



Food Insecurity and the Unsustainable Hunting of Wildlife in a UNESCO World Heritage Site

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Madagascar faces dual challenges in biodiversity conservation and public health. In order to identify strategies to reduce the unsustainable hunting of threatened species while maintaining or improving child nutrition, we quantified interactions among ecosystem indicators (lemur density and habitat biodiversity indices), health indicators (stunting, underweight, wasting, and anemia), nutrition, food security, and wildlife hunting through interviews of 1,750 people in 387 households and surveys of 28 wildlife transects with 156 habitat plots at 15 sites on Madagascar's Masoala Peninsula, a UNESCO World Heritage Site. The surveyed population ate 6,726 forest animals (mammals and birds), or a mean of 3.27 kg of wild meat per person (4.48 kg per adult equivalent) during the prior year. Local Malagasy were also highly food insecure (78% of households) and malnourished (for children under five, as many as 67% were stunted, 60% were underweight, 25% were wasted, and 40% were anemic). In some communities, nearly 75% of animal-sourced calories, 76% of protein, and 74% of iron came from forest animals—demonstrating a strong dependence on wild foods. Few micronutrient-rich alternatives to wild meats were available in adequate supply and many were highly volatile; for example, 79% of chickens died from Newcastle disease in the prior year. The survivorship of lemurs (94% of lemur species are threatened with extinction) depends on providing food security to a malnourished human population who commonly hunts wildlife for food. Currently, wildlife provides a critical source of micronutrients, yet the hunting of threatened species is an untenable solution to poor diet and food insecurity. Given the established connection between wild foods and human nutrition, reductions in forests and wildlife populations will also threaten the local food supply. In order to reduce the unsustainable hunting of threatened species while improving household food security and child health, we suggest testing the effects of increasing the affordability, accessibility, and stability of micro-nutrient rich animal-sourced foods in communities where forests contribute the most to food security.

Keywords: bushmeat, conservation, food security, hunting, lemur, Madagascar, Masoala National Park, nutrition

INTRODUCTION

While unsustainable hunting is widely recognized as a primary contributor to global biodiversity loss (Wilkie et al., 2016), little is known about the relationships between hunting, biodiversity, nutrition, and food security surrounding many of the world's protected areas. Malnutrition is a primary driver of the global burden of disease (International Food Policy Research Institute, 2016); with half of the deaths of all children worldwide associated with undernutrition (Black et al., 2013). If a child's diet is deficient in key micronutrients, such as zinc, iron, and vitamin A, their cognitive and physical growth can be delayed or impaired and their risk of infection and early death is significantly increased (Ezzati et al., 2002; Lopez et al., 2006; Black et al., 2013).

The country of Madagascar is one of the least food secure nations in the world (Economist Intelligence Unit, 2017). Its people spend proportionally more of their cash income on food than anywhere else on the planet (Economist Intelligence Unit, 2014, 2016). Further, Madagascar has one of the highest rates of stunting in the world (International Food Policy Research Institute, 2016), and faces high health burdens including poor maternal outcomes and high rates of both anemia and malaria (WHO, 2012; Mould et al., 2016; Rice et al., 2016).

Madagascar is also one of the most biodiverse places on earth. The nation has long been a global priority for conservation; most of the plant and animal species in Madagascar are found nowhere else on earth (Myers et al., 2000). Among these animals are lemurs, euplerid carnivorans, and tenrecs. Nearly 90% of all tenrecs, and 100% of all lemurs and euplerid carnivorans are only found in Madagascar. Lemurs are the most threatened group of primates on earth, and nearly all species (94%) are threatened with extinction because of habitat loss and unsustainable hunting (Schwitzer et al., 2013).

Recent global evidence shows many complex pathways by which forests can improve dietary diversity, health, and nutrition (Golden et al., 2011; Food Agriculture Organization, 2013; Johnson et al., 2013; Ickowitz et al., 2014; Rowland et al., 2016; Tata et al., 2019). While forest foods are rarely the staple food in a diet (Rowland et al., 2016), children who live in areas with greater forest cover eat more nutritious diets than those who do not (Ickowitz et al., 2014; Tata et al., 2019). In addition to primary forests, swidden and agro-forests also provide opportunities for families to increase the diversity of their diet and their access to many micronutrient rich foods (Ickowitz et al., 2016). Among these wild foods, wild animals provide an important source of calories, fat, protein, and bio-available micronutrients (Fa et al., 2003; Siren and Machoa, 2008; Golden et al., 2011; Sarti et al., 2015; van Vliet et al., 2017). Yet the unsustainable hunting of many wild species threatens their survival, the functioning of their ecosystems, and the food security and cultural identity of many people worldwide (Wilkie et al., 2016).

The interactions between biodiversity and food security are poorly understood within Madagascar. The Masoala National Park—a UNESCO World Heritage site—is one of Madagascar's most intact and biodiverse forest ecosystems (Kremen et al., 1999; Kremen, 2003). Yet, this national park is under significant threat

from deforestation and unsustainable hunting (Allnutt et al., 2013; Borgerson, 2016; Zaehring et al., 2017). Here, we aim to (a) describe the state of food security, nutrition, biodiversity, and hunting on the Masoala Peninsula; and (b) understand how their interactions affect the future of public health and biodiversity conservation in Madagascar.

METHODS

We used the following four multi-disciplinary methods to examine the interactions among human health, nutrition, and biodiversity at 13 sites surrounding the Masoala National Park. We collected this data during May until December 2015. All research was approved by Human Subjects Institutional Review Boards (Protocols #15-0331 Wildlife Conservation Society and #15-2230 Harvard T. H. Chan School of Public Health), the Republic of Madagascar and Madagascar National Parks (Permits 111/13, 325/14, 111/15, 218/15, 270/15, /MEEF/SG/DGF/DCB.SAPP/SCB). We obtained oral informed consent and/or assent from all participants.

Extensive Structured Interviews

All authors are either fluent in, or native speakers of, the local dialect of Betsimisaraka Malagasy. CB and BJRR asked members of 387 households in 13 communities about their hunting, collection of forest products for food, demographics, diet, health, income, and food security in a 1–2 h interview. We surveyed all households in small communities. In communities with >50 households, we randomly selected study households by using a grid system in each village, assigning a number to each household in each grid, and selecting a subset of households in all quadrants using a random number array. Individuals provided information about each type of cash-generation activity in Malagasy Ariary (MGA) and we converted estimates of cash income to United States Dollar (USD) at a rate of 3,000 MGA to the dollar (the conversion rate at the time of data collection). Because subsistence (and not cash) income was high, we also scored houses based on their size and the building materials used for their walls, floors, and roofs (ranked 1–3 based on local perceptions of quality), to provide a secondary indicator of wealth in addition to reported cash income. This total score was divided by the number of household members to control for the possibility that house size may increase with household size.

We determined food security using multiple methods. We used the Coping Strategies Index (CSI) (CARE, 2008) and the Household Food Insecurity Access Scale (HFAIS) (Coates et al., 2007) to measure changes in feelings, perceptions, and behaviors during the prior year (HFAIS) and prior week (CSI) in response to insufficient access to food (coping strategies). We then weighted CSI values based on the qualitative perception of the severity of each coping strategy in each community (categorically ranked on a scale of 1–4). A CSI or HFAIS score of 0 reflects a household which perceives itself as food secure and higher CSI or HFAIS scores reflect greater perceived food insecurity. We defined a food insecure household as any household that could not access adequate food to feed their family one or more days during the prior week. In order to

TABLE 1 | Masoala food security (2015)[†].

	Village 1	Village 2	Village 3	Village 4	Village 5	Village 6	Village 7	Village 8	Village 9	Village 10	Village 11	Village 12	Village 13	Masoala average
1) Affordability														
1.1) Food consumption as a share of household expenditure	45.3	64.8	61.6	58.6	57.2	60.4	60.8	34.5	29.0	41.4	49.3	46.0	38.3	51.6
1.2) Proportion of population under global poverty line	87.5	96.7	95.0	92.5	93.3	90.0	100.0	100.0	85.7	100.0	100.0	95.1	96.7	95.09
1.3) Gross domestic product per capita (PPP)	271	117	200	1,136	204	247	34	89	409	15	38	233	217	266.5
1.4) Presence of food safety net programs	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1.5) Access to financing for farmers	0	0	0	1	1	0	0	0	0	0	0	0	2	0.3
2) Availability														
2.1) Sufficiency of supply														
2.1.1) Average food supply	3495.8	3642.7	2820.7	2908.9	2646.9	2443.5	2558.5	2173.0	2542.6	1781.4	2297.7	2368.8	2558.9	2672.7
2.1.2) Dependency on chronic food aid	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2.2) Agricultural infrastructure														
2.2.1) Existence of adequate crop storage facilities	1	1	1	1	0	0	1	0	1	1	0	0	1	0.6
2.2.2) Road infrastructure	0	0	0	1	1	2	0	0	0	0	0	1	1	0.5
2.2.3) Port infrastructure	1	1	1	0	0	0	0	0	0	0	0	2	1	0.6
2.3) Corruption	1	1	2	3	2	2	1	3	0	0	0	1	2	1.6
2.4) Food loss	68.7	71.3	70.3	63.5	66.6	53.2	40.9	53.8	79.3	19.4	15.3	56.4	56.0	55.3
3) Quality and safety														
3.1) Diet diversification														
3.1) Diet diversification	37	33	35	42	35	47	29	33	21	15	21	46	61	37.0
3.2) Micronutrient availability														
3.2.1) Dietary availability of vitamin A	0.19	0.30	0.20	0.30	0.23	0.43	0.11	0.20	0.43	0.26	0.20	0.27	0.23	0.2
3.2.2) Dietary availability of animal iron	3.7	2.4	5.3	1.4	2.7	2.3	0.9	1.4	2.1	0.8	1.4	4.9	2.3	2.6
3.2.3) Dietary availability of vegetal iron	17.8	17.2	11.5	15.6	11.9	12.5	12.3	10.7	12.3	9.0	12.3	9.4	14.8	13.0
3.3) Protein quality														
3.3) Protein quality	103.6	86.3	78.0	66.4	68.8	72.7	59.3	54.5	61.3	40.7	54.6	80.1	70.6	71.0
3.4) Food safety														
3.4.1) Percentage of population with access to potable water	100	100	100	100	100	100	100	100	100	100	0	100	100	92.2

(Continued)

TABLE 1 | Continued

	Village 1	Village 2	Village 3	Village 4	Village 5	Village 6	Village 7	Village 8	Village 9	Village 10	Village 11	Village 12	Village 13	Masoala average
3.4.2) Presence of a store	1	1	1	1	1	1	1	1	0	0	1	1	1	0.93
4) Background variables														
4.1) Prevalence of undernourishment	15.6	0.0	20.0	25.0	10.0	20.0	28.6	26.7	0.0	57.9	40.0	31.7	20.0	23.3
4.2) Child growth														
4.2.1) Percentage of children under 5 stunted	40.0	11.1	25.0	33.3	0.0	12.5	33.3	27.3	66.7	27.3	30.0	28.6	33.3	28.9
4.2.2) Percentage of children under 5 underweight	42.9	12.5	33.3	38.9	0.0	11.1	9.1	15.4	33.3	30.8	25.0	60.0	16.7	27.4
4.2.3) Percentage of children under 5 wasted	20.0	0.0	25.0	6.7	0.0	0.0	0.0	9.1	0.0	0.0	0.0	4.8	0.0	5.0
4.3) Anemia														
4.3.1) Percentage of pop anemic	22.2	16.8	32.7	31.2	17.7	19.5	22.4	14.6	23.3	10.4	22.5	40.1	27.0	24.5
4.3.2) Percentage of children under 5 anemic	16.7	18.2	27.8	27.8	40.0	18.2	20.0	16.7	28.6	11.1	17.7	27.8	40.0	23.7
4.4) Intensity of food deprivation	347.9	363.9	280.2	289.3	263.9	242.1	254.7	213.5	253.0	177.8	228.7	235.7	255.7	265.9
4.5) Prevalence of obesity	7.5	2.5	9.8	5.4	2.1	10.3	0.0	3.4	0.0	0.0	0.0	1.4	5.9	4.4
5) Forest provisioning services														
5.1) Availability														
5.1.1) Abundance of plant life	266846.6	228049.2	111555.9	182937.5	203982.2	106778.3	145019.3	221906.0	231200.1	234808.2	265571.2	43589.7	163031.0	175519.0
5.1.2) TBA trees	31828.3	34787.4	587.9	1382.4	12146.3	294.4	4891.5	7027.3	10024.4	3770.9	5520.7	9.4	334.6	8216.6
5.1.3) Biomass wildlife	1344.5	916.9	2103.0	1365.3	2641.3	8344.8	2602.7	2204.5	4511.5	4418.4	4052.4	8272.4	4944.8	3624.0
5.2) Quality														
5.2.1) Habitat SWDI	3.8	3.7	2.1	2.9	3.1	1.2	2.8	2.7	3.0	3.2	3.0	1.1	2.4	2.6
5.2.2) Wildlife SWDI	0.6	0.0	0.0	0.1	0.3	0.0	0.2	0.2	0.2	0.5	0.3	0.0	0.0	0.2
5.3) Contribution/Use														
5.3.1) Food supply														
5.3.1.1) Average vegetable food supply from forest	18.3	3.4	7.6	22.2	13.4	10.0	37.6	9.5	24.6	6.6	0.0	9.5	6.1	12.4
5.3.1.2) % of vegetable food supply from forest	0.4	0.1	0.3	0.9	0.5	0.4	1.8	0.3	1.2	0.4	0.0	0.4	0.2	0.5
5.3.1.3) Average animal food supply from forest	22.5	15.0	20.0	17.7	9.7	22.9	14.3	40.9	48.5	7.8	14.4	12.2	15.5	18.5
5.3.1.4) % of animal food supply from forest	20.3	17.3	18.1	43.9	39.2	18.8	73.7	61.4	75.2	61.2	55.1	10.5	31.9	36.2

(Continued)

TABLE 1 | Continued

	Village 1	Village 2	Village 3	Village 4	Village 5	Village 6	Village 7	Village 8	Village 9	Village 10	Village 11	Village 12	Village 13	Masoala average
5.3.1.5) % of all food supply from forest	1.2	0.5	1.0	1.4	0.9	1.3	2.0	2.3	2.9	0.8	0.6	0.9	0.8	1.2
5.3.2) Diet diversification														
5.3.2.1) Dietary availability of vitamin A from forest	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.1	0.4	0.1	0.1	0.0	0.1	0.1
5.3.2.2) Dietary availability of iron from forest	1.3	0.4	0.8	1.2	0.7	0.8	1.9	1.2	2.5	0.5	0.5	0.8	0.8	0.9
5.3.2.3) % of Dietary availability of iron from forest	5.1	2.2	3.7	6.5	3.3	5.4	8.5	5.8	14.3	5.1	4.0	4.9	4.9	5.1
5.3.3) Protein														
5.3.3.1) Protein quality from forest	3.5	1.6	2.3	2.7	1.5	2.2	3.8	4.0	8.3	1.4	2.0	2.2	2.9	2.6
5.3.3.2) % of quality protein from forest	3.9	1.9	2.3	4.0	2.0	2.6	5.7	4.5	9.9	3.7	3.8	2.6	4.0	3.5

[†]The unit and method used to calculate each variable is explained in detail in Table 2.

gain a more detailed and holistic perspective of household food security, we also used a modified version of the Economist Intelligence Unit's (EIU) food security index (Myers et al., 2000), with additional data collected on forest provisioning services (Tables 1, 2).

We asked households about the quantity of 160 different types of food they ate, including 24 forest mammals (Table 3), during the prior 24-h, week, month, and year (depending on how frequently the food was regularly consumed) and used data from the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2012) and GENUS (Smith et al., 2016) to calculate dietary nutrient intake. We converted all household members into their adult-equivalent score using FAO guidelines (Food Agriculture Organization, 2004; Weisell and Dop, 2012). We recorded the quantities of foods eaten in local serving sizes and the weighed each serving size 10 times to determine a mean weight for calculations. For rarely consumed animals, we calculated the mean body mass of animals using previously published data (Goodman, 2011, 2012; Soarimalala and Goodman, 2011; Borgerson, 2015, 2016). Dietary diversity was measured using the Women's Dietary Diversity Scale (WDDS) (FAO, 2010).

Measurements of Human Health

During interviews, CB and BJRR collected 27 indicators of human health from 1,750 individuals aged 2 weeks to 91 years old (all available members of the 387 interviewed households). We measured individual height and weight, and used non-invasive photospectrometry to assess oxygen saturation and hemoglobin status using a MASIMO Pronto 7 hemoglobinometer. We also asked about each individual's overall morbidity. We used WHO and CDC guidelines to determine whether individuals were stunted, underweight, wasted, had severely low BMIs, or were anemic (WHO, 2006, 2011; Centers for Disease Control Prevention, 2012).

Lemur and Bird Surveys

BR used distance sampling methods (Buckland et al., 1993; Buckland, 2001) to assess the density, biomass, abundance, and population demographics of all diurnal lemur and bird species (groups of animals which are hunted and can be reliably surveyed using distance sampling methods). We established a total of 172 kilometers of transects (using a GPS) on the peninsula. Each of the 13 village sites contained two 2 km long transects. BR and a local field assistant walked each transect line at a maximum rate of 1 km/h, a minimum of 20 times. Two additional transects (total of 140 areal km in length) extended from the western border of the Masoala National Park through the interior, and ended at the eastern border, through the parks northern and southern regions. Each interior transect was walked twice. Each time we saw a lemur or bird, we recorded the age class, sex, group size/composition, height (m), angle, and the perpendicular distance (m) of the animal (or the center of the group of animals) from the transect line. We used published and estimated body weight data (Goodman, 2011, 2012; Soarimalala and Goodman,

TABLE 2 | Units and methods used to calculate Masoala food security variables (2015).

Variable	Basis of calculation
1) Affordability	
1.1) Food consumption as a share of household expenditure	% of total household expenditures that were spent on food during prior week from household weekly dietary and economic recall surveys
1.2) Proportion of population under global poverty line	% of population (individuals) living under \$2/day PPP (exchange rate 3,000 MGA:\$US1) from household and individual annual income recall surveys
1.3) Gross domestic product per capita (PPP)	Mean cash income last year in US\$ at PPP / capita from household and individual annual income surveys
1.4) Presence of food safety net programmes	Village qualitative assessment (0–4) from village group interviews, e.g., Seecaline, Care, school breakfasts
1.5) Access to financing for farmers	Village qualitative assessment (0–4) from village group interviews, e.g., OTIV, CARE
2) Availability	
2.1) Sufficiency of supply	
2.1.1) Average food supply	Mean calories/adult male equivalent/day calculated from household 24 h dietary recalls
2.1.2) Dependency on chronic food aid	Village qualitative assessment (0–2) from village group interviews
2.2) Agricultural infrastructure	
2.2.1) Existence of adequate crop storage facilities	Village qualitative assessment (0–1) from village group interviews
2.2.2) Road infrastructure	Village qualitative assessment (0–4) from village group interviews (incl. quality of roads, transportation availability, quality, frequency, cost, and capacity)
2.2.3) Port infrastructure	Village qualitative assessment (0–4) from village group interviews (incl. transportation availability, quality, frequency, cost, and capacity)
2.3) Corruption	Rating 0–4; 4 = highest risk from village group interviews (incl. frequency and perceived severity)
2.4) Food loss	Total % of chickens that died of disease from annual household recalls of livestock loss
3) Quality and safety	
3.1) Diet diversification	Average % of grams of diet from non-starchy foods calculated from household 24 h dietary recalls
3.2) Micronutrient availability	
3.2.1) Dietary availability of vitamin A	Proportion of population that ate foods high in Vit A in the last 24 h, from 24 h dietary recall surveys
3.2.2) Dietary availability of animal iron	Average mg/person/day calculated from household 24 h, weekly, and annual diet dietary recalls
3.2.3) Dietary availability of vegetal iron	Average mg/person/day calculated from household 24 h, weekly, and annual dietary recalls
3.3) Protein quality	Average grams/person/day calculated from household 24 h, weekly, and annual diet dietary recalls
3.4) Food safety	
3.4.1) Percentage of population with access to potable water	% of population with access to clean rivers (no upstream villages) or improved water sources (wells, pumps, etc.) from village group interviews
3.4.2) Presence of a store	Village qualitative assessment (0–2) (0 no stores, 1 stores, 2 bazaar) from village group interviews
4) Background variables	
4.1) Prevalence of undernourishment	% of households whose members (adult male equivalent) do not receive the min calories/person as defined by the FAO/WHO/UNU expert consultation 2001, mean age 21.11 = 1,680 cal
4.2) Child growth	
4.2.1) Percentage of children under 5 stunted	% of children under 5 whose height is more than two standard deviations below the mean for their age and sex, using WHO standards, calculated from individual health assessments
4.2.2) Percentage of children under 5 underweight	% of children under 5 whose weight is more than two standard deviations below the mean for their age and sex, using WHO and CDC standards, calculated from individual health assessments
4.2.3) Percentage of children under 5 wasted	% of children under 5 whose weight for height is more than two standard deviations below the mean for their age and sex, using WHO and CDC standards, calculated from individual health assessments
4.3) Anemia	
4.3.1) Percentage of pop anemic	% of total population with Hb levels below the min recommended range for their respective age and sex, calculated from individual health assessments
4.3.2) Percentage of children under 5 anemic	% of children under 5 with Hb levels below the min recommended range for their respective age and sex, calculated from individual health assessments
4.4) Intensity of food deprivation	Average kcal/person/day calculated from household 24 h, weekly, and annual diet recall surveys
4.6) Prevalence of obesity	% of population over age 20 with a BMI >30, calculated from individual health assessments
5) Forest provisioning services	
5.1) Availability	
5.1.1) Abundance of plant life	Mean N plants per hectare, calculated from habitat plots

(Continued)

TABLE 2 | Continued

Variable	Basis of calculation
5.1.2) TBA trees	TBA of trees >3 cm in diameter per hectare, calculated from habitat plots
5.1.3) Biomass wildlife	Estimated biomass (in grams) of diurnal lemur and birds per hectare, calculated from transects
5.2) Quality	
5.2.1) Habitat SWDI	SWDI of trees over 10 cm in diameter, calculated from habitat plots
5.2.2) Wildlife SWDI	SWDI of diurnal wildlife species, calculated from transects
5.3) Contribution/Use	
5.3.1) Food supply	
5.3.1.1) Average vegetable food supply from forest	Mean kcal/capita/day calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.1.2) % of vegetable food supply from forest	% of total kcal/capita/day from vegetable/fruit products calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.1.3) Average animal food supply from forest	Mean kcal/capita/day calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.1.4) % of animal food supply from forest	% of total kcal/capita/day from animal products calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.1.5) % of all food supply from forest	% of total kcal/capita/day from all food and drinks calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.2) Diet diversification	
5.3.2.1) Dietary availability of vitamin A from forest	Proportion of population that ate foods high in Vit A yesterday from forest, calculated from household 24 h dietary recalls
5.3.2.2) Dietary availability of iron from forest	% of total mg/person/day, calculated from household 24 h dietary recalls
5.3.2.3) % of Dietary availability of iron from forest	Mean mg/person/day calculated from household 24 h dietary recalls
5.3.3) Protein	
5.3.3.1) Protein quality from forest	Mean grams/person/day calculated from household 24 h, weekly, and annual diet dietary recalls
5.3.3.2) % of quality protein from forest	% of total grams/person/day calculated from household 24 h, weekly, and annual diet dietary recalls

2011; Borgerson, 2015, 2016) for different age/sex classes to determine biomass.

Habitat Sampling

DR and a local assistant collected botanical information using 156 forest plots, each 20 m in diameter. We employed the same 15 transect lines used for wildlife surveys for habitat sampling. At each of the village sites, 10 habitat plots were established in 200 meters increments at a 20 m distance from each of the wildlife transects. For the interior transects, plots were located every 5 km. Each plot was composed of three concentric circles. In the first circle (1 m radius), we sampled all small plants, i.e., woody seedlings and herbaceous ground cover with a diameter <2.5 cm, and estimated the percentage of ground cover for each species. In the second circle (3 m radius) we identified, counted, and measured the diameter at breast height (DBH) and height of woody stems of all medium plants, i.e., shrubs, saplings, and woody and herbaceous climbers (vines and lianas) between 2.5 and 10 cm in diameter. In the third circle (10 m radius), we identified the local species name of each large plant with a DBH ≥ 10 cm, and measured its DBH, crown width, height, bole height, and angle and distance from the plot center.

RESULTS

Food Security

We found a high prevalence of both food insecurity and poverty on the Masoala Peninsula with 78% of Malagasy households

being highly food insecure, experiencing food insecurity a mean of 3.26 days during the prior week [CSI mean 4.88 (range: 0–42); weighted CSI mean 11.74 (range: 0–99)]. We recorded data across 8 months which included prior week recalls of food insecurity during seasons of both low and high food security. The most frequently reported mechanisms for coping with food insecurity during the prior week were to: limit the portion size of all household members (16% of all incidences of coping strategies used); eat at the households of friends or family (13%); and rely on less preferred or less expensive foods (12%).

The mean household HFAIS score was 2.86 (household range 0–11). Participants reported two lean seasons, one in the austral winter and one in the summer, just before each rice harvest. The winter lean period was reported to be the most severe. During the prior year, nearly half of households (43.9%) worried that their household would not have enough food. Because of a lack of food-resources, 38.0% were unable to eat preferred foods and a third of households ate just a few kinds of food day after day (30.2%). A quarter of households ate less during meals than needed (27.1%) and believed they lost weight because of inadequate food (24.6%). One in every five households experienced a time during the prior year when there was no food at all in their household and/or fields and no financial resources to acquire more (19.4%), and/or reduced the number of meals they ate in a day (17.6%). Nearly one in ten (8.0%) households sold assets, land, or livestock to buy food during the prior year.

Over 95% of the surveyed population was under the global poverty line (defined as the percentage of individuals living

TABLE 3 | Consumption and hunting of forest mammals during the prior year by members of 387 households in 13 communities surveyed near the Masoala National Park (2015).

Species	Mean eaten per household	Total number eaten [†]	Eaten as a guest	Opportunistic hunting	Pursuit hunting	Trapping	Purchasing	Unknown provenance	Price per whole animal
	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(USD)
Lemurs	0.62	240	19	58	31	103	17	12	
<i>Eulemur albifrons</i>	0.35	136	10	7	22	79	9	9	2.70
<i>Varecia rubra</i>	0.05	19	4	0	5	3	7	0	6.00
<i>Microcebus</i> sp.	0.02	9	0	9	0	0	0	0	–
<i>Allocebus trichotis</i>	0.01	2	0	2	0	0	0	0	–
<i>Cheirogaleus</i> sp.	0.05	19	0	16	0	2	0	1	–
<i>Phaner furcifer</i>	0.00	1	0	0	1	0	0	0	–
<i>Lepilemur scottorum</i>	0.01	5	1	4	0	0	0	0	–
<i>Haplemur griseus</i>	0.06	24	2	7	0	14	1	0	1.00
<i>Avahi mooreorum</i>	0.06	24	2	12	3	5	0	2	–
<i>Daubentonia madagascariensis</i>	0.00	1	0	1	0	0	0	0	–
Carnivorans	0.22	85/100	18	23	8	48	3	0	
<i>Galidia elegans</i>	0.06	25	1	13	5	6	0	0	
<i>Galidictis fasciata</i>	0.00	1	0	0	0	1	0	0	
<i>Salanoia concolor</i>	0.01	4	0	3	0	1	0	0	
<i>Cryptoprocta ferox</i> (min whole animals caught/portions)	0.06	23/38	15	4	3	14	2	0	0.33 per kg
<i>Fossa fossana</i>	0.03	13	0	1	0	12	0	0	–
<i>Eupleres goudotii</i>	0.05	19	2	2	0	14	1	0	1.00
Tenrecs	4.53	1,755	116	1,031	532	8	47	21	
<i>Tenrec ecaudatus</i>	4.13	1599	115	913	500	8	47	16	0.36
<i>Setifer setosus</i>	0.18	71	1	53	12	0	0	5	–
<i>Hemicentetes semispinosus</i>	0.22	85	0	65	20	0	0	0	–
Bats	0.57	222	17	7	63	38	93	4	
<i>Pteropus rufus</i>	0.52	201	17	0	49	38	93	4	0.88
<i>Rousettus madagascariensis</i>	0.02	9	0	7	2	0	0	0	–
Microchiroptera sp.	0.03	12	0	0	12	0	0	0	–
Introduced species	1.05	407	17	1	53	105	224	7	
<i>Potamochoerus larvatus</i> ^{††}	0.90	347	12	0	53	54	224	4	1.15
<i>Viverricula indica</i>	0.16	60	5	1	0	51	0	3	–
Total mammals	7.00	2,709/2,724	187	1120	687	302	384	44	

[†]Total number of whole animals of each species eaten by the 387 households in 13 communities during the prior year.

^{††}Pieces of meat weighing a mean of 1.1 kg.

The bold text is the total number eaten in each animal group.

under \$2 per person per day) (Tables 1, 2), and cash income was primarily spent on food (Mean = 51.7%). Of food expenses, 73.2% of these were used to purchase ingredients for a meat or vegetable sauce to complement their rice staple. Comparatively, only 22% was spent on rice, 1% on tubers, and 4% on snacks.

Nutrition, Dietary Diversity, and Health

Overall nutrition was poor and dietary diversity was low (Tables 1, 2). A mean of 37.0% of all grams of food eaten during the prior week were from non-starchy foods. The diets of most households (77.3%) were moderately diverse during the prior

week (Tables 1, 2, 4). One in four households ate any food high in Vitamin A within the previous 24 h (Tables 1, 2), and individuals ate a mean of 2.63 mg of iron from animal sources, 12.97 mg from all other food sources, and 70.97 g of quality protein per day.

We found high levels of stunting, underweight, wasting, and anemia and a moderate to high prevalence of anemia throughout all sub-populations measured on the Masoala (Tables 5, 6). There was notable variation between communities in these variables. Focusing on children under five, some communities reached levels of 67% stunting, 60% underweight, 25% wasting, and 40% anemia (Tables 1, 5). On average, however, the severity of the prevalence of stunting, underweight, wasting, and anemia in

children under five on the peninsula is classified as medium for stunting, high for children who are underweight, and medium for wasting (Table 6; WHO, 2012).

Natural Resource Use

Local people reported a high reliance on the forest for food. Surveyed households ate 6,726 forest animals during the prior year (Table 3). Of the micro- and macro-nutrients provided by domestic and wild animal products (including fish, eggs, insects, honey, etc.), a mean of 36.2% of all calories (kcal) from animal products, 44.5% of all animal iron, and 38.4% of animal protein came from wild forest animals (Tables 1, 2). There was significant variation among communities. In some communities, as much as 75.2% of animal products came from forest animals, while in others, as little as 10.5% did (Tables 1, 2). People relied less on the forest for vegetables than they did for meat. Only 0.5% of all vegetables (kcal) eaten came from the forest, and communities were similar in their reliance on the forest for vegetable foods

(Tables 1, 2). In total, an average of 1.2% of all kcal consumed per day came from forest products (village range = 0.5–2.9%).

Members of almost all households reported eating the meat of forest animals during the prior year (89.1%); 73.4% had eaten at least one forest mammal and 72.9% at least one forest bird. Household members ate a mean of 6.9 forest mammals and 10.4 forest birds, or 14.56 kg of wild meat per household per year. Nearly a third of households (30.0%) had eaten a threatened mammal during prior year. These households ate a mean of 1.3 threatened mammals. Tenrecs were eaten by the greatest percentage of households (50.9%), followed by the meat of bushpigs (34.9%), lemurs (18.9%), euplerids (13.7%), introduced carnivorans (10.6%), and bats (10.6%). The vast majority of catch was eaten by members of the hunter's own household and was not sold (Table 3). Of the 6,726 forest animals eaten, 40.3% were mammals and 59.7% were birds. Tenrecs were the most frequently caught forest mammal (64.8% of the total number of forest mammals caught), followed in number by bushpigs (12.8%), lemurs (8.9%), bats (8.2%), native euplerid carnivorans (3.1%), and introduced carnivorans (2.2%) (Table 3). Because the hunting of many species is prohibited, the hunting and consumption of many animal species is likely under-reported. Actual levels of hunting are likely higher than reported here.

Eighty-six percent of measured households ate any kind of fish or meat during the prior week, and 57.1% ate the meat of domestic animals. Chickens were the most commonly owned domestic livestock, followed by ducks (Table 7). Yet, over three-quarters of poultry (79.0%) died during the prior year from an illness consistent with the symptoms and timing of Newcastle disease.

Biodiversity

The availability and quality of habitat varied greatly between villages (Tables 1, 2). A total of 0.64 km² of forested land were cleared for new (not in fallow) agricultural lands over the prior year; 13.7% of households cleared this land at a mean distance

TABLE 4 | Foods characterizing diets with low, moderate, and high diversity using a WDDS scale[†].

Low dietary diversity (WDDS 0–3) 1.6% of households	Moderate dietary diversity (WDDS 4–6) 77.3% of households	High dietary diversity (WDDS 7–9) 2.6% of households
Starchy staples	Starchy staples	Starchy staples
Dark green leafy veg.	Dark green leafy veg.	Dark green leafy veg.
	Other fruits and veg.	Other fruits and veg.
	Fish/seafood and meat	Fish/seafood and meat
		Organ meat
		Eggs
		Legumes, nuts, seeds

[†]Food categories listed were found in >75% of households in that subclass.

TABLE 5 | Percentages of individuals ($n = 1,750$) classified as stunted, underweight, wasted, and anemic in the 13 communities surveyed near the Masoala National Park (2015)[†].

Age range (yrs)	Sex	Sample size (n)	Underweight	Stunted	Wasted	Sample size (n)	Anemic
0 < 6	Male and Female	192	27.87	33.33	4.76	215	19.53
6 < 13	Male and Female	192	22.92	24.85	5.88	312	12.18
13 < 21	Male	104	25.96	27.66	7.45	188	29.51
13 < 21	Female	87	35.63	33.33	8.00	153	45.75
0 < 21	Male and Female	859	25.61	31.32	6.18	–	–
0 < 21	Male	433	23.09	29.79	5.43	–	–
0 < 21	Female	424	28.30	32.89	6.95	–	–
21 < 55	Male and Female	–	–	–	–	466	24.03
55+	Male and Female	–	–	–	–	70	42.86
0+	Male and Female	–	–	–	–	1,338	24.51
0+	Male	–	–	–	–	613	17.33
0+	Female	–	–	–	–	725	30.69

[†]Children are defined as stunted, underweight, or wasted if their height-for-age, weight-for-age, or weight-for-height is more than two standard deviations below the CDC (2000) or WHO (2006) Child Growth Standards median.

of 81 min from their home. Households cleared an average of 12,065 m² of land (or 1,652 m² when including households that did not clear land); 84.2% of this land was subsequently used for subsistence agriculture, 11.3% for cash crops, 1.9% for livestock, and 1.9% was sold.

Lemurs were more abundant and found in larger cluster sizes within the Masoala National Park than near villages. *Varecia rubra* were found throughout the park interior at a mean density of 8.3 animals per square kilometer (expected cluster size = 5.6), and *Eulemur albifrons* were found at a mean density of 58.1 animals per square kilometer (expected cluster size = 5.5). *V. rubra* were present at five of the thirteen village sites at densities ranging from 0–13.6 per km². The mean density of *V. rubra* at all village sites was 2.9 animals per square kilometer (expected cluster size = 2.2). *E. albifrons* were present at eight of the thirteen village sites at densities ranging from 0 to 91.3 animals per square kilometer. The mean density of *E. albifrons* at all village sites was 16.5 animals per square kilometer, with an expected cluster size of 4.3.

Forest plots were significantly richer, in all plant size classes, within the Masoala National Park than near villages (Small plants: $T = 17.56$, $DF = 151$, $P < 0.0001$; Medium plants: $T = 16.66$, $DF = 151$, $P < 0.0001$; Large plants: $T = 14.40$, $DF = 151$, $P < 0.0001$). Medium and large plants also had significantly larger DBH (Medium plants: $T = 5.33$, $DF = 1,036$, $P < 0.0001$; Large plants: $T = 2.29$, $DF = 1,315$, $P = 0.02$) and were significantly taller (Medium plants: $T = 7.21$, $DF = 1,036$, $P < 0.0001$; Large plants: $T = 22.06$, $DF = 1,315$, $P < 0.0001$). There were significantly more medium and large plants and significantly fewer small plants in forest plots within the Masoala National Park than those plots near villages (Small plants: $T = 4.11$, $DF = 151$, $P < 0.0001$; Medium plants: $T = 11.82$, $DF = 151$, $P < 0.0001$; Large plants: $T = 6.10$, $DF = 151$, $P < 0.0001$). Further, there were 10 times as many stems of small plants whose identity was unknown within the park. These differences in habitat resulted in a total basal area of plants per hectare 50% larger and a total available crown area per hectare twice as large within the park than outside of it (Total basal area:

9,027.13 vs. 6,927.63 m²; Total available crown area: 19,112.39 vs. 7,606.61 m²).

DISCUSSION

The future of lemurs, 94% of which are threatened with extinction (Schwitzer et al., 2013), depends on the sustainable diets of a malnourished human population who commonly hunts them for food (Borgerson, 2015; Borgerson et al., 2016). We found a high prevalence of both food insecurity and poverty surrounding the Masoala National Park, a UNESCO World Heritage Site. Eighty percent of households on the Masoala experienced food insecurity over the course of a year and 95% lived in persistent poverty. Both food insecurity and poverty on the Masoala are higher than national averages (WHO, 2012), which already place Madagascar as the third least food secure nation in the world (Economist Intelligence Unit, 2017). The prevalence of poverty on the Masoala exceeds that of Burundi and the Democratic Republic of Congo, the only two nations that are ranked below Madagascar in food security, and, unlike Madagascar, are recovering from violent civil wars (Economist Intelligence Unit, 2017).

Children on the Masoala were highly malnourished and one-quarter of the population was anemic, far higher than in other regions of Madagascar (Mould et al., 2016). In order to meet the requirements for a healthy diet, local people relied on the forest for food, yet still often failed to meet these objectives. While wild meats are not a staple food, most households depended on them. Wildlife consumption was common throughout the region; 89% of households ate wildlife within the prior year on the Masoala, nearly twice the prevalence of other regions worldwide (Rowland et al., 2016). Those surveyed ate 6,726 forest animals (mean of 7 mammals and 10 birds per household), or ~3.27 kg of wild meat per person (4.48 kg per adult equivalent) during the prior year. This amount of wildlife is much higher than that reported in other regions of Madagascar including Kianjavato (Borgerson et al., 2018a), Alaotra (Borgerson et al., 2018b), and Betampona (Golden et al., 2014b), but it is similar to that reported in nearby Makira (Golden et al., 2014a; Brook et al., 2019), and far less than the amount eaten in the Amazon and Congo basins (63 and 51 kg/capita/year, respectively; Nasi et al., 2011). Further, as much as 75% of all meat eaten in some communities was from forest animals. People ate very low quantities of iron and protein and in some communities as much as 76% of protein and 74% of iron came from forest meats.

Healthy forests can support the food security of the most vulnerable households in a region by directly supplying a wide variety of wild foods that increase the quality, security, and diversity of local diets. The meat of wild animals provided

TABLE 6 | The percentage of communities measured ($n = 13$) experiencing different levels of severity for child malnutrition (under age 5) on the Masoala Peninsula (2015) using WHO standards (2017).

Measurement of malnutrition	Low severity %	Medium severity %	High severity %	Very high severity %
Stunting	30.8	30.8	30.8	7.7
Low weight	15.4	30.8	7.7	46.2
Wasting	69.2	7.7	0.0	15.4

TABLE 7 | The range and mean of household livestock assets on the Masoala Peninsula (2015).

Type of livestock	Cows	Pigs	Ducks	Chickens	Geese	Cats	Dogs
Range (n per household)	0–18	0–12	0–43	0–69	0–41	0–6	0–5
Mean (n per household)	1.19	0.20	2.73	9.62	0.42	0.40	0.41

valuable micronutrients to people experiencing food insecurity and malnutrition, yet the hunting of threatened species is an untenable solution to food insecurity. Further, continued habitat loss in the region will likely only reduce access to wild foods in the future and increase the reliance on less-diverse foods (Powell et al., 2011; Sunderland, 2011; Sunderland et al., 2017). In order to improve human well-being in the long term, forests must be conserved and hunting must be reduced to sustainable levels.

Conservation efforts to reduce the unsustainable hunting of threatened species are unlikely to alter the behavior of hunters unless they address the goals, reasons, and incentives for hunting. Improving food security can increase the sustainability of hunting, improving both forest conservation and human nutrition in the long term, allowing for forests to provide essential services to those who live near them. Yet, few micronutrient-rich alternatives to wild meats were available in adequate supply and many were highly volatile; 79% of all chickens died from Newcastle disease in the prior year. In order to reduce the unsustainable hunting of threatened species while improving household food security and child health, we suggest testing the effects of increasing the affordability, accessibility, and stability of micro-nutrient rich animal-sourced foods in remote communities, where forests contribute the most to food security.

In conclusion, we believe that by using an integrated approach to improve food security in one of the world's most biodiverse and least food secure nations, we can both conserve Madagascar's unique biodiversity and improve the nutrition and health of Madagascar's people.

ETHICS STATEMENT

We collected this data during May until December 2015 and all research was approved by Human Subjects Institutional

Review Boards (Protocols #15-0331 Wildlife Conservation Society and #15-2230 Harvard T. H. Chan School of Public Health), the Republic of Madagascar and Madagascar National Parks (Permits 111/13, 325/14, 111/15, 218/15, 270/15, /MEEF/SG/DGF/DCB.SAPP/SCB). We obtained oral informed consent and/or assent from all participants.

AUTHOR CONTRIBUTIONS

CB, BR, DR, and BJRR collected the data. CB designed the study and completed data analysis. CB and CG interpreted the data and wrote this manuscript. All authors approved the final manuscript.

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REFERENCES

- Allnutt, T. F., Asner, G. P., Golden, C. D., and Powell, G. V. N. (2013). Mapping recent deforestation and forest disturbance in northeastern Madagascar. *Trop. Conserv. Sci.* 6, 1–15. doi: 10.1177/194008291300600101
- Black, R. E., Victora, C. G., Walker, S. P., Bhutta, Z. A., Christian, P., de Onis, M., et al. (2013). Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* 382, 427–51. doi: 10.1016/S0140-6736(13)60937-X
- Borgerson, C. (2015). The effects of illegal hunting and habitat on two sympatric endangered primates. *Int. J. Primatol.* 36, 74–93. doi: 10.1007/s10764-015-9812-x
- Borgerson, C. (2016). Optimizing conservation policy: the importance of seasonal variation in hunting and meat consumption on the Masoala peninsula of Madagascar. *Oryx* 50, 405–418. doi: 10.1017/S003060531500307
- Borgerson, C., Johnson, S. E., Louis E. E., Holmes, S. M., Gasta, A. E. J., Randriamady, H. J., et al. (2018a). The use of natural resources to improve income, health, and nutrition within the forests of Kianjavato, Madagascar. *Madag. Conserv. Dev.* 13, 45–52. doi: 10.4314/mcd.v13i1.6
- Borgerson, C., McKean, M.A., Sutherland, M.R., and Godfrey, L.R. (2016). Who hunts lemurs and why they hunt them. *Biol. Conserv.* 197, 124–130. doi: 10.1016/j.biocon.2016.02.012
- Borgerson, C., Vonona, M. A., Vonona T et al. (2018b). An evaluation of the interactions among household economies, human health, and wildlife hunting in the Lac Alaotra wetland complex of Madagascar. *Madagascar Conservation & Development* 13, 25–33. doi: 10.4314/mcd.v13i1.5
- Brook, C. E., Herrera, J., Borgerson, C., Fuller, E., Andriamahazoarivosoa, P., Rasolofoniaina, B. J. R., et al. (2019). Population viability and bushmeat harvest sustainability for Madagascar lemurs. *Conserv. Biol.* 33, 99–111. doi: 10.1111/cobi.13151
- Buckland, S. T. (2001). *Introduction to Distance Sampling: Estimating Abundance of Biological Populations*. London, UK: Oxford University Press
- Buckland, S. T., Anderson, D. R., Burnham, K. P., and Laake, J. L. (1993). *Distance Sampling: Estimating Abundance of Biological Populations*. London, UK: Chapman and Hall London.
- CARE (2008). *Coping Strategies Index: Field Methods Manual*. Atlanta, GA: CARE.
- Centers for Disease Control and Prevention (2012). *National Center for Health Statistics CDC Growth Charts*. CDC. Available online at: <http://www.cdc.gov/growthcharts/> (accessed July 10, 2019).
- Coates, J., Swindale, A., and Bilinsky, P. (2007). *Household Food Insecurity Access Scale (HFIAS) for Measurement of Household Food Access: Indicator Guide (v. 3). Food and Nutrition Technical Assistance Project*. Washington, DC: Academy for Educational Development.
- Economist Intelligence Unit (2014). *Global Food Security Index 2014: An Annual Measure of the State of Global Food Security*. London, UK: The Economist Intelligence Unit Limited.
- Economist Intelligence Unit (2016). *Global Food Security Index 2016: An Annual Measure of the State of Global Food Security*. London, UK: The Economist Intelligence Unit Limited.

- Economist Intelligence Unit (2017). *Global Food Security Index 2017: An Annual Measure of the State of Global Food Security*. London, UK: The Economist Intelligence Unit Limited.
- Ezzati, M., Lopez, A. D., Rodgers, A., Hoorn, S. V., and Murray, C. J. L. (2002). Selected major risk factors and global and regional burden of disease. *Lancet* 360, 1347–1360. doi: 10.1016/S0140-6736(02)11403-6
- Fa, J. E., Currie, D., and Meeuwig, J. (2003). Bushmeat and food security in the Congo Basin: linkages between wildlife and people's future. *Environ. Conserv.* 30, 71–8. doi: 10.1017/S0376892903000067
- FAO (2010). *Guidelines for Measuring Household and Individual Dietary Diversity*. Rome: Nutrition and Consumer Protection Division, Food and Agriculture Organization of the United Nations. 60.
- FAO (2012). *West African Food Composition Table*. Rome: Food and Agriculture Organization of the United Nations. 171.
- Food and Agriculture Organization (2004). *Human Energy Requirements. Report of a Joint FAO/WHO/UNU Expert Consultation*. FAO Food and Nutrition Technical Report Series No. 1. Rome: FAO.
- Food and Agriculture Organization. (2013). "Forests and trees outside forests are essential for global food security and nutrition," in *Summary of the International Conference on Forests for Food Security and Nutrition* (Rome: FAO).
- Golden, C. D., Bonds, M. H., Brashares, J. S., Rasolofoniaina, B. J. R., and Kremen, C. (2014a). Economic valuation of subsistence harvest of wildlife in Madagascar. *Conserv. Biol.* 28, 234–243. doi: 10.1111/cobi.12174
- Golden, C. D., Fernald, L. C. H., Brashares, J. S., Rasolofoniaina, B. J. R., and Kremen, C. (2011). Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *Proc. Natl. Acad. Sci. U.S.A.* 108:19653–19656. doi: 10.1073/pnas.1112586108
- Golden, C. D., Rabehatonina, J. G. C., Rakotosoa, A., and Moore, M. (2014b). Socio-ecological analysis of natural resource use in Betampona Strict Natural Reserve. *Madagas. Conserv. Dev.* 9, 83–89. doi: 10.4314/mcd.v9i2.4
- Goodman, S. M. (2011). *Les Chauves-Souris de Madagascar*. Madagascar: Association Vahatra Antananarivo.
- Goodman, S. M. (2012). *Les Carnivora de Madagascar*. Madagascar: Association Vahatra Antananarivo.
- Ickowitz, A., Powell, B., Salim, M. A., and Sunderland, T. C. H. (2014). Dietary quality and tree cover in Africa. *Glob. Environ. Change* 24, 287–294. doi: 10.1016/j.gloenvcha.2013.12.001
- Ickowitz, A., Rowland, D., Powell, B., Salim, M. A., and Sunderland, T. (2016). Forests, trees, and micronutrient-rich food consumption in Indonesia. *PLoS ONE* 11:e0154139. doi: 10.1371/journal.pone.0154139
- International Food Policy Research Institute (2016). *Global Nutrition Report 2016: From Promise to Impact: Ending Malnutrition by 2030*. Washington, DC: IFPRI.
- Johnson, K. B., Jacob, A., and Brown, M. E. (2013). Forest cover associated with improved child health and nutrition: evidence from the Malawi demographic and health survey and satellite data. *Glob. Health Sci. Pract.* 1, 237–248. doi: 10.9745/GHSP-D-13-00055
- Kremen, C. (2003). "The Masoala Peninsula," in *The Natural History of Madagascar*, eds S. M. Goodman and J. P. Benstead (Chicago, IL: The University of Chicago Press), 1459–1466.
- Kremen, C., Razafimahatratra, V., Guillery, R. P., Rakotomalala, J., Weiss, A., and Ratsimopatrarivo, J. S. (1999). Designing the Masoala National Park in Madagascar based on biological and socioeconomic data. *Conserv. Biol.* 13, 1055–1068. doi: 10.1046/j.1523-1739.1999.98374.x
- Lopez, A. D., Mathers, C. D., Ezzati, M., Jamison, D. T., and Murray, C. J. L. (2006). Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. *Lancet* 367, 1747–1757. doi: 10.1016/S0140-6736(06)68770-9
- Mould, D., Carlson, A., Christofides, N., and Greiner, K. (2016). *Socio-Cultural Determinants for the Adoption of Essential Family Practices in Madagascar*. Athens, OH: The Institute for the African Child.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858. doi: 10.1038/35002501
- Nasi, R., Taber, A., and van Vliet, N. (2011). Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins. *Int. Forestry Rev.* 13, 355–368. doi: 10.1505/146554811798293872
- Powell, B., Hall, J., and Johns, T. (2011). Forest cover, use and dietary intake in the East Usambara Mountains, Tanzania. *Int. Forestry Rev.* 13, 305–317. doi: 10.1505/146554811798293944
- Rice, B. L., Golden, C. D., Anjaranirina, E. J. G., Matella Botelho, C., Volkman, S. K., and Hartl, D. L. (2016). Genetic evidence that the Makira region in northeastern Madagascar is a hotspot of malaria transmission. *Malaria J.* 15, 596–608 doi: 10.1186/s12936-016-1644-4
- Rowland, D., Ickowitz, A., Powell, B., Nasi, R., and Sunderland, T. (2016). Forests foods and healthy diets: quantifying the contributions. *Environ. Conserv.* 44, 102–114. doi: 10.1017/S0376892916000151
- Sarti, F. M., Adams, C., Morsello, C., van Vliet, N., Schör, T., Yagüe B, Tellez, L., et al. (2015). Beyond protein intake: bushmeat as source of micronutrients in the Amazon Tri- Frontier region. *Ecol. Soc.* 20:22. doi: 10.5751/ES-07934-200422
- Schwitzer, C., Mittermeier, R. A., Davies, N., Johnson, S., Ratsimbazafy, J., Razafindramanana, J., et al. (eds.). (2013). *Lemurs of Madagascar: A Strategy for Their Conservation 2013–2016*. Bristol: IUCN SSC Primate Specialist Group; Bristol Conservation and Science Foundation, and Conservation International, 1–197.
- Siren, A., and Machoa, J. (2008). Fish, wildlife, and human nutrition in tropical forests: a fat gap? *Interciencia* 33, 186–193.
- Smith, M. R., Micha, R., Golden, C. D., Mozaffarian, D., and Myers, S. S. (2016). Global Expanded Nutrient Supply (GENuS) model: a new method for estimating the global dietary supply of nutrients. *PLoS ONE* 11:e0146976. doi: 10.1371/journal.pone.0146976
- Soarimalala, V., and Goodman, S. M. (2011). *Les Petits Mammifères de Madagascar*. Madagascar: Association Vahatra Antananarivo.
- Sunderland, T., Powell, B., Ickowitz, A., Foli, S., Pinedo-Vasquez, M., Nasi, R., et al. (2017). *Food Security and Nutrition: The Role of Forests*. Discussion Paper. Bogor: CIFOR. 1–20.
- Sunderland, T. C. H. (2011). Food security: why is biodiversity important? *Int. Forestry Rev.* 13, 265–274. doi: 10.1505/146554811798293908
- Tata, C. Y., Ickowitz, A., Powell, B., and Colecraft, E. K. (2019). Dietary intake, forest foods, and anemia in Southwest Cameroon. *PLoS ONE* 14:e0215281. doi: 10.1371/journal.pone.0215281
- van Vliet, N., Moreno, J., Gómez, J., Zhou, W., Fa, J. E., Golden, C. D., et al. (2017). Bushmeat and human health: Assessing the evidence in tropical and sub-tropical forests. *Ethnobiol. Conserv.* 6, 1–45. doi: 10.15451/ec2017-04-6.3-1-45
- Weisell, R., and Dop, M. C. (2012). The adult male equivalent concept and its application to household consumption and expenditures surveys (HCES). *Food Nutr. Bull.* 33, S157–S162 doi: 10.1177/15648265120333S203
- WHO (2006). *WHO Child Growth Standards*. Geneva: World Health Organization. Available online at: <http://www.who.int/childgrowth/standards/en/> (accessed July 10, 2019).
- WHO (2011). *Hemoglobin Concentrations for the Diagnosis of Anemia and Assessment of Severity. Vitamin and Mineral Nutrition Information System*. Geneva: World Health Organization. Available online at: <http://www.who.int/vmnis/indicators/haemoglobin.pdf> (accessed March 21, 2017).
- WHO (World Health Organization) (2012). *WHO Global Database on Child Growth and Malnutrition*. Available online at: <https://goo.gl/1JsvCd> (accessed July 10, 2019).
- Wilkie, D. S., Wieland, M., Boulet, H., Le Bel, S., van Vliet, N., Cornelis, D., et al. (2016). Eating and conserving bushmeat in Africa. *Afr. J. Ecol.* 54, 402–414. doi: 10.1111/aje.12392
- Zaehring, J. G., Schwilch, G., Andriamihaja, O. R., Ranamonjosa, B., and Messerli, P. (2017). Remote sensing combined with socio-ecological data: the importance of diverse land uses for ecosystem service provision in north-eastern Madagascar. *Ecosyst. Serv.* 25, 140–152. doi: 10.1016/j.ecoser.2017.04.004

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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