGT AR is significantly correlated with the lithogenic AR (Spearman correlation: $r = 0.54$, $p < 0.01$; Table S2 in Supporting Information S1). The ratio of brGDGT AR to lithogenic AR remains relatively constant through the past 5,000 years (Figure S3 in Supporting Information S1).

We use the AR of levoglucosan, a molecular marker for low-intensity fires (Suciu et al., 2019), to indicate past fire activity in the catchment (Figure 2h). The levoglucosan AR increased from a mean value of 110 ng cm^{-2} kyr^{-1}

between 5,000 and 3,500 years B.P. to ∼150 ng cm^{-2} kyr^{-1} around 3,000 years B.P. It then rose from a mean value of 190 ng cm^{-2} kyr^{-1} between 2,000 and 1,500 years B.P. to a mean value of 230 ng cm^{-2} kyr^{-1} over the past 500 years (Figure 3a). The value of standard deviation/mean, a measure of variability, based on the levoglucosan AR record is 0.42. It is higher than the standard deviation/mean of brGDGT AR (0.24) (Text S8 in Supporting Information S1). The ratios of levoglucosan AR to lithogenic AR/brGDGT AR are calculated after normalization to identical time intervals (spaced by 150 years). The levoglucosan/lithogenic ratio is a measure of the mass of levoglucosan per mass of terrigenous sediment. The levoglucosan/brGDGTs ratio is a measure of the mass of levoglucosan per mass of soil-derived organic matter. Both of the two ratios are significantly correlated with levoglucosan AR (Spearman correlation: $r = 0.81$ and 0.85, $p < 0.001$; Table S2 in Supporting Information S1) while lack significant correlation with brGDGT AR/lithogenic AR. Together, the ratios indicate how extensive fire occurrence was at a certain time of the record. They are higher than the upper quartile levels (9 for levoglucosan/lithogenic and 43 for levoglucosan/brGDGTs) from 3,500 to 3,000 years B.P. and from 2,000 to 1,500 years B.P. (Figures 2i and 2j).

The stable carbon isotope compositions ($\delta^{13}C$) of leaf wax derived *n*-alkanes from our sediment core reflect the relative contributions of waxes from C_3 versus C_4 vegetation in the catchment area (Dubois et al., 2014; Ruan et al., 2019). Our $\delta^{13}C$ record (Figure 2c) shows a gradual C_4 vegetation expansion since 3,000 years B.P., which reached the greatest extent between 2,000 and 1,000 years B.P. The *n*-C_{33} alkane homolog showed the largest positive isotopic excursion (Figure S2a in Supporting Information S1), further supporting the C_4 expansion (Ruan et al., 2019; Text S6 in Supporting Information S1). Another C_4 vegetation expansion occurred around 300 years B.P. (Figure 2c and Figure S2a in Supporting Information S1).

The leaf wax δD changes in response to changes in the δD values of precipitation (Sachse et al., 2012), which primarily reflect changes in rainfall intensity via the "amount effect" in the study area: more negative precipitation δD values indicate higher rainfall intensity (Belgaman et al., 2017; Ruan et al., 2019; Suwarman et al., 2013). The most prominent negative shift in our leaf wax δD record occurred between 2,000 and 1,000 years B.P. (Figure 2e), indicating that the East Javanese catchment area experienced the most intense monsoonal rainfall during this period. This shift occurred concurrently with the positive excursion in the $\delta^{13}C$ record (Figure 2c). Another negative shift in leaf wax δD, though smaller in extent, is seen around 300 years B.P., also concurrent with a positive excursion in the $\delta^{13}C$ record (Figures 2c and 2e).

4. Discussion

4.1. Enhanced Soil Erosion Around 3,500 Years Before Present Related to Human Activities

Regarding GeoB10053-7, the lithogenic AR reflects fluvial sediment discharge, since fluvial transport was the major process of terrigenous sediment supply over the past 5,000 years (Mohtadi et al., 2011). Its significant correlation with the AR of brGDGTs, as well as the relatively constant ratios of brGDGT/lithogenic through the record, suggest that both reflect soil erosion, even though lithogenic AR also has contributions from bedrock and/or river channel material (Syvitski et al., 2022). By comparing these two time intervals before and after 3,500 years B.P., the lithogenic AR increased significantly (*t*-test statistic = 3.92, *p*-value <0.01), while the increase in the AR of brGDGTs was substantial but less significant (*t*-test statistic = 1.78, *p*-value = 0.11) (Figures 2f and 2g). Altogether they both suggest a rise in the level of soil erosion during this time period. The rise in the AR of levoglucosan around 3,500 years B.P. (*t*-test statistic = 2.02, *p*-value = 0.10) (Figure 2h) suggests a substantial increase in fire occurrence. We interpret this as an increase in fire activity, which is further exemplified by rises in both the levoglucosan/lithogenic ratio and the levoglucosan/brGDGTs ratio—measures to assess the mass of levoglucosan content per mass of eroded soil (Figures 2i and 2j). The primary drivers of fire on the landscape are hydroclimate, vegetation, and human activities (Bowman et al., 2011). Previous work based on the same sediment core GeoB10053-7 has concluded that climate-driven fire occurrence in East Java over the past 22,000 years increases with changes in regional vegetation cover and/or rainfall regime (Ruan et al., 2020). However, between 4,000 and 3,000 years B.P. there was no change in either regional vegetation cover as indicated by the leaf wax $\delta^{13}C$ record, or rainfall intensity as indicated by the leaf wax δD record (Figures 2c and 2e). Therefore, the substantially enhanced soil erosion and fire occurrence between 4,000 and 3,000 years B.P. was most likely caused by early human activities rather than hydroclimatic or vegetation changes. The palynological data from GeoB10053-7, despite their relatively low temporal resolution, show a rise in the percentage of *Arenga* (Palmae) type pollen (sugar palm, an economically important plant) after 3,500 years B.P., together with increasing percentages of grass and sedge pollen (Figure 2b) (Ruan et al., 2019). Such a palynological pattern points to anthropogenic clearance of tree species and the resultant development of grasses and sedges (van der Kaars & van den Bergh, 2004; Poliakova et al., 2017). Our evidence for increased fire use further suggests swidden cultivation as the early farming practices on Java, which caused the change in palynological record. The average levoglucosan AR from 5,000 to 3,500 years B.P. is ∼100 ng cm^{-2} kyr^{-1}, while the average from 3,500 to 1,500 years B.P. is ∼150 ng cm^{-2} kyr^{-1}. It implies that swidden cultivation may account for around 1/3 increase in levoglucosan AR in this environment. These results indicate that the presently intensely used lands of Java had already been affected by human fire use and human-induced soil erosion thousands of years ago, indicating the "deep root of the Anthropocene" (Roberts et al., 2021).

The changes around 3,500 years B.P. are roughly associated with the transition of the East Javanese human society from the Keplek Phase to the Gupuh Phase (Simanjuntak & Asikin, 2004). The Keplek Phase (pre-neolithic layer in archeological sites of East Java, named after the cave Song Keplek), is characterized by lithic artifacts and bone tools that date from 12,000 to 4,000 years B.P. (Simanjuntak & Asikin, 2004). The inhabitants during that period were mostly hunters and gatherers, who used stone axes and shell adzes but did not use pottery (Bellwood, 2007). Charred materials were found in the Keplek Phase (Simanjuntak & Asikin, 2004), implying that the inhabitants already used fire as a tool by then but not for agriculture. The Gupuh Phase (named after the cave Song Gupuh, also called the Neolithic stage) in East Java is potentially associated with the arrival and expansion of Austronesian-speaking people who are thought to have had an agricultural economy and introduced pottery use and stone adze manufacture, while pre-Austronesian hunters and gatherers survived in diminishing numbers (Bellwood, 2007; Hung, 2019).

The onset date of the Gupuh Phase, however, is still debated (Simanjuntak, 2002). Since most of the Austronesian archeological sites identified in Java are open-air, conclusive dating on the pottery or stone adzes is challenging (Simanjuntak, 2002). The earliest secured Neolithic date in Java so far is at Kendeng Lembu with pottery dated to around 1,300 years B.P. (Noerwidi, 2009), which is substantially later than the youngest dates of the Keplek Phase around 4,000 years B.P. Since fire is more essential in early (swidden) agriculture than in hunting and gathering, the rise in fire occurrence around 3,500 years B.P. in our record, together with the change in the palynological record toward economically important plants, can be considered a signal of regional Austronesian arrival around that time in East Java. It is noteworthy that no substantial change in our leaf wax $\delta^{13}C$ record occurred around 3,500 years B.P. (Figure 2c). This shows that the large-scale vegetation composition of C_3 versus C_4 plants remained relatively stable during that period despite early farming practices.

Possible evidence of rice cultivation as early as 5,000 years B.P. has been found in a swamp in the Gunung Sewu region (southeast coast of Java, Figure 1a), although the age uncertainty of that date is as large as about 1,500 years (Chacornac-Rault, 2005). In the same layer where the phytolith of rice is present, economically important plants (*Arecaceae* and *Arenga*) were found together with a peak in charred plant debris, indicative of fire use, and presence of *Casuarina* pollen indicates a disturbance in vegetation (Chacornac-Rault, 2005). These lines of evidence indicate that humans selectively modified the vegetation of the Gunung Sewu region, both by protecting certain existing plants that became important to the economy as well as by initiating the cultivation of rice (Chacornac-Rault, 2005; Sémah & Sémah, 2012). Despite the limited age constraints of these findings, they do generally agree with our results, suggesting an early onset of agriculture around 3,500 years B.P.

Over the entire 5,000 years of the record, the significant correlations in between levoglucosan AR, brGDGT AR and lithogenic AR suggest a close connection between fire occurrence and soil erosion. A closer examination, however, shows that the correlations before and after 3,500 years B.P. differ (Figure S4 in Supporting Information S1). This suggests that the onset of early farming changed the connection between human activities and soil erosion.

4.2. Soil Erosion and Sediment Discharge Amplified by Hydroclimate

The period of 2,000–1,500 years B.P. was characterized by the most negative leaf wax δD values in our record and in general negative $\delta^{18}O$ values of a high-resolution speleothem record from Liang Luar Cave in Flores, Indonesia (Griffiths et al., 2009), suggesting the most intense monsoonal rainfall in East Java and beyond (Figures 2d and 2e). Our leaf wax $\delta^{13}C$ record documents a distinct shift toward positive values around 2,000 years B.P., indicating an expansion in regional C_4 vegetation in the East Javanese catchment (Figure 2c). Substantial forest canopy opening during this period is documented in palynological data from a core in the lowland swamp Rawa

Danau, West Java (Figure 2a) and from a marine sediment core off the Solo River mouth (offshore northern Java) (Poliakova et al., 2017; van der Kaars et al., 2001; site locations in Figure 1a). A leaf wax $\delta^{13}C$ record based on marine sediment core GeoB10065-7 offshore Sumba Island displays a similar shift around 2,000 years B.P. (Dubois et al., 2014) as shown in our $\delta^{13}C$ record. The relatively concurrent vegetation response seen in the above-mentioned records suggests a common forcing over a broad region, especially since the catchments of these records differ in size (Figure 1a) whereas there is variance in intensity of past human activities (Bellwood, 2007). Rainfall seasonality (i.e., the variability of rainfall amount throughout the year) has been shown to mainly control the relative abundance of C_3 versus C_4 vegetation in the humid Maritime Continent by its effect on dry season water stress (Dubois et al., 2014). Thus, high rainfall seasonality (characterized by an intensified and longer dry season) around 2,000 years B.P. over a broad region likely caused the expansion of C_4 vegetation reflected by both isotopic and pollen data (Poaceae and Cyperaceae as major C_4 representations).

Taken together, the rainfall regime in East Java around 2,000 years B.P. was characterized by strong rainfall seasonality with a long dry season (reflected by high leaf wax $\delta^{13}C$ values), and was additionally marked by the most intense monsoonal rainfall (reflected by low leaf wax δD values) compressed in a short wet season (Ruan et al., 2019). A comparison with the time interval 3,500–3,000 years B.P. shows a higher (but statistically insignificant) level of fire occurrence during 2,000–1,500 years B.P. as shown by levoglucosan AR (t-test statistic = 0.42, p-value = 0.69). During both time intervals, elevated ratios of levoglucosan to lithogenic or brGDGTs suggest extensive fire occurrence (Figures 2h–2j). In contrast, significantly higher lithogenic ARs (t-test statistic = 4.28, p-value <0.01) and to a lesser extent brGDGT ARs (t-test statistic = 1.54, p-value = 0.17) occurred during 2,000–1,500 years B.P. than those during 3,500–3,000 years B.P. (Figure 3a). Therefore, more pronounced rainfall seasonality likely amplified soil erosion via rainfall erosivity in addition to human impact around 2,000 years B.P.

When looking at the entire 5,000 years of the record, the significant correlation between $\delta^{13}C$ and δD throughout the record ($r = -0.71$, $p < 0.001$; Table S2 in Supporting Information S1) suggests that both isotopic records reflect changes in hydroclimate, and more specifically, rainfall seasonality. A period with high rainfall seasonality (with the Last Glacial Maximum around 21,000 years B.P. as an example) would favor increased fire occurrence (Ruan et al., 2020). Likewise, the correlation between $\delta^{13}C/\delta D$ and levoglucosan AR ($r = 0.36$, $p < 0.05$ and $r = -0.48$, $p < 0.01$; Table S2 in Supporting Information S1) over the past 5,000 years suggests that such a hydroclimatic impact on fire occurrence persisted on top of the increasing human influence. A drier and longer dry season likely promoted the extensive spread of fires. As an example, the abnormally long dry season in 1997 caused many human-set "managed" fires to evade out of control (Page et al., 2002). In contrast, the significant correlation between $\delta^{13}C/\delta D$ and lithogenic AR ($r = 0.43$, $p < 0.05$ and $r = -0.5$, $p < 0.01$; Table S2 in Supporting Information S1) suggests a hydroclimatic impact on soil erosion. Intense rainfall in the tropics causes high soil erosivity (Labrière et al., 2015), which leads to rivers delivering higher sediment loads (van Noordwijk et al., 2017). In addition, strong rainfall seasonality and human land use limit tree cover and expose soil (Staver et al., 2011), especially in tropical regions where forests stabilize soil and prevent soil erosion (Bruijnzeel, 2004). As a positive feedback, the opening-up of the forest canopy likely provides an environment suitable for expanding farming practices, which in turn leads to more soil exposure and further enhances soil erosion (Labrière et al., 2015). Therefore, strong and seasonally amplified rainfall likely caused the observed high levels of both fluvial sediment discharge and soil erosion in East Java on top of the human impact, in line with modern observations (Suescún et al., 2017).

4.3. Changing Agriculture Regimes and Anthropogenic Forcing of Soil Erosion

Despite the correlation over the entire 5,000-year record, the period of the most pronounced rainfall seasonality (2,000 to 1,500 years B.P.) did not co-occur with the highest levels of fire occurrence or soil erosion. Instead, the highest level of fire occurrence and soil erosion occurred over the past 500 years of the 5,000-year record. A closer comparison between the last 500 years and 2,000–1,500 years B.P. shows a more substantial increase in soil erosion based on either brGDGT AR (t-test statistic = 1.93, p-value = 0.10) or lithogenic AR (t-test statistic = 1.19, p-value = 0.30) than the increase in levoglucosan levels (t-test statistic = 1.0, p-value = 0.34) (Figure 3a). As a result, the levels of both the ratio of levoglucosan/lithogenic and the ratio of levoglucosan/brGDGTs over the last 500 years are not as high as between 2,000 and 1,500 years B.P. (Figures 2i and 2j).

The negative (positive) excursion in the leaf wax δD ($\delta^{13}C$) around 300 years B.P., indicates an enhanced rainfall seasonality (Figures 2c and 2e). A shift toward negative isotopic values is also observed in the $\delta^{18}O$ record of Liang Luar Cave (Griffiths et al., 2009) (Figure 2d). Such a hydroclimatic pattern was similar to that around 2,000 years B.P. but shorter in duration and smaller in amplitude. Therefore, the difference in hydroclimate is not sufficient to explain the different levels of fire occurrence and soil erosion during these two time intervals. It instead suggests the intensification of human land use being the major cause.

Several lines of evidence are in support for this explanation. Economically important plants in two swamp records at Gunung Sewu were little seen around 2,000 years B.P. but became dominant after 1,000 years B.P. (Chacornac-Rault, 2005). The magnitude of increase in grasses and sedges based on pollen records of the Solo River mouth as well as in Rawa Danau is greater around 300 years B.P. than around 2,000 years B.P. (Figure 2a; Poliakova et al., 2017; van der Kaars et al., 2001). In the Solo River record, intense land use around 300 years B.P. is highlighted by the low abundances of arboreal pollen and highest pollen percentages of grasses and sedges; crop cultivation is evidenced by *Zea mays* and *Oryza* type pollen; pine plantation establishment is concluded from the occurrence of *Pinus* pollen (Poliakova et al., 2017). In Rawa Danau, a similar intensification in land use around 300 years B.P is shown by the occurrence of cultivars *Arenga* (sugar palm) and *Cocos nucifera* type (coconut) pollen (van der Kaars et al., 2001). Following the Dutch East India Company (VOC)'s consolidation of power in the 17th–18th centuries, land-use priorities shifted from flexible land-use strategy toward state-managed extraction, favoring wet rice systems in lowlands and coercive cash-crop cultivation (e.g., coffee, sugar) on uplands. VOC policies, including land privatization and forced labor, disrupted the regenerative cycles of swidden cultivation, replacing fallow forests by permanent monocultures to maximize economic yields (Boomgaard, 1992; Kian, 2008). Colonization and the related transition toward permanent agriculture coincides with the highest levels of soil erosion in the 5,000-year record. Since the swidden induced soil erosion during the cultivation phase is one order of magnitude higher than that during the fallow period (Valentin et al., 2008), either shortening or getting rid of the fallow period would largely enhance soil erosion, as reflected by the significant rise in lithogenic and brGDGT AR.

A closer comparison between the last 1,000 years and 4,000–3,000 years B.P. roughly differentiates the regional impact during the onset of swidden cultivation versus the onset of permanent agriculture. The AR of both brGDGTs and lithogenic doubled over the last 1,000 years of the record. Such a rate of increase in soil erosion was about 5 times faster than the increase between 4,000 and 3,000 years B.P. In the meanwhile, the AR of levoglucosan tripled over the last 1,000 years, that is 1.5 times faster than between 4,000 and 3,000 years B.P. This suggests that permanent agriculture largely accelerated the erosion rates compared to swidden cultivation, and thus has a more pronounced environmental impact. The acceleration of fire occurrence, although at a slower pace compared to soil erosion, suggests that fire remained an important part in permanent agriculture such as clearing the land. It is noteworthy that the rise in the ratio of levoglucosan to lithogenic/brGDGTs over the last 1,000 years was not as pronounced as between 4,000 and 3,000 years B.P. It suggests that the regional fire occurrence since 1,000 years B.P. was not as extensive as during the earlier time interval. Human fire use was potentially more controlled with the introduction of fire regulations (Boomgaard, 1992).

5. Implications

Elucidating the patterns and mechanisms of soil erosion in East Java in the past, carries important implications for how tropical regions with human agricultural influence may respond to future climate shifts. In the coming decades, a higher frequency of extreme climate and adverse weather events are predicted for the tropical Indian Ocean (Cai et al., 2014), tropical Pacific (Cai et al., 2018) and tropical Atlantic (Yang et al., 2021). Extrapolating from the results of our study, such intensified rainfall anomalies will further amplify the level of soil erosion in the tropics.

Our study shows that swidden cultivation and the related controlled fire use has been a fundamental agricultural practice in East Java since at least the late Holocene. Our study also shows that the general transition from swidden cultivation to permanent agriculture is associated with an acceleration of soil erosion. Such a transition mimics the trend over the past decades in tropical regions (van Vliet et al., 2012). Yet both the intensity and extent of human land use today (such as the ongoing establishment of new palm oil plantation) are even higher than those shown in our study. More broadly, many regions in the tropics that experienced colonization are still going through a subsequent shift from swidden cultivation toward permanent land use types such as monocultures, which has a more severe environmental impact by making soils in this region very vulnerable to erosion (van Vliet et al., 2012). This will be of particular concern given the predicted future climate changes (Meijaard et al., 2020). Such soil loss and the accompanying removal of fertile soil layers present urgent risks for the livelihoods that depend on agricultural practices and harvest of natural resources within and beyond the Maritime Continent, with severe consequences such as food insecurity, starvation and poverty (Intergovernmental Panel on Climate Change, 2019).

Data Availability Statement

All data in this study are available at Ruan (2023).

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