Supporting Information Appendix

Magill CR, Ashley GM and Freeman KH

Supporting Information (SI) Table of Contents:

Dataset description. We compile and review published leaf-lipid δD data to form a compilation ($n = 159$) of 76 plant species from 31 sites (1-13). Sites are located within 5 biomes and have mean annual precipitations ranging from 183 mm to more than 1200 mm. Leaf-lipid data derive from living subtropical and tropical plants belonging either to the monocot clade or the two largest dicot clades (rosid and asterid) in ecosystems with discontinuous woody cover and herbaceous understory. We calculate species means for individual sites to remove within-species variability (14). We use modeled annual δD_{rain} values to calculate representative $\varepsilon_{lipid/water}$ values because measured δD_{rain} values rarely accompany published leaf-lipid δD values.

Salinity reconstructions. Today, saline-alkaline lake waters in eastern Africa show remarkably consistent trends in major solute compositions of water (15). In closed basins, water chemistry is primarily a function of dissolved Cl^-, Na^+, CO_3–HCO_3^-, and K^+ species (16). The presence of distinctive minerals such as trona ($NaHCO_3 \cdot Na_2CO_3 \cdot 2H_2O$) in Bed I lake sediments suggests a similar water chemistry for paleolake Olduvai (17, 18).

Species diversity and composition of aquatic organisms are influenced by the interplay between salinity and habitat availability (19, 20). Fossil remains of two fish taxa (*Clarias* sp. (catfish) and *Orechromis* sp. (tilapia)) occur in Bed I sediments from about 1.835 Ma (18, 21). Today, catfish similar to those occurring in Bed I sediments (*e.g.*, *C. gariepinus* and *C. lazera*) survive at salinities of up to 20 ppt in shallow benthic habitats (22, 23). Extant tilapias can survive in open waters at salinities of up to 40 ppt (24), but most species reproduce in littoral habitats of between 4 and 5 m depth at salinities of 20 ppt or less (21, 24-26).

In shallow saline-alkaline lakes, salinity is controlled primarily by water level fluctuations over long timescales (10^1 to 10^3 kyr) (27-29). Solute balance is largely a function of mineral precipitation and solute diffusion at water-sediment interfaces (30, 31), and we use a conservative solute balance for paleolake Olduvai during deposition of Bed I sediments.

Paleolake Olduvai occupied an elliptical conic basin with high surface area-to-volume ratio (32, 33). Today, closed basins with similar morphology show strong correlations between water level and surface area (27, 34). Stratigraphic evidence in lake-margin deposits suggests a maximum water level of about 5 m (18, 33), which is consistent with fossil occurrences of tilapia (21). During maximum expansion, paleolake Olduvai extended to 15 km in average diameter (32).

Relative lake levels correlate strongly with sedimentary total organic carbon (%TOC) in many shallow lakes in eastern Africa (35, 36). Although this relationship may not be purely mechanistic, in part, low lake levels result in low %TOC values due to selective removal of unstable organic compounds during bacterial respiration and to sediment dilution (36). Thus, we interpret %TOC values as a reflection of relative lake levels.

Reconstructed levels for paleolake Olduvai agree closely with independent records for lake level (lithological and faunal) during deposition of Bed I sediments (18, 33, 37, 38).

We develop a conservative lake-water evaporation model for paleolake Olduvai based on the strong empirical relationship between observed and modeled salinity in modern saline-alkaline lakes (27, 34) (SI Figure 2):

$$S = 55000\,(E/D)\,(0.55/U)\,(\sqrt{A_L}/D)^{2/3}$$

Here, S is salinity in parts per million, E is annual potential evaporation in feet, D is average lake level in feet, U is the coefficient of variation for lake area change (about 1.75 for shallow lakes in eastern Africa) (34, 39, 40) and A_L is lake area in square miles. Thus, based on stratigraphic evidence for average lake level (about 6.5 feet)(18, 32) and area (about 70 square miles) (32, 33) during maximum lake expansion, we calculate a salinity of about 20 ppt for paleolake Olduvai during maximum lake expansion, which is consistent with faunal evidence for salinity (SI Figure 1). Evidence for wave or current action at several localities in lake sediments from central parts of the paleolake Olduvai basin suggest lake levels ranged between a maximum of 1 to 2 m (average depth of about 1.5 feet) (18, 32) during lake contraction with lake areas of about 10 square miles (32, 33); thus, we calculate salinity of about 105 ppt during lake contraction, which is consistent with mineralogical evidence for high salinity during low lake levels (*e.g.*, trona and gaylussite) (18, 32). Overall, reconstructed salinity primarily fluctuates between about 20 and 80 ppt during and is consistent with the range of modern fluctuations in nearby lakes considered as chemical and sedimentary analogues for paleolake Olduvai (*e.g.*, Natron and Nakuru) (15, 18, 39, 40).

Monthly and regional amount effects. Amount effects are strongest in tropical regions and function via re-evaporation and diffusive exchange during precipitation events (41). Thus, amount effects are sensitive to relative humidity and precipitation rate (42), resulting in monthly and regional variability (43). Modeled monthly δD_{rain} values (44) and precipitation averages (45) for rainy seasons and the climatologically important (46, 47) months that precedes them (February (long rains) and September (short rains)) from 48 stations in central eastern Africa show amount effects of about –0.125‰ mm^{-1} (SI Figures 3 and 4). Interestingly, the *x*-intercept for short rains is about 10‰ more negative than for long rains. Thus, amount effects for central eastern Africa are broadly consistent with those for Central America (about –0.125‰ mm^{-1}) (ref. 48) and for tropical and coastal regions receiving less than 750 mm of MAP (about –0.145‰ mm^{-1}) (ref. 49).

Evaporative balance reconstructions. Isotopic mass balance for evaporative loss in well-mixed lakes with constant volume is equal to (50):

$$I\,\delta_{\text{input}} = Q\,\delta_{\text{outflow}} + E\,\delta_{\text{evaporation}} \qquad (1)$$

I is input, Q is outflow and E is lake evaporation. Variables δ_{input}, δ_{outflow} and $\delta_{\text{evaporation}}$ represent isotopic compositions of input, outflow and evaporation, respectively. Since δ_{outflow} is similar to the composition of lake water (δ_{lake}):

$$E/I = (\delta_{\text{input}} - \delta_{\text{lake}}) / (\delta_{\text{evaporation}} - \delta_{\text{lake}}) \qquad (2)$$

Values for $\delta_{\text{evaporation}}$ cannot be measured directly, but fractionation between $\delta_{\text{evaporation}}$ and δ_{lake} depends on temperature, boundary layer and atmospheric conditions. Assuming negligible resistance to mixing (51):

$$\delta_{\text{evaporation}} \approx (\alpha^* \delta_{\text{lake}} - h\,(\delta_{\text{input}} - \varepsilon^*) - \varepsilon) / (1 - h + 10^{-3}\,\varepsilon_{\text{K}}) \qquad (3)$$

Here, α^* is equilibrium isotopic fractionation between lake-water and vapor and h is relative humidity. The variable ε equals the sum of equilibrium (ε^*) and kinetic (ε_{K}) fractionations. We calculate ε^* for deuterium using the empirical equation (52):

$$\varepsilon^* = 1158.8\,(T^3/10^9) - 1620.1\,(T^2/10^6) + 794.84\,(T/10^3) - 161.04 + 2.9992(10^9/T^3)$$

T is lake surface temperature in Kelvin. We also calculate ε_{K} for deuterium (53):

$$\varepsilon_{\text{K}} = 12.5\,(1 - h) \qquad (5)$$

Next, we substitute equation (3) into equation (2):

$$E/I = (\delta_{\text{input}} - \delta_{\text{lake}}) / (-\varepsilon^* - \varepsilon_{\text{K}}) = (\delta_{\text{lake}} - \delta_{\text{input}}) / \varepsilon \qquad (6)$$

We calculate the ratio of lake evaporation to input for Olduvai Gorge during arid and wetter intervals. We define δ_{lake} based on reconstructed δ_{lake} values, but must define several other variables based on historical observations:

1. Mean annual δD_{input} value equals –22‰ (refs. 44, 53-57).

2. Mean annual h rose to 75% during wetter intervals but fell to 55% during arid intervals (47, 58). Mean annual h is currently about 65% (ref. 58).
3. Mean annual temperature of 23°C with little seasonal variability (18).

Then, we use equation (8) to calculate E/I of 2.9 ($\delta_{lake}=+59$ ‰) during arid intervals and 1.3 ($\delta_{lake}=+16$ ‰) during wetter intervals. Values vary by less than 0.5 if mean annual h is used to calculate E/I. These values are in close agreement with modeled E/I ($0.5°\times 0.5°$) (ref. 59) near Olduvai Gorge using prescribed MAP values of 250 mm ($E/I=3.2$) and 700 mm ($E/I=1.3$) (ref. 60).

Uncertainty in $\varepsilon_{31/model}$ values. We propagate uncertainty in $\varepsilon_{landscape}$ values (95% confidence intervals, $\sigma_{landscape}$) using a linear combination of 95% confidence interval values for individual C_4 graminoids (±8‰, σ_{gram}), C_3 herbs (±10‰, σ_{herb}) and C_3 woody plants (±8‰, σ_{woody}) and modeled annual δD_{rain} values (±6‰, σ_{rain}) (ref. 60). We account for uncertainty in $\delta^{13}C_{31}$-based estimates of relative plant functional type abundances (about 20%) (ref. 61) by multiplying respective standard error values by 1.2:

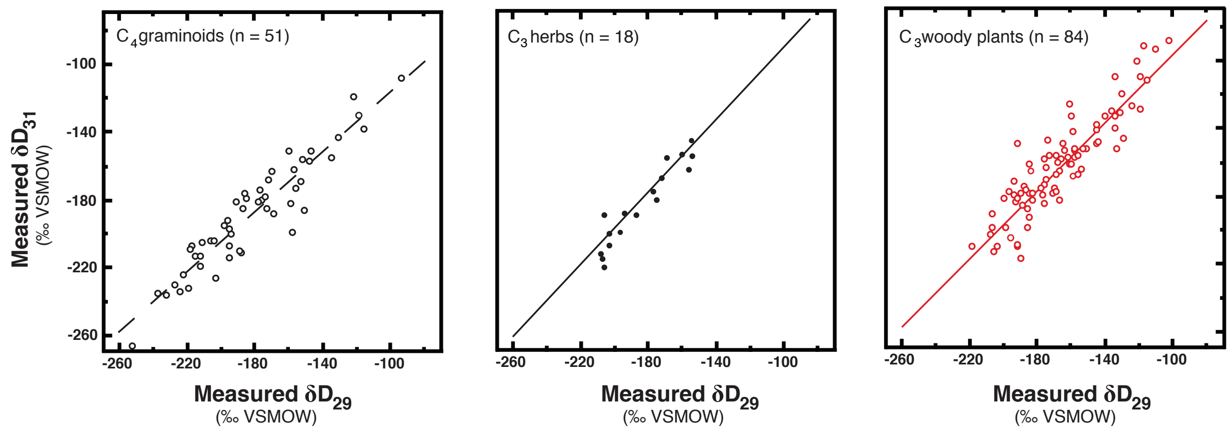
$$\sigma^2_{landscape} = 1.2\sigma^2_{gram} + 1.2\sigma^2_{herb} + 1.2\sigma^2_{woody} + 3\sigma^2_{rain}$$

Thus, $\sigma_{landscape}$ is equal to about 20‰.

Determination of environmental water $\delta^{18}O$ values. In this study, we use a single soil carbonate sample (nodule with sparry calcite) from the eastern lake-margin of Olduvai Gorge that has a $\delta^{18}O$ value of –6.2‰ (62) to determine $\delta^{18}O_{rain}$ values. We assume a mean annual soil temperature (MAsT) of 25°C in order to calculate apparent fractionation values for oxygen isotopes between environmental water and soil carbonate minerals ($\varepsilon_{carb/water} = (R_{carb}/R_{water}) - 1$) (refs. 62, 63). Uncertainty of ±5°C in MAsT results in about 1‰ uncertainty in $\delta^{18}O_{rain}$ values.

We determine apparent fractionation values for oxygen isotopes between environmental water and clay minerals ($\varepsilon_{clay/water} = (R_{clay}/R_{water}) - 1$) according to bond-type calculations of Savin and Lee (ref. 64) from structural formulas. Our determination of $\delta^{18}O_{lake}$ values derives from a single sediment sample composed of 97% illite and 3% analcime (*w*/*w*). Mean annual temperature at Olduvai Gorge during the deposition of Bed I sediments has been estimated as 14-16°C (refs. 18, 62), as compared to about 22°C in the present, and we use 15°C to calculate

$\varepsilon_{clay/water}$ values. Bulk clay minerals show a $\delta^{18}O$ value of 27.1‰, to which we apply a $\varepsilon_{clay/water}$ value of 24.8‰.

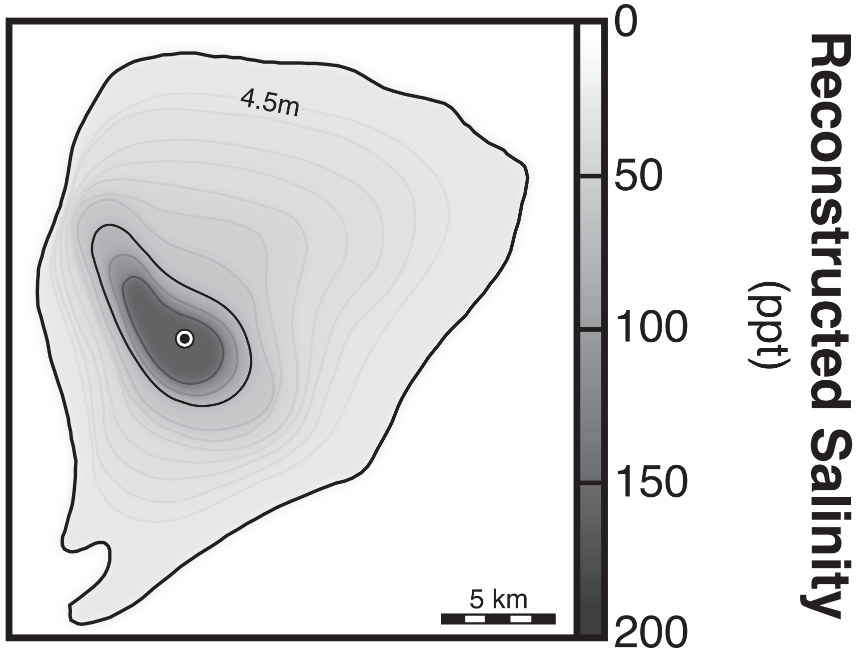


SI Figure 1: Published δD values for the lipids nC$_{31}$ (δD_{31}) and nC$_{29}$ (δD_{29}) (1-13), cross-plotted by photosynthetic pathway and growth habit.

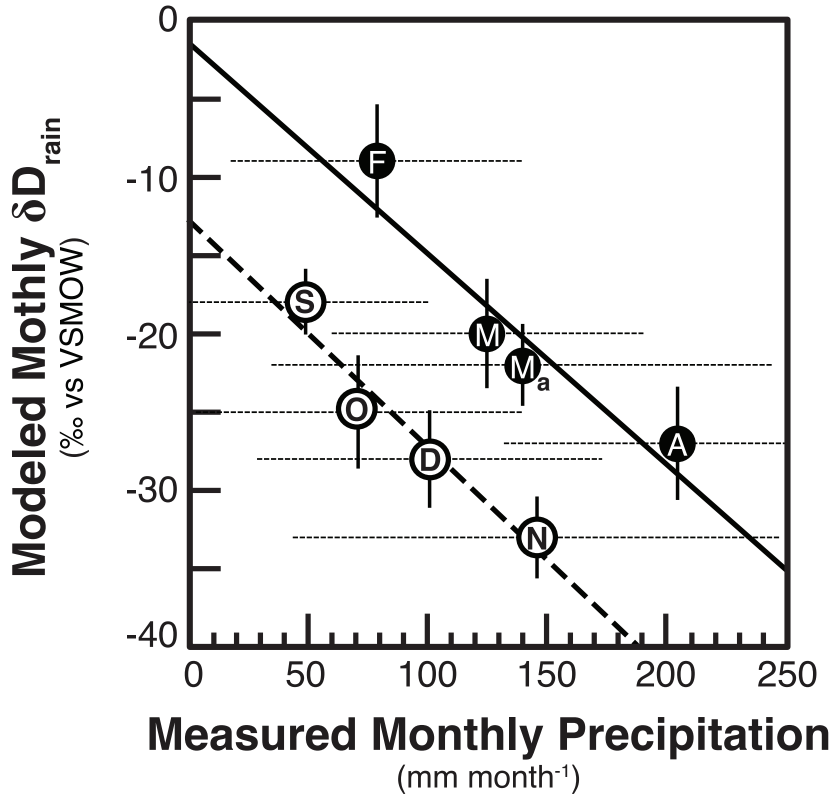
C$_4$ graminoids: $\delta D_{31} = 0.94\ \delta D_{29} - 26‰$ $\quad$ $r^2 = 0.88$

C$_3$ herbs: $\delta D_{31} = 1.1\ \delta D_{29} + 15‰$ $\quad$ $r^2 = 0.88$

C$_3$ woody plants: $\delta D_{31} = 1.0\ \delta D_{29} + 1‰$ $\quad$ $r^2 = 0.81$



SI Figure 2: Bathymethric contours (lines) and reconstructed salinity (shading) for paleolake Olduvai. Bold outlines represent ancient shorelines during expanded and contracted phases (18, 33, 66). Fish fossils constrain salinity to 20 ppt or less during maximum lake expansion (21-26), and we use 20 ppt for our conservative lake water evaporation model. Bathymetric contours occur at approximately 0.5 m intervals.

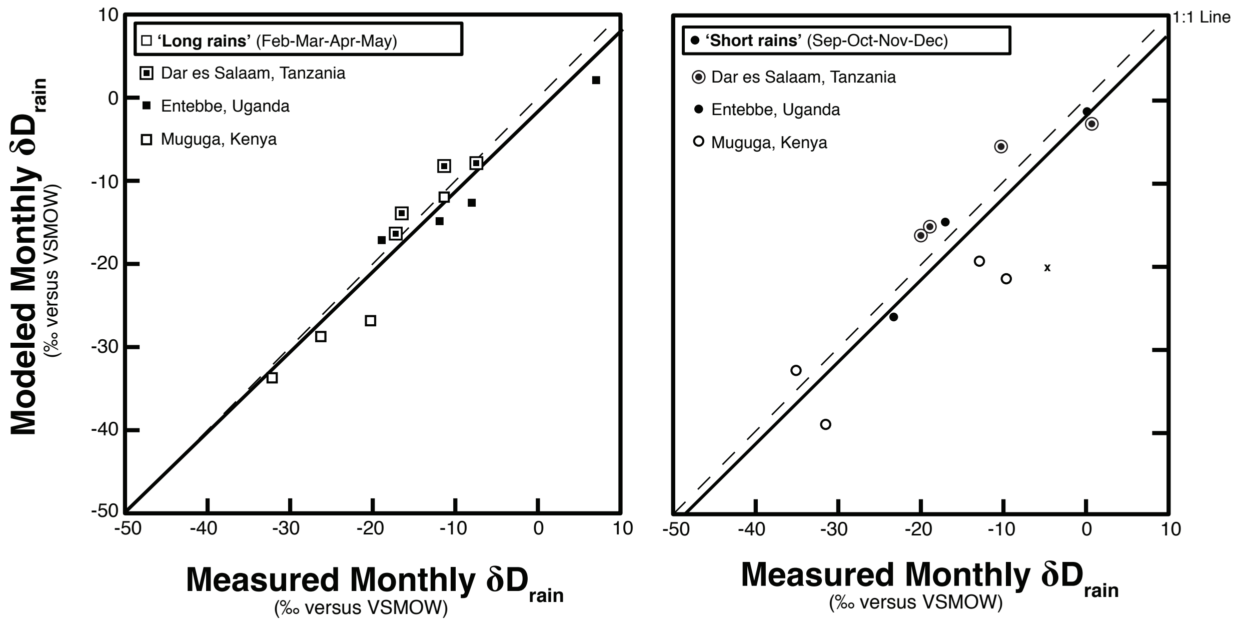


SI Figure 3: Modeled monthly δD_{rain} values (44) versus measured monthly precipitation (P in mm) (ref. 45) for rainy seasons from 48 stations in central eastern Africa (SI Figure 4). Short rains ($n = 6200$) and long rains ($n = 6335$) show amount effects of about –0.125‰ mm^{-1}:

'Long rains': $\delta D_{rain} = -0.132\,P - 2‰$ ($r^2 = 0.87$; bold regression)

'Short rains': $\delta D_{rain} = -0.138\,P - 12‰$ ($r^2 = 0.90$; dashed regression)

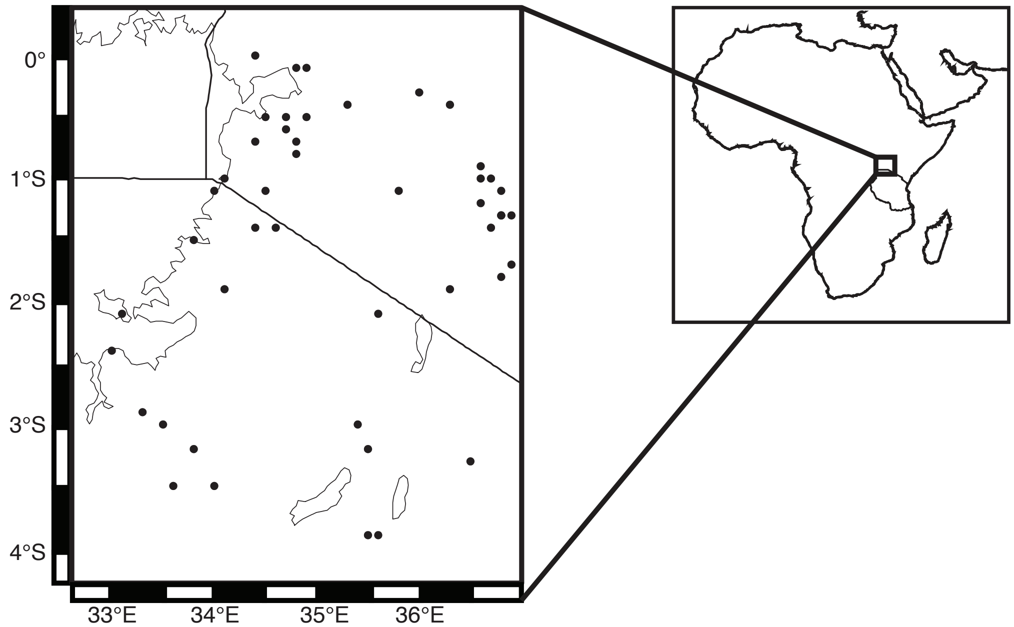
Bold vertical lines represent uncertainty in modeled monthly δD_{rain} values (95% confidence interval) and dotted horizontal lines represent average monthly precipitation variability. Long rains include the months February (F), March (M_a), April (A) and May (M); short rains include the months September (S), October (O), November (N) and December (D) (refs. 46, 67).



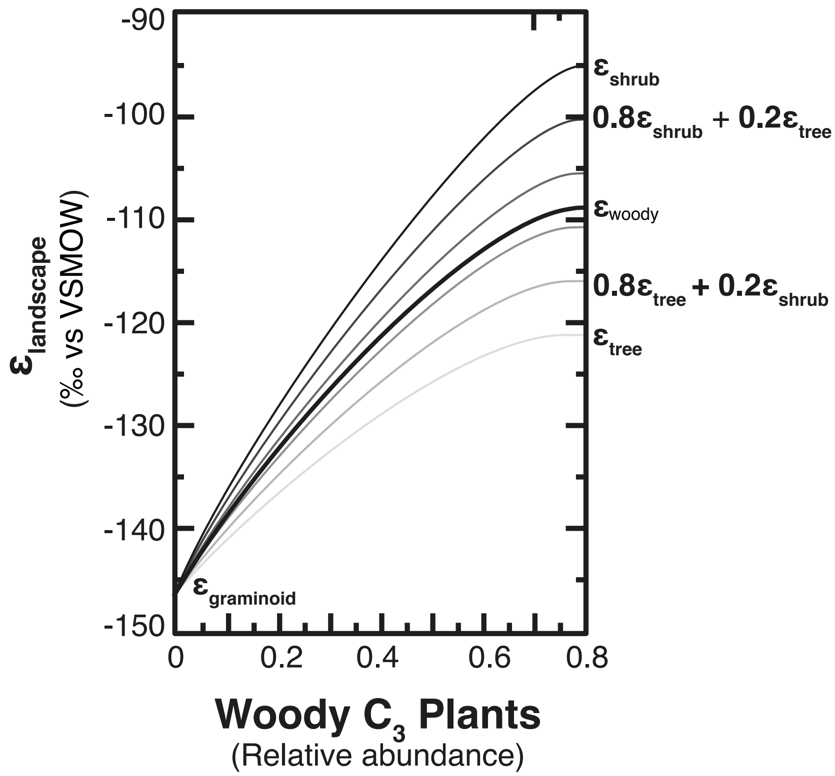
SI Figure 4: Measured (65) versus modeled (44) monthly δD_{rain} values for eastern African sites with at least 2 years of rainy season precipitation data (Dar es Salaam, Tanzania; Entebbe, Uganda; Muguga, Kenya). One 'short rains' data point (marked *x*) has been omitted from linear regression analysis because it is an outlier (jackknife estimate).

'Long rains': Modeled $\delta D_{rain} = 0.9621\,\delta D_{rain} - 2‰$ $(r^2 = 0.91;\ n = 12)$

'Short rains': Modeled $\delta D_{rain} = 0.9362\,\delta D_{rain} - 3‰$ $(r^2 = 0.80;\ n = 11)$



SI Figure 5: Geographic locations of the 48 stations used to calculate amount effects for eastern Africa.



SI Figure 6: Alternative $\varepsilon_{\text{landscape}}$ values based on modified proportions of trees versus shrubs in C_3 woody plants. We use median $\varepsilon_{31/\text{model}}$ values for C_4 graminoids ($\varepsilon_{\text{gram}} = -146‰$), C_3 non-woody plants ($\varepsilon_{\text{herb}} = -124‰$), C_3 shrubs ($\varepsilon_{\text{shrub}} = -87‰$) and C_3 trees ($\varepsilon_{\text{tree}} = -121‰$) (refs. 1-13).

$$\varepsilon_{\text{landscape}} = f_{\text{gram}}\, \varepsilon_{\text{gram}} + f_{\text{herb}}\, \varepsilon_{\text{herb}} + f_{\text{shrub}}\, \varepsilon_{\text{shrub}} + f_{\text{tree}}\, \varepsilon_{\text{tree}}$$

Taken together, the $\varepsilon_{31/\text{model}}$ value for combined C_3 woody plants is –109‰. Alternative scenarios yield $\varepsilon_{\text{landscape}}$ values that vary by up to 15‰, although differences are nominal for relative C_3 woody plant abundances of less than about 50%.

References.

1. Chikaraishi Y & Naraoka H (2003) Compound-specific δD-δ^{13}C analyses of *n*-alkanes extracted from terrestrial and aquatic plants. *Phytochemistry* 63:361.

2. Chikaraishi Y & Naraoka H (2006) Carbon and hydrogen isotope variation of plant biomarkers in a plant-soil system. *Chemical Geology* 231:190.

3. Bi X, Sheng G, Liu X, Li C & Fu J (2005) Molecular and carbon and hydrogen isotopic composition of *n*-alkanes in plant leaf waxes. *Organic geochemistry* 36:1405.

4. Krull E, Sachse D, Mügler I, Thiele A & Gleixner G (2006) Compound-specific δ^{13}C and δ^{2}H analyses of plant and soil organic matter: a preliminary assessment of the effects of vegetation change on ecosystem hydrology. *Soil Biology and Biochemistry* 38:3211.

5. Liu W, Yang H & Li L (2006) Hydrogen isotopic compositions of *n*-alkanes from terrestrial plants correlate with their ecological life forms. *Oecologia* 150:330.

6. Liu Z & Huang Y (2008) Hydrogen isotopic compositions of plant leaf lipids are unaffected by a twofold pCO$_2$ change in growth chambers. *Organic geochemistry* 39:478.

7. Sachse D, Radke J & Gleixner G (2006) δD values of individual *n*-alkanes from terrestrial plants along a climatic gradient: implications for the sedimentary biomarker record. *Organic geochemistry* 37:469.

8. Sachse D, Kahmen A & Gleixner G (2009) Significant seasonal variation in the hydrogen isotopic composition of leaf-wax lipids for two deciduous tree ecosystems (*Fagus sylvativa* and *Acer pseudoplatanus*). *Organic geochemistry* 40:732.

9. Smith F & Freeman K (2006) Influence of physiology and climate on δD of leaf wax *n*-alkanes from C_3 and C_4 grasses. *Geochimica et Cosmochimica Acta* 70:1172.

10. Hou J, D'Andrea W, MacDonald D & Huang Y (2007) Hydrogen isotopic variability in leaf waxes among terrestrial and aquatic plants around Blood Pond, Massachusetts (USA). *Organic geochemistry* 38:977.

11. Hou J, D'Andrea W & Huang Y (2008) Can sedimentary leaf waxes record D/H ratios of continental precipitation? Field, model, and experimental assessments. *Geochimica et Cosmochimica Acta* 72:3503.

12. Mügler I*, et al.* (2008) Effect of lake evaporation on δD values of lacustrine *n*-alkanes: a comparison of Nam Co (Tibetan Plateau) and Holzmaar (Germany). *Organic geochemistry* 39:711.

13. Feakins S & Sessions A (2010) Controls on the D/H ratios of plant leaf waxes in an arid ecosystem. *Geochimica et Cosmochimica Acta* 74:2128.

14. Diefendorf A, Mueller K, Wing S, Koch P & Freeman K (2010) Global patterns in leaf ^{13}C discrimination and implications for studies of past and future climate. *Proceedings of the National Academy of Sciences* 107:5738.

15. Talling J & Talling I (1965) The chemical composition of African lake waters. *Internationale Revue der gesamten Hydrobiologie und Hydrographie* 50:421.

16. Eugster H & Jones B (1979) Behavior of major solutes during closed-basin brine evolution. *American journal of science* 279:609.

17. Renaut R, Tiercelin J & Owen R (1986) Mineral precipitation and diagenesis in the sediments of the Lake Bogoria basin, Kenya Rift Valley. *Geological Society, London, Special Publications* 25:159.

18. Hay R & Kyser T (2001) Chemical sedimentology and paleoenvironmental history of Lake Olduvai, a Pliocene lake in northern Tanzania. *Geological Society of America Bulletin* 113:1505.

19. Hammer U & Heseltine J (1988) Aquatic macrophytes in saline lakes of the Canadian prairies. *Hydrobiologia* 158:101.

20. Verschuren D, Tibby J, Sabbe K & Roberts N (2000) Effects of depth, salinity, and substrate on the invertebrate community of a fluctuating tropical lake. *Ecology* 81:164.

21. Stewart K (1996) A report on the fish remains from Beds I and II sites, Olduvai Gorge, Tanzania. *Darmst Beitrag Naturgesch* 6:263.

22. Chervinski J (1984) Salinity tolerance of young catfish, *Clarias lazera* (Burchell). *Journal of fish biology* 25:147.

23. Britz P & Hecht T (1989) Effects of salinity on growth and survival of African sharptooth catfish (*Clarias gariepinus*) larvae. *Journal of applied ichthyology* 5:194.

24. Kamal A & Mair G (2005) Salinity tolerance in superior genotypes of tilapia, *Oreochromis niloticus*, *Oreochromis mossambicus* and their hybrids. *Aquaculture* 247:189.

25. Reite O, Maloiy G & Aasehaug B (1974) pH, salinity and temperature tolerance of Lake Magadi Tilapia. *Nature* 247:315.

26. Stickney R (1986) Tilapia tolerance of saline waters: a review. *The Progressive Fish-Culturist* 48:161.

27. Mason I, Guzkowska M, Rapley C & Street-Perrott F (1994) The response of lake levels and areas to climatic change. *Climatic change* 27:161.

28. Yechieli Y & Wood W (2002) Hydrogeologic processes in saline systems: playas, sabkhas, and saline lakes. *Earth-Science Reviews* 58:343.

29. Rimmer A (2003) The mechanism of Lake Kinneret salinization as a linear reservoir. *Journal of Hydrology* 281:173.

30. Lerman A & Jones B (1973) Transient and steady-state salt transport between sediments and brine in closed lakes. *Limnology and Oceanography* 18:72.

31. Yuretich R & Cerling T (1983) Hydrogeochemistry of Lake Turkana, Kenya: mass balance and mineral reactions in an alkaline lake. *Geochimica et Cosmochimica Acta* 47:1099.

32. Ashley G & Hay R (2002) Sedimentation patterns in a Plio-Pleistocene volcaniclastic rift-platform basin, Olduvai Gorge, Tanzania. *SEPM Special Publication* 73:107.

33. Hay R (1976) *Geology of the Olduvai Gorge* (University of California Press).

34. Langbein W (1961) Salinity and hydrology of closed lakes. *Geological Survey Professional Paper* 412:1.

35. Talbot M & Livingstone D (1989) Hydrogen index and carbon isotopes of lacustrine organic matter as lake level indicators. *Palaeogeography, palaeoclimatology, palaeoecology* 70:121.

36. Verschuren D (2001) Reconstructing fluctuations of a shallow East African lake during the past 1800 yrs from sediment stratigraphy in a submerged crater basin. *Journal of Paleolimnology* 25:297.

37. Ashley G (2007) Orbital rhythms, monsoons, and playa lake response, Olduvai basin, equatorial East Africa (*ca.* 1.85-1.74 Ma). *Geology* 35:1091.

38. Fernandez-Jalvo Y, *et al.* (1998) Taphonomy and palaeoecology of Olduvai Bed I (Pleistocene, Tanzania). *Journal of Human Evolution* 34:137.

39. Hay R (1968) Chert and its sodium-silicate precursors in sodium-carbonate lakes of East Africa. *Contributions to Mineralogy and Petrology* 17:255.

40. Vareschi E (1982) The ecology of Lake Nakuru (Kenya): abiotic factors and primary production. *Oecologia* 55:81.

41. Lee J & Fung I (2008) 'Amount effect' of water isotopes and quantitative analysis of post-condensation processes. *Hydrological Processes* 22:1.

42. Risi C, Bony S, Vimeux F, Chong M & Descroix L (2010) Evolution of the stable water isotopic composition of the rain sampled along Sahelian squall lines. *Quarterly Journal of the Royal Meteorological Society* 136:227.

43. Vimeux F, Gallaire R, Bony S, Hoffmann G & Chiang J (2005) What are the climate controls on δD in precipitation in the Zongo Valley (Bolivia)? Implications for the Illimani ice core interpretation. *Earth and Planetary Science Letters* 240:205.

44. Bowen G & Revenaugh J (2003) Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research* 39:1299.

45. Oldenborgh G (2011) Koninklijk Nederlands Meteoroligisch Instituut (KNMI) Climate Explorer: http://www.knmi.nl/

46. Camberlin P & Okoola R (2003) The onset and cessation of the " long rains" in eastern Africa and their interannual variability. *Theoretical and Applied Climatology* 75:43.

47. Tierney J, Lewis S, Cook B, Legrande A & Schmidt G (2011) Model, proxy and isotopic perspectives on the East African Humid Period. *Earth and Planetary Science Letters* 307:103.

48. Lachniet M & Patterson W (2006) Use of correlation and stepwise regression to evaluate physical controls on the stable isotope values of Panamanian rain and surface waters. *Journal of Hydrology* 324:115.

49. Risi C, Bony S & Vimeux F (2008) Influence of convective processes on the isotopic composition ($\delta^{18}O$ and δD) of precipitation and water vapor in the tropics: physical interpretation of the amount effect. *Journal of Geophysical Research* 113:D19306.

50. Gibson J, Edwards T & Prowse T (1996) Development and validation of an isotopic method for estimating lake evaporation. *Hydrological Processes* 10:1369.

51. Gat J (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences* 24:225.

52. Horita J & Wesolowski D (1994) Liquid-vapor fractionation of oxygen and hydrogen isotopes of water from the freezing to the critical temperature. *Geochimica et Cosmochimica Acta* 58:3425.

53. Araguás-Araguás L, Froehlich K & Rozanski K (2000) Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. *Hydrological Processes* 14:1341.

54. Bergonzini L, Gibert E, Winckel A & Merdaci Q (2001) Water and isotopic (^{18}O and ^{2}H) budget of Lake Massoko, Tanzania. Quantification of exchange between lake and groundwater. *Comptes Rendus de l'Academie des Sciences* 333:617.

55. Delalande M, Bergonzini L, Branchu P, Filly A & Williamson D (2008) Hydroclimatic and geothermal controls on the salinity of Mbaka Lakes (SW Tanzania): limnological and paleolimnological implications. *Journal of Hydrology* 359:274.

56. Nkotagu H (1996) Application of environmental isotopes to groundwater recharge studies in a semi-arid fractured crystalline basement area of Dodoma, Tanzania. *Journal of African Earth Sciences* 22:443.

57. Bohté R*, et al.* (2010) Hydrograph separation and scale dependency of natural tracers in a semi-arid catchment. *Hydrology and Earth System Sciences Discussions* 7:1343.

58. Williams K, Wilsey B, McNaughton S & Banyikwa F (1998) Temporally variable rainfall does not limit yields of Serengeti grasses. *Oikos* 81:463.

59. Willmott C, Rowe C & Mintz Y (1985) Climatology of the terrestrial seasonal water cycle. *Journal of Climatology* 5:589.

60. Matsuura K, Willmott C & Legates D (2009) Web-Based, Water-Budget, Interactive, Modeling Program (WebWIMP): http://climate.geog.udel.edu/~wimp/

61. Cerling T*, et al.* (2011) Woody cover and hominin environments in the past 6 million years. *Nature* 476:51.

62. Cerling T & Hay R (1986) An isotopic study of paleosol carbonates from Olduvai Gorge. *Quaternary Research* 25:63.

63. Friedman I & O'Neil J (1977) Compilation of stable isotope fractionation factors of geochemical interest. *U.S. Geological Survey Professional Papers* 440:1.

64. Savin S & Lee M (1988) Isotopic studies of phyllosilicates. *Reviews in Mineralogy and Geochemistry* 19:189.

65. IAEA (2006) Isotope Hydrology Information System. Accessible at: http://www.iaea.org/water.

66. Pickering R (1958) *A Preliminary Note on the Quaternary Geology of Tanganyika* (Proceedings of the CCTA Joint Committee on Regional Geology).

67. Nicholson S (2000) The nature of rainfall variability over Africa on time scales of decades to millenia. *Global and Planetary Change* 26:137.