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East African soil erosion recorded in a 300 year old coral colony from Kenya

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[1] Soil erosion is a key socio-economic and environmental problem in Kenya, which has been poorly documented due to the lack of long, continuous records. Here we present Ba/Ca records from *Porites* corals from the Malindi coral reef documenting the flux of suspended sediment from the Sabaki River with a sub-weekly resolution for the last 300 years. While sediment flux from the Sabaki River is almost constant between 1700 and 1900, a continuous rise in sediment flux is observed since 1900, first due to British settlements and afterwards due to steadily increasing demographic pressure on land use. The peak in suspended sediment load and hence soil erosion occurred between 1974 and 1980 when there is a five to tenfold increase relative to natural levels. This is attributed to the combined effects of dramatically increasing population, unregulated land use, deforestation and severe droughts in the early 1970's. We conclude that despite laudable attempts to instigate soil conservation measures, it is unlikely that there will be a sustainable reduction in soil erosion without a significant improvement in socio-economic conditions. **Citation:** Fleitmann, D., R. B. Dunbar, M. McCulloch, M. Mudelsee, M. Vuille, T. R. McClanahan, J. E. Cole, and S. Eggins (2007), East African soil erosion recorded in a 300 year old coral colony from Kenya, *Geophys. Res. Lett.*, *34*, L04401, doi:10.1029/2006GL028525.

1. Introduction

[2] Soil erosion and land degradation threatens the food security of 2.6 billion people worldwide. The situation is particularly dire in East and Sub-Saharan Africa where per capita food production has declined over the past 45 years [*Sanchez*, 2002]. Erosion and the resultant loss of fertile soil is a key socio-economic and ecological problem in Kenya, affecting all important sectors of its economy (agriculture, production of hydro-power, fisheries, tourism) and damaging marine and terrestrial ecosystems. Yet, the temporal pattern of soil erosion is almost unknown and currently only sparse and rather anecdotal information exists [*McClanahan and Obura*, 1997; *Cole*, 2003]. As a result, the causes, extent and severity of soil erosion in Kenya are subject of ongoing and controversial discussions [e.g., *Ovuka*, 2000]. Developing highly resolved and continuous records of soil erosion is therefore important for (1) evaluating climatic and anthropogenic contributions to soil erosion, (2) placing present-day soil erosion into a longer historical context, (3) assessing the effectiveness of soil conservation programs and other land management measures, and (4) enhancing the awareness of policy makers to this major environmental problem. To aid in filling this gap of knowledge, we present a 300-year long Barium record from two Kenyan coral colonies (*Porites sp.*, 3°15′S, 40°9′E; Malindi Marine National Park; Figure 1a), which documents a dynamic history of soil erosion in the Sabaki river drainage basin.

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2. Sabaki River Sediment Flux to Malindi Reef

[3] The Sabaki River, Kenya's second largest river with a drainage basin of 66,800 km^2 or almost 11% of Kenya's area, flows through both densely populated humid highlands and less populated semi-arid savanna plains where precipitation totals 800–1200 mm yr^{-1} and 400–800 mm yr^{-1} respectively (Figure 1a). Discharge is highly seasonal and varies between 0.52 $m^3\ s^{-1}$ and 758 $m^3\ s^{-1}$ (mean: 48.8 $m^3\ s^{-1}$, 1957–1979), with discharge peaks in November–December and April–May coinciding with the short (October–December, OND) and long (March-May, MAM) rainy seasons respectively (Figure 1b). In spite of two discharge peaks, reversal of the monsoons ensures that sediment flux to Malindi reef only occurs between November and February when northeast monsoon winds entrain the river sediment plume southward to the coral site, whereas between April and September strong southeast monsoon winds and northward currents transport the Sabaki sediment plume northward away from Malindi reef [*Brakel*, 1984; *McClanahan and Obura*, 1997]. Modern sediment flux is estimated to range from 7.5 to 14.3 million t yr^{-1} [*van Katwijk et al.*, 1993], translating to an annual soil erosion rate of 110 – 210 t km^{-2} (1.1 – 2.1 tons ha^{-1}). Up to 80% of the total annual sediment load can occur within a period of a few days [*Dunne*, 1979].

3. Methods

[4] To reconstruct Sabaki River sediment flux to the Malindi coral reef Ba/Ca ratios were measured in the skeleton of two *Porites* colonies (Mal 96-1 and Mal 95-3). Well-developed annual bands allow us to develop annually

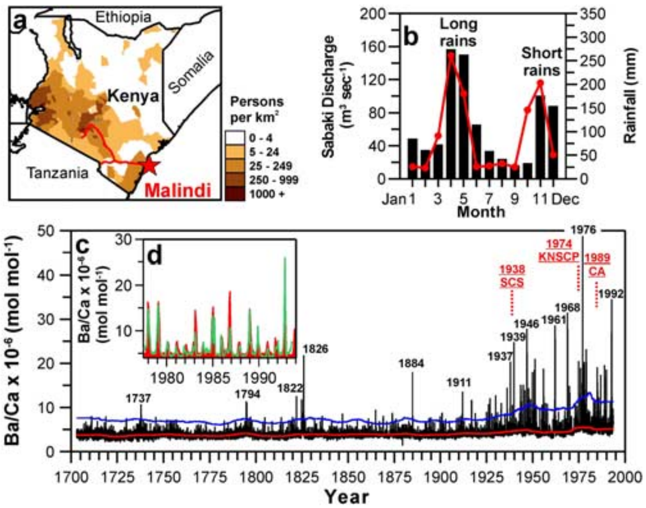

Figure 1. (a) Location of Malindi reef (red star). Red solid line marks the Sabaki river. Also shown is the population density in Kenya (available at http://sedac.ciesin.columbia.edu/). (b) Mean monthly Sabaki-river discharge (black bars; 1959 – 1997). The two peaks in river discharge coincide with the long (MAM) and short rains (OND) (red line). (c) Ba/Ca ratios (black line) of coral Mal 96-1. Background Ba/Ca signal (red line) and threshold for peak detection (blue line) are also shown (see auxiliary material for further details). The number of detected Ba/Ca peaks exceeding the threshold (blue line) is 110. Abbreviations (red) denote national soil conservation programs: SCS = Soil Conservation Service; KNSCP = Kenyan National Soil Conservation Project; CA = Catchment Approach. (d) Small insert figure shows comparison of Ba/Ca profiles of coral Mal 95-3 (red line) and Mal 96-1 (green line), determined using wet chemistry ICP-MS and LA-ICP-MS respectively.

precise chronologies (auxiliary material Figures A1 and A2[1]). Ba/Ca ratios were measured in core Mal 96-1 at continuous 40 μm intervals ($\sim$400 to 500 samples yr^{-1}) using laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; Figure 1c) [*McCulloch et al.*, 2003]. To test for reproducibility and accuracy of the Mal 96-1 Ba/Ca profile, coral core Mal 95-3 was analyzed at lower resolution (1 to 12 samples yr^{-1}) using discrete micro-drill sampling and isotope dilution ICP-MS (Figures 1d and 2a). Details on measurements are provided in the auxiliary material accompanying this article.

[5] The close similarity between both coral Ba/Ca profiles, in absolute values as well as general pattern (Figure 1d), underscores the accuracy of the LA-ICP-MS technique and adds confidence to our interpretation of the 300 year long Mal 96-1 Ba/Ca profile.

4. Ba/Ca Ratios and Their Environmental Significance

[6] Barium concentrations in coral skeletal aragonite respond to either upwelling of cold nutrient-rich water [*Lea et al.*, 1989] or flux of suspended sediment to coastal waters from rivers [*McCulloch et al.*, 2003]. Due to the very weak and irregular upwelling [*Grumet et al.*, 2002] and close proximity of the Malindi coral site to the Sabaki river mouth ($\sim$20 km), coral Ba/Ca ratios most likely reflect the flux of suspended sediments transported by the plumes to the reef. After desorbing from fine-grained suspended material in the low salinity (0–5 p.p.t.) estuarine mixing zone [*Li and Chan*, 1979], Ba becomes a conservative tracer and is then incorporated into the coralline skeleton proportionally to its concentration in sea water [*Lea et al.*, 1989]. Furthermore, Ba can also be incorporated with detrital

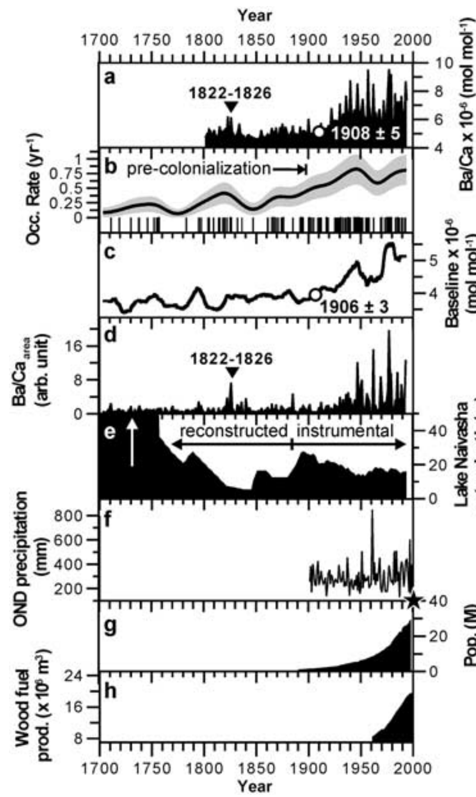

Figure 2. (a) Annually-resolved Mal 95-3 Ba/Ca record. (b) Occurrence rate of extreme sediment flux events to Malindi. We analyzed the occurrence of Ba/Ca peaks, shown as vertical bars, by employing a kernel technique, which estimates the occurrence rate [*Mudelsee et al.*, 2003]. The grey shaded area marks the confidence band at 90% level. (c) Barium baseline (red line in Figure 1c). White numbered dots (a, c) mark change points, as determined using statistical change-point estimation with bootstrap simulations [*Mudelsee*, 2000]. (d) Calculated Ba/Ca$_{area}$ (arbitrary units) for OND ($\pm$1 month to ascribe for chronological uncertainties) (auxiliary material Figure A4). (e) Naivasha lake level record [*Verschuren et al.*, 2000]. (f) CRU TS 2.1 time series (averaged for 36°–37.5°E; 0°–1.5S) of OND precipitation (in mm) in the highlands of Kenya [*Mitchell and Jones*, 2005]. (g) Population growth (available at www.library.uu.nl/wesp/populstat/Africa/kenyac.htm). Black star marks projected population in 2015. (h) Wood fuel production in Kenya (available at http://apps.fao.org). Wood fuel production can be regarded as a fairly good estimate for the rate of deforestation and land clearance.

[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028525. Other auxiliary material files are in the HTML.

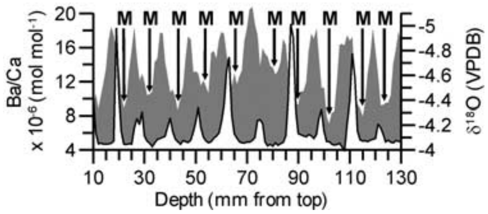

Figure 3. Seasonal phasing of Ba/Ca (white shaded curve) and δ^{18}O (grey shaded curve) in coral Mal 95-3. Ba/Ca peaks follow the δ^{18}O summer monsoon SST minimum (more positive δ^{18}O values; marked with bold M and black arrow), indicating that sediment influx is associated with the short rains (OND).

particles, which are commonly rich in Ba [e.g., *Sinclair and McCulloch*, 2004]. Supporting evidence comes from the coincidence of all Ba/Ca peaks with bright ultraviolet fluorescence bands, an additional river discharge indicator thought to result from either the incorporation of terrestrial organic compounds in the coral skeleton [*Isdale*, 1984] (auxiliary material Figure A3) or changes in porosity due to stress from the low salinity flood plumes [*Barnes and Taylor*, 2001]. These fluorescent bands, coincident with high Ba/Ca portions, form following the summer monsoon season and therefore represent a riverine signal delivered during and immediately after the time of the short rains (OND) associated with the Northeast Monsoon [*Kayanne et al.*, 2006]. This is also supported by the seasonal phasing of coral δ^{18}O and Ba/Ca (Figure 3), satellite images of Sabaki river sediment plumes [*Brakel*, 1984] and frequent reef observations [*McClanahan and Obura*, 1997]. Thus, Ba/Ca ratios in corals from Malindi reef provide detailed information on Sabaki River discharge and sediment flux associated with the short rains (OND).

[7] Important for this study, OND Sabaki river discharge [*McClanahan and Obura*, 1997] between 1953 and 1992 is positively correlated with same-year OND precipitation [*Mitchell and Jones*, 2005], with highest correlation coefficients ($r = 0.6–0.8$; $p = 0.01$) observed in the upper high rainfall drainage basins (Figure 4a and auxiliary material Table A1). Although the short rains contribute only ~35–45% to total annual rainfall, they experience a higher degree of interannual variability than the long rains [e.g., *Hastenrath et al.*, 2004], and – important for this study – "short rains" are often intense and have high erosive power as they occur after a prolonged dry season and coincide with the harvest season, a time when soils are prone to water erosion [*Moore*, 1979].

5. Results and Discussion

[8] The Mal 96-1 and Mal 95-3 Ba/Ca profiles exhibit a distinct long-term pattern in sediment flux to Malindi reef (Figures 1c and 2a). From 1700 to 1905 Ba/Ca ratios are low and show similar and reduced interannual variance with only a few pronounced peaks at 1737, 1794, 1822–1826 and 1884. These peaks most likely relate to drought-breaking flood events [*McCulloch et al.*, 2003], which occur after or within prolonged droughts when desiccated landscapes are prone to water-induced soil erosion. Ba/Ca peaks at 1794, 1822–1826 fall within the well-documented Lapanarat-Mahlatule drought (~1750 to 1820–1830's), the latter Ba/Ca peaks match a major regional lake-filling phase dated to 1815 ± 8 in the central Kenya Rift Valley [*Verschuren et al.*, 1999, 2000]. This is beyond the upper Sabaki river catchment but within the area of high correlation between OND precipitation and Sabaki river discharge (Figure 4a). Ba/Ca ratios begin to increase between 1905 and 1910, as revealed by change point estimates [*Mudelsee*, 2000] at 1906 ± 3 and 1908 ± 5 (1σ error) (Figures 2a and 2c). In addition, after ~1905–1910, Ba/Ca ratios exhibit higher interannual variance, with consistently higher peak ratios in the 1940's and late 1970s. Rising sediment flux is even more evident in the occurrence rates of extreme events (Figure 2b). Prior to ~1905–1910, occurrence rates vary between 0.2 to 0.4 extreme sediment influx events per year and then rise through 1940, to present mean values of ~0.75 events per year. Additionally, Ba/Ca baseline ratios (Figure 2c) increase from $3–4 \times 10^{-6}$ mol mol^{-1} to current ratios of around 5×10^{-6} mol mol^{-1}, indicating a general rise in sediment flux to Malindi reef. Overall, increases in 1) Ba/Ca ratios (maximum and baseline), 2) interannual Ba/Ca variance, and 3) the occurrence rate of extreme sediment flux events reveal that from ~1905–1910 onward Sabaki sediment flux exceeds the natural, background sediment flux baseline of the 1700s and 1800s.

[9] The dramatic increase in sediment flux to Malindi reef after 1905–1910 cannot be explained by a significant increase in precipitation in the Sabaki river drainage basin as there is no evidence for such a trend in meteorological data [*Mitchell and Jones*, 2005] and nearby lake level records, such as the Lake Naivasha lake level record [*Verschuren et al.*, 2000] (Figures 2e and 2f). Rather, the dramatic increase in Mal 96-1 and Mal 95-3 Ba/Ca ratios (Figures 1c and 2a) is concurrent with the start of British settlement in the fertile, humid highlands of Kenya, the source region of the Sabaki River. The resultant change from traditional subsistence agriculture to intensive European land-use practices resulted in a significant increase in soil erosion [e.g., *Champion*, 1933]. Colonialism was accompanied by large-scale deforestation and the replacement of traditional crops (e.g., sorghum, millet) with

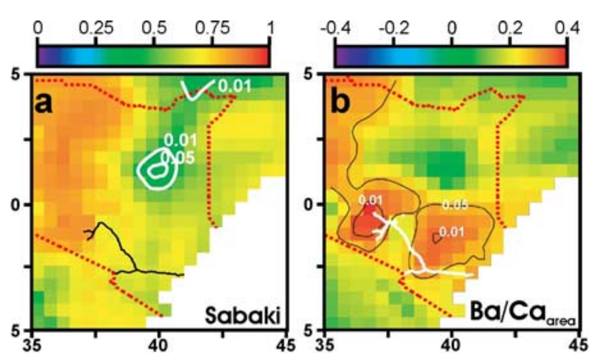

Figure 4. (a) Correlation map for Sabaki river discharge and OND precipitation obtained from the CRU TS 2.1 dataset [*Mitchell and Jones*, 2005]. (b) Correlation map between Ba/Ca$_{area}$ (OND) and OND precipitation for the period from 1941–1992. Highest correlation is observed in the densely populated and cultivated upper Sabaki River drainage basins where precipitation is highest.

new, less drought resistant crops (e.g., maize), and forced resettlement into what soon became overpopulated native reserves [e.g., *Anderson*, 1984; *Throup*, 1985]. The first written warning about the extent of soil erosion in Kenya appeared in 1909 and shortly thereafter the first soil conservation measures, such as planting grasses and contour trenching, were introduced [*Moore*, 1979]. To combat soil erosion, the Soil Conservation Service (SCS) was established in 1938 (Figure 1c), although several studies suggest that the formation of the SCS was mainly triggered by international anxieties about the American dust bowl and the aim to confiscate more fertile lands for white settlers [e.g., *Anderson*, 1984]. The coral record of erosion from the Malindi reef shows two prominent Ba/Ca peaks in 1937 and 1939, which together with more frequent extreme sediment influx events (Figures 1c and 2b) reveal that soil erosion was indeed so severe to justify the establishment of the SCS. Despite the implementation of soil conservation measures by the SCS, such as terracing, contour farming and prohibition of certain farming methods, Ba/Ca ratios from the Mal 96-1 and Mal 95-3 coral cores indicate an acceleration in soil erosion in the 1940s and early 1950s (Figures 1c and 2a). This trend is linked to languishing soil conservation measures during World War II due to an expansion of agricultural activities (maize acreage increased from 80,000 in 1941 to 131,563 acres at the end of the war) to increase food production for export and, immediately afterwards, a second phase of British settlement [e.g., *Throup*, 1985]. Relatively low Sabaki river sediment flux is observed between the mid 1950s and 1960s, possibly the result of an increase in soil conservation measures by indigenous farmers due to a large-scale land reform in 1954. The so-called "Swynnerton Plan" was launched to accelerate production of quality cash crops by providing agricultural education and loans to African farmers. At this time indigenous farmers gained access to cash crops that had been previously monopolized by white settlers (N. Koning, personal communication, 2005). This and remunerative prices for agricultural products encouraged farmers to use more sustainable land management techniques that mitigated against soil degradation. After Kenya's independence in 1963, however, soil conservation efforts such as terracing were minimized because of their association with colonialism and declining prices for cash crops [*Koning and Smaling*, 2005]. Furthermore, a dramatic increase in population following independence (Figure 2g), together with unregulated land use, deforestation (Figure 2h), and severe droughts in the early 1970s all contributed to an unprecedented rate of soil erosion and flux of suspended sediment to Malindi reef between 1974 and 1980, with the highest recorded coral Ba/Ca ratios observed in 1976 (Figure 1c).

[10] The Malindi coral Ba/Ca profiles reveal that more recent national soil conservation programs, such as the Kenyan National Soil Conservation Project (KNSCP), initiated in 1974, and the Catchment Approach (CA), begun in 1989, failed to reduce soil erosion within the Sabaki catchment area. This is likely due to the still increasing demographic pressure on the land (Figures 2g and 2h), although the proximate cause is that the landscape remains out of equilibrium with the existing climatic regime. In addition to poor farming practices, other factors such as forest clearance for wood fuel consumption (current loss rate is $\sim$1.4% yr^{-1}; Figure 2h), a denser network of poorly constructed roads, sand mining from river beds by the concrete industry, footpaths, animal tracks and the expansion of urban centers became significant contributors to soil erosion, all of which are directly related to demographic pressure.

[11] In addition to anthropogenic influences, sediment flux to Malindi reef depends on the intensity and amount of OND precipitation as both factors are important determinants of soil erosion potential and sediment transport capacity by the Sabaki River. Unfortunately, daily precipitation and discharge data are not available and thus we cannot assess the impact of intense and short-lived rainfall events on soil erosion and Sabaki sediment flux respectively. Nevertheless, the comparison between monthly-resolved instrumental and gridded OND precipitation data [*Mitchell and Jones*, 2005] with calculated total Sabaki sediment flux – expressed as Ba/Ca_{area} for Mal 96-1 above the baseline for OND (±1 month to ascribe for chronological uncertainties) (Figure 2d; A4)[1] – reveals a strong linkage between the amount of OND precipitation, Sabaki River discharge and river-borne sediment flux to Malindi. The correlation coefficient between Mal 96-1 Ba/Ca_{area} and OND precipitation averages from 27 meteorological stations (1959–2002; unpublished data) within the Sabaki drainage basins is r = 0.46 (n = 34; p = 0.01), similar to various other meteorological stations in the highlands (auxiliary material Figure A5 and Table A2). Ba/Ca_{area} and Sabaki river discharge (OND) correlate at r = 0.64 (n = 30; p = 0.001; auxiliary material Table A2). The correlation map between Ba/Ca_{area} and gridded OND precipitation [*Mitchell and Jones*, 2005] shows highest correlation coefficients in the upper Sabaki drainage basins (Figure 4b). This correlation pattern is not surprising as this area is most densely populated (Figure 1a), highly cultivated, and high precipitation rates and steep deforested slopes are prone to water induced erosion. Overall, there is clear evidence that sediment flux to Malindi reef is closely related to the amount of OND precipitation and Sabaki river discharge, and related sediment transport capacity. However, as there is no distinct upward trend in OND precipitation in the highlands (Figures 2e and 2f), the general rise in sediment influx and soil erosion from 1905 onward is unambiguously of anthropogenic origin.

6. Conclusions

[12] The Malindi coral Ba/Ca profiles clearly document the human-induced rise in soil erosion over the last 300 years in an area of approximately 66,800 km^2 or 11% of Kenya's total area, whereas previous soil erosion studies were restricted to considerably smaller areas and much shorter timescales [e.g., *Ovuka*, 2000]. The coral Ba/Ca profiles suggest that three major national soil conservation programs, the SCS (1938), KNSCP (1974) and CA (1989), failed to reverse soil erosion in the densely populated Sabaki river drainage area. Although progress was made in some Sabaki river drainage basins, such as the Machakos district [*Tiffen et al.*, 1994], the growing intensification in land-use, cultivation of steep slopes, deforestation for wood fuel production, urban sprawl and increasing network of rural roads made present soil conservation efforts insuffi-

cient, as revealed by our Ba/Ca time series. It is improbable that Kenya, currently ranked 151 among 171 countries by the United Nations Development Program (UNDP) based on the Human Development index (available at http://hdr.undp.org/), will be able to achieve a sustainable reduction in soil erosion in the near future on its own. A synergy of growing population and more intense precipitation events predicted by climate model simulations [e.g., *McHugh*, 2005] will hamper the effectiveness of soil conservation measures and further exacerbate the problem of soil erosion in Kenya, with consequences for the socio-economic conditions, and terrestrial and marine environments, including the region's coral reefs.

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