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Title:
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Publication Date:
04-01-2015

Series:
UC Santa Barbara Previously Published Works

Permalink:
http://escholarship.org/uc/item/3d76m1g6

DOI:
http://dx.doi.org/10.1890/ES14-00514.1

Published Web Location:
http://www.esajournals.org/doi/full/10.1890/ES14-00514.1

Local Identifier:
957545
Abstract:
© 2015 McCauley et al. The common hippopotamus, *Hippopotamus amphibius*, transports millions of tons of organic matter annually from its terrestrial feeding grounds into aquatic habitats. We evaluated whether carbon stable isotopes (δ<sup>13</sup>C) can be used as tracers for determining whether *H. amphibius*-vectored allochthonous material is utilized by aquatic consumers. Two approaches were employed to make this determination: (1) lab-based feeding trials where omnivorous river fish were fed a *H. amphibius* dung diet and (2) field sampling of fish and aquatic insects in pools with and without *H. amphibius*. Lab trials revealed that fish fed exclusively *H. amphibius* dung exhibited significantly more positive δ<sup>13</sup>C values than fish not fed dung. Fish and aquatic insects sampled in a river pool used for decades by *H. amphibius* also exhibited more positive δ<sup>13</sup>C values at the end of the dry season than fish and insects sampled from an upstream *H. amphibius*-free reference pool. Fish sampled in these same pools at the end of the wet season (high flow) showed no significant differences in δ<sup>13</sup>C values, suggesting that higher flows reduced retention and use of *H. amphibius* subsidies. These data provide preliminary evidence that δ<sup>13</sup>C values may be useful, in certain contexts, for quantifying the importance *H. amphibius* organic matter.

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Carbon stable isotopes suggest that hippopotamus-vectored nutrients subsidize aquatic consumers in an East African river

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Citation: McCauley, D. J., T. E. Dawson, M. E. Power, J. C. Finlay, M. Ogada, D. B. Gower, K. Caylor, W. D. Nyingi, J. M. Githaiga, J. Nyunja, F. H. Joyce, R. L. Lewison, and J. S. Brashares. 2015. Carbon stable isotopes suggest that hippopotamus-vectored nutrients subsidize aquatic consumers in an East African river. Ecosphere 6(4):52. http://dx.doi.org/10.1890/ES14-00514.1

Abstract. The common hippopotamus, *Hippopotamus amphibius*, transports millions of tons of organic matter annually from its terrestrial feeding grounds into aquatic habitats. We evaluated whether carbon stable isotopes (δ13C) can be used as tracers for determining whether *H. amphibius*-vectored allochthonous material is utilized by aquatic consumers. Two approaches were employed to make this determination: (1) lab-based feeding trials where omnivorous river fish were fed a *H. amphibius* dung diet and (2) field sampling of fish and aquatic insects in pools with and without *H. amphibius*. Lab trials revealed that fish fed exclusively *H. amphibius* dung exhibited significantly more positive δ13C values than fish not fed dung. Fish and aquatic insects sampled in a river pool used for decades by *H. amphibius* also exhibited more positive δ13C values at the end of the dry season than fish and insects sampled from an upstream *H. amphibius*-free reference pool. Fish sampled in these same pools at the end of the wet season (high flow) showed no significant differences in δ13C values, suggesting that higher flows reduced retention and use of *H. amphibius* subsidies. These data provide preliminary evidence that δ13C values may be useful, in certain contexts, for quantifying the importance *H. amphibius* organic matter.

Key words: allochthonous organic matter; aquatic invertebrate; carbon; fish; freshwater; *Hippopotamus amphibius*; hydrology; isotope; Kenya; river; subsidy; watershed.

Received 17 December 2014; revised 19 December 2014; accepted 8 January 2015; published 13 April 2015. Corresponding Editor: D. P. C. Peters. Copyright © 2015 McCauley et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. http://creativecommons.org/licenses/by/3.0/
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INTRODUCTION

Stable isotopes of carbon, nitrogen, and hydrogen are commonly employed to measure how freshwater consumers use terrestrially generated allochthonous organic matter (Finlay 2001, Doucett et al. 2007, Finlay and Kendall 2008). The ecological importance of a wide range of such terrigenous allochthonous subsidies have been considered in lakes and rivers including litterfall, fruitfall, organic rich soil runoff, and terrestrial insect input (Polis et al. 1997, Nakano et al. 1999, Wantzen et al. 2002, Caraco et al. 2010, Roach 2013).

One potentially important but little studied route of terrestrial to aquatic organic matter subsidization in African watersheds may be maintained by the common hippopotamus, *Hippopotamus amphibius*. This herbivorous semi-aquatic mega-consumer forages widely on land at night consuming largely terrestrial C4 grasses and some browse (Eltringham 1999, Grey and Harper 2002, Cerling et al. 2008). Individual *H. amphibius* consume approximately 40–50 kg (wet mass) of terrestrial organic matter per night (Lewison and Carter 2004) and then spend all or most of the daylight hours in aquatic refuges where a large proportion of this nutrient rich terrestrial intake is excreted (Fig. 1; Appendix A; Subalusky et al. 2014).

The potential ecological importance of *H. amphibius* as a vector of terrestrial organic matter subsidies to watersheds has been hypothesized by other researchers (Naiman and Rogers 1997, Grey and Harper 2002, Jacobs et al. 2007, Mosepele et al. 2009, Jackson et al. 2012, Subalusky et al. 2014). In this study we use carbon stable isotope ($\delta^{13}C$) measurements to evaluate whether the organic matter that *H. amphibius* excrete into riverine ecosystems is utilized by aquatic consumers. To this end, we
carried out feeding trials of captive river fish fed exclusively *H. amphibius* dung and conducted field sampling of aquatic vertebrates and invertebrates in parts of a river in central Kenya that did and did not harbor *H. amphibius*.

**METHODS**

**Site description**

Field sampling was conducted in Ewaso Ng’iro River in Laikipia District, Kenya (36°54' E, 0°19' N). Rainfall in the region is weakly trimodal with peak rainfall occurring in April–May, July–August, and October–November. The Ewaso Ng’iro has extremely high sediment loads, amongst the highest measured in Kenya (Gichuki 2002). This loading suppresses light penetration and severely inhibits in situ algal growth. The hydrologically dynamic nature of the Ewaso Ng’iro largely prevents the establishment of large stands of marginal plants or floating aquatic vegetation.

Field sampling was concentrated at two focal pools in the Ewaso Ng’iro: one pool that has been identified by local experts as a long-term occupancy site for an aggregation of *H. amphibius* (hereafter “*H. amphibius* pool”) and a second pool, 1.8 km upstream, where resident *H. amphibius* were not seen (hereafter “reference pool”). The lower boundary of the reference pool is intersected by a public bridge and the disturbance from this crossing is in part presumed to deter use by *H. amphibius*. Sampling was conducted in a 185 × 40 m (mean depth = 2.9 m) region of the *H. amphibius* pool and in a 150 × 25 m (mean depth = 2.7 m) section of the reference pool.

**Hippopotamus amphibius surveys**

The presence or absence of *H. amphibius* at the *H. amphibius* pool and the reference pool were monitored visually throughout the study. During daylight hours observers counted numbers of *H. amphibius* present in the pool or on the bank. The presence and abundance of *H. amphibius* were also estimated at the *H. amphibius* pool using camera traps (Reconyx). The presence/absence and maximum number of *H. amphibius* observed at any point between 0700 and 1855 hours were recorded each day. To estimate patterns of long-term *H. amphibius* use of the *H. amphibius* and reference pools, we interviewed nine persons with >10 years of permanent or intermittent residency in this region. In February 2012, we surveyed approximately 125 km of the Ewaso Ng’iro watershed near to our study site from fixed wing aircraft, recording the number and location of *H. amphibius*.

**Hydrological monitoring**

Daily records of river discharge were collected by a stream gauging station at Hulmes Junction on the Ewaso Ng’iro River, located 30 km upstream of the *H. amphibius* pool. These data were obtained from the Water Resources Management Authority (WRMA) and used to determine the seasonal variation in river discharge during this period of study. Any gaps in these discharge measurements were estimated using daily regional rainfall records from the Tropical Rainfall Measurement Mission (TRMM) and discharge/rainfall correlations.

**Feeding trials**

To determine, in a controlled environment, how consumption of *H. amphibius* dung may influence the isotopic composition of river consumer tissue, we monitored the isotopic composition of wild-caught guppies, *Poecilia reticulata*, fed exclusively *H. amphibius* dung. For these trials fresh *H. amphibius* dung was collected from four wild *H. amphibius* individuals at our study site, homogenized, frozen, and fed to *P. reticulata* throughout the duration of the experiment. *P. reticulata* are an introduced species in the Ewaso Ng’iro that have a broadly omnivorous diet. All *P. reticulata* used in these trials were originally captured from the reference pool lacking *H. amphibius*. Fifteen of these *P. reticulata* were lethally sampled immediately upon collection from the river (i.e., not held in captivity) to provide baseline values for isotopic comparison (“control *P. reticulata*”). Remaining captive *P. reticulata* were fed *H. amphibius* dung daily to satiation. Dung fed *P. reticulata* were starved for 24 h to completely clear their gut prior to collection (Potts 1998). *P. reticulata* fed the *H. amphibius* dung diet were collected three months (n = 11) and six months (n = 12) after their switch to a dung diet (“dung fed” *P. reticulata*). All *P. reticulata* were measured (total length; TL), frozen, air-dried, ground whole, and
analyzed for $\delta^{13}$C and $\delta^{15}$N values as described below. Because ultimately no isotopic differences were observed between dung fed *P. reticulata* sampled at three and six months (Appendix B), these groups were pooled for analysis. To determine if tissue compositional changes (e.g., changes in lipid concentration) influenced the isotopic values measured in dung-fed and control *P. reticulata* populations, we compared the C:N values (atomic) of both dung fed and control populations as well as the C:N values of dung fed *P. reticulata* sampled at month three and month six of the experiment.

**In situ sampling**

We collected and measured the isotopic composition of three putatively important allochthonous terrestrial organics sources in the Ewaso Ng’iro River: *H. amphibius* dung (*n* = 11); leaves of the C4 grass *Cynodon plectostachyus* (*n* = 8); and the abundant C3 riparian tree *Acacia xanthophloea* (*n* = 9). Samples were collected periodically over the course of the study. *C. plectostachyus*, like most of the grasses at our study site, employ the C4 photosynthetic pathway (Tieszen et al. 1979). *Acacia xanthophloea* is a deciduous/semi-deciduous C3 tree that often forms monodominant stands along rivers in East Africa (Young and Lindsay 1988). We also sampled the isotopic composition of particulate organic matter (POM) in the *H. amphibius* pool (*n* = 9) and reference pool (*n* = 9) by filtering 25 ml of river water pumped 75 cm from the bottom of these pools onto pre-combusted glass fiber filters (Whatman 0.7 μm).

To examine potential patterns of use of these allochthonous sources by aquatic residents, we sampled in situ two abundant and ecologically important river consumers: the omnivorous cyprinid fish *Labeobarbus oxyrhynchus* (maximum length ~ 50 cm TL) and larvae of the dragonfly *Trithemis* spp. Both *Labeobarbus oxyrhynchus* and *Trithemis* spp. were collected from *H. amphibius* pool and the reference pool. *Labeobarbus oxyrhynchus* were sampled at two different times: once at the end of a particularly pronounced wet season (*n* = 9 *H. amphibius* pool; *n* = 10 reference pool) in January 2012 and once at the conclusion of the prolonged dry season in April 2012 (*n* = 8 both pools) (Fig. 2). All *L. oxyrhynchus* were measured (TL), fin clipped, and a sample of whole blood was drawn. *Trithemis* spp. were sampled only during the dry season in April 2012 (*n* = 8 *H. amphibius* pool; *n* = 7 reference pool). All
Trithenis spp. collected were taken by net, weighed, and ground whole. Isotopic turnover in whole blood and whole insects can vary but has been estimated to occur on the order of approximately one month (Hobson and Clark 1992, Buchheister and Latour 2010) and several weeks respectively (Gratton and Forbes 2006). C:N values of Trithenis spp. were compared between the H. amphibius pool and reference pools as a means of assaying potential differences in their lipid concentrations. All isotope samples were run in bulk form without the extraction or isolation of lipids or other compounds. Only POM samples were faced to an IsoPrime100 mass spectrometer. All isotopy using a CHNOS Elemental Analyzer interfaced to an IsoPrime100 mass spectrometer. All samples were run in bulk form without the extraction or isolation of lipids or other compounds. Only δ13C values were measured in POM samples.

Statistics

Data were compared using either Welch’s t-tests (when parametric assumptions were met) or Wilcoxon tests (i.e., δ13C values of L. oxyrhynchus wet season; δ15N values, TL, and C:N values of P. reticulata; mass of Trithenis spp.; and δ13C values of A. xanthophloea). Error is reported throughout as standard deviation (SD). As a complement to direct observations of isotopic differences in consumers, we used Bayesian isotope mixing models to estimate the relative contribution of H. amphibius dung to L. oxyrhynchus and Trithenis spp. sampled in H. amphibius and reference pools. A two isotope (δ13C, δ15N), two source (H. amphibius dung/C4 grass and C3 riparian tree material) mixing model was implemented in R using MixSIAR (Parnell et al. 2013, Stock and Semmens 2013). Additional details of mixing model construction are listed in Appendix C. All statistics were run in R (R Core Team 2014).

RESULTS

Hippopotamus amphibius surveys

A total of 38 visual surveys split evenly between the H. amphibius pool and reference pool were conducted in January and April 2012. H. amphibius were present in 100% of the surveys at the H. amphibius pool and were never detected at the reference pool. From the camera traps, we analyzed 13,103 images representing 91 consecutive days of monitoring. H. amphibius were present during 100% of these monitored days at the H. amphibius pool. The average daily maximum number of H. amphibius recorded at the H. amphibius pool was 19 (±3.7 SD) individuals and their numbers varied little across the wet and dry season (Appendix D).

All interview respondents stated that a H. amphibius pod had been continuously resident at the H. amphibius pool since their arrival to the region (i.e., >10 years ago). Based on these reports, H. amphibius have been largely resident at H. amphibius pool since at least 1947. All but one respondent reported having never observed resident H. amphibius at the reference pool (the single observation was of a mother and calf pair that used the reference pool briefly in 2005). Aerial surveys indicated that the nearest pod of consistently resident H. amphibius (~5 animals) was located 43 km upstream of our study reference pool.

Hydrological monitoring

Discharge data for the Ewaso Ng’iro River during the period of November 1, 2011 to May 31, 2012 at the Hulmes Junction station are shown in Fig. 2. Discharge in the Ewaso Ng’iro declined sharply before the January 2012 (high flow) in situ isotope sampling period and increased shortly after the April 2012 (low flow) in situ isotope sampling period.

Feeding trials

The δ13C values of captive, dung fed P. reticulata were significantly more positive than δ13C values of control P. reticulata collected from the control pool (lacking hippos) and not fed a dung diet (δ13C = −19.77 ± 1.31 vs. δ13C = −21.20 ± 1.41; t = 3.2, p < 0.01). This shift in the δ13C values of dung fed P. reticulata was in the direction of the more positive C4 plant values measured for H. amphibius dung (Fig. 3). No difference was observed in the δ15N values of dung fed and control P. reticulata (δ15N = 11.07 ± 0.45 vs. δ15N = 10.81 ± 0.47; W = 209, p = 0.28). There was no difference in the total length of dung fed and control P. reticulata (W = 175; p = 0.94). C:N values of dung fed and control P. reticulata were not significantly different (W = 138; p = 0.31). C:N values of dung fed P. reticulata
Fig. 3. Carbon and nitrogen stable isotope composition (δ¹³C and δ¹⁵N values; mean (±SD)) of three potential sources of allochthonous organic matter to the Ewaso Ng’iro River: Hippopotamus amphibius dung (red circle), the near-river C4 grass Cynodon plectostachyus (blue circle), and the C3 riparian tree Acacia xanthophloea (green circle). The δ¹³C values of particulate organic carbon (POM) sampled in the Ewaso Ng’iro are also plotted (mean blue line with ±SD plotted in light blue); nitrogen concentrations were too low to measure the δ¹⁵N values of POM. The δ¹³C and δ¹⁵N values were measured relative to the standards V-PDB and air, respectively. The δ¹³C values of river POM in the H. amphibius pool were not significantly different from the δ¹³C values of POM measured in the reference pool (δ¹³C = -21.17 ± 0.66 vs δ¹³C = -22.17 ± 1.09; t = -1.4, p = 0.24; Fig. 3).

The δ¹³C values of the river fish L. oxyrhynchus were not significantly different between the H. amphibius and reference pools during wet season sampling (W = 33, p = 0.36; Fig. 4). During the dry season, however, δ¹³C values of L. oxyrhynchus sampled in the H. amphibius pool were significantly more positive than δ¹³C values of fish sampled in the reference pool lacking H. amphibius (t = -2.3, p = 0.04). There was no significant difference between δ¹⁵N values of L. oxyrhynchus in the H. amphibius and reference pools during either the wet or the dry season (wet: t = 0.57, p = 0.58; dry: t = 1.8, p = 0.10). No difference was observed between the mean length of the fish L. oxyrhynchus collected in the H. amphibius and reference pools during either sampling period (wet: t = -0.30, p = 0.77; dry: t = -1.9, p = 0.08).

In situ sampling
Hippopotamus amphibius dung and the dominant C4 grass C. plectostachyus differed in δ¹³C values (t = 2.5, p = 0.04), but not in δ¹⁵N values (t = -0.55, p = 0.59; Fig. 3). Dung was more positive with respect to both δ¹³C values (W = 99, p < 0.001) and δ¹⁵N values (t = 6.5, p < 0.001) than the C3 riparian tree A. xanthophloea (Fig. 3). The δ¹³C values of river POM in the H. amphibius pool were not significantly different from the δ¹³C values of POM measured in the reference pool (δ¹³C = -21.17 ± 0.66 vs δ¹³C = -22.17 ± 1.09; t = -1.4, p = 0.24; Fig. 3).

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Fig. 4. Carbon stable isotope values (δ¹³C; mean ± SD) of river fish Labeobarbus oxyrhynchus (circles) and aquatic larvae of the dragonfly Trithemis spp. (triangle) sampled in an Ewaso Ng’iro River pool hosting a resident pod of Hippopotamus amphibius (black) and a nearby reference pool lacking H. amphibius (white). Labeobarbus oxyrhynchus were sampled in both pools at the end of the wet and dry seasons. Trithemis spp. were sampled only after the dry season. More positive δ¹³C values suggest an increased affinity to the observed heavier δ¹³C values of H. amphibius dung. An asterisk indicates statistically significant differences between pools. The δ¹³C and δ¹⁵N values were measured relative to the standards V-PDB and air, respectively.
Median values from the posterior distributions of Bayesian isotope mixing models suggested that intake of *H. amphibius* dung/C4 grass was higher in the *H. amphibius* pool than in the reference pool for both *L. oxyrhynchus* and *Trithemis* spp. (Appendix C: Table C1). The difference between the median estimated contribution of *H. amphibius* dung/C4 grass to *L. oxyrhynchus* in the *H. amphibius* pool and the reference pool was much higher during the dry season.

**Discussion**

Results from laboratory feeding trials and field sampling preliminarily suggest that fish and aquatic invertebrates in Kenya’s Ewaso Ng’iro River make use of organic matter vectored into the river by resident *H. amphibius*. Field monitoring of our Ewaso Ng’iro River pool study sites confirmed that *H. amphibius* are common at our *H. amphibius* pool and absent at the reference pool, and that this difference has likely been consistent for a minimum of six decades. Controlled dung feeding trials provided some indication of the magnitude and direction of isotopic shift that could be expected for an aquatic consumer that becomes heavily reliant upon *H. amphibius* dung. The δ¹³C values of *P. reticulata* guppies fed exclusively on dung shifted towards the more positive C4 δ¹³C values measured in *H. amphibius* dung. These differences were similar to those observed among field sampled aquatic consumers measured in the *H. amphibius* and reference pools of the Ewaso Ng’iro River. The δ¹³C values of one of the most abundant large consumers in this watershed, the fish *L. oxyrhynchus*, were more positive in the *H. amphibius* pool (Fig. 4). This difference, however, was only significant for *L. oxyrhynchus* during the dry season. The δ¹³C values of the predatory aquatic insect *Trithemis* spp. were also found to be significantly more positive in the *H. amphibius* pool during the dry season (the only season in which it was sampled; Fig. 4).

Results from isotope mixing models mirrored patterns exhibited in direct comparisons of δ¹³C value differences. Median values of the posterior distributions generated by the mixing models (Appendix C: Table C1; indicative of the most probable estimates of source contribution) indicated a higher contribution of *H. amphibius* dung/C4 grass to both *L. oxyrhynchus* and *Trithemis* spp. sampled in the *H. amphibius* pool. This between pool difference was five times more pronounced for *L. oxyrhynchus* during the dry season than the wet season.

The observation that differences in the δ¹³C values for the river fish *L. oxyrhynchus* were only significantly different during the dry season (low flow period) and that estimated dung contributions were higher during this period suggests that river hydrology may influence consumer use of *H. amphibius* derived subsidies. Increased river flow during wet periods may dilute and flush away organic material that *H. amphibius* import to sites like the *H. amphibius* pool. Conversely, dry/low flow periods may concentrate these subsidies and facilitate increased ecological utilization of *H. amphibius* derived organic matter. River flow rates are known to regulate the ecological impacts of allochthonous subsidies in other contexts, although increased flow rates are often associated with increased delivery rather than increased removal of allochthonous materials (Huryn et al. 2001, Abrantes and Sheaves 2010, Roach 2013).

Our conclusions assume that the sourcing dynamics of non-*H. amphibius* organic carbon are largely the same in these two hydrologically similar river pools. Inter-site variation in the dynamics of this delivery was not apparent and this lack of difference is partially supported by the observed lack of difference in the δ¹³C values of POM between study pools. Consequently, we provisionally suggest that the tens of thousands of kilograms of dung (Subalusky et al. 2014) produced by the aggregation of *H. amphibius* resident year round in this relatively small (~0.75 ha surface area) river pool presents a more parsimonious explanation for the recorded shifts in river consumer δ¹³C values.

Determining whether *H. amphibius*-derived nutrient subsidies are important to river consumers is a broadly important question. For example, *Labeobarbus*, the genus of fish studied in this work, is a commercially important group of fishes in East Africa and hundreds of tons of *Labeobarbus* are harvested annually (Lake Fisheries Development Program (LFDP) 1997, Dadebo et al. 2013). This harvest is particularly important...
in protein deficient regions (de Graaf et al. 2006, Dadebo et al. 2013). If, as these results suggest, Labeobarbus draws directly or indirectly upon H. amphibius-vectored subsidies in ecologically important ways, then these findings provide provisional support for the hypothesized links between H. amphibius and fisheries productivity (Mosepele et al. 2009). Such connections should be considered when evaluating the broader ecological significance of historical and contemporary reductions in the abundance and range of H. amphibius (Manlius 2000, Van Kolfschoten 2000, Lewison et al. 2008). Firmly establishing the ecological importance of H. amphibius subsidies will require further study carried out at more comprehensive spatial and temporal scales.

It is likely that $\delta^{13}C$ values will not be useful for tracing utilization of H. amphibius vectored subsidies in all contexts. A careful review of the isoscape of any particular study region will be required to evaluate the local utility of carbon stable isotopes for identifying potential use of H. amphibius excreta. For example, $\delta^{13}C$ values would likely be a less powerful diagnostic tool for studying H. amphibius subsidies in systems where C4 marginal plants (e.g., plants that have $\delta^{13}C$ values similar to H. amphibius dung), such as papyrus, are abundant and make a substantial contribution to river detrital pools (Grey and Harper 2002). The overall degree of landscape-watershed coupling must also be considered. In watersheds where the physical transport of C4 derived organic matter into rivers is continuously high or spatially heterogeneous, it will be challenging to discern H. amphibius contributions to aquatic food webs. Further research will help to better clarify how these issues of context shape the global utility of carbon stable isotopes for tracking and contextualizing the importance of H. amphibius subsidies to freshwater ecosystems.

**Acknowledgments**

For invaluable field support we thank Lacey Hughey, Jamie Gaymer, Diane Goheen, Gilbert Kosgei, Jennifer Guyton, Margaret Kinnaard, Peter Lokeny, the Kenya Wildlife Service, the Kenya National Commission for Science, Technology and Innovation, the Mpala Research Centre, National Museums of Kenya, Ol Jogi Ltd, Stefania Mambelli, Laban Njoroge, Tristan Nuñez, Everlyn Ndinda, Matthew Snider, Noelia Solano, Hillary Young, Truman Young, and Ian Warrington. We would also like to thank Kinyanjui John at the Isiolo Office of the Water Resources Management in Kenya for his help obtaining discharge records. Funding for this work was provided by the National Science Foundation (IRFP OISE #1064649 and DEB #1146247).

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SUPPLEMENTAL MATERIAL

APPENDIX A

*Underwater video of *Hippopotamus amphibius* dunging*

Video of *Hippopotamus amphibius* defecating while taking refuge in its diurnal aquatic refuge. Dung is rapidly consumed by resident fish *Labeo* sp. nov. ‘Mzima.’ This video footage was collected from Mzima Springs in Kenya, a site with uniquely high water clarity which permits observation of interactions between *H. amphibius* and river consumers. Video © Deeble and Stone Productions (markdeeble.wordpress.com); used with permission. doi: http://dx.doi.org/10.1890/ES14-00514.2

APPENDIX B

![Graph](image)

Fig. B1. Time partitioned results of lab-based *Hippopotamus amphibius* dung feeding trials. Stable isotope composition ($\delta^{13}$C and $\delta^{15}$N) of guppies *Poecilia reticulata* fed exclusively *Hippopotamus amphibius* dung in the laboratory for three months and six months. $\delta^{13}$C and $\delta^{15}$N values were measured relative to the standards V-PDB and air, respectively. There were no significant differences between dung fed *P. reticulata* sampled at three months and six months ($\delta^{13}$C: $t = -1.51$, $p = 0.15$; $\delta^{15}$N: $W = 63$, $p = 0.88$), suggesting that the majority of the isotopic transitioning in these *P. reticulata* occurred in less than three months.

APPENDIX C

*Isotope mixing model results*

A two isotope ($\delta^{13}$C, $\delta^{15}$N) two source Bayesian isotope mixing model was used to estimate potential differences in utilization of *Hippopotamus amphibius* dung by aquatic consumers sampled in *H. amphibius* and reference pools. The sources utilized in this model were *H. amphibius* dung/C4 grass (represented by *H. amphibius* dung (n = 11)) and C3 riparian tree material (represented by leaves of the abundant C3 riparian tree *Acacia xanthophloea* (n = 9)). Published fractionation values for aquatic consumers used in all models were taken from McCutchan et al. (2003): $\Delta\delta^{13}$C: $+0.4 \pm 0.2$ (mean ± SD); $\Delta\delta^{15}$N: $+2.3 \pm 0.3$. These fractionation values were applied in the case of both *Labeobarbus oxyrhynchus* and *Trithemis* spp. consumers.
Appendix D

Table C1. Median values of the posterior distributions generated from stable isotope mixing models predicting reliance of consumers *L. oxyrhynchus* (fish) and *Trithemis* spp. (dragonfly larvae) on the two sources examined. The difference between predicted contributions of *H. amphibius* dung/C4 grass and C3 riparian tree material in *H. amphibius* and reference pools are reported. The disparity between the estimated contribution of *H. amphibius* dung/C4 grass to *L. oxyrhynchus* sampled in the *H. amphibius* pool and those sampled in the reference pool was much greater during the low flow dry season.

| Carbon source         | Wet season |                   | Dry season |                   |
|-----------------------|------------|-------------------|------------|-------------------|
|                       |            | *H. amphibius*    | Reference  | Difference        | *H. amphibius* | Reference  | Difference |
| *Labeobarbus*         |            |                   |            |                   |
| Dung *H. amphibius* /C4 grass | 0.62 0.60 0.02 | 0.59 0.49 0.10 |
| C3 riparian tree      | 0.38 0.40 0.02 | 0.41 0.51 −0.10 |
| *Trithemis*           |            |                   |            |                   |
| Dung *H. amphibius* /C4 grass | NA NA NA | 0.27 0.21 0.07 |
| C3 riparian tree      | NA NA NA | 0.73 0.80 −0.07 |

Fig. D1. *Hippopotamus amphibius* abundance as measured at *H. amphibius* pool site. Plot of daily maximum counts of *Hippopotamus amphibius* individuals recorded at the *H. amphibius* pool via camera trap images taken at 5-min intervals during daylight hours over the study period.