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Original Research

Wild Foods Are Positively Associated with Diet Diversity and Child Growth in a Protected Forest Area of Madagascar

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A B S T R A C T

Background: Concurrent losses in biodiversity and human dietary diversity are evident in Madagascar and across many food systems globally. Wild food harvest can mitigate nutrition insecurities but may also pose species conservation concerns.
Objectives: This study aimed to examine the association of wild plant and animal species consumption during hunger season with diet diversity and child growth near the Alandraza-Agnalavelo protected forest in Southwestern Madagascar. Second, we studied the conservation status of the consumed wild plants.
Methods: Methods from public health nutrition (24-h recall dietary intake, anthropometry using World Health Organization [WHO] Growth Standards), ethnobotany, and forest ecology (ecologic studies of abundance, habitat preference, associated species, food chemistry assays, and species richness) were applied.
Results: Malnutrition in children ($n = 305$) was highly prevalent: stunting (32.3%); wasting (18.8%); and low-dietary diversity (4% meeting WHO minimum dietary diversity threshold). Animal foods were consumed in small quantities, providing <10% of Dietary Reference Intakes for all limiting nutrients. Twenty-two wild plant species were consumed during hunger season, prominently tubers (*Dioscoreaceae*), and leafy greens (*Asteraceae, Blechnaceae, Portulacaceae,* and *Solanaceae*). Eight of the 9 target species were identified as abundant and "Least Concern," whereas *Amorphophollus taurostigma* was abundant and "Vulnerable." Regression modeling showed wild food consumption was associated with an increased household dietary diversity score [$\beta = 0.29$ (0.06 standard error); $P < 0.001$], and total wild animal foods positively correlated with height-for-age Z score [$\beta = 0.14$ (0.07 standard error); $P = 0.04$].
Conclusions: Wild plant and animal foods may be an important element of food systems to support human nutrition while maintaining ecosystem viability.

Keywords: wild foods, diet diversity, child growth, rural food systems, protected forest

Introduction

Madagascar is recognized as one of the world's most important biodiversity hotspots, yet despite its resource richness, there are some of the lowest levels of dietary diversity globally and consequent severity of malnutrition [1]. More than 80% of the population lives in rural communities dependent on subsistence agriculture and the natural environment [1]. Climate change has altered these dynamics through shifting patterns of temperature, precipitation, and seasonality [2]. The converging assaults on ecosystems and human health are increasingly evident. Chronic malnutrition, indicated as stunted growth, affects 39.8% of young children, whereas wasting or acute malnutrition has reached crisis levels, prevalent in 7.7% of young children nationally and reaching 15% in some regions [1]. In parallel, Madagascar has also experienced significant losses in biodiversity. Since 1950, there has been a reduction in natural forests by 44% from wild bushfires, slash-and-burn agriculture, illegal logging, and mining exploitations [3,4]. Among the 2904 endemic Malagasy tree species, 63% are threatened with extinction [5], and 12% of accepted plant species are considered lost [6].

Abbreviations: ASF, animal source food; CI, confidence interval; HAZ, height-for-age Z; HDDS, household dietary diversity score; MBG, Missouri Botanical Garden; MDD, minimum dietary diversity; TAN, National Herbarium of Madagascar; WASH, water; sanitation, and hygiene; WAZ, weight-for-age Z; WHZ, weight-for-height Z.

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Wild food acquisition has been implicated for its role in diminishing biodiversity [7], but as well, for its potential in providing multiple micronutrients and mitigating chronic disease [8–10]. Wild foods, although not well characterized in terms of contributions to public health, are relied upon by ~1 billion people to supplement diets and in low-resource countries, an estimated 77.3% of rural households harvest foods from forest and nonforest environments [11]. In the wake of the COVID-19 pandemic and amid concerns about zoonotic diseases, there has been a movement toward prohibiting wild animal meat in food systems. This action, however, would heighten risks for food insecurity and likely increase industrial meat production [12]. In terms of public health, nutrient and bioactive factors differ in the wild compared with domesticated foods, with possible health advantages conferred from the former [13,14].

Wild food consumption in Madagascar has been studied in relation to both biodiversity losses [15] and human nutrition [16]. We previously conducted research in the Agnalavelo forest that showed people seek out 40 wild edible plant species for consumption to mitigate hunger during drought periods, forming the basis of the present study [17]. This study aimed to examine the association of wild plant and animal species consumption during the hunger season with diet diversity and child growth near the Alandraza-Agnalavelo protected forest in Southwestern Madagascar. Second, we studied the conservation status of the consumed wild plants. The hypotheses were as follows: *1*) during hunger season, people acquire a variety of nutrients from wild edible plants to supplement their usual diets consisting of rice and cassava; and *2*) wild edible plant species, if consumed with animal source foods (ASFs) and abundant in the environment, provide a more diverse diet accruing growth advantages for infants and young children especially.

Methods

Study site and sample

The Alandraza-Agnalavelo conservation site is located in the Southwestern region of Madagascar. It is a subhumid climate typically with 2 seasons, dry winter and humid summer, and prone to frequent severe droughts averaging ~1 every 3 y over the last decade. The forest, deemed sacred by the local population, is an important biodiversity hotspot, housing >660 plant species, 82 species of birds, and 16 species of mammals, including 6 species of lemur [18]. However, this ecosystem is highly threatened by the hunting of wild animals (lemurs, birds, and bats), illegal logging, and the use of fire to clear areas for cattle grazing. Forest fragments spot the region and isolate plants and animals that are unable to shift ranges to respond to changing patterns of temperature, precipitation, and seasonality. The human population in the region largely relies on subsistence and rain-fed agriculture (rice, maize, cassava, and sweet potatoes) and thus, is similarly vulnerable to variability in climate conditions.

The field study team involved was composed of Missouri Botanical Garden (MBG) staff (PhD trained professionals in botany, ethnobotany, and forest ecology), residents from the communities surrounding Agnalavelo, and students from the Agroecology and Environment Institute in Toliara. Public health nutrition technical expertise was provided by Washington University in St. Louis.

Human subjects' research approval was obtained for this study from Malagasy regional administrative authorities, and official committees of Ambararata Besavoa, Ankiliarivo Besavoa, and Marotsiraka Betsileo. The study was deemed in full compliance with the ethical standards and treatment procedures of participants as established by the authorities. Training of the study field team was carried out over a period of 20 d on conducting field interviews, collecting anthropometric measures, and laboratory analysis techniques as relevant to their respective roles.

Socioeconomic and demographic surveys

We conducted this study in November and December 2020 to capture the nutrition situation and foraging activities of households during hunger season, which typically occurs in Madagascar during the months of October, November, and December. Surveys included a range of questions intended to capture information about socioeconomic status, demographics, water, sanitation, and hygiene (WASH) conditions, and health status of the household. These factors were later used for descriptive analyses, as well as to adjust for any potential biases and confounding in regression modeling. They were administered in the household together with dietary intake and anthropometric measures.

Dietary intakes and anthropometry

The nutrition assessment portion of this study focused on children aged <5 y as the most vulnerable group to nutrient deficiencies in terms of growth and health outcomes [19]. Usual dietary intakes of children aged <5 y were collected using a 24-h dietary intake recall and semiquantitative food frequency recall with caregivers [20,21]. First, a series of questions regarding breastfeeding practices were asked. Next, caregivers were asked to recall over a 24-h period: the types of foods given to the index children; preparation and cooking methods; recipes; side dishes or accompaniments; and whether any wild foods were included. Follow-up inquiries were made specifically for wild foods identified in the dietary intake surveys to gain precision on food types. Nutrient densities for the foods reported consumed were calculated using the USDA FoodData Central food composition database and combined with quantities consumed to estimate child intake [22].

To assess, dietary diversity, 3 indicators were applied with varying purposes. First, to characterize child dietary diversity, we used the standardized indicator of minimum dietary diversity (MDD) for children aged 6–23 mo recommended by WHO and the UNICEF [23]. To generate this marker, 8 food groups were created, and the equation was used:

$$\frac{\text{Number of children 6-23 months of age who received foods 5 or more food grouping esterday during the day or night}}{\text{Children 6-23 months of for whom data on breast feeding and diet were collected}}$$

Counts toward a food group were added based on any consumption of foods falling into the category. Spices and herbs were considered part of the "other fruits and vegetables" category. The MDD indicator for children aged 6–23 mo is defined as 5 or more food groups in a day [23].

Second, we used the household dietary diversity score (HDDS), a population-level indicator of household food access [24]. To generate the HDDS, 12 food groups were created from dietary intake data and summed: roots and tubers; vegetables; fruits; meat, poultry, offal; eggs; fish and seafood; pulses, legumes and nuts; milk and milk products; oils and fats; sugar and honey; and miscellaneous. Finally, to connect the nutrition and conservation objectives in our study, we applied the species richness marker, calculated as a count of the number of species consumed by each individual. Other markers such as Simpson's diversity index and functional diversity were considered, but the species richness was selected based on previous findings for a stronger association with micronutrient adequacy [10]. Several indicators of wild food consumption were also generated, including the total quantity of wild ASF food consumption; the proportion of wild ASF consumed out of total ASF; the total number of distinct wild foods consumed; and the proportion of wild food types out of total food types reported.

Anthropometry measures of height, weight, and midupper arm circumference were collected from all children aged <5 y, using standardized WHO protocols. *Z* scores were generated for these children only using WHO Child Growth Standards (2006): height-for-age *Z* (HAZ); weight-for-age *Z* (WAZ); weight-for-height *Z* (WHZ); BMI-for-age *Z*, and arm circumference-for-age *Z*. In view of measurement error and recall bias observed in reporting child age in months after 1 y, we included only children aged <12 mo in regression modeling.

Plant species: identification, diversity, abundance, and nutritional composition

Specimen collection and identification

The collection of botanical voucher specimens of wild foods followed standard MBG protocols [25]. For plants reported as food, we collected fertile samples (with flowers or fruits) if possible, or sterile samples (without flowers or fruits), if necessary. Global Positioning System units were used to record precise latitude, longitude, and elevation at each collection locality. Voucher information included collection number, specimen description, locality, dates, habitat descriptions, vernacular names, and local uses. Photographs were also taken for each collected specimen.

Specimen identification was conducted at the 2 national herbaria in Madagascar [National Herbarium of Madagascar (TAN) and TEF], by comparing newly collected voucher specimens with existing herbarium specimens and consulting available published flora treatments as well as the MBG's database records [26]. Animals reported as food were identified by photographs in consultation with specialists.

One specimen of each collection was deposited in the national Madagascar herbarium (TAN). The available remaining duplicate specimens were distributed to the following herbaria: Missouri (MO), Paris (P), Kew (K), and Geneva (G). After botanical specimens have been fully identified, the MBG's TROPICOS database will make collection data publicly available, including information about microhabitat, abundance, regeneration, seed/fruit dispersal, and human use. Local names (in Bara and Malagasy languages) were identified by individuals from study communities with knowledge of plants. Information from the plant collection records in the Catalogue of Plants of Madagascar [27] was used to determine conservation status and extinction risk by International Union for Conservation of Nature (IUCN) Red List Categories and Criteria of wild species.

Nine species were assessed in the ecologic element of the larger study, and 7 species were examined for their nutrient composition as being most tractable to these analyses. Ecologic studies including abundance, habitat preference, and associated species were conducted for the target species: *Dioscorea maciba* ("ovy"); *Dioscorea antaly* ("antaly"); *Dioscorea sansibarensis* ("papa"); *Dioscorea soso* ("sosa"); *Dioscorea ovinala* ("angily"); *Dioscorea fandra* ("kinjiky"); *Dioscorea humboka* ("katro"); *Dolichos fangitsa* ("fangitsy"); and *Amorphophallus taurostigma* ("tavolo"). As target species are found in different habitats, 9 plots of 50 m × 20 m after the Braun Blanquet (1932) method were installed. In each plot, the team inventoried: the number of individuals for the species; density [28]; phenologic status; overlay and regeneration type; in the case of lianas, which are woody vines, the name of the plant species that supports the target liana species (the "tutor species"); and other associated species.

Kjeldahl's method [29] was applied for the determination of protein content in the wild edible plant species. Then, starch content was determined by polarimetry [30]. The content of reducing sugars and total sugars is obtained by the Luff–-Schoorl method [31]. In addition, dosage of specific minerals was identified according to the method described by Dubois [32]. A literature review was made for the nutrient composition of the wild leafy greens and wild insects to supplement these methods.

Statistics

Descriptive statistics were applied initially to characterize the diet diversity and nutritional status of young children and socioeconomic, demographic, and WASH conditions of households. Subsequently, univariate statistics examined relationships between wild food consumption patterns, diet diversity, anthropometry, and other potential correlates. For multivariate analyses, 2 sets of models were generated to evaluate the relationship between child wild food consumption behaviors and levels and nutritional outcomes. In the first, we applied truncated Poisson regression modeling to assess dietary diversity as indicated by HDDS among children in the sample ages 6 mo (after the exclusive breastfeeding period)–5 y of age. The zero-truncated Poisson distribution was selected for modeling as no zeroes occur in the HDDS and there was no evidence of overdispersion in the data. The zero-truncated Poisson distribution is defined by the following equation [33]:

$$P_r = \lambda^r e^{-\lambda} / r!\left(1 - e^{-\lambda}\right)$$

In the second set of models, child anthropometric measures (HAZ, WAZ, and WHZ) were the outcomes of interest evaluated in relation to wild food consumption and other determinants. Multiple linear regressions were applied with a Gaussian family distribution and identity link function. Children aged >24 mo were excluded from these analyses in view

TABLE 1
Characteristics of sample

Characteristics	Children consuming no wild foods ($n = 179$)	Children consuming any wild foods ($n = 127$)	All ($n = 306$)	P value[1]
Child				
Age, mo (SD)	30.52 (18.98)	34.98 (17.20)	32.37 (18.63)	0.033
Sex of child (%)				0.097
Female	44.69	54.33	48.69	
Male	55.31	45.67	51.31	
Height-for-age Z score (SD)	−0.93 (1.87)	−1.51 (1.79)	–1.17 (1.86)	0.008
Weight-for-age Z score (SD)	−1.24 (1.41)	−1.16 (1.43)	–1.20 (1.41)	0.621
Weight-for-height Z score (SD)	−0.90 (1.60)	−0.41 (1.56)	–0.70 (1.60)	0.008
Stunted (%)	29.31	36.29	32.21	0.204
Underweight (%)	33.71	26.19	30.59	0.161
Wasted (%)	21.84	14.52	18.79	0.111
Total food groups, HDDS[2] (SD)	2.32 (1.18)	2.95 (1.20)	2.59	<0.001
Total food groups, MDD[3] (SD)	1.78 (0.94)	2.45 (1.19)	1.98 (1.06)	0.170
Percent meeting, MDD[3] (%)	2.17	10.00	4.55	0.216[4]
Caregiver/respondent				
Marital status (%)				0.667[4]
Married	88.37	88.98	88.62	
Single	9.88	9.32	9.66	
Separated	0.58	1.69	1.03	
Widowed	1.16	0.00	0.69	
Any formal education (%)	8.05	10.26	8.93	0.517
Literate (%)	20.11	27.35	23.02	0.151
Household				
Total number of household members (SD)	5.82 (3.15)	6.97 (3.49)	6.28 (3.33)	0.005
Main income source (%)				0.177[4]
Farming	98.82	96.55	97.90	
Farming and livestock rearing	0.59	1.72	1.05	
Livestock rearing	0.59	0.00	0.35	
Fishing	0.00	1.72	0.70	
Land ownership				
Owns any land (%)	90.29	90.24	90.27	0.990
Number of fields owned (SD)	2.97 (1.93)	2.93 (2.08)	2.96 (1.99)	0.876
Livestock ownership				0.004
Owns any livestock (%)	76.0	60.6	72.0	
Primary water source (%)				0.003[4]
River	63.37	73.91	67.60	
Well	35.47	20.00	29.27	
Creek/Stream	1.16	5.22	2.79	
Other	0.00	0.87	0.35	
Distance to water, m (SD)	918.68 (802.24)	1015.93 (905.28)	956.25 (843.26)	0.351
Fokontany (%)				0.049
Ambararata Besavoa	34.48	21.19	29.11	
Ankiliarivo Besavoa	19.54	23.73	21.23	
Marotsiraka Betsileo	46.0	55.1	49.7	
Commune (%)				0.127
Amboronabo	54.02	44.92	50.34	
Mahaboboka	45.98	55.08	1.66	

Abbreviations: HDDS, household dietary diversity score; MDD, minimum dietary diversity.
[1] By t test for continuous variables and chi-squared for categorical variables unless otherwise noted, statistically significant $P < 0.05$.
[2] HDSS defined as the total number of food groups were calculated for children 6–60 mo of age ($n = 285$).
[3] MDD scores defined as the percentage of young children ages 6–23 mo consuming ≥5 food groups in the previous 24 h, ($n = 66$).
[4] Fisher exact test applied (expected values < 5), statistically significant $P < 0.05$.

of the clumping observed at year intervals from 2 to 5 y. For both sets of models, covariates were introduced based on the results of the univariate analyses and the evidence-based surrounding determinants of child growth, and retained if improving model fit. Diagnostics were applied to assess linearity, normality of residuals, homoscedasticity, collinearity, and goodness of fit. Aikake and Bayesian Information Criterion compared models and assessed complexity in generalized linear models (GLM). Stata 16.0 (StataCorp LLC, 2019) was used for all statistical analyses. ArcGIS (Esri Inc., 2020) was used to geocode the study site using Global Positioning System coordinates obtained from Google Maps.

Results

Socioeconomic and demographic characteristics

Nearly all households (97.9%) indicated farming as their primary source of income, with livestock production and fishing activities as supplementary. Ownership of land (90.3%) and of livestock (72.0%) was widespread, although small-scale. The majority of families reported accessing water for the household from rivers (67.6%) or wells (29.3%); no piped water or water treatment before drinking was indicated. The average household size was 6.3 (±3.3) members, and self-reported literacy was 23.0% with a small number of caregivers reporting any formal education (8.9%). When stratifying by the primary variable of interest—consumption of any wild foods—older children on average were found to more often have wild foods in their diet (Table 1). Similarly, wild foods were more frequently reported in the diets of children from larger households and those with river or creek water sources as their primary water source. Different forms of malnutrition were highly prevalent: stunting (32.2%); underweight (30.6%); and wasting (18.8%). Among infants ages 0–12 mo, stunting was prevalent in 10.6%, underweight in 23.8%, and wasting in 25%.

Dietary intakes

Rice was the most common food consumed by young children (73.2%) followed by cassava (42.8%), mango (22.2%), and *Dioscorea* species (yam, 18.6%) (Figure 1). The number of food groups consumed by children was low, with only 4.6% of children meeting MDD. Meal frequency for the majority of young children was 3 times a day (75%), whereas 7% received meals only 2 times a day and the remaining had 4 times including snacks with bananas and mangos. Species richness of the child's diet was 2.02 (±0.98), ranging from 1 to 6 species consumed in a day. There were 35.4% of children with a species richness of 1, 72.0% with 2, and 19.4% with 3. Ten children were found to vary species in consumption of tubers, taking 2 types (*Dioscorea antaly* and *Dioscorea sansibarensis*).

Approximately half (54.6%) of the young children were reported to have consumed any animal food in the previous 24 h, with small fish (12.4%), crayfish (10.1%), and cow milk (9.5%) being the most common. Wild leafy greens were reported in the diets of 6.5% of children; cultivated plants of taro and sweet potato were also in the diets for a small number of children. There were a variety of ASFs reported consumed, including the wild foods of pig, tenrec, cicada, and a variety of different river

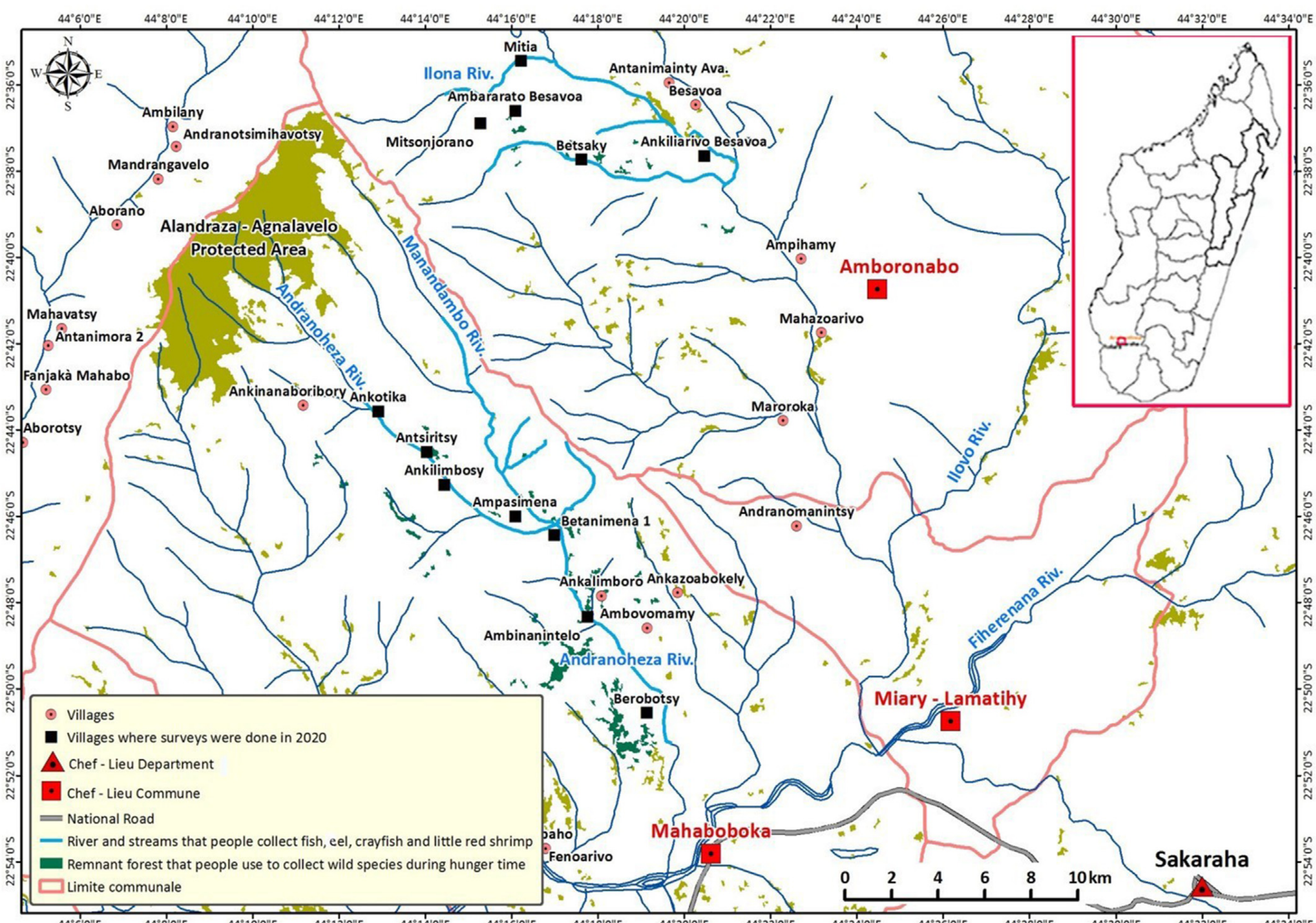


FIGURE 1. Analavelona map.

foods, including small bony fish, specifically ray-finned fish (eel), and crustaceans (shrimp and crayfish) (Supplemental Table 1). Weekly quantities of ASFs were reported in 84 children and transformed to daily intakes to evaluate levels relative to Dietary Reference Intakes, by age category (Table 2). Across all nutrients including those primarily delivered by ASF (vitamins A, B12, iron, and zinc), intake levels fell <10%.

Wild plant and animal species nutritional value and conservation status

During the initial field study, 27 wild plant taxa (including native and nonnative species that grow in unmanaged populations) were identified as consumed by adults during hunger season (Table 3). The most frequently consumed wild plants were tuberous species (reported from diets of >40% of children) in the plant families Dioscoreaceae (*Dioscorea maciba* "ovy," *D. antaly* "antaly," *D. sansibarensis* "papa," and *D. soso* "sosa") and Araceae (*Amorphophallus taurostigma* "tavolo"). In the category of wild leafy greens locally known as "traka," species from multiple families were reported, including in the Asteraceae (*Bidens bipinnata* "trakavatany" and *Sonchus oleraceus* "trakangiso"), Amarathaceae (*Amaranthus spinosus* "tsipitihy"), Blechnaceae (*Stenochlaena tenuifolia* "boreoky"), Portulacaceae (*Portulaca olearacea* "tsibotrabotra"), and Solanaceae (*Solanum nigrum* "melo"). The leafy greens were considered by interviewees to be side dishes as compared with the main dish tuberous species. The wild animal species reported consumed by children living in communities around Alandraza-Agnalavelo were crayfish, small red or white shrimps, cicada, wild pig, eel, and small fish. Crayfish, small fish, and small red shrimps were the most cited species (>12%) (Figure 2). Moreover, during the second follow-up field trip at the beginning of February 2022, we observed people collecting and consuming the soil-dwelling cricket *Brachytrupes membranaceus* "sahobaka." Seasonal consumption of the locust *Locusta migratoria* "Valala" was reported to occur annually in late May and early June.

Seven tuberous species were included in the nutrient composition analyses. All species—*Dioscorea* (*Dioscorea antaly*, *D. maciba*, *D. ovinala*, *D. soso*, and *D. sansibarensis*), *Dolichos fangitsa*, and *Amororphophallus taurostigma*—contain high concentrations of carbohydrates and energy. The protein composition of *Dioscorea maciba* (11.5%) and *Dioscorea ovinala* (10.8%) exceeded those of other tubers (Supplemental Table 2). Calcium concentrations were highest in *Dolichos fangitsa.*

For the ecologic analysis of 9 target species, all were lianas (woody vines) except *Amorphophollus taurostigma* (common name is elephant food yam), which is an herbaceous plant growing at the edge of the forest. All 9 species are abundant in the study area and at the national level and all are classified by IUCN as "Least Concern" species except *A. taurostigma* which is categorized as "Vulnerable" [34–37]. Because some species are preferentially harvested, they may be at higher risk for depletion. We observed that *D. sansibarensis* "papa" is selected over *D. ovinala* "ovy" and *D. soso* "sosa," because it is a more shallow tuber and easier to access, despite the taste preference expressed for the latter 2 species. This behavior could lead to more rapid depletion of this species in the absence of a protection strategy. The application of bushfires to create grazing pasture for livestock could also elevate the species of *Dolichos fangitsa* "fangitsy" and *Discorea hombuka* "katro" to a "Vulnerable" classification as their habitats are destroyed or reduced.

Regression models: dietary diversity and child growth

The total number of distinct wild foods reported consumed showed an association with HDDS {$\beta = 0.29$ [95% confidence interval (CI): 0.14, 0.39]} (Supplemental Table 3). Mangoes and the quantity of ASF consumed in a 24-h period were also strongly associated with HDDS. Sensitivity analyses for specific food types showed wild leafy greens [$\beta = 0.42$ (95% CI: 0.08, 0.77)] were also associated with increased diet diversity at relatively high effect sizes. In regression models, dietary intake of wild ASF was positively associated with the anthropometric indicators HAZ, and WAZ (Supplemental Table 3). Conversely, continued breastfeeding negatively correlated with the same indicators. The age of the child showed a negative association with HAZ and WAZ. In terms of socioeconomic correlates, the number of fields owned by families showed a strong, positive relationship with child nutritional status and accessing household water from the river negatively correlated with WAZ.

Discussion

Our findings confirmed the original hypotheses that wild foods would be associated with increased household dietary diversity, in particular leafy greens and animal foods, and positively correlated with child anthropometric growth. Even low levels of ASF broadly showed a positive association with HDDS, and wild ASF specifically, correlated with 2 important child growth parameters, HAZ and WAZ. Wild yams (the *Dioscorea* spp., *Amorphophallus taurostigma*, and *Dolichos fangitsa*) were prevalent in 18.6% of child diets, and among the more commonly consumed foods after rice, cassava, and mango. These tubers provide a more nutrient-dense source of energy relative to other starchy staples. To confront the concurrent environmental and public health nutrition crises ongoing in Madagascar, this study highlights the importance of understanding the array of wild foods for both human and ecosystem health.

Wild edible plants, fungi, and animals may be regularly part of a population's diet or sought out only in response to periods of greater food insecurity or extreme famine events [11,38]. Our study was carried out from October to December 2020, a season typically associated with hunger in these communities while fields are under cultivation. Another study in Northeastern Madagascar collected diet data over several months, showing wild meat consumption throughout the year, but increases evident in a similar period from November to January [39]. This study also found poorer households relied more heavily on wild ASF meats (tenrec) and fish compared with wealthier households. Wild foods have been shown to confer particular nutritional advantages such as diet diversity and high percentages of total intake of critical nutrients such as vitamin A [40,41]. Removal of access to wildlife in Madagascar was previously linked to an increased risk of nutrition-related anemias in children [16]. Our findings underscored the contribution made by wild foods to diet diversity and HAZ, a proxy marker of healthy

TABLE 2
Nutrient intakes from animal source foods relative to Dietary Reference Intakes[1]

	Daily intake from ASF, for those consuming any ASF[2] ($n = 84$)	DRI[3] 6–12 mo	Percent of DRI met from ASF in 6–12 mo ($n = 11$)	DRI 1–3 y	Percent of DRI met from ASF in 1–3 y ($n = 41$)	DRI 4–8 y	Percent of DRI met from ASF in 4–5 y ($n = 32$)
Macronutrients							
Carbohydrate (g/d)	0.14 (0.38)	95	0.08	130	0.10	130	0.13
Fat (g/d)	1.09 (1.89)	30	3.13	ND		ND	
Protein (g/d)	3.08 (3.34)	11	18.06	13	22.88	19	18.94
Vitamins							
Vitamin A (μg/d)	3.75 (9.04)	500	0.83	300	0.63	400	1.50
Vitamin C (mg/d)	0.05 (0.11)	50	0.08	15	0.25	25	0.27
Vitamin D (μg/d)	0.19 (0.47)	10	3.34	15	0.94	15	1.36
Vitamin E (mg/d)	0.13 (0.16)	5	2.31	6	1.96	7	2.09
Thiamin (mg/d)	0.01 (0.01)	0.3	2.96	0.5	1.53	0.6	1.99
Riboflavin (mg/d)	0.03 (0.03)	0.4	5.16	0.5	4.49	0.6	5.09
Niacin (mg/d)	0.38 (0.49)	4	6.17	6	5.96	8	5.82
Vitamin B6 (mg/d)	0.02 (0.03)	0.3	4.63	0.5	3.55	0.6	4.43
Folate (μg/d)	2.15 (2.56)	80	2.18	150	1.17	200	1.41
Vitamin B12 (μg/d)	0.18 (0.17)	0.5	29.06	0.9	19.35	1.2	17.61
Elements							
Calcium (mg/d)	9.24 (13.27)	260	2.15	700	1.36	1000	1.01
Copper (μg/d)	32.22 (47.03)	220	7.75	340	9.01	440	8.97
Iron (mg/d)	0.2 (0.25)	11	1.08	7	2.97	10	2.14
Magnesium (mg/d)	7.34 (11.84)	75	7.44	80	8.09	130	6.97
Manganese (mg/d)	0.0 (0.01)	0.6	0.41	1.2	0.26	1.5	0.44
Phosphorous (mg/d)	25.76 (23.34)	275	7.54	460	5.10	500	6.09
Zinc (mg/d)	0.33 (0.41)	3	6.26	3	11.20	5	7.48
Potassium (mg/d)	33.79 (32.09)	860	2.81	2,000	1.56	2300	1.76
Sodium (mg/d)	14.96 (18.22)	370	2.72	800	1.63	1000	1.91

Abbreviations: ASF, animal source foods; DRI, Dietary Reference Intakes.
[1] Values for daily intake from ASF are means and SD. Rows shaded in blue indicate essential nutrients found bioavailable or more highly concentrated in ASF.
[2] Daily nutrient intake only in children who consume ≥1 ASF in a week.
[3] DRI values are from the Food and Nutrition Board of the National Academies of Sciences, Engineering, and Medicine (National Institutes of Health, 2022). All values for children 6–12 mo and those for the elements only for children 1–3 y and 4–5 y are adequate intakes. All other values are Recommended Dietary Allowance, calculated as 2 SD above the Estimated Average Requirement.

growth and development with long-term well-being implications [42].

Diet diversity is among the leading recommendations by the WHO for infant and young child feeding practices [43]. Countries around the world have incorporated dietary diversity guidelines into national policies [44]. Despite this, trends show increasing homogenization of diets, particularly in low-resource settings. Humans now consume >60% of their daily energy from 3 plants (rice, maize, and wheat) and a dwindling number of animal species [45]. In our study, young children were found to primarily consume rice, consistent with previous research in Madagascar [39]. A typical diet in this sample of children consisted of rice, maize, or tubers (cassava and sweet potatoes) with small amounts of seasonal fruits or vegetables, consumed in a day, again comparable with other studies in Madagascar [46]. Only 3 children aged 6–23 mo were found to meet the threshold of 5 or more foods required for the MDD. Findings from the species richness analysis were similar to indicators the food group diversity calculated for MDD, with 2.02 (±0.98) and 1.98 (±1.06), respectively. Wild leafy greens, mangoes, and ASF all appeared to mitigate the problem in this sample.

Mangoes (*Mangifera indica L.*), although introduced and associated with human communities, are considered a hedgerow food in this area and were reported by respondents as "wild." Congruent with other studies showing the importance of wild fruit trees in hunger seasons [47], we found that mangos in 22.2% of child diets and strongly related to diet diversity. Mangos can contribute to vitamins A, C, and folate sufficiency in children and provide food for other endemic vertebrates in the short term as the restoration of native plants resume [48–50]. Leafy greens are generally incorporated into meals as side dishes in Madagascar, among them 5 recognized for their nutritional benefits. *Portulaca oleracea* (common purslane) is rich in potassium, magnesium, calcium, and some omega-3 fatty acids, whereas *Sonchus oleraceus* (sow-thistle) offers vitamins A and E, iron, and calcium, among others [22,51]. Leaves of *Stenochlaena tenuifolia* are considered highly nutritious in Madagascar, as a good source of protein, mineral salts, and polyphenols. The powder has been used to model a high-quality infant food, although the product has not been tested empirically [52]. Interestingly, edible forest or woodland mushrooms were not reported consumed in this population although they are found in the Alandraza-Agnalavelo sacred forest. *Cantharellus platyphyllus* subsp. *bojeriensis* have been identified in native forests of Madagascar with potential for nutrition (ergosterol, provitamin D_2, antioxidant phenolids, among others) and economic benefits [53–55].

Foods derived from animals are a biologically efficient source of critical nutrients, such as iron, zinc, and vitamins B12 and A, generally conveyed within protein and lipid matrices

TABLE 3
Plants gathered from the wild that were reported consumed during hunger period, range of natural occurrence, and conservation status

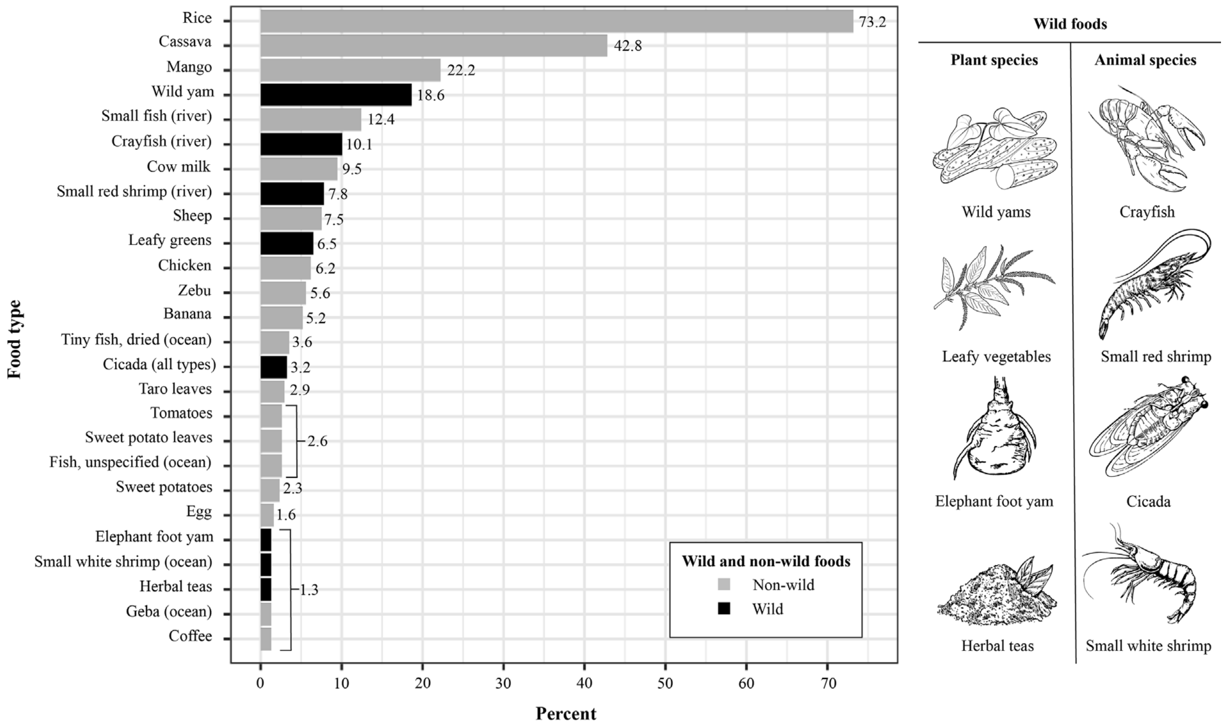
Local names	Scientific names	Prevalence, % (*n*)[1]	Endemicity[2]	IUCN status[3]
Ovy	*Dioscorea maciba* Jum. & H. Perrier	67.9 (233)	Native	LC
Antaly	*Dioscorea antaly* Jum. & H. Perrier	62.4 (214)	Endemic	LC
Papa	*Dioscorea sansibarensis* Pax	62.1 (213)	Naturalized	NT
Manga	*Mangifera indica* L.	46.9 (161)	Introduced	DD
Sosa	*Dioscorea soso* Jum. & H. Perrier	39.7 (136)	Endemic	LC
Tsinefo	*Ziziphus spina-christi* (L.) Desf	14.0 (48)	Introduced	invasive
Kily	*Tamarindus indica* L.	13.7 (47)	Native	LC
Goavy	*Psidium guajava* L.	13.4 (46)	Introduced	invasive
Angily	*Dioscorea ovinala* Baker	12.2 (42)	Endemic	LC
Tsoa	*Citrus* aff. *reticulata* Blanco	6.7 (23)	Introduced	unknown[4]
Kilimbazaha	*Pithecellobium dulce* (Roxb.) Benth.	5.2 (18)	Introduced	invasive
Lamoty	*Flacourtia ramontchii* (Burm. f.) Merr.	3.8 (13)	Native	LC
Bemako	*Dioscorea alata* L.	2.9 (10)	Naturalized	cultivated
Babo	*Dioscorea bemandry* H. Perrier	2.0 (7)	Endemic	DD
Kinjiky	*Dioscorea fandra* H. Perrier	1.2 (4)	Endemic	LC
Cœur de bœuf	*Annona reticulata* L.	0.9 (3)	Introduced	cultivated
Kida	*Musa* spp.	0.6 (2)	Introduced	cultivated
Raketa	*Opuntia* spp.	0.6 (2)	Introduced	invasive
Sakoa	*Sclerocarya birrea* (A. Rich.) Hochst.	0.6 (2)	Native	LC[5]
Fangitsy	*Dolichos fangitsa* R. Vig.	0.3 (1)	Endemic	LC
Fompoa	*Ficus botryoides* Baker	0.3 (1)	Endemic	LC
Katro	*Dioscorea hombuka* H. Perrier	0.3 (1)	Endemic	LC
Mokonazy	*Ziziphus mauritiana* Lam	0.3 (1)	Introduced	invasive
Sakay	*Capsicum annuum* L.	0.3 (1)	Introduced	cultivated
Tavolo	*Amorphophallus taurostigma* Ittenb., Hett. & Bogner	0.3 (1)	Endemic	VU
Vontaka	*Strychnos spinosa* Lam.	0.3 (1)	Introduced	LC[5]

Abbreviations: DD, data deficient; IUCN, International Union for Conservation of Nature; LC, least concern, NT, not threatened, VU, vulnerable.
[1] The percentage of people in the sample reporting wild plants consumed during the hunger period ($n = 343$).
[2] Native: species not introduced either directly or indirectly by people to Madagascar. Endemic: native species naturally occurring only in Madagascar. Introduced: species introduced directly or indirectly by people to Madagascar.
[3] IUCN statuses derive from a set of precise criteria to evaluate the extinction risk of species and subspecies. The aim is to convey the urgency of conservation issues to the public and policymakers, as well as help the international community to reduce species extinction.
[4] Because species were not assessed yet, conservation status is unknown.
[5] Provisional IUCN status given in Beech et al. [5].

that enable absorption and metabolism. Dietary intakes were highest in this sample for foods from livestock animals (poultry, zebu, and cow milk) followed by aquatic ASF foods (a range of fin fish and crustaceans). The majority of households owned livestock (72%), although very few reported livestock rearing as their primary income source (<2%). Livestock ownership was negatively associated with any ASF consumption suggesting the use of livestock for other purposes besides household food consumption, for example, as draft animals or for income generation. On a global scale, aquatic ASF contributes high proportions of docosahexaenoic acid, choline, and vitamin B12 nutrition, and crustaceans more specifically are associated with reduced stunting [56]. Small fish are often more accessible to low-resource populations and provide high concentrations of critical micronutrients comparable with fortified food supplements [57,58]. We found that a low percentage of children in this study consumed locusts (*Yanga* spp.). Entomophagy is practiced in Madagascar consistent with patterns of insect categories found globally [59,60]. Insects are rich in protein and minerals and could be a more affordable, sustainable alternative during food-insecure seasons if concerns for allergies, parasite infection, and environmental contaminants are addressed [61–64]. Ultimately if gleaned sustainably and safely to minimize zoonotic disease risk [65], wild ASF, leafy greens, and tree fruits could be leveraged to bridge periods of food insecurity.

Breastmilk is among the foods considered highly bioavailable in a young child's diet and critically important during the first 2 y of life. The WHO recommends continued breastfeeding during the complementary feeding period ≤2 y of age and beyond [43]. We found a negative association between this practice and HAZ and a trend for WAZ, which could potentially be explained by a lack of access to high-quality complementary foods and the use of breastfeeding during times of high food insecurity [66]. However, given the small number of children no longer breastfeeding in the subsample analyzed in the regression modeling ($n = 7$, 10.14%), the reasons remain unclear.

Our findings suggest a health paradox for households living in proximity to the Andranoheza River. As described, the wild-caught aquatic foods from the river enriched child diets, but models also showed that households whose primary water source was the river were negatively associated with child anthropometry scores (WAZ and WHZ). Suboptimal WASH conditions can suppress child growth through increases in enteric infection [67]. Further, drought concentrates the pathogen load in river systems and impedes river discharge with effects on beta diversity [68]. More research is needed to understand the full picture of freshwater fisheries, WASH, and river ecosystem fragility in this site. An estimated 158 million people globally depend heavily on inland freshwater fisheries for livelihoods and nutrition security, but there remains only a coarse spatial resolution of information compared with marine



[1]The figure does not include foods consumed by ≤ 1% children. The following non-wild foods were consumed by ≤ 1% of children: onions, tiny fish (river), donut balls, peanuts, black-eyed peas, eggplant, dried little fish (ocean), eel (river), noodles, goose, fermented cow milk, sugar, and Farilac baby formula. The following wild foods were consumed by ≤ 1% of children: tenrec, solanum, and wild pig. Yams include any Dioscorea species, wild or cultivated. Wild food images are not to scale.

FIGURE 2. Child dietary intakes of wild and nonwild foods (%)[1].

fisheries [69,70]. Riverine catches come largely from river basins with excess stress levels and threats to biodiversity, and climate change through drought and floods has damaged these ecosystems [70,71]. Our study presents a compelling case for addressing WASH behaviors and protecting the riverine ecosystem.

Madagascar has an incredible richness in biodiversity arising from a vast array of habitats and multiple types of terrestrial ecosystems [72]. The South biome of the Southwestern region is characterized by arid or subarid climate and covered by xerophytic bush represented primarily by *Euphorbia* species. Alandraza-Agnalavelo and the surrounding areas, included in the South biome, are rich in different vegetation types owing to the coexistence of 6 different types of microhabitats [73]. For example, humid and dry forests are proximal to riparian vegetation and rocky formations. The Alandraza-Agnalavelo sacred forest was recently classified as a critically threatened *Critically threatened* ecosystem [74]. We previously showed the forest provides 3 types of services to people at local, regional, and national levels, including ecologic, cultural and provisioning services [17]. This study adds the vitally important service of providing nutritious food to local communities in vulnerable periods of the year.

An integrated conservation approach may be critical for optimizing nutrition security and environmental sustainability [75]. Some efforts have been made to merge indicators of biodiversity and dietary diversity or nutritional quality of diets, showing strong associations between species richness and micronutrient adequacy [10]. Agrobiodiversity and farm crop species richness can mitigate nutrition-related problems, such as anemia, while contributing to environmental sustainability [76].

A number of limitations were present for this study. First, we applied an observational, cross-sectional study design with an elevated risk of biases. A range of socioeconomic, demographic, and environmental conditions were considered in our regression modeling, but there remains the possibility of residual confounding. Second, our sample size and statistical power were limited by problems with child age reporting. Recall bias was evident in the age data prompting us to include only children aged <1 y in the anthropometry models, with the necessary precision for age in months. Nonetheless, infancy is considered 1 of the most important periods of human growth which likely allowed us to detect important determinants in the 12-mo timeframe. Finally, the COVID-19 pandemic presented some obstacles to training and travel logistics, largely overcome by the field team. Despite these limitations, our findings suggest plausible and consistent relationships between wild foods and household dietary diversity and child growth.

Wild foods were found to be associated with increased child growth and household dietary diversity offered during hunger periods. More evidence is needed to fully understand how these foods may be gleaned while preserving ecosystem balance and vitality. Biodiversity and human dietary diversity can unfold in synergistic ways if sustainability principles are maintained. As climate change imposes a great burden in Madagascar, novel complementary approaches are needed to protect the well-being of both human and natural communities.

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Author contributions

The authors' responsibilities were as follows – LI, TR, AR, RH: designed the study; TR, FR, TA: supervised and participated in data collection; LI, ML, SV, EG, AN-G: performed literature reviews and conducted statistical analyses; LI, ML, TR, AR, RH: wrote the manuscript; and all authors: read and approved the final manuscript.

Conflict of interest

The authors report no conflicts of interest.

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Data availability

Data described in the manuscript, code book, and analytic code will be available upon request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cdnut.2024.102101.

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